NEW APPROACH TO DETECTION OF CRACKS IN COMPOSITE MATERIALS USING HYBRID NON-DESTRUCTIVE TESTING METHOD

Vibro-thermography is a new Non-Destructive Inspection method that can be applied to the diagnosis of aircraft fuselage parts and wind turbine propeller blades. In this method, the ultrasound source of energy is used to excite internal particles of the examined composite material damaged by an impact to induce thermal differences between the solid part of material and the damaged area. The results of experiments obtained by the vibrothermography method conducted on the damaged area of carbon fiber samples were combined with the spectrum and time-frequency analysis of signals obtained from the vibroacoustic sensor, attached to the damaged area to verify existing cracks.

Keywords: vibro-thermography, ultrasound, composite, thermogram, time-frequency

1. INTRODUCTION

Implementation of new technologies based on composite materials to aircraft structures forced development of new methods for non-destructive testing. A method, presented in this article, combines the advantages of thermal imaging with spectral analysis of ultrasonic excitation signal. It is a hybrid method in which we investigate infrared picture of the composite material sample heated by ultrasonic signal simultaneously with the analysis of signal’s spectrum recorded after passing through the test composite material. In order to clearly identify the damage, thermograms showing the temperature rise in areas of structural defects, caused by the propagation of elastic waves in ultrasonic frequency range over the inspected materials, were analyzed [Pietrzyk 2005]. However, in order to verify the accuracy of
anomalies detected by the camera, spectral analysis and time–frequency analysis of ultrasonic vibration signal in the damaged area were used. The proposed hybrid method gives more accurate diagnosis of damages and opens an interesting path to study phenomena occurring in composite materials [Pao 1978]. Based on this developed method, it will be possible in the future to design devices that would use properly controlled packets of transmitting ultrasonic heads creating synthetic aperture, which in conjunction with a change in amplitude, phase, and level of signal power would allow to conduct more detailed analysis of composite material damage, regardless of the technology of their manufacturing and dimensions. Detecting and analysis of the excitation signal using piezoelectric sensors package (receiving head) or laser scanning vibrometers (example Polytec PSV–400–3D) will make possible to create images of internal damage to the composite samples.

2. DESCRIPTION OF TEST METHOD

In order to conduct tests, a test stand (Fig. 1.1) was designed.

Fig. 1.1. Test stand for testing two different samples of damaged carbon composite materials using developed hybrid method
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The test stand consisting of the following devices: an ultrasonic head, based on ultrasound piezoelectric transducer (operating frequency (40 +/− 1) kHz, capacitance 3020 pF, impedance greater than 20 Ω, insulation resistance 10 GΩ, max. power 50 W); sample mounting fixture; ultrasonic generator based on NE555 circuit with a control panel; and piezoelectric vibration sensor LDT0–028 (reception head), coupled with a measurement module based on a digital oscilloscope MSSCOPE (sampling frequency 107.1 kHz, length of buffer 131 072 samples), which allows to send digitized signal data of the received vibrations, proportional to changes in voltage of the head’s piezoelectric element, to a computer via the USB port.

Thermal images were obtained by FLIR infrared camera. The collected data were analyzed in Matlab environment. During study, cracks and delaminations in two different carbon composite materials were analyzed. The first sample contains damage such us artificially introduced delamination such us foil strips (Fig. 1.2). The second sample was damaged due to impact (Fig. 1.3).

Fig. 1.2. Composite plate of dimensions of 175 × 300 × 4 mm³, made of carbon fibers oriented at an angle of 0–90°, smooth surface of a fabric structure, resistant to bending, made using pressing prepregs technology with artificially introduced delamination in the form of foil strips

Fig. 1.3. Composite plate of dimensions of 175 × 150 × 0.45 mm³, made of carbon fibers oriented at an angle of 0–90°, smooth surface of a fabric structure, resistant to bending, made using pressing prepregs technology, damaged by impact

The study was divided into two stages. The first stage consisted of measuring temperature of the sample with the infrared camera in the presence of ultrasonic
excitation. The vibrations were generated in the piezoelectric head driven by a sinusoidal signal with a frequency of 40 kHz and a power of 30 W or 50 W. During the test the materials were exposed to ultrasonic vibrations for 12 minutes which resulted in a gradual heating of the sample at the damaged area.

