Algorithms for Damage Localization and Characterization – Estimation of Optimal Sensors Placement – Novel Signal Processing Methods

Wieslaw Ostachowicz
Polish Academy of Sciences
Institute of Fluid–Flow Machinery
Department of Mechanics of Intelligent Structures
14 Fiszera Street
80231 Gdansk
POLAND

wieslaw@imp.gda.pl

ABSTRACT

Along with the application of guided waves for structural health monitoring means for quantification of damage with regard to location, type and size become relevant. This chapter covers different signal processing methods and how those can be applied also for simulation to allow one to optimise excitation signal parameters and sensor placement, as well as enable analysis of signals reflected from damage. It also includes a variety of techniques being related to diagnostics (damage size estimation and damage type recognition) and prognostics. Different means of visualization do play a significant role.

1.0 DAMAGE DETECTION AND LOCALIZATION

Damage detection and localization needs effective algorithms and optimal sensor placement. The list of methods presented in relevant literature is very long. Also a visualisation of elastic waves excited by the piezoelectric actuator in selected structures is widely reported in many publications. The table presented below shows two major concepts for damage localization and characterization.

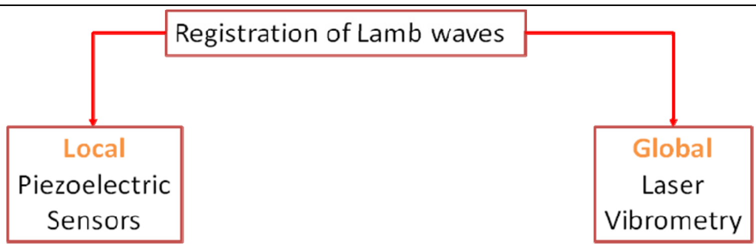
The next important problem concentrates on applications of distributed and concentrated piezoelectric networks. Both networks are widely used for elastic wave generation and acquisition. Elastic wave propagation phenomenon is used for damage localisation in metallic (isotropic) and composite (anisotropic / orthotropic) materials. This approach uses a fact that any discontinuities existing in structural elements cause local changes of physical material properties which affect elastic wave propagation.

Generally concentrated piezoelectric networks are used for metallic structures. Distributed networks are used for composite structures (because of higher attenuation).

Elastic waves can be excited and received using piezoelectric transducer networks with different element arrangement. Transducer network configuration and the number of used piezoelectric elements have influence on the accuracy of damage localisation algorithm. Obviously the more elements there are the more data has to be processed.

Acquired signals are deteriorated with noise, therefore they have to be filtered before extraction of features. For this purpose algorithms for filtering are used. After filtering process further signal processing is conducted in order to create damage influence maps. The maps present elastic wave energy connected with reflection from discontinuities.

Measurement techniques



Local	Global
▪ *Response in the form of signal at sensor locations* ▪ *Various transducer networks = different damage identification* ▪ *Reference signals are needed* ▪ *Problematic damage localization*	▪ *Response in the form of full wavefield* ▪ *Reference signals are not needed* ▪ *Perfect damage localization* ▪ *Offline monitoring (long measurement time, bulky devices)*

2.0 OPTIMUM SENSOR PLACEMENT

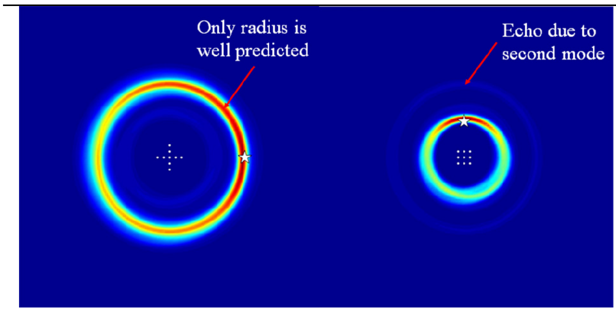


Figure 1 (a): Transducer configurations [1].

