Journal of Automation,
Electronics
and Electrical Engineering

APPLICATION OF ACTIVE THERMOGRAPHY IN STUDY OF THE ROTORS DYNAMICS

Jarosław BEDNARZ[1]

[1] AGH University of Science and Technology, Department of Robotics and Mechatronics, al. Mickiewicza 30, 30-059 Kraków, Poland, bednarz@agh.edu.pl

DOI: https://doi.org/10.24136/jaeee.2021.001

Abstract – The article presents the infrared measurement techniques for analyzing and monitoring the dynamic state of the structure using advanced thermal imaging techniques. The article present an overview of the infrared measurement techniques and algorithms proposed research design based on the selected infrared measurement techniques. The article presents the results of a series of studies on the possibility of applying the vibrothermography methods in SHM systems. In particular it focuses on the analysis of the possibility of studying the dynamics of the rotor and the detection of its failures during operation. The results of vibrothermography studies of impeller made of plastic are presented. The results of studies based on algorithms developed by the authors. The article also presents the concept of the use of thermal imaging research in fault detection and monitoring of the dynamic state of real objects.

Keywords – active thermography, blade crak detection, rotor dynamic

INTRODUCTION

The basic characteristic of a thermal radiation (electromagnetic radiation emit-ted by the particles which are electrically charged as a result of their thermal mo-tion in the matter) is the temperature emissivity. The emissivity is a physical quantity characterizing the radiation properties of solids. Emissivity of a body depends on the characteristic parameters of a material such as temperature, chemical composition and physical state of the surface.

Methods of active thermography use the phenomenon of abnormal thermal state of the test object through controlled delivery of energy to the object [7]. As the result obtained in this way disturbances of the state of thermal non-uniformity is possible to observe the radiation emitted from the object whose source are damaged areas or defects [4-5]. One method of active thermography is vibrothermography. It involves calling the thermal phenomena in the structure of the material of tested objects by forcing a structure by an external delivery system energy in the form of vibration. Vibration causing deformation processes on the level of atomic phenomena (dislocation diffusion). The relationship between the deformation (strain) and temperature change describes the following relationship:

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

Where:
$\Delta\varepsilon$ - change of major strain,
$\Delta\sigma$ – change of principal stresses,
ν - Poisson's ratio,
ΔT – temperature change,
α – coefficient of thermal expansion,
E – Young's modulus.

Assuming that stress changes occur very quickly it can be assumed that the change of deformation $\Delta\varepsilon$ causes a change in temperature ΔT:

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

Where:
K - compressibility factor [Pa],
C_v - specific heat [J/kg·K] at constant volume,
ρ - density [kg/m3],
T - the temperature of the investigated object [K].

The result is an approximate relationship that describes the phenomenon of thermoelasticity as:

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

Where:
C_p - specific heat at constant pressure,
K_m - thermoelasticity factor.

I. THEORETICAL BASIS

Depending on the applied excitation, the techniques of thermovision measurements can be divided into the following groups [8, 9, 10, 11]:

1. Optical Excited Thermography (OT),
2. Ultrasound Lockin Thermography (ULT),
3. Ultrasound Burst Phase Thermography (UBP),
4. Pulse Thermography (PT),
5. Transient Thermography (TP).

OPTICAL EXCITED THERMOGRAPHY

Thermography with optical excitation is a method of dynamic measurements based on measurement with an external excitation, the source of which is thermal radiation The forcing is carried out by means of: halogen lamps, lasers or heat guns. Thermal energy is directed towards the tested structure. The thermal wave delivered to the tested object propagates inside and is reflected or slowed down at the edges coming from internal cracks and sudden changes in thermal emission. The measurement can be carried out in the form of amplitude or phase time analysis. The recorded phase image shows the color-coded time delays of the temperature flow in the structure. The advantage of phase images analysis is that they show almost complete suppression of optical or infrared images of the analyzed structures, and only thermal responses of the examined objects are visible. The range of depths in which it is possible to identify defects is greater than in the case of applying amplitude modulation of the forcing signal and depends on the frequency modulation. As a result, this method can be adapted to the properties of different materials. Thanks to frequency modulations, it is possible to carry out a measurement that allows obtaining images presenting the spatial distribution of temperature (thermal tomography).

