Grzegorz GRALEWICZ, Grzegorz OWCZAREK
Central Institute for Labour Protection National – Research Institute, Lodz
Bogusław WIĘCEK, Krzysztof TOMALCZYK
Technical University of Lodz, Lodz

OPTICAL AND ULTRASOUND LOCK-IN THERMOGRAPHY SYSTEMS FOR DETECTION OF STRUCTURAL DEFECTS

Keywords

Lock-in thermography, ultrasound, optical systems.

Abstract

This paper presents optical and ultrasound excitation lock-in thermography systems for the detection of structural defects. Both systems can be used for the remote monitoring of thermal features like cracks, delaminations and other irregularities. The method consists of the excitation of thermal effects in a tested structure with the use of external heat or an ultrasound source. These effects result from propagation and reflection of thermal waves, which are input through the surface into the tested structure by absorption of modulated heat radiation or ultrasound waves.

Introduction

Dynamic thermography is a method of non-destructive measurements in which the tested structure is being excited by the energy that turns into heat. The excitation can take the form of a single pulse of pre-set duration or a series of pulses. The absorption of intensity modulated heat radiation or ultrasound waves on the surface forms a thermal wave. It propagates into the interior where it is reflected at boundaries and returns to the surface where it is superimposed to the initial wave (Fig. 1). The thermovision system measures surface temperature distribution in time. Thereafter, Fourier transform of the response of the tested structure to excitation is determined. Phase angle images obtained by superposition of the initial thermal wave and its reflection display hidden structures down to a certain depth below the surface. In this way, a defect is revealed by the local change of the phase angle.

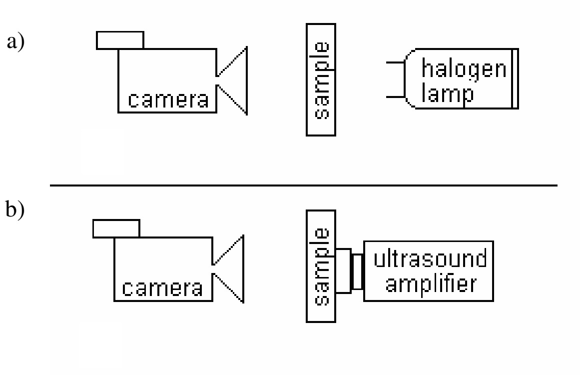

Fig. 1. Lock-in thermography systems: A – optical excitation, B – ultrasound excitation

1. Optical lock-in thermography system

The principle of measurement by this method is presented in Fig. 1a. A computer-controlled thermal source (halogen lamp) supplies energy to the tested sample. As the heat flow penetrates the sample, it is disturbed in the areas of material defects, which is indicated by a change in the surface temperature distribution of the sample. The process of heat penetration is synchronically recorded by a thermal camera during the action of the pulsating source of heat (halogen lamp). Measurement data is saved in computer memory and then analysed by special software.

The response of the object provides information in a wide frequency spectrum, which allows analysing heat penetration at various depths inside the tested sample. Also important is that the method does not require repeated testing in order to evaluate various layers of the sample.

Specifications:

- wavelength band: 500–1700 nm,
- power band: 150–1500 W,
- spectral band: 3–5 μm,
- sensitivity: 0.1°C,
- optional use of various optical exciters,

- synchronised and separate control modes,
- measurement data acquisition time from ms till hours.

The optical lock-in thermography system is presented in Fig. 2 (the optical exciter setup and front and back panels of the control unit). The control unit provides separate and synchronised control modes of four optical exciters. The system does not require a computer or any special software.