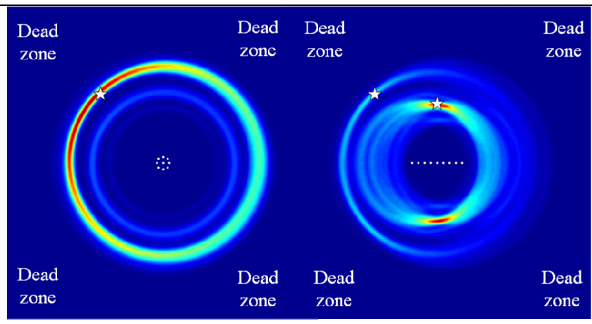


Figure 1 (b): Transducer configurations [1].

Determination of the optimal placement of sensors is a very challenging mission. The purpose is to consider various configuration of piezoelectric sensors and find the optimal solution. Figures 1(a) and 1(b) show some examples published in [1].

Determination of the optimal placement of sensors is a very challenging mission. The purpose was to consider various configurations of piezoelectric sensors and find the optimal solution. Various sensors networks geometries were picked out from the measured points.

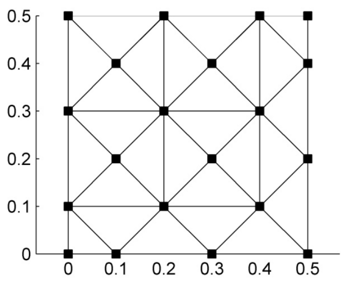


Figure 2 (a): Transducer configurations [1].

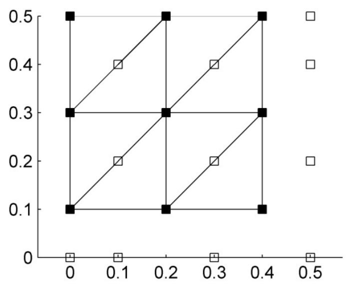


Figure 2(b): Transducer configurations [1].

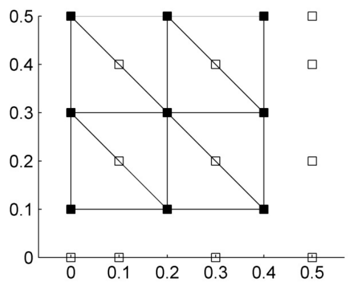


Figure 2(c): Transducer configurations [1].

Figures 2(a) – 2(c) show the multi triangular grid features for triangular grids of piezo elements (black box – active, empty box – inactive).

Damage influence maps for triangular grids given above are presented in Figures 3(a) – 3(c).

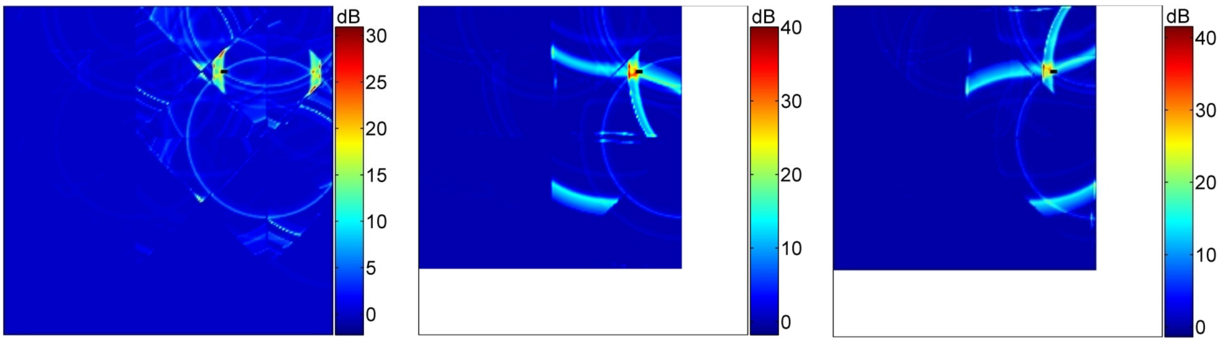


Figure 3(a)-(c): Damage influence maps for different damage configurations [1].

In the multi triangular method particular damage influence maps are combined into one map by summation (see Figures 4(a) and 4(b)). It is obvious that mesh density is strictly correlated with accuracy of the damage localisation method.