ULTRASOUND LOCKIN THERMOGRAPHY

This method is very sensitive to the occurrence of damages in the tested structure, thus increasing the measurement reliability. It enables the detection of mechanical damages inside the tested object. Forcing ultrasonic signal delivered to the structure by means of a high-frequency resonant system. The initiated elastic wave propagates through the structure, is damped and dispersed on the defects, which generates a thermal response recorded on the surface of the object. If the amplitude of the ultrasonic signal is modulated by a low-frequency signal, the effect of the thermo-emission takes the form of an oscillation.

In such a situation, in the places where the damage occurs inside the structure, a thermal wave is emitted, which is visible in the recorded thermal image as a heterogeneity of the temperature distribution field.

ULTRASOUND BURST PHASE THERMOGRAPHY

The method combines the advantages of using the techniques of synchronous and pulse thermography Vibrations in the examined structure are induced by short series of pulses (duration 10... 1000 ms). Variable distribution of the temperature field on the surface of the tested structure, caused by internal phenomena of generating a portion of heat in the damaged areas, is recorded by a thermal imaging camera. In the next stage, the image is processed using, inter alia, the Fourier transform, as a result of which, as in the case of Lockin Thermography, the image of the phase and amplitude is obtained, with its typical properties (temperature attenuation gradient and determination of the depth of the location of structural defects).).

Another advantage of using the forcing with a series of ultrasonic pulses in relation to the techniques of thermovision measurements using harmonic forcing in one frequency is the wide spectrum of the thermal response. Thus, it is possible to analyze different modulation frequencies when carrying out a single measurement in a situation where the other methods require a series of measurements with excitation for subsequent frequencies.

Phase images obtained during such a measurement provide direct information on the location, detection, and even the depth of defects in the tested object, significantly reducing the measurement time. It is also possible to estimate the reliability of the measurement at the same time.

PULSE THERMOGRAPHY

The basis of impulse thermography is the disturbance of the thermal equilibrium in short time intervals (typically a few thousandths of a second) by providing the system with an instantaneous portion of thermal energy. This method uses controlled discharge lamps or laser systems for thermal forcing.

The thermal imager records a sequence of images after being supplied to the system with a thermal pulse and analyzes the change in thermal emission for each pixel of the image. The energy supplied to the tested structure should be large enough to cause visible temperature changes that can be recorded by the camera. Temperature changes that can be registered using this method immediately after the thermal impulse is delivered to the tested object are greater than in the case of using synchronous thermography.

TRANSIENT THERMOGRAPHY

Time thermography enables the detection of defects located deep inside the tested structure, especially for materials with a low coefficient of thermal conductivity. The tested sample is heated for a long time to a temperature that does not damage it (depending on the material). Then it is transferred to a measuring station with a set ambient temperature and while it is cooling down, its surface is monitored with a thermal imaging camera. During cooling, the sample loses heat, releasing it to the environment in proportion to the material's thermal emission coefficients. Heat flows from the inside to the surface of the sample, where it is exchanged with the environment. Internal defects, which are a barrier to the flow of heat, are visible in thermal images as inhomogeneities in the field of temperature distribution. Since the energy during this measurement travels only half the way compared to the other methods, it enables the registration of defects located deep inside the structure.

II. GENERAL RESEARCH CHARACTERISTIC

This chapter contains the research results of plastic bladed rotor. The main aim of the research was to check the possibility of using a vibro-thermography method in SHM of rotating machinery. The researches were divided into a several stages:

1. Delimitation of natural frequencies of rotor blades;
2. Analysis of influence of input signal amplitude value on stress field of blade;
3. Analysis of blade stress field;
4. Examination of influence of „double-synchronization" on stress field of blade using the active vibro-thermography method;
5. Verification of proposed algorithm during the tests on laboratory test rig.

During the experiment the following equipment was used:

1. Scanning vibrometer POLYTEC PSV-400;
2. Infrared camera CEDIP SILVER 420M;
3. Electrodynamic exciter ROBOTRON;
4. Specialized electromagnetic exciter built-in on laboratory test rig.