Fig. 1.4. First image: a) it is a thermogram of the composite plate from Fig. 1.2, b) the image created in the Matlab program – it is the difference of first two thermal images with visible white spots at areas of damage, c) the thermogram charts are the graphs of temperature changes on the surface of the sample measured along the line, indicated above
To excite material, ultrasonic transverse wave with a frequency of 40 kHz and power of 30 W or 50 W was used. Bright fields on thermogram show the concentration of high temperature (Fig. 1.4, Fig. 1.6) corresponding with the location of defects.

In order to verify the results obtained during the test, the comparative analysis in Matlab software was used. The resulting thermogram being a difference of temperatures of good and damaged element clearly showed the damaged areas in the form of white spots (Fig. 1.4a, Fig. 1.6b).

Fig. 1.5. Ultrasonic desintegrator UD–20 the power of excitation signal is 200 W

For the sample with delamination it was necessary to increase the heating time period and the power of excitation signal up to 200 W using another device the ultrasonic disintegrator UD–20 (Fig. 1.5) [Raghavan and Cesnik 2007]. The excitation signal in this case is a continuous sine wave. Power of constructed equipment based on pulse ultrasonic signal appears to be insufficient. After locating the initial damage with a thermal imaging camera ultrasonic pulse signal was applied again, recorded and analyzed at the damage area. In the case of the sample being a thin composite plate, to localize the damage the exposure time might be shorter and the power of the excitation signal might be lower (Fig. 1.6a) and we can use signal from the design equipment with less excitation power [Raghavan and Cesnik 2007].

In both cases, to compare good and damaged composite material samples, an absolute temperature of the object under excitation and the background temperature must be eliminated, and such test conditions should be applied that would not lead to a large difference in temperatures on the surfaces of the samples (even heating) [Doebling et al 1996]. Noteworthy is the fact that there was a necessity to select the appropriate emission factor, different for each of tested composite materials [Uhl 2004]. Otherwise, the difference between the matrices of temperature on surfaces of the material samples can give unreadable image.

The proposed method is a hybrid non-destructive testing method and it combines two methods of testing, the first of which has already been discussed. The second part discusses the vibration measurements performed by the ultrasound
sensor in the damaged areas of the sample, initially located by thermal imaging camera.

This stage of the test consists of measuring the vibration signal recorded at the crack area. The piezoelectric element changes its shape proportionally to vibrations of the sample and gives voltage changes transmitted via the USB port to the computer by digital oscilloscope MSSCOPE (sampling frequency 107.1 kHz, length of buffer 131,072 samples).

Data are stored in a file. The next phase of the analysis was carried out in the MATLAB software by calculating the Fourier transform of the signal of transducer voltage changes as a function of time for the samples of the first and second type of material (Fig. 1.7, Fig. 1.8).

Fig. 1.6. Composite plate from Fig 1.3: a) carbon fiber sample with impact damage b) the image created in MatLab program—the difference of two thermal images (good and damaged sample) with visible white spots at areas of damage b) the graphs of temperature changes on the surface of the sample measured along the horizontal line marked on thermogram.

