Processing infrared (IR) images in non-destructive testing multilayer aramide composite by IR thermography methods

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Abstract

Typical defects in multilayer composite structures are delamination, lack of adhesion, density, crushing, and inclusions of other materials. These defects can be detected by non-destructive testing methods. One of the more effective methods in testing of composite materials reinforced with aramid fiber is infrared thermography. Non-destructive testing via thermographic methods, as well as other test methods, has limitations on types, geometric dimensions, and depth of defect below the surface of tested materials. It is used to process images (thermograms) obtained during experimental testing. In the process of analyzing hundreds of images containing details, they are replaced by a limited set of distinct features, prone to use of methods and algorithms for recognition. In addition to standard methods used in digital image processing, special data processing techniques are used, the most important of which are: thermal tomography, Fourier transform, wavelet analysis, thermographic signal reconstruction, dynamic thermography standardization, principle component analysis, neural networks, and data synthesis. Selected examples of special methods of thermogram processing are shown in the example of pulsed thermography with the source of thermal stimulation of the examined samples, by means of a flash lamp and ultrasonic thermography. The examples presented in this paper show the role that thermogram processing can play by using special methods for detecting a defect in tested materials.

1. Introduction

Most currently used materials are composites of some sort. The concept of composites comprises a very large and diverse group of materials with different physical and chemical properties. Today, they increasingly enter frontline areas of modern life. Their properties depend primarily on the components used, i.e. the type of reinforcement and matrix [1]. In fibrous composite materials, fiber components responsible for transfer of loads and provision of rigidity and strength of the structure are found. The matrix acts as a load transfer medium between the individual fibers and protects the fibers against the harmful influences of the external environment. One type of fiber used in composites is organic (aramid) fiber. Aramid fibers are characterized by strong anisotropic properties, high stiffness, high chemical stability, and low specific brittleness. They have been used in military applications, especially in lightweight ballistic armors, in many cases eliminating traditionally used steel. Most often these applications are in the form of laminates. Typical defects in multilayer composite structures are delamination, lack of adhesion, density, crushing, and inclusions of other materials. These defects can be
detected by non-destructive testing methods. One of the more effective methods in testing of composite materials reinforced with aramid fiber is infrared thermography.

2. Image processing methods

Non-destructive testing via thermographic methods, as well as other test methods, has limitations on types, geometric dimensions, and depth of defect below the surface of tested materials. It is used to process images (thermograms) obtained during experimental testing. In the process of analyzing hundreds of images containing details, they are replaced by a limited set of distinct features, prone to use of methods and algorithms for recognition [2]. In addition to standard methods used in digital image processing, special data processing techniques are used, the most important of which are [3]: thermal tomography, Fourier transform, wavelet analysis, thermographic signal reconstruction, dynamic thermography standardization, principle component analysis, neural networks, and data synthesis.

This paper analyses the use of two special image (thermogram) processing techniques: principle component analysis (PCA) and wavelet analysis.

2.1 Principle component analysis

Principal Component Analysis is a transformation process that converts a large amount of information contained in mutually correlated input data into a set of statistically independent components according to their validity. Therefore, it is a form of lossy compression known in information theory as a Karhuen-Loeve transform [4]. It is used in statistical procedures which in recent years have been increasingly disseminated in issues of image recognition and data compression, especially very large volumes [5].

In thermography testing, the PCA method is a relatively recent addition. PCA uses decomposition for spatial and temporal extraction of information from the thermographic data matrix. A three-dimensional matrix (sequence of recorded thermal images) is converted into two-dimensions, where the time values are arranged in columns and spatial data in rows. Next, the two-dimensional matrix is decomposed, and the resulting matrix can be represented again in the form of a sequence of images.

The most common use of the above-described method is reduction of the data dimension. This task consists of describing data of a large size (large number of features) using a smaller number of features, while maintaining maximum information. In the case of PCA, this information is measured by variance, which is a classic statistical measure of variation. The principal components analysis allows describing multidimensional data by means of a small number of uncorrelated coordinates (determined by the eigenvectors of the covariance matrix), preserving the spread between the data. A new dimension of space will depend on how many of the features you want to keep [6].

2.2 Wavelet analysis
Wavelet analysis or wavelet transforms were developed in the 80s of the last century as a tool for analysing seismograms. In thermography testing, wavelet analysis was used for the first time by X. Maldague’s team as an alternative to Fourier transform [7, 8].

Wavelet transform enables simultaneous presentation of time and frequency signals and leads to approximation of signals by isolation of their characteristic structural elements. In contrast to Fourier transform, in wavelet transformation, the signal is decomposed into elementary signals called wavelets, which are continuous waveforms with different durations and with a different spectrum [9]. The disadvantage of Fourier transform, which is the most popular method for analysing temperature signals, is that the transition from the time-value system to the frequency-value system causes loss of time information. On the other hand, wavelet transform allows analysis of changes to signal frequency as a function of time. Therefore, wavelet analysis is a useful tool in the analysis of short time signals, transient data or complex images.