DELIMITATION OF NATURAL FREQUENCIES OF ROTOR BLADES

A proper estimation of resonant frequencies of the examined object is a key problem for vibro-thermography method. During the examination the resonant frequencies of blades were estimated for two cases:

1. Rotor placed on electrodynamic exciter (Fig. 1);
2. Rotor placed on laboratory test rig ((Fig. 2);

Fig. 1. Laboratory test stand

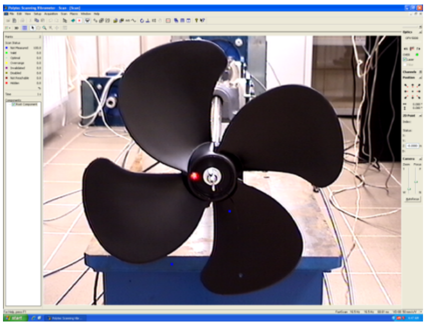


Fig. 2. Laboratory test stand

The main parameters of experiment were as follows:

1. Random excitation signal was used („white noise");
2. The frequency range of the measurement was set to 0 Hz – 50 Hz;
3. The frequency resolution of the measurement was set to 0.25 Hz;
4. The response signals to the applied random excitation (the vibration velocity signals) were measured;.
5. Based on the measured signals the spectra of response signals for every blade were estimated ;
6. The estimated spectra were averaged at least 15 times in the frequency domain.
7. In the case when rotor was placed on electrodynamic exciter direction of excitation was perpendicular to the blade, in the case when rotor was placed on laboratory test rig direction of excitation was tangential to the blade.

Example of experimental results is presented in figure 3.

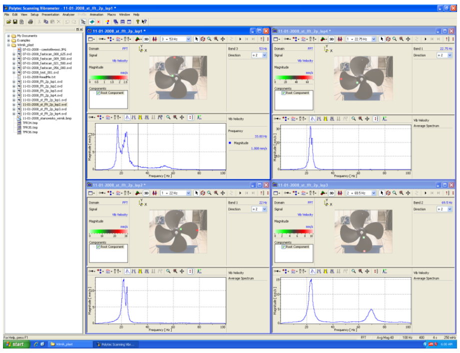


Fig. 3. Resonant frequencies of blades

Experimental results show that for both cases the resonant frequencies of blades are as follows:

1. Cracked blade – 17.25 [Hz];
2. Undamaged blades – ~ 22 [Hz];

A several experiments were done to check the influence of mounting and dismounting the blades on laboratory shaft. The results of these experiments clearly showed that mounting and dismounting the blades on shaft has no influence on their resonant frequencies.

ANALYSIS OF BLADE STRESS FIELD

Analysis of cracked blade stress field was the next step of researches. Rotor was placed on electrodynamic exciter, the blade was excited with harmonic signal – sinus with frequency 17.25Hz and amplitude about 1V. During the experiment direction of excitation was perpendicular to the blade. Due to avoid a temperature measuring error the sequence of 1000 images recorded by infrared camera was taken to estimate a stress field. Research results are presented in figures 4÷6.