Figures 1.7b, d and 1.8b, d show representations of the signal in time domain after filtering via a band-pass filter of frequency band between 25 kHz and 80 kHz. Vibration signals of good and bad samples for both types of materials after filtration have been subjected to Fourier analysis. The spectrum of the vibration signal originating from the damaged samples of both types of materials has the additional frequencies that are not present in the spectrum of the signal obtained from the
good elements (Fig. 1.7d and 1.8d the additional frequency marked by arrows). In both graphs a peak of the frequency within the 40 kHz range representing the excitation signal is clearly visible. Unfortunately, representations of the signal spectrum shown in Fig. 1.7b, d and 1.8b, d contain a number of disturbances caused by white noise and by the resonant frequencies signals from the measuring circuit. In both cases, there was continuous rise in signal amplitude for all the harmonic frequencies in the spectrum [Cempel 1982].

a)

![Waveform](image1)

b)

![Spectrum](image2)

c)

![Waveform](image3)
Fig. 1.7. Time and frequency representation of ultrasonic vibration signal filtered by the band-pass filter measured at the place of damage in composite plate from Fig. 1.4: a) signal in time-domain obtained from good sample, b) spectrum of the signal obtained from good sample, c) signal in time-domain obtained from damaged sample, d) spectrum of the signal obtained from damaged sample.
Fig. 1.8 Time and frequency representation of ultrasonic vibration signal filtered by the band-pass filter measured at the place of damage in composite plate from Fig. 1.6: a) signal in time-domain obtained from good sample, b) spectrum of the signal obtained from good sample, c) signal in time-domain obtained from damaged sample, d) spectrum of the signal obtained from damaged sample.

In order to determine the moments in time, in which peaks of frequencies start to appear as an evidence of damage, difficult to determine in the spectrum of excitation signal, the signal was transferred into the time–frequency domain and the spectrogram was calculated in the Matlab environment based on the Wigner–Ville (WV) transformation and Continuous Wavelet Transform (CWT) (Fig. 1.9, Fig. 1.10).

a) undamaged sample
Fig. 1.9. Time and frequency representation of ultrasonic vibration signal filtered by the band-pass filter measured at the place of damage in composite plate from Fig. 1.2: a) signal obtained from good sample (WV, CWT), b) signal obtained from damaged sample (WV, CWT). Arrows show the appearing changes in frequencies that indicate cracks in the sample material.

In this publication, the Short Time Fourier Transform (STFT) method is abandoned. STFT is strongly dependent on the type of the analysis window. To determine the differentiation in the time domain it should be noted that the properties of the signal are averaged for the time equal to the length of the window. For example, if a break in the broadcasting signal is to be visible in the spectrogram, it must be comparable in length to the length of the window. A more detailed analysis can be performed using the instantaneous spectral interpretation, as the output of the filter bank and analyzing the impulse response of a single filter.

Complicated windows are not the best for all applications, because the price for side lobe reduction is the main lobe extension. When selecting the windows to determine the instantaneous spectrum, there is another problem to be considered: not only the shape but also the length of the window should be chosen in an appropriate manner. By changing the length of the window we can exchange time distinguishability into frequency one. Unfortunately, it is impossible to improve the distinguishability in both dimensions at the same time.
b) damaged sample

Fig. 1.10. Time and frequency representation of ultrasonic vibration signal filtered by the band-pass filter measured at the place of damage in composite plate from Fig. 1.3: a) signal obtained from good sample (WV, CWT), b) signal obtained from damaged sample (WV, CWT). Arrows show the appearing changes in frequencies that indicate cracks in the sample material.

The foregoing restriction is very important for the analysis of signals with fast-changeable parameters. If a large variation in parameters results that there is a need to apply a short window, frequency distinguishability may be reduced so that it fails to distinguish signal components. It is worth mentioning that other methods of time–frequency analysis, other than the instantaneous spectrum calculated using STFT method may be used. There are many such methods, and perhaps one of them will better replicate properties of the analyzed signal. We should mention only a few of the main methods:

- Wigner–Ville transformation – best for the analysis of signals with fast-changing frequency (high resolution in frequency),
- Continuous Wavelet Transform – best for the analysis of signals centered in time domain (high resolution in time).