In thermography testing, the basic Morlet function is most often used being a function of form of sinusoids modulated by Gaussian functions. The distribution parameters are translation coefficient $T_r$ and scale factor $S$. Therefore, the wavelet transform formula ($W$) is:

$$W(S, T_r) = \int_{-\infty}^{+\infty} T(\tau) h_{ST_r}(\tau) d\tau$$  \hspace{1cm} (1)

where $h_{ST_r}$ is wavelet function related to parent function:

$$h_{ST_r}(\tau) = \frac{1}{\sqrt{S}} h\left(\frac{\tau-T_r}{S}\right)$$  \hspace{1cm} (2)

Because scaling factor is related to frequency and factor of translation to time, the wavelet function method does not lose any time information necessary to assess the depth of defect.

The wavelet transformation de-correlates a one-dimensional signal (time function) into two-dimensional (time function and scaling factor), which leads to an increase in accompanying calculations. For their shortening, two expressions are used in thermography testing:

- observation time related with the defect depth $\tau = \frac{l^2}{\alpha}$   \hspace{1cm} (3)

- thermal diffusion length related to frequency $\mu = \frac{2\alpha}{\sqrt{\omega}}$   \hspace{1cm} (4)

Based on these equations, under the condition where $l = \mu$ is obtained:

$$\tau = \frac{2}{\omega}$$  \hspace{1cm} (5)

The translation factor $T_r$ corresponds to observation time $\tau$ and scaling $S = \omega_0/\omega$. Linking these two parameters leads to the following equation:

$$S = \frac{\omega_0}{2} T_r$$  \hspace{1cm} (6)
The use of the above equation allows maintaining the parameters of the analysed signal, calculating scaling factor $S$ for each value $T_r$. The values $T_r$ are limited measurement time, therefore:

$$W(S, T_r) = \int_{-\infty}^{\infty} T(\tau) \frac{1}{\sqrt{0.5 \omega_0 T_r}} h\left(\frac{T_r^{-1}}{0.5 \omega_0}\right) d\tau$$  \hspace{1cm} (7)

As in the case of the Fourier image, the wavelet image contains both real and imaginary elements, therefore, it is possible to determine phase characteristics in the image space (which allows transfer of this method to pulsed phase thermography). Wavelet images are characterized by the same properties as Fourier images. Wavelet transforming phases are used to detect defects, with the defect segmentation being performed using a Sobel operator. Calibration of the translation factor (difference in pixel values) allows assessment of the depth of defects [10].

The translation factor, which is in fact the time-domain, provides the maximum "visibility" of defects of a specific dimension at a given depth. Therefore, in order not to introduce double calibration to depth and size defect, it has been proposed to use early observation times, where temperature signals are weakly dependent both on transverse dimensions of defects and their thickness, maintaining a strong dependence on position of depth.

Wavelet analysis is a certain generalization of the Fourier analysis. In the latter, the signal is decomposed into sum or integral of sinusoidal signals whose physical sense is relatively easy to interpret. Unfortunately, these sine waves are uniform in time, while the output signal is not always so. In particular, it can be in the form of oscillations whose amplitude and frequency change over time, and this heterogeneity is not clearly reflected in the transform.

3. Experimental testing

Selected examples of special methods of thermogram processing are shown in the example of pulsed thermography with the source of thermal stimulation of the examined samples, by means of a flash lamp and ultrasonic thermography. Aramid composite samples of approx. 10 mm thickness were intentionally introduced at various depths in the form of thin sheet steel, Teflon film and an air gap with a surface area of 10x10 mm for each of the defects. A FLIR 7600 SC camera with a frequency of 100 Hz was used for recording. In the pulsed method, a flash of about 6 kJ power and a pulse time of 5 ms were used. In this work, a reflection approach was used where the IR camera and heating lamp are on the same face of the testing object (Fig. 1).

Ultrasonic stimulation was performed with an ultrasound generator at a frequency of 25 kHz. Output power was 300 W (the maximum allowed power was 2 kW). The ultrasonic signal was generated for 1 sec. Figure 2 shows the experimental set-up vibrothermography with ultrasonic stimulation.

ThermoFit™Pro software developed by V. Vavilov was used to analyze thermograms [11].
Examples of the results are presented in Figures 3 and 4. Fig. 3a shows a source thermogram made using a pulsed method in which no defect in the form of thin sheet steel is visible and Fig. 3b shows a defect after the analysis of principle components. Figure 4a shows a source thermogram made by ultrasonic thermography with one defect in the form of air gap and Fig. 4b shows two defects after application of wavelet analysis. Figure 5a shows a source thermogram made by ultrasonic thermography with one defect in the form of thin Teflon foil and Fig. 5a shows this thermogram after the analysis of principle component.

Figure 1. Experimental set-up (1 - sample, 2 - lamp, 3 - IR camera) - pulsed thermography

Figure 2. Experimental set-up (1 - sample, 2 - ultrasound generator, 3 - IR camera) - vibrothermography
4. Conclusions

The examples presented in this paper show the role that thermogram processing can play by using special methods for detecting a defect in tested materials.
A more common method of image processing than wavelet analysis in IR thermography testing is PCA. This results from the fact that it is relatively poorly studied. The superiority of wavelet analysis is in many cases debatable because changes of signals $\Delta T(\tau)$ in time have a non-pulsed but smoothed character. However, as well as showing our results in some applications, it allows detecting of defects invisible using other image processing methods.

We would, therefore, like to focus further work on more accurate studies of wavelet analysis to better determine the possibilities of its use as well as its limitations.

References

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