ACTIVE THERMOGRAPHY AND IT'S APPLICATION FOR DAMAGE DETECTION IN MECHANICAL STRUCTURE

Tadeusz UHL, Mariusz SZWEDO

Akademia Górniczo-Hutnicza w Krakowie, Katedra Robotyki i Mechatroniki
Al. Mickiewicza 30, +48 12 634 35 05, tuhl@agh.edu.pl

Summary

Development of measurements techniques helps to apply new more effective tools for damage detection and localization of damage in composite and metal based structure. One of the most intensively developing technology is active thermography which can be directly use for damage detection under operational conditions. The paper presents active thermography techniques, proposed image processing methods and application of vibrothermography for damage (crack) detection in aluminum plate. The experimental results confirm high sensitivity of the methods and its applicability for mechanical structure diagnostics.

Keywords: SHM, NDT, thermography, damage detection, image processing, 2D wavelets analysis.

AKTYWNA TERMOGRAFIA I JEJ WYKORZYSTANIE DO DETEKCJI USZKODZEŃ STRUKTUR MECHANICZNYCH

Streszczenie

Rozwój technik pomiarowych umożliwia zastosowanie nowych, bardziej efektywnych narzędzi do detekcji oraz lokalizacji uszkodzeń w kompozytowych i metalowych strukturach. Jedną z najbardziej intensywnie rozwijających się technologii jest aktywna termografia, która może zostać użyta bezpośrednio do detekcji uszkodzeń w trakcie normalnych warunków pracy urządzenia. W artykule przedstawiono techniki aktywnej termografii, zaproponowano metodę przetwarzania obrazów termograficznych oraz aplikację wykorzystującą wibrotermografię do detekcji uszkodzeń dla płyty aluminiowej. Wyniki przeprowadzonego eksperymentu potwierdzają wysoką czułość metody oraz jej przydatność w diagnostyce.

Słowa kluczowe: SHM, NDT, termografia, detekcja uszkodzeń, przetwarzanie obrazów, dwuwymiarowa analiza falkowa.

1. INTRODUCTION

Nowadays a reliability of the mechanical structures is one of the mostly required feature of many structures like bridges, airplanes, rail vehicles, and many different industrial installations. Indicated below structures due to their responsibility should damage free and should be monitored continuously. The techniques of the assessment of state of operating structures are defined as Structural Health Monitoring (SHM) in the literature [1]. Among many new methods two main classes can be distinguished, passive methods and active methods [1, 2]. In passive methods, the response of the structure, due to any operation excitations (even not measured) is under observation. Based on relation of given signal parameter and its correlation with a state of the structure the damage can be detected, localize and sometimes predicted. In active methods the structure is excited by controlled and measured excitation using external or build in actuators and response is measured. Measured response or estimated based on input and output signals system characteristics can be a measure of system damage. One of the most commonly use in SHM method are methods based on vibration measurements. Within these methods the symptom based methods and model based methods are in use, now. In the second one the measure of the state of the system are parameters of the model or changes of model parameters [3]. Many methods which are in use for SHM are methods which are directly adopted from the area of Nondestructive Testing (NDT).

Classical NDT methods used during system operation continuously like acoustic emission measurements [1], Lambda waves analysis [2], electromechanical impedance identification [3], are good examples of SHM oriented techniques. The difference between NDT and SHM methods is illustrated in the Fig. 1 and Fig. 2.