From the time–frequency spectrum of STFT, WV and CWT, it can be seen easily that the three methods in time–frequency analysis can not only reveal the frequency contents, but also reveal the trend of frequency changes with time changing as well. But from Fig. 1.9, it can be seen that there is frequency cross terms in the short time Fourier transform spectrum. Because of the existence of the frequency cross terms, the accuracy of the WV is decreased. The time resolution and frequency resolution of CWT spectrum is better than the WV spectrum which can be revealed from Fig. 1.9. In the low frequency range, there is also no frequency cross terms. The CWT is still similar to the WV from the ultimate sense. The difference is that the window function used in WV is scale adjustable window. So, WV still cannot exactly describe the trend of frequency changing with time changes because of the affection of window function.

CWT method applied to create spectrogram clearly shows an increase in the amplitude of the resonant frequency in the damaged samples of both materials Fig. 1.9, Fig. 1.10 (frequencies indicated by the arrows). Moreover, the frequency of the
excitation signal changes its amplitude over time. Comparing a WV and CWT method it must be concluded that the CWT gives much better results than WV due to the presence of crossterms.

This proves the damages detected in the first phase of spectrogram analysis. Proposed methods of analysis, other than instantaneous spectrum, are subject for a separate publication and should provide some interesting results.

3. DESCRIPTION OF PHENOMENA OCCURING AT BOTH STAGES OF RESEARCH

Temperature of the material sample under excitation by ultrasonic vibration increases significantly due to friction of the particles of the composite material internal structure. Physics of this phenomenon is still under research. It seems likely that there are local plastifying zones of material, for example in the vicinity of cracks, resulting in the increase in temperature in these areas. It is also possible that the heat is generated in structural defects resulting from friction of the cracks’ opposite walls or delamination. Based on [Balageas, Fritzen and Guemes 2006] it can be stated that any material manifests excitation from the ideal elastic behavior, even for small strains. In the case of periodic forcing, deviations manifest themselves as the irreversible loss of energy in the material. This type of energy loss can be caused by conversion of mechanical energy into heat, augmentations of micro-cracks and other structure discontinuities, plastic deformation of the crystal structure, among others. The energy loss in the material is defined by suppression, dissipation of energy, imperfect elasticity or internal friction. Such phenomena occurred in both stages of research and had an effect on the generation of heat in the samples during the tests. They were also a source of interference for the measured ultrasound signal in the damaged area of the composite material. When a structural damage occurs, there is an increasing compliance; hence more energy is lost as heat [Inman et al. 2005]. Analysis of images, obtained during the infrared measurements allows identifying structural defects. The heat generated in the areas of the damage propagates to the surface of the object, where it can be measured by the infrared camera. Thus, obtained thermograms allow the identification of structural defects. One of the physical parameter which describes the range of thermal radiation is emissivity. Emissivity of the object dependents on specific parameters of the material [Balageas, Fritzen and Guemes 2006, Adams, Farrar 2002], i.e. temperature, chemical composition, physical condition of the surface (emissivity is defined during test as one of the parameters from the infrared camera menu). The main purpose of the ultrasonic excitation is to induce thermal effects in the structure of the examined material by excitation with external source of ultrasound signal. The relationship between the deformation, stress and temperature change is described by the following formula [Balageas, Fritzen and Guemes 2006]:
\[ \Delta \varepsilon = \left( \frac{1 - 2 \nu}{E} \right) \Delta \sigma + 3 \alpha \Delta T \] (1)

Changing the main deformation \( \Delta \varepsilon \) is dependent on: changes in principal stress \( \Delta \sigma \), Poisson’s ratio \( \nu \), temperature changes \( \Delta T \), thermal expansion coefficient \( \alpha \), and Young’s modulus \( E \).

Assuming that stress changes occur very quickly (for the frequency change greater than 3 Hz, it can be assumed that thermodynamic transformations are adiabatic and that there is no need to take the heat exchange with the environment into consideration), it can be assumed that the change in strain \( \Delta \varepsilon \) causes a change of temperature \( \Delta T \) [Balageas, Fritzen and Guemes 2006]:

\[ \Delta T = -\frac{3T \alpha K \Delta \varepsilon}{\rho C_v} \] (2)

The temperature change \( \Delta T \) is dependent on the compressibility coefficient \( K \) [Pa], specific heat \( C_v \) [J/kg*K] at constant volume, \( \rho \) – density [kg/m³], the test body temperature \( T \) [K].