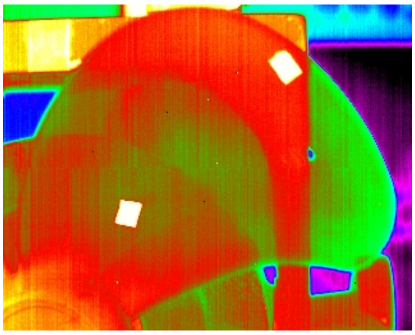


Fig. 4. Temperature field

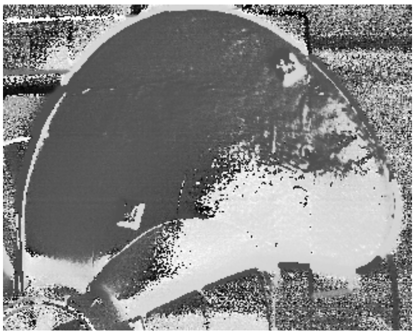


Fig. 5. Phase image showing time delays due to heat propagation

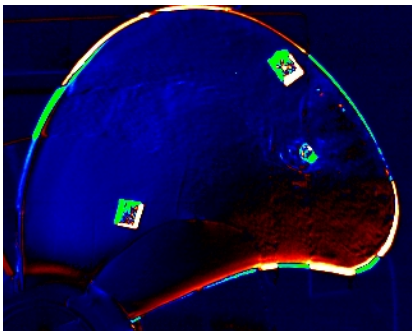


Fig. 6. Stress field estimated with active thermography method

ANALYSIS OF INFLUENCE OF INPUT SIGNAL AMPLITUDE VALUE ON STRESS FIELD OF BLADE

Analysis of influence of input signal amplitude value on stress field of blade was the next step of researches. Rotor was placed on electrodynamic exciter, the blade was excited with harmonic signal – sinus with frequency 17.25Hz and amplitude from 0.07V to 0.7V. During the experiment direction of excitation was perpendicular to the blade. Due to avoid a temperature measuring error the sequence of 1000 images recorded by infrared camera was taken to estimate a stress field. Research results are presented in figures 7÷12.

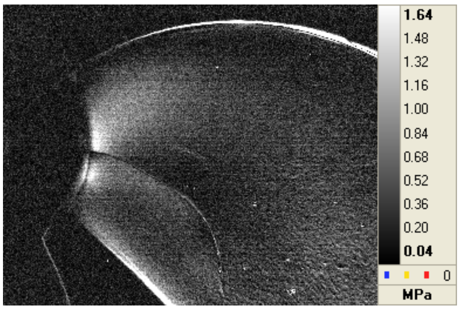


Fig. 7. Value of exciter voltage input ~0.07V

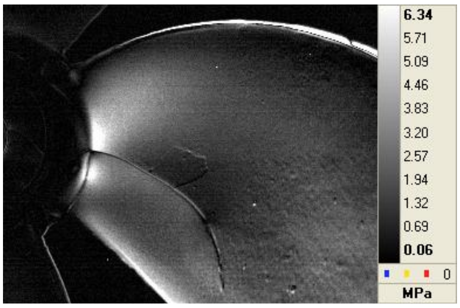


Fig. 8. Value of exciter voltage input 0.14V

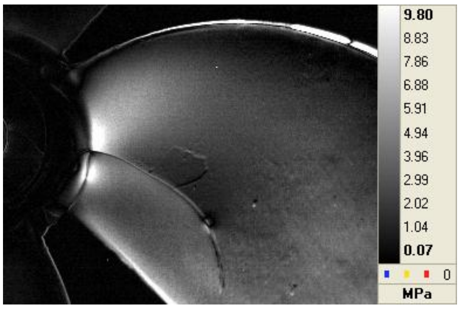


Fig. 9. Value of exciter voltage input 0.28V

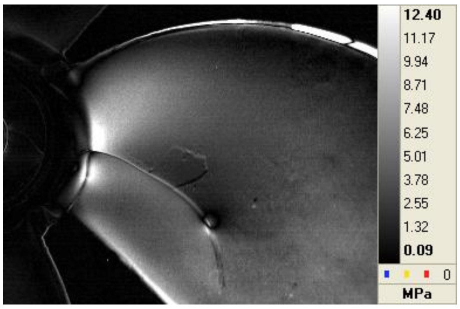


Fig. 10. Value of exciter voltage input 0.42V

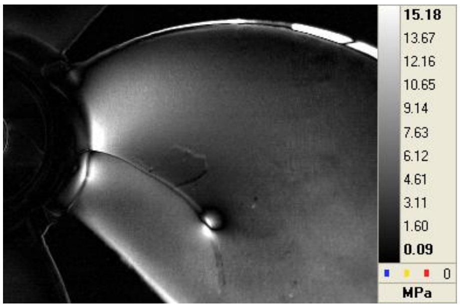


Fig. 11. Value of exciter voltage input 0.56V

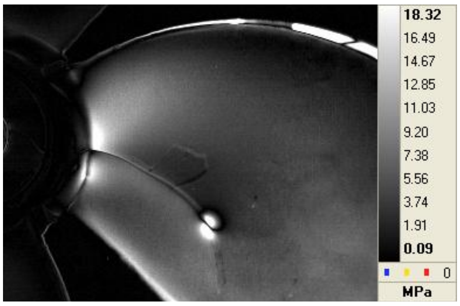


Fig. 12. Value of exciter voltage input 0.7V

Experimental results clearly show that value of excitation signal amplitude has significant influence on their quality. According to increasing amplitude of excitation not only the maximal values of stress field increase but also a fracture propagation direction and friction effects can be observed in blade.