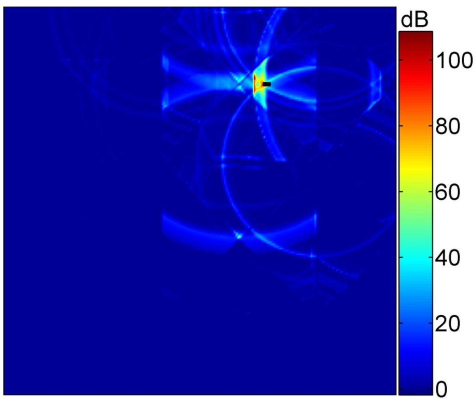


Figure 4(a): Sum of maps for triangular grids [1].

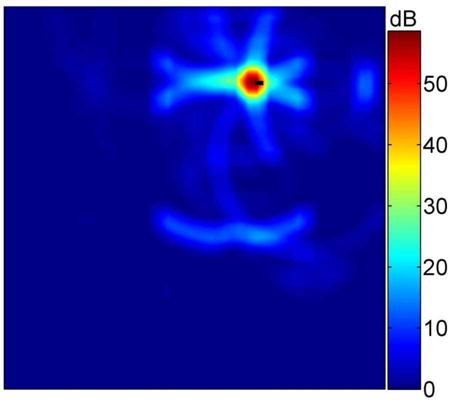


Figure 4(b): Smoothed map by mean average filter [1].

3.0 SHM SIGNAL PROCESSING AND VISUALIZATION

3.1 Laser Scanning Vibrometry

In [2] an interesting embedded signal processing subsystem has been presented. The subsystem is a part of a whole Structural Health Monitoring System (see Figures 5 and 6). Embedded signal processing subsystem is realized on Field Programmable Gate Array (FPGA). In FPGA system on programmable chip (SoPC) and damage localization algorithm are implemented. The aim of this algorithm is to create damage map which presents places in the structure where elastic wave reflections occur.

Distributed PZT System	*System used for excitation and record of elastic waves*	*System used for signal processing*	*System used for result display*

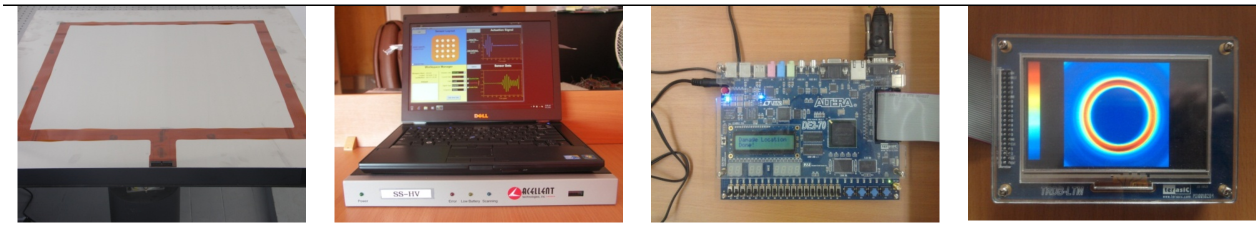


Figure 5: System for failure monitoring (SHM) [2].

Elastic waves are generated and received using prototype of electronic system developed especially in this purpose. Piezoelectric transducers are arranged as a networks with different geometrical configurations.

Embedded system for signal processing (application: elastic wave propagation)

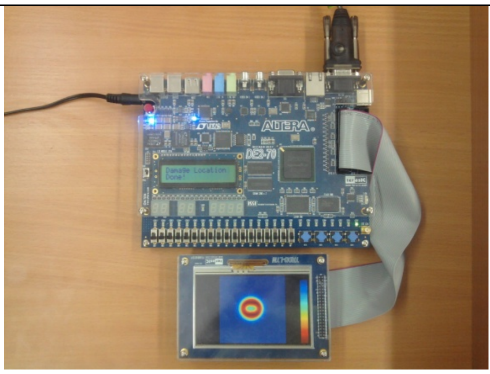


Figure 6(a):System based on FPGA Cyclone2 EP2C70.