As a result, an approximate relationship describing the phenomenon of thermoelasticity is obtained in the following form:

\[ \Delta T = \frac{\alpha}{\rho C_p} T \Delta \sigma = K_m T \Delta \sigma \] (3)

The temperature change \( \Delta T \) is dependent on specific heat \( C_p \) at the constant pressure and thermoelasticity ratio \( K_m \).

The temperature change is proportional to the change of stress in a piece of object under the test. In this method the absolute temperature of the object should be eliminated. This is done by filtering a constant component at the stage of processing the captured images or using special techniques of the image sampling synchronization with thermal activation of the object [Boller, Staniszewski 2004]. This method allows the detection of changes in the stress field caused by damage to the structure [Adams 2007].

In order to verify damage in the composite samples, detected based on thermograms, the analysis of ultrasound excitation signal was made at the determined place of crack.

Based on the spectral analysis of the signals and their time–frequency representation, in both cases, there was continuous rise in signal amplitude for all the harmonic frequencies in the spectrum and variables of excitation signal frequency of 40 kHz can be observed. It is related with a change in the intensity of the ultrasonic wave propagating in solid materials. This is due to two factors:

- absorption caused by loss of part of the wave energy due to heat generated as a result of the internal friction of particles at the place of the damage,
- dispersion (undirected reflection) and wavelength dispersion of the individual boundaries, which occur in the polycrystalline centers, non-homogeneous in terms of a structure, or even having internal defects with macroscopic dimensions.

The speed of the ultrasonic signal in a given medium depends on various factors, including stress and density. The amount of the energy loss determines the energy attenuation coefficient $\gamma$. It helps to determine the intensity of the wave $I$ as a function of its path $l$.

$$I = I_0 \cdot e^{-\gamma l} \quad (4)$$

Wave intensity $I$, is proportional to the intensity of the output waveform $I_0$ and the natural logarithm $e$.

The value of the attenuation coefficient increases along with the frequency increase. A similar effect induces an increase in grain size of the material.

The study used the transverse waves, so-called shear waves which cause tangential stresses. The material particles vibrate in a plane perpendicular to the direction of wave propagation. Propagation of these waves is not accompanied with changes in the density of the medium. These waves propagate only in the fixed media.

Characteristic for the study of non-metallic materials, opposite to metal ones, is boarder using of measurements of velocity and attenuation of ultrasonic waves. These parameters often characterize not only microscopic structures but also other important properties, such as: compressive strength, tensile strength, porosity. This allows controlling both, the finished products and production processes.

In the test samples all of these effects occurred, which was manifested by the presence of the resonant frequency as well as the absorption of excitation wavelength.

Phenomena in the tested material require additional research. The measurement accuracy was affected by the noise in the measurement circuit, which was eliminated by filtering using band-pass filter. Further analysis of signals from good and damaged samples being examined will be aimed at defining the correlation functions of signals from both kinds of samples and determining the periodic component due to the fact that the excitation signal has periodic nature. Diagnostic correlation function will be used for the detection of non-existing periodic components of the signal that can be derived from the damage of the internal structure of the sample and also for showing the change in the ratio of signal power compared to noise ratio [Cempel 1982].
CONCLUSION