In these two solution two different classes of methods can be distinguish; methods with integrated sensors [4] and methods based on contactless measurements [3]. The last one are more and more often use because of lower installation costs and miniaturization of monitored structures.
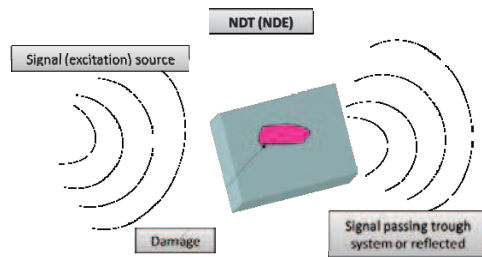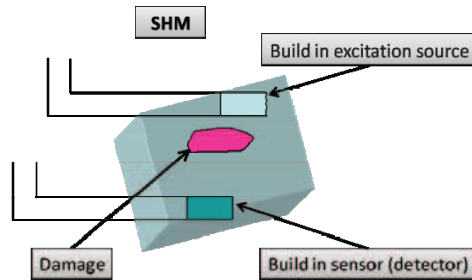
Fig 1 NDT like system

Fig. 2. SHM system

One of the method which can be applied as active and passive method based on contactless measurements is the method based on investigation of thermo-elasticity effect which goes with damage of the structure (lose structural integrity) like cracks in metal structures, delamination or disbonding in composites [5]. The method is under very intensive development, because thermography techniques are significantly developed recently [6]. The paper deals with testing of relation between structural damage and thermo elastic effect. The pattern recognition techniques developed by authors are applied to show sensitivity of the method and its applicability to detect cracks nucleation and propagation in the structure.

2. OVERVIEW OF ACTIVE THERMOGRAPHY TECHNIQUES

Basic theoretical relation employed for dynamic thermography is formula which describe relation between changes of strain, stress and changes of temperature of a body surface [6]:

$$\Delta\varepsilon = \frac{(1-2\nu)\Delta\sigma}{E} + 3\alpha\Delta T \qquad (1)$$

where: $\Delta\varepsilon$- changes of main strains, $\Delta\sigma$ – changes of main stress, ν- Poisson ratio, ΔT – changes of temperature, α – coefficient of thermal expansion, E- Young modulus. Assuming adiabatic transformation (high speed transformation of stress) the following relation between changes of strains $\Delta\varepsilon$ and changes of temperature ΔT is valid:

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

where: K – compression factor [Pa], Cv heat capacity [J/kg K] at constant volume, ρ – density [kg/m³], T temperature of a body [K].

As the result the formula which approximate relation between changes of temperature and changes of stress is obtained in the form:

$$\Delta T = -\frac{\alpha}{\rho C_p}T\Delta\sigma = K_m T\Delta\sigma \qquad (3)$$

where: C_p heat capacity at constant pressure, K_m thermo elastic constant.

As it can be easily notice from formula (3) a change of temperature is proportional to changes of stress. To measure pure stress changes only temperature should be filtered using common signal processing procedure as DC component filtering. DC component filtering can be realized after pattern capture using special pattern processing technique or using dedicated technique for frame capturing using synchronization signal from energy source (thermal excitation).

The method helps to detect changes in stress fields due to damage of structure under active test. The structure should be thermally excited to achieve stress changes which can be measured using thermography. Applying the method the damage can be detected even if have very small dimension immediately after occurring.

To employ the method effectively the following conditions should be fulfilled:

1. The structure is loaded with dynamic load with frequency higher the 3 Hz (all formulas are valid for adiabatic transformation);
2. The DC component of temperature (T) can be filtered;
3. The damage occurred on the surface or very close to surface of a structure
4. Emissivity of the structure is equal or almost equal on the whole surface of a structure.

Listed above assumptions seriously limit classes of structure which can be tested using active thermography in order to detect damages.

Basic assumption in application of active thermography for SHM is that each structure has characteristic response for given excitation. In active thermography several different kind of excitation can be employed; ultrasound waves, vibrations and thermal excitation like infrared or microwaves excitations and other thermal radiation source. The excitation can have character of short impulse or continuous harmonic signal The response of the structure in a form of temperature distribution on surface which changes during system excitation is recorded using thermo camera. In the next step of thermography based SHM procedure the thermographic pattern of the structure in current

state is compared with pattern recorded for healthy system.

Within active thermography four different techniques can be distinguished which differ each other by the way of pattern acquisition or pattern processing.