Fig. 2. Optical lock-in thermography system

2. Ultrasound Lock-in Thermography System

This method employs a piezoelectric transducer of a 30 kHz resonance frequency, modulated with frequency $fm = 0.015\text{-}1$ Hz. The transducer generates an ultrasound mechanical wave that excites the tested sample. Mechanical vibration energy transforms into heat in the areas of cracks, stratification and other material defects, which influences the surface temperature distribution. The ultrasound lock-in thermography system (Fig. 3) consists of two modules:

- ZGU-1 – power supply unit - provides transducer power amplifier supply voltage ±60V/5A and auxiliary voltages ±15V, +5V and +9V to generator and control circuits.
- GU-1/200W – consists of power amplifier, internal 30 kHz ± 2 kHz ultrasound signal generator, modulation signal generator with adjustable modulation depth and control section with two digital meters displaying current values of peak output voltage and current. An external signal generator and/or modulator can be connected and used instead of internal ones.

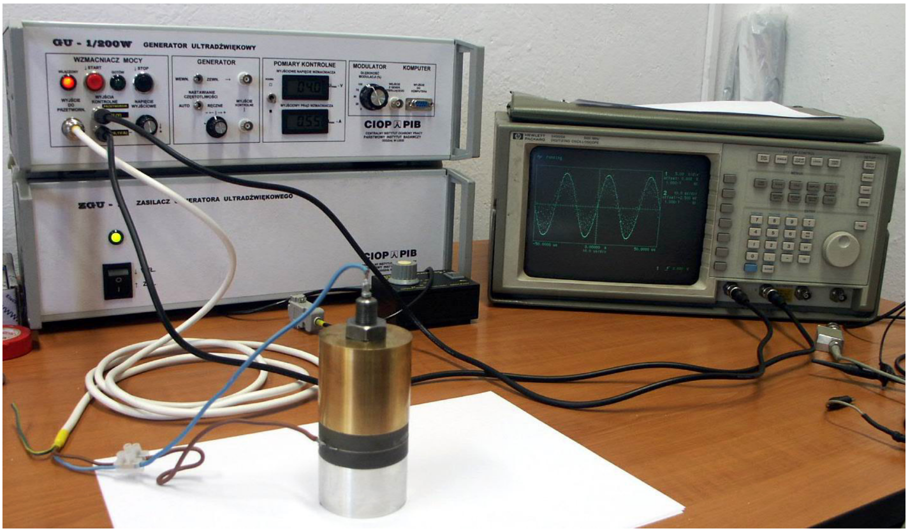

Fig. 3. Ultrasound lock-in thermography system

GU-1/200W is connected to an ultrasound exciter (metal-ceramic-metal sandwich structure).

The design of metal-ceramic-metal sandwiches to resonate at a given fundamental frequency, 2πω in the plate thickness direction is based on the following equation [1]:

$$\frac{\omega l_c}{V_c} + arctg\left[\frac{A_1\rho_1V_1}{A_c\rho_cV_c}tg\left(\frac{\omega l_1}{V_1}\right)\right] + arctg\left[\frac{A_2\rho_2V_2}{A_c\rho_cV_c}tg\left(\frac{\omega l_2}{V_2}\right)\right] = n\pi \qquad (1)$$

where: l_1, l_2, l_c – length of 1 st metal, 2 nd metal and ceramic sections
V_1, V_2, V_c – sound velocity in 1 st metal, 2 nd metal and ceramic sections
A_1, A_2, A_c – cross section of 1 st metal, 2 nd metal and ceramic sections
ρ_1, ρ_2, ρ_c – density of 1 st metal, 2 nd metal and ceramic sections

2.1. Ultrasound exciter with identical metal sections

This case is a common type of sandwich structure in which the calculation can be greatly simplified by an approximation - the metal plates are identical and the ceramics are placed symmetrically between them. In this case, the effect of the ceramic on the resonant frequency is almost entirely due to its compliance

– the effect of its mass is negligible. This is fairly obvious when it is considered that the section at the centre subjected to high stress and strain levels and, therefore, contributes to the total potential energy; but it experiences little vibratory motion and, therefore, contributes little to the total kinetic energy [2].