EXAMINATION OF INFLUENCE OF „DOUBLE-SYNCHRONIZATION" ON STRESS FIELD OF A BLADE USING THE ACTIVE VIBRO-THERMOGRAPHY METHOD

The main aim of research was confirmation applicability of synchronization signals in experimental determination of stress field of a blade. The following synchronization signals were used:

1. Lockin – synchronization of stress field computing with excitation signal
2. Signal which allows recording thermal images „on demand " – Trigger TTL (simulation of signal for image recording with rotation phase synchronization).

During the examination the bladed rotor was placed on electrodynamic exciter, the blade was excited with harmonic signal – sinus with frequency 17.25Hz and amplitude about 1V. The direction of excitation was perpendicular to the blade. As a Trigger TTL signal from generator was used. Due to avoid a temperature measuring error the sequence of 1000 images recorded by infrared camera was taken to estimated a stress field. Experimental results (fig. 13÷15) clearly show that estimation of blade stress field during the normal work of rotating machinery is possible.

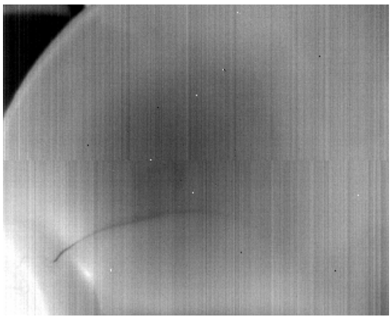


Fig. 13. Temperature field

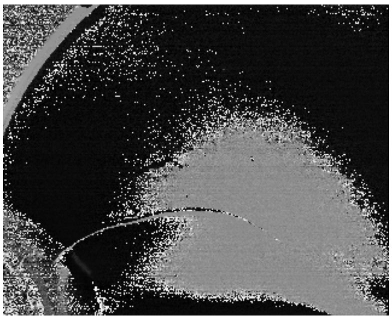


Fig. 14. Phase image showing time delays due to heat propagation

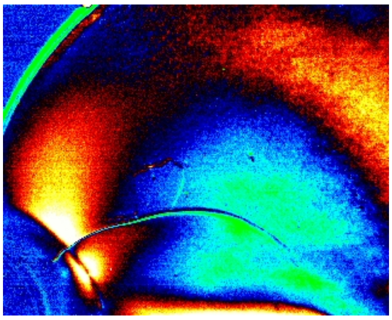


Fig. 15. Stress field estimated with active thermography method

VERIFICATION OF PROPOSED ALGORITHM DURING THE TESTS ON LABORATORY TEST RIG

Verification of proposed algorithm during the tests on laboratory test rig was the last stage of researches. The view of laboratory test stand is presented in figure 16.

Fig. 16. Laboratory test stand

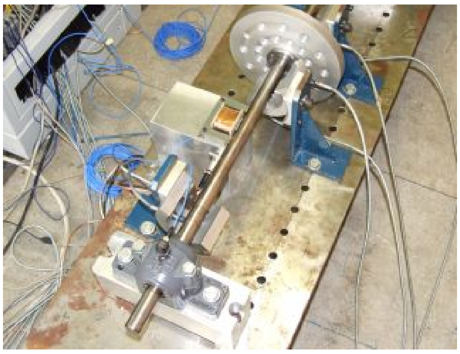
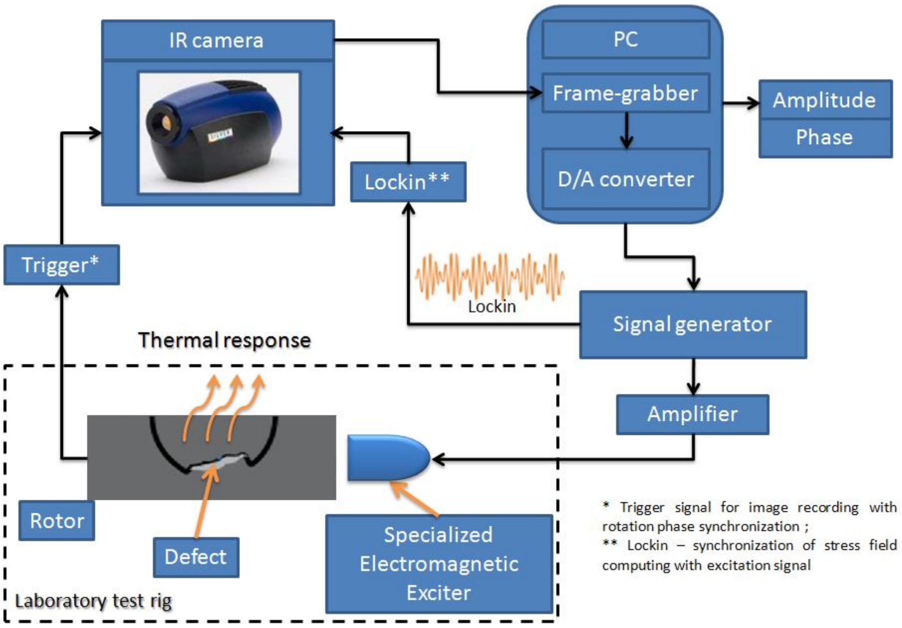