1) Pulsed Thermography – the source of thermal excitation are heat impulses with duration from milliseconds to several seconds. Measurements of the response during cooling of the surface helps to avoid disturbances due to radiation of different heat source in surrounding of structure under the test. Recorded changes of temperature distribution and its comparison with the same temperature distribution for healthy system allows to assess damage location and damage dimension.

2) Lock-in Thermography – the source of thermal excitation In his case is harmonic heat flux. Reconstruction of the temperature distribution can be achieved in this method thanks detection of the amplitude and phase of temperature on a surface against excitation signal for given frequency.

3) Step-heating Thermography – the source of thermal excitation. In his method are short laser impulses which heat structure locally. The response in a form of a temperature changes (increasing) is recorded and process to find thermal conductivity. The local changes of thermal conductivity for the structure can help to detect damage In the structure.

4) Vibrothermography – the source of thermal excitation is vibration in a frequency range between 10 Hz till 20 kHz. The thermal response of the structure due to vibration is heat waves which are recorded using thermo camera The damage in a form of composite delamination or cracking of the structure can be detect based on measured thermal waves propagation disturbances. In the vibrothermography the temperature distribution is measured synchronically with vibration.

Typical scheme of a measurement system for vibrothermography of mechanical structures is shown in Fig. 3.
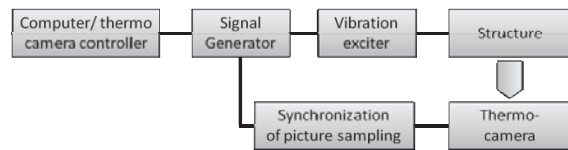

Fig. 3. Measurements set up for vibrothermography of mechanical structures

Due to vibrations the heat is radiated on the surface of a structure under test. This heat is generated on the level of micromechanical phenomena like particle dislocations, friction on a contact surface of cracks or delaminations of composites [6]. At vibrating structure in locations of damages, local deformations of mode shapes are observed, which can be visualize using thermo camera. Time history of this deformations recorded during vibrothermography test is recorded and analyzed off-line, usually. Heat flux due to structural vibration depends strongly on frequency range [7, 8, 9]. In practical application of vibrothermography for SHM, test of sensitivity of the thermal field on the system surface due to change of excitation frequency should be done, and for the damage detection this frequency interval, in which the sensitivity is biggest has to be chosen. Employing of vibrothermography require external excitation of structural vibration in high frequency range (in higher frequency of vibration, intensity of heat radiation is significantly bigger then for low frequency) that can be done using external electromagnetic exciter or using build in small piezo actuators.

The vibrothermography permits to track changes in stress distribution directly, but classical active thermography in principle allows for testing only changes of thermal conductivity of the structure and cannot be directly applied for SHM like vibrothermography.

Authors experiences in application of the technique indicate that using vibrothermography the defects located deeper under the structure surface can be detected then with application of classical active thermography.

Nowadays many laboratories are intensively investigate possibilities of application of described above technologies for SHM purpose.

3. IMAGE PROCESSING TECHNIQUES APPLIED FOR THERMOGRAPHY BASED DAMAGE DETECTION

For damage detection in mechanical structure using active thermography authors proposed two steps image processing algorithm. Preprocessing image analysis Fig. 4, this step provide normalization of recorded images. Based on thermographic images non defected and defected structure, images differences were computed.
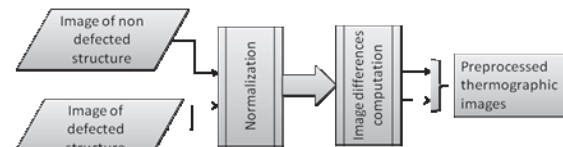

Fig. 4. Preprocessing part of defection detect procedure

This step preparing data for another step of computation. Normalization image data from thermographic camera is necessary for proper correlation of data acquired for destructed and non destructed structure.

Preprocessed thermographic data let us for detecting areas of changed thermal energy flow (strain field).