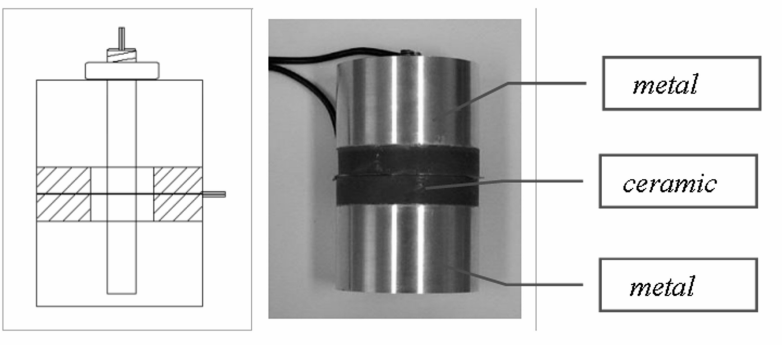

Fig. 4. Ultrasound exciter (metal-ceramic-metal sandwich)

Table 1. Metal – ceramic – metal sandwich parameters

	Parameter	Metal	Ceramic
1	Length [m]	$30.2 \cdot 10^{-3}$	$20.0 \cdot 10^{-3}$
2	Sound velocity [m/s]	5100	2910
3	Cross section [m^2]	$2.08 \cdot 10^{-3}$	$1.77 \cdot 10^{-3}$
4	Density [kg/m^3]	2720	5600

2.2. Ultrasound exciter with different metal sections

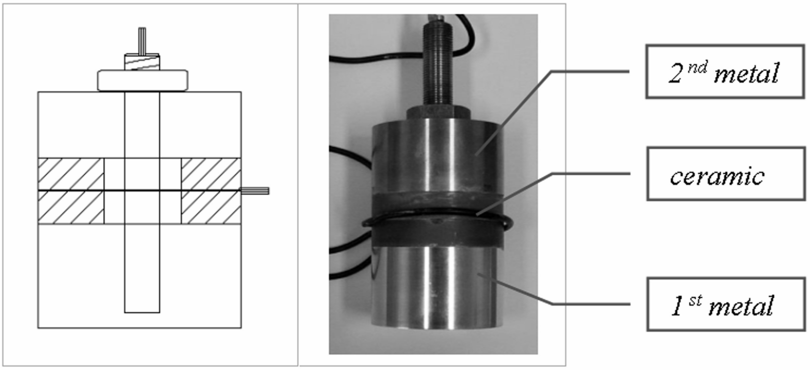

Fig. 5. Ultrasound exciter (1 st metal-ceramic-2 nd metal sandwich)

Table 2. 1 st metal – ceramic – 2 nd metal sandwich parameters

	Parameter	1 st metal	2 nd metal	ceramic
1	Length [m]	$30.2 \cdot 10^{-3}$	$26.7 \cdot 10^{-3}$	$20.0 \cdot 10^{-3}$
2	Sound velocity [m/s]	5100	2997	2910
3	Cross section [m^2]	$2.08 \cdot 10^{-3}$	$1.97 \cdot 10^{-3}$	$1.77 \cdot 10^{-3}$
4	Density [kg/m^3]	2720	8600	5600

2.3. Resonant frequency calculation

The electrical resonant frequencies are taken to be the frequencies at which the reactive component of the motional impedance goes to zero. Frequencies at which the reactive components do not have a zero minimum are designated as the secondary resonance. When damping is ignored in such a system, the resistive load on the radiating face of the ceramic is taken as equal to zero. It is desirable, however, to have resonant frequency curves for systems which have a reactive load on each end. Formulas giving the resonant frequencies [2] are as follows:

$$\gamma_c + \alpha_1 + \alpha_2 = n\pi \qquad n = 1,2,3... \tag{2}$$

and $n = 1$ gives the condition for first resonance, $n = 2$ gives the condition for second resonance, etc.