Fig. 17. Specialized electromagnetic exciter

During the experiment rotational speed of shaft was 900 [RPM], vibrations of blades was excited by specialized electromagnetic exciter (Fig. 17), which allows to excite a blade vibrations in resonant frequencies (17.25Hz). During the research the direction of excitation was tangential to the blade.

Scheme of laboratory test stand is presented in figure 18. During the experiment the infrared camera was release by a special electronic device which allows image recording with rotation phase synchronization. Due to avoid a temperature measuring error the sequence of 1000 images recorded by infrared camera was taken to estimated a stress field. Research results are presented in figures 19÷21. Experimental results clearly show that blade stress field was properly computing during the normal work of rotating machinery. On recorded thermal images the localization of damage can be easily found. On these images the energy flow path and the values of stresses at particular locations can be also observe.



* Trigger signal for image recording with rotation phase synchronization ;
** Lockin – synchronization of stress field computing with excitation signal

Fig. 18. Laboratory test stand

III. CONCLUSIONS

Conducted research was related to the applicability of active thermography technique in the study and assessment of the rotating machines dynamic state. Based on the results of these studies the following conclusions can be provide:

Active thermography can be successfully used in machine and devices diagnosis

It is possible to detection and localization of damage that occur not only on the surface of the object but also those occurring in the inner layers of the structures [2-3].

Thermal imaging techniques may also be used in the diagnosis of devices for which there is no possibility of a classic measurement using vibration sensors. By using appropriate algorithms and synchronization trigger a thermal imager with a duty cycle of the device ones can record the stress field objects during operation. This approach enables the detection and location of cracks in rotor blades at an early stage of their before his appearance can be registered by measuring eg vibration acceleration at bearings [1].

It should be noted, however, that active thermography is amethod which is sensitive for changing environmental conditions (heating and cooling of air). Method requires accurate determination of the resonant frequency of the object and there must be the possibility of connecting to the camera reference signal lockin what in the real conditions is not always possible.

In summary, the active thermography can be successfully used to diagnose the state of machinery however there is necessity for very precise planning and preparation of a diagnostic experiment with application of this method [6].