Second step Fig. 5 established algorithm are based on wavelet transform for two dimensional signals.
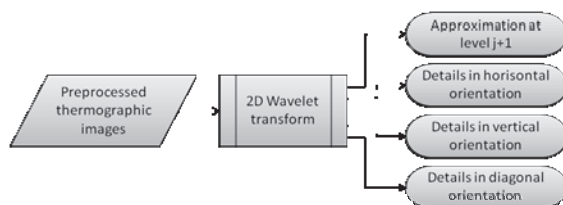

Fig. 5. Wavelet transform of preprocessed thermographic images

Authors picked up multilevel 2D stationary wavelet decomposition: **sym4** Fig. 6 (orthogonal wavelet).

This wavelet type were selected experimentally checking decomposition result for different types of them. Selected wavelet type gives mostly representative and wavelet decomposition results based on this type were best for damaged detection of the mechanical structure algorithms.
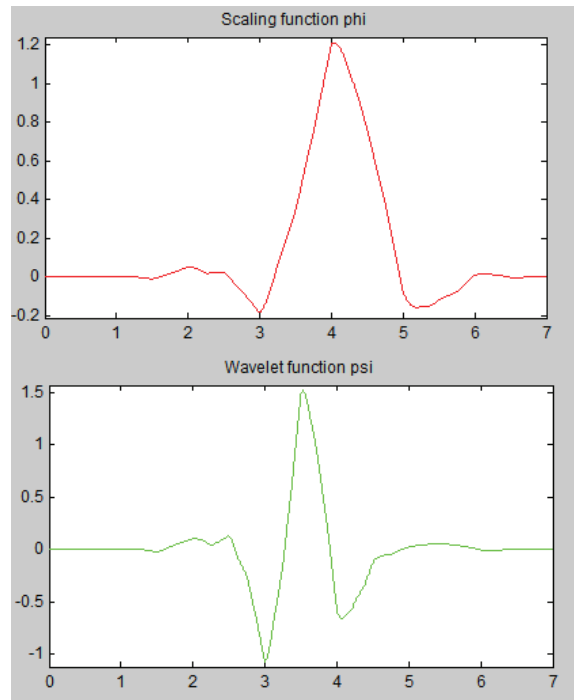

Fig. 6. **Sym4** wavelet selected for decomposition computing

3.1. Improving quality of images

For improving quality resulting image, optical noise computed from first level 2D wavelet are used as background signal subtracted from next levels of wavelet decomposition Fig. 7.
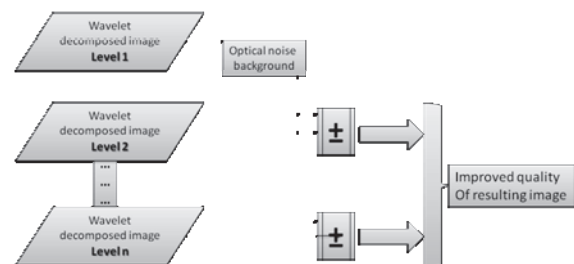

Fig. 7. Improving results quality.

Bad pixel effect are easy for removing in initial part of proposed algorithm. Calibration thermographic camera contain module for bad pixel search. This allow for reject bad pixel from recorded images during preparing data.

4. EXPERIMENTAL VALIDATION OF PROPOSED TECHNIQUE

Proposed algorithm for damage detection in mechanical structure were tested on real data from experiment prepared by authors. Firstly, frequency resonance of tested mechanical structure were setting up during standard modal analysis.

Secondly, active thermography method were used for acquiring thermal image (strain) data with infrared camera.