The applied research method has shown that it is possible to determine damaged areas of composite structures using the infrared camera in the presence of ultrasonic excitation and verify their existence through the use of Fourier analysis of the excitation signal detected by the vibration sensor at the place of damage. To display the results of signal analysis accurately, the analysis in MATLAB software was performed. Proper filtration allowed to eliminate the interferences in the signal measurement circuit, derived from a white noise and the elements of the measuring circuit. The continuous rise in signal amplitude for all the harmonic frequencies in the spectrum and variation of excitation signal frequency of 40 kHz can be observed and is related with a change in the intensity of the ultrasonic wave propagating in solid materials. In addition, a comparison of the spectra from the good and the damaged samples for both types of materials enables to eliminate common frequencies, which can be derived from the interference introduced by the elements of the measurement path. The applied method can be used in a modernized measurement path based on the package of switched ultrasonic heads and switched vibration sensors, allowing application of correlation function to analyze signals propagating in different directions in the same material sample. This article proposes a number of new avenues of research, particularly in relation to the analyzed signals to improve the detection of the vibration at the damaged area by expanding the number of sensors and the mode of their switching, the use of the correlation function to improve the comparative analysis. To develop further the potential of the described method, it is advisable to conduct more tests on other composite materials samples, or even parts of aircraft structures and wind turbines. Based on research it is possible to create a device to compare two maps the of damaged areas, the first one obtained from a thermogram, and the second one developed based on the analysis of detecting frequency from ultrasound excitation signal representing attenuation, reflection or resonance of wave in the sample areas designated during the test. What is more the selection of power and shape of signal requires further study in order to develop the required equipment.

REFERENCE

NOWE PODEJŚCIE DO WYKRYWANIA USZKODZEŃ W MATERIAŁACH KOMPOZYTOWYCH PRZY POMOCY HYBRYDOWEJ METODY BADAŃ NINIESZCZĄCYCH

Streszczenie

W prezentowanym artykule opisano hybrydową metodę pomiaru uszkodzeń materiałów kompozytowych, która składa się z analizy termogramów wykonanych dla podgrzewanych ultradźwiękowo próbek materiałów oraz analizy widmowej i częstotliwościowo-czasowej sygnału pobudzenia mierzonego w miejscu zdeterminowanego na termogramie uszkodzenia. Na potrzeby artykułu opracowano stanowisko badawcze składające się z piezoelektrycznej głowicy nadawczej generatora sygnału ultradźwiękowego pochodzącego z myjki ultradźwiękowej, głowicy odbiorczej oraz układu do pomiaru drgań podłączonego do komputera za pośrednictwem portu USB. W jednym przypadku zastosowano dezintegrator UD-20 dla próbki o większej grubości w celu odpowiedniego jej podgrzania. Wyniki, jakie otrzymano potwierdzają zasadność stosowania wybranych metod i pokazują jednoznacznie uszkodzenia w próbkach kompozytowych z różnymi typami uszkodzeń zarówno przy pomocy metody vibro-termograficznej jak i analizy widmowej oraz częstotliwościowo-czasowej. W artykule podjęto próbę omówienia fizyki zjawisk zachodzących w badanych próbkach materiału, podczas pobudzenia ultradźwiękowego, co stanowi podstawę do zastosowania opisywanej metody badawczej. W celu poprawy otrzymanych wyników badań zaproponowano sposoby filtracji odbieranego sygnału ultradźwiękowego oraz wstępnie rozpoczęto dyskusję nad zastosowaniem innych metod analizy częstotliwościowo-czasowej sygnału pobudzenia. Publikacja stanowi wstęp do opracowywania urządzeń wykorzystujących założenia proponowanej metody badawczej. W proponowanym urządzeniu porównane zostaną dwie mapy uszkodzeń pierwsza otrzymana w wyniku analizy termo-
gramu a druga po analizie czasowo-częstotliwościowej ultradźwiękowego sygnału pobudzającego. Wzrost temperatury związany jest z wystąpieniem zjawiska tarcia wewnętrznego struktury kompozytu w obecności pobudzenia ultradźwiękowego. Kolejna analiza, polega na badaniu wzrostu amplitudy składowych częstotliwościowych w widmie oraz śledzeniu ich zmian. Wskazuje to na występowanie zjawisk tłumienia i rezonansu oraz odbicia fali we wskazanych miejscach badanego elementu. Dobór mocy i kształtu sygnału pobudzającego wymaga serii dodatkowych badań, co pozwoli dopracować zaproponowane urządzenia pomiarowe.

Słowa kluczowe: wibrotermografia, ultradźwięki, kompozyt, czasowo-częstotliwościowa