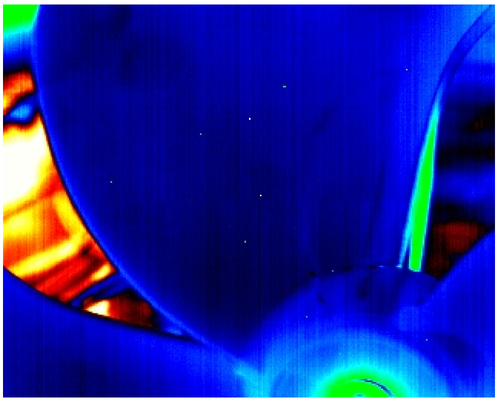


Fig. 19. Temperature field

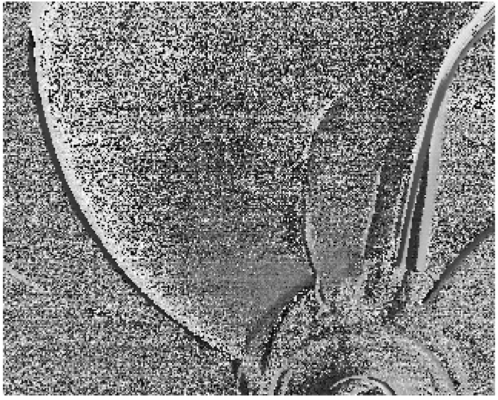


Fig. 20. Phase image showing time delays due to heat propagation

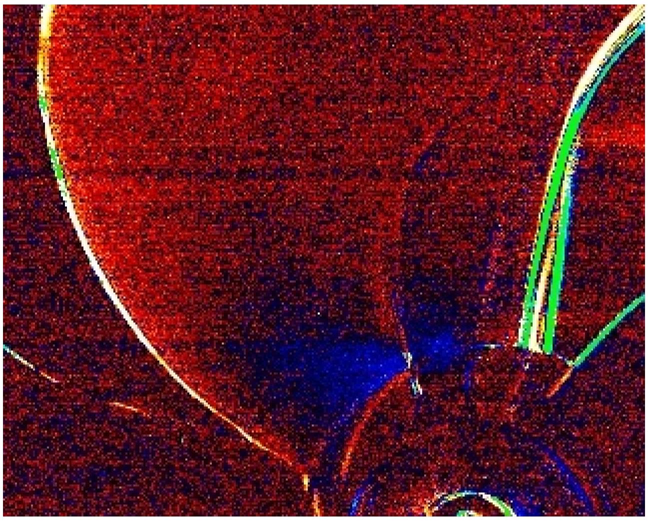


Fig. 21. Stress field estimated with active thermography method

ZASTOSOWANIE TERMOGRAFII AKTYWNEJ W BADANIACH DYNAMIKI WIRNIKÓW

W artykule zaprezentowano techniki pomiarów termowizyjnych umożliwiających analizę oraz monitorowanie stanu dynamicznego konstrukcji za pomocą zaawansowanych technik termowizyjnych. Przedstawiono przegląd termowizyjnych technik pomiarowych oraz zaproponowano algorytmy badań konstrukcji w oparciu o wybrane techniki pomiarów termowizyjnych. W artykule przedstawiono wyniki serii badań dotyczących możliwości zastosowania metod wibrotermograficznych w systemach SHM. W szczególności skupiono się na analizie możliwości badania dynamiki wirników oraz detekcji ich uszkodzeń w czasie pracy. Przedstawiono wyniki badań wibrometrycznych i termowizyjnych wirnika z tworzywa sztucznego. Zaprezentowano wyniki badań opartych na algorytmach opracowanych przez autorów. W artykule zaprezentowano również koncepcję zastosowania badań termowizyjnych w detekcji uszkodzeń oraz monitorowania stanu dynamicznego obiektów rzeczywistych.

Słowa kluczowe: aktywna termografia, detekcja pęknięć łopatek, dynamika wirników

BIBLIOGRAFIA

[1] Balageas D., Fritzen C.P., Guemes A., (Ed.)- "Structural Health Monitoring", ISTE, London, Newport Beach, 2006.,

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

[3] 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.

[4] Farrar C.R., Worden K., "An introduction to structural health monitoring", Philosophical Transactions of the Royal Society A, vol. 365, no. 1851, 2007, str. 303- 315.

[5] Inman D. J., Farrar C.R., Lopes V., Valder S., (Ed.) "Damage Prognosis for aerospace, civil and mechanical systems", Wiley & Sons, Chichester, 2005.

[6] Madura H. (red.), „Pomiary termowizyjne w praktyce". Agenda Wydawnicza PAK, Warszawa, 2004.

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

[8] Maldague X.,"Applications of infrared thermography in nondestructive evaluation", Electrical and Computing Engineering Dept., Université Laval, Quebec City (Quebec), G1K 7P4, Canada, 2008;

[9] Staszewski W., Boller C., Tomlinson G., (Ed.), "Heath Monitoring of Aerospace structures, Smart sensors and signal processing", Wiley & Sons, Chichester, 2003,

[10] 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,

[11] Walle, M., Abuhamad, E. Toma, Netzelmann U., "Defect indications in sono-thermography in relation to defect location and structure", Fraunhofer Institute for Nondestructive Testing, Saarbrücken, Germany, 2007.