4.1. Experimental setup

Experiment were lead in laboratory of Department Robotics and Mechatronics – AGH. Experimental setup is shown on Fig. 8, Fig. 9.
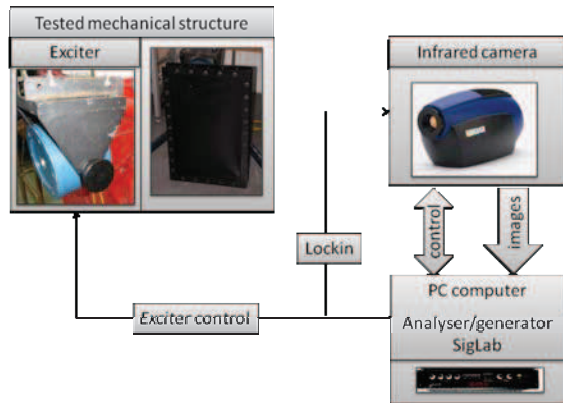

Fig. 8. Experimental setup

Components which are part of the experimental setup:

1. Thermographic measurement:
   o PC computer with CAMLINK interface compatible card;
   o SILVER 480M – advanced IR cooled camera featuring ultra fast temporal analysis, simultaneously with analogue signal recording;
   o Exciter;
2. Initial measurement:
   o Accelerometer;
   o Analyzer SigLab;
   o PC computer with SCSI interface compatible card;
   o Exciter.

Fig. 9. Experimental setup during measurement

Experiment setup were split in parts. First part were approach for detecting resonance frequency of tested mechanical structure. For this subject white noise signal were set up on control equipment. Accelerometer placed in few points on tested structure were used to measure time series signal vibrating structure. Modal analysis were used for resonance frequency identification based on time series data from accelerometer based measurement. In second step result of detected resonance frequency were used for control exciter to set up resonance on structure. The same signal where used also as Lockin signal for infrared camera, which allows synchronize frame rate of camera with resonance frequency of the structure.

Measurement were repeated for non defected and defected structure Fig. 10. Recorded by infrared camera images were used as input data for proposed processing algorithm to detect crack place on tested structure using active thermography method.
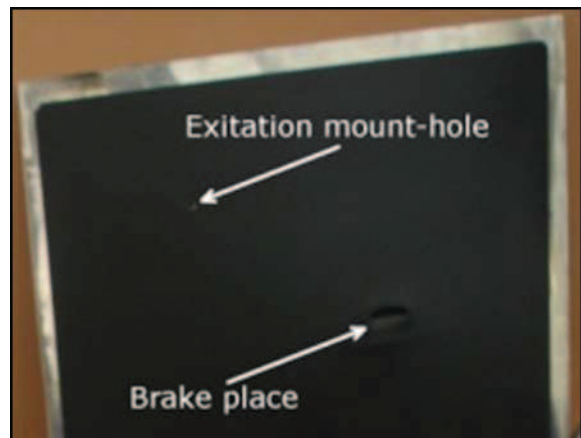

Fig. 10. Defected structure

4.2. Experiment results

After experiment, acquired thermographic images were used for testing proposed by authors algorithm. On Fig. 11 is shown thermographic image acquired by infrared camera for non defected structure. Excitation place is very representative, caused by hi level thermal stresses area.
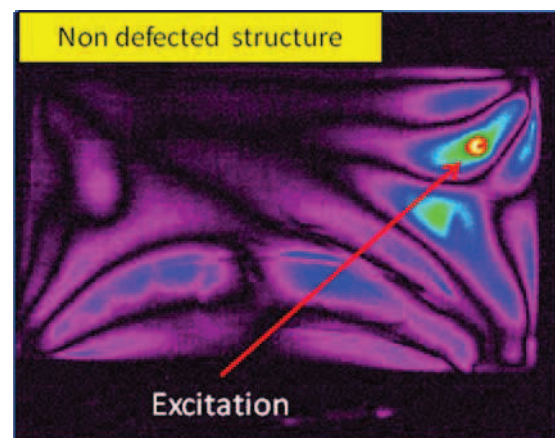

Fig. 11. Thermographic image non defected test structure

Fig. 12 is showing resulting image from acquiring thermographic image for defected structure. Strains (thermal areas) deviation can be seen on this image. Without any a priori knowledge crack place cannot be fined (for different resonance frequencies images can be more noisily).