Table 3. Resonant frequency

	Resonant frequency [kHz]								
The metal plate are identical	35.9	66.4	97.9	103.9	-	-	-	-	-
The metal plate are different	19.6	31.3	37.8	48.9	58.2	60.4	63.6	71.7	75.2

An undesirable effect of heat generation in the ultrasound exciter appears for higher input powers. This can influence the physical dimensions of the exciter and consequently change its resonance characteristics. The heat generation is concentrated in the electrode areas – positive electrode (thin copper plate situated between two piezoelectric rings) and ground connection point (at the top fixing screw). This effect is presented in Fig. 6.

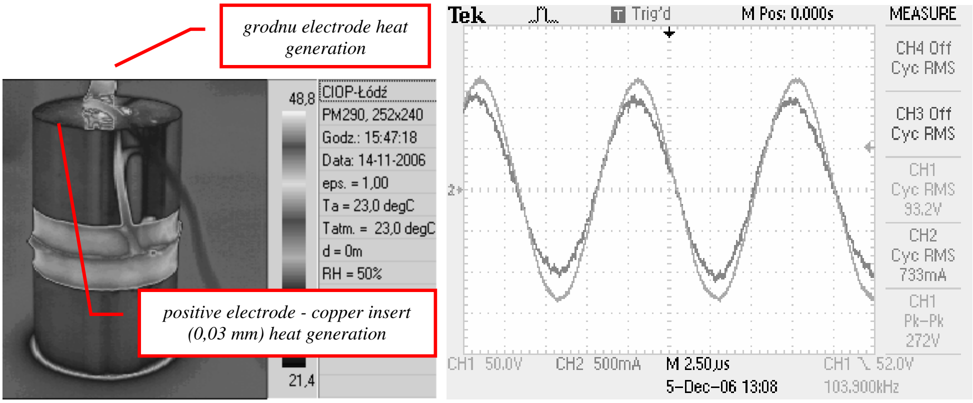

Fig. 6. Termal image of ultrasound exciter (metal-ceramic-metal sandwich)

Conclusions

Two practical lock-in thermography systems were designed, built and tested:

Optical lock-in thermography system:

- dimmer pack with maximum power output of 1.5 kW,
- generation and recording of sinusoidal temperature modulations,
- evaluation of modulation images (amplitude and phase) at different frequencies,
- control of the high performance flash lamps for pulse excitation, synchronised with data acquisition.

Ultrasound lock-in thermography system:

- Work frequency 30 kHz,
- Amplitude modulation possible,
- Ultrasound converters,
- Evaluation of modulation images (amplitude and phase) at different frequencies.

Acknowledgements

Scientific work financed by the Ministry of Science and Higher Education and carried out within the Multi-Year Programme "Development of innovativeness systems of manufacturing and maintenance 2004–2008".

References

1. Fry W.J, Taylor J.M., Henvis B.W.: Design of crystal vibrating systems for projectors and other applications. Dover Publications, Inc., New York, 1948.
2. Technical Publication TP-235 Morgan Electro Ceramics: The design of piezoelectric sandwich transducers, www.morgan-electroceramics.com

Reviewer:
Krzysztof WIERZBANOWSKI

Optyczny i ultradźwiękowy system termografii synchronicznej do wykrywania strukturalnych defektów

Słowa kluczowe

Termografia synchroniczna, ultradźwięki, optyczny, systemy.

Streszczenie

W pracy przedstawiono optyczny i ultradźwiękowy system termograficzny do wykrywania defektów strukturalnych. Obydwa z prezentowanych systemów poprzez monitorowanie termicznych parametrów struktury pozwalają wykrywać pęknięcia, rozwarstwienia oraz inne nieciągłości materiału. Metoda polega na wywołaniu zmian rozkładu pola temperatury w miejscu występowania defektu poprzez zewnętrzne modulowane źródła ciepła (lampy halogenowe) lub ultradźwiękowe źródła energii.