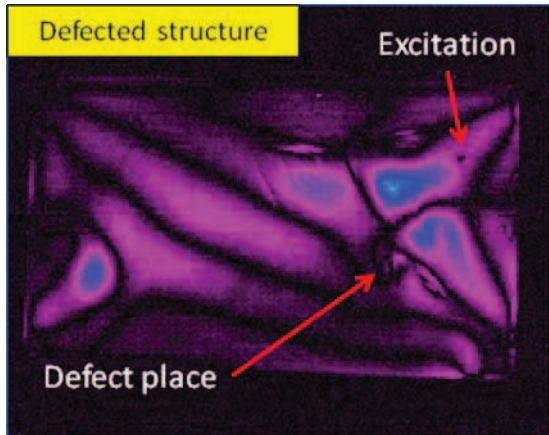Defected place were shown on image for better orientation.

Fig. 12. Thermographic image defected test structure

Presented images were used as starting point data to testing damage detection in mechanical structure algorithm.

4.3. Preprocessing images

Preprocessing image analysis step were approach. Results from this step are shown on Fig. 13. Once, normalization of thermographic images for defected and non defected mechanical structure were computed.
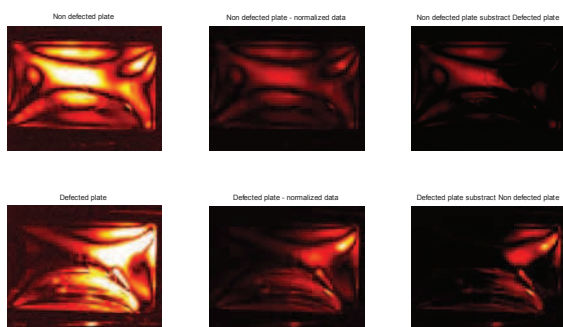

Fig. 13. Preprocessing results. (left – input images; middle – normalized images; right – images differences computation results)

Second, differences between normalized images (defected and non defected) were computed. As can be seen on Fig. 13, differences between thermal energy non defected and defected structure shows dumped values for place where crack were approach. In backwards, defected subtract non defected normalized images, thermal energy areas

were boosted for crack place and excitation neighborhood.

4.4. Separating defect place

Selected **sym4** wavelet type were used for wavelet decomposition computation. Full experiment analysis contained six levels decomposition but level 4th and higher are to blurred and are useless for damage detection purpose Fig. 14 and Fig. 15.
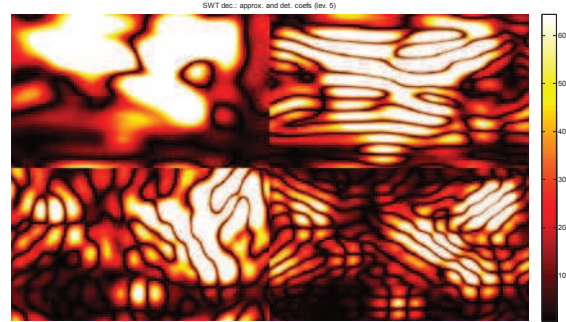

Fig. 14. Fifth level of 2D wavelet decomposition – results useless for damage detection proposed algorithm

Fig. 15. Sixth level of 2D wavelet decomposition – results useless for damage detection proposed algorithm

First level of wavelet decomposition is shown on Fig. 16. On this level only optical noise and just a little of useful information are shown. This level of wavelet decomposition will be used as background for improving quality for last step defect detection algorithm.

On Fig. 16 approximation at actual level is shown on left-up part. Details coefficient in horizontal (right-up), vertical (left-down) and diagonal (right-down) orientation are displayed.

Bad pixel effect are shown in details coefficients as small single bright dot.
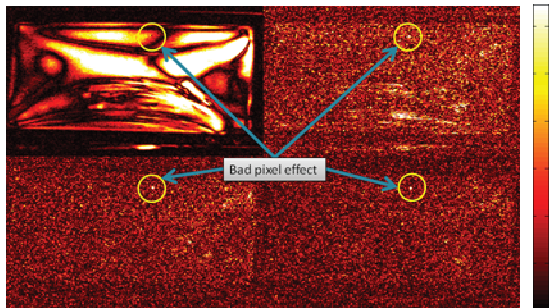
Fig. 16. First level of 2D wavelet
decomposition

Second level of decomposition results are shown on Fig. 17. Here can be seen very easily representative areas for each of the interesting points (excitation, defect place, bad pixel effect). Best result gives wavelet decomposition on details coefficient in diagonal orientation (Fig. 17 right-down). On edges images for details coefficient in horizontal and vertical orientation errors from bad boundary conditions (moving structure in-plane with low frequency during measurement).
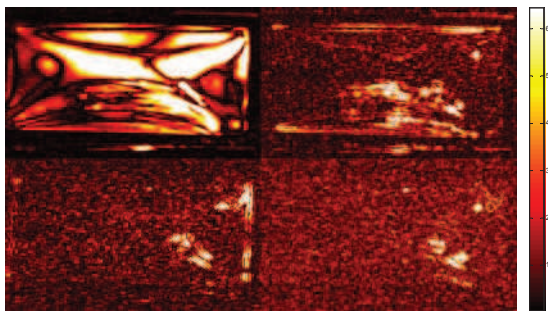

Fig. 17. Second level of 2D wavelet
decomposition

Results for third level decomposition are shown in Fig. 18. As can be seen for this decomposition level images are much more blurred and more optical noise effect can be seen.
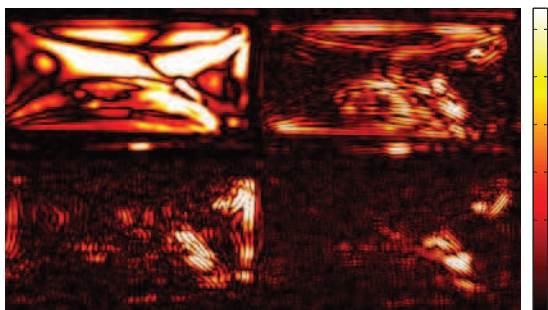

Fig. 18. Third level of 2D wavelet
decomposition

For obtain more clearly image as result subtracting of background (first level of wavelet decomposition) from image which gives most accurate results (second level of wavelet decomposition) were obtain. Result of improving quality images processed thermographic data are

shown on Fig. 19. Coefficient in diagonal direction from wavelet decomposition give best result for damage detection for mechanical structure.
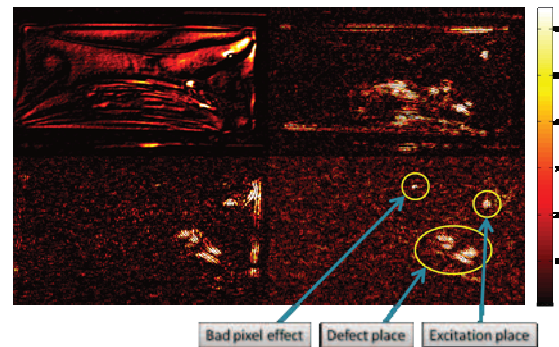

Fig. 19. Result image after
background removing for second level
of 2D wavelet decomposition

Areas representative for excitation, crack and bad pixel effect were marked on Fig. 19. This information proved proposed by authors algorithm for damage detection based on active thermography images analysis.

5. CONCLUSIONS AND FUTURE RESEARCH

Presented and evaluated SHM techniques gives possibility for detection of even very small damages in vibrating structure. The method is relatively simple in application and can be used for many different plate – like structures of metallic or composite materials. Future investigations, at Robotics and Mechatronics group, in direction of development of vibrothermography technique will go in application for rotating structures using de-rotation techniques.

6. ACKNOWLEDGMENT

BIBLIOGRAPHY

[1] Balageas D., Fritzen C. P., Guemes A., (Ed.): *Structural Health Monitoring*, ISTE, London, Newport Beach, 2006.,
[2] Staszewski W., Boller C., Tomlinson G., (Ed.): *Heath Monitoring of Aerospace structures, Smart sensors and signal processing*, Wiley & Sons, Chichester, 2003,
[3] Inman D J, Farrar C. R., Lopes V., Valder S., (Ed.): *Damage Prognosis for aerospace, civil and mechanical systems*, Wiley & Sons, Chichester, 2005.
[4] Farrar C. R., Worden K.: *An introduction to structural health monitoring*, Philosophical

84   DIAGNOSTYKA'4 (44)/2007

        UHL, SZWEDO, Active Thermography And It's Application For Damage Detection ...

Transactions of the Royal Society A, vol. 365, no. 1851, 2007, str. 303- 315.

[5] Madura H. (red.): *Practical problems In thermovision*. Agenda Wydawnicza PAK, Warszawa, 2004. (in Polish).

[6] Maladague X. P. V: *Theory and practice of infrared technology for nondestructive testing*, Wiley, & Sons, New York, 2001.

[7] Tenek L. H, Henneke E. G.,Gunzburger M. D.: *Vibration of delaminated composite plate and some applications to non-destructive testing*, Composite Structures, vol.28, no.3, pp.253-262,1993,

[8] Busse G., Bauer M., Rippel W., Wu D.: *Lockin vibro thermal inspection of polymer composites* Proc. of QIRT – 92 Eurotherm Seminar, vol. 27, pp. 154-159, 1992.

[9] Bauer M., Guntrum Ch., Ota M., Rippel W., Busse G.: *Thermografic characterization of defects and failure in polymer composites*, of QIRT – 92 Eurotherm Seminar, vol. 27, pp. 141-144, 1992.

[10] Ritter G. X., Wilson J. N.: *Handbook of Computer Vision Algorithms in Image Algebra*, CRC Press, 1996.

[11] Tadeusiewicz R., Korohoda P.: *Komputerowa analiza i przetwarzanie obrazów*, Wydawnictwo Fundacji Postępu Telekomunikacji, Kraków 1997.

[12] Ge M, Zhang GC, Du R, Xu Y.: *Feature extraction from energy distribution of stamping processes using wavelet transform*. J Vib Control 2002;8:1023–32

[13] Skorpil V., Stastny J.: *Wavelet transform for image analysis*, Control and Communications, 2003. SIBCON 2003. The IEEE-Siberian Conference on 1-2 Oct. 2003 Page(s):50 – 55

[14] Rioul O. & Vetterli M.: *Wavelets and Signal Processing*, IEEE Signal Processing Mag., 8 October 1991, s. 14-38.

Prof. dr hab. inż. **Tadeusz UHL** jest kierownikiem Katedry Robotyki i Mechatroniki Akademii Górniczo-Hutniczej w Krakowie. W swoich pracach zajmuje się zagadnieniami dynamiki konstrukcji, a zwłaszcza analizą modalną. Jego zainteresowania obejmują także układy aktywnej redukcji drgań, układy sterowania i szeroko pojętą mechatronikę oraz monitorowanie stanu konstrukcji. Jest autorem 15 książek i kilkuset artykułów dotyczących wspomnianych zagadnień.

Mgr inż. **Mariusz SZWEDO** jest doktorantem w Katedrze Robotyki i Mechatroniki Akademii Górniczo – Hutniczej w Krakowie. Jego zainteresowania związane są z przetwarzaniem i analizą obrazów, zastosowaniem technik wizyjnych w robotyce oraz wykorzystaniem wizji maszynowej w zagadnieniach sterowania układami mechatronicznymi. Jest współautorem 7 artykułów dotyczących wspomnianych zagadnień.