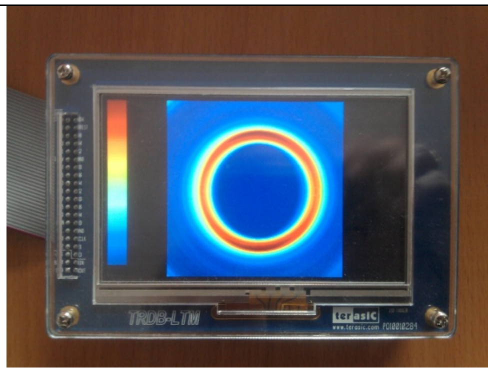


Figure 6(b): Display LCD 4,3” 480×800 points.

The second major concept for damage localization and characterization is based on a global guided wave registration method. For this purpose measuring devices like scanning laser vibrometers or scanning air coupled transducers are used. These devices allow one to measure propagating guided waves on the whole surface of the specimen. In this way new possibilities arise, enabling high spatial resolution visualization of guided wave interaction with various types of damages. Figure 7 presents an equipment for 3D laser scanning vibrometer.

Measurement of the wave field is realized using laser scanning vibrometer that register the velocity responses at points belonging to a defined mesh. This non–contact tool allows phenomena related to wave propagation in considered aircraft elements to be investigated (Figures 8 and 9) [3]. The excited waves are measured in defined points by the vibrometer obtaining the wavefield, (Figures 9(a)–(c)). Signal processing procedures are used in order to visualize the interaction of elastic waves with specimen failures (cracks, delaminations, etc.). The signal features are applied in order to detect and localize the presence of damages.

Figure 7: Laser scanning vibrometry (Institute of Fluid Flow Machinery, PAS, Gdansk).

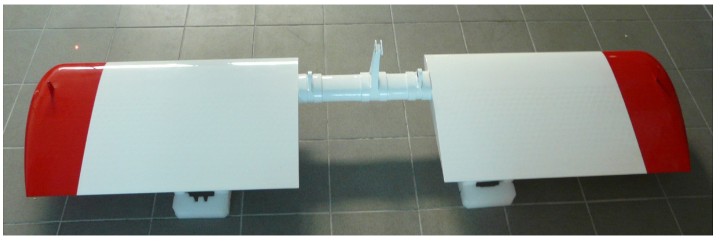


Figure 8: Honeycomb aircraft control surface used for analysis.

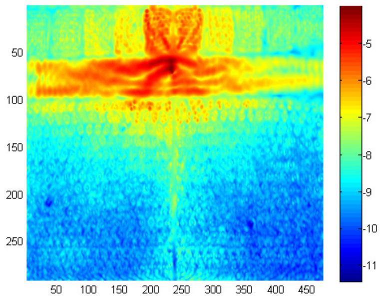


Figure 9(a): Frequency 16.5 kHz.

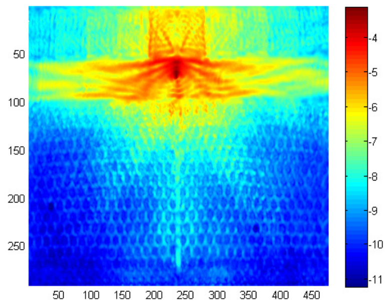


Figure 9(b): Frequency 35 kHz.

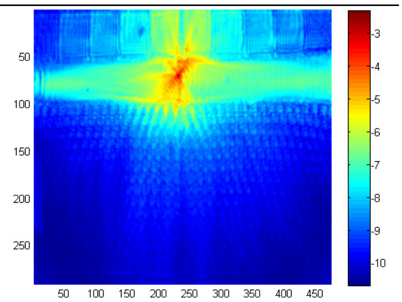


Figure 9(c): Frequency 100 kHz.

In the first step damage detection is based on full wavefield measurements. In this way it is possible to obtain amplitude contrast between region with discontinuities and without them. In the second step a point–wise damage detection is conducted. It was based on several laser measurement points treated as sensors. Some results of damage detection are shown in Figures 10(a)–(c) [4].

In recent years many researchers develop new methods of filtering and processing of guided wavefield images acquired by the laser vibrometers. One of the proposed damage localization method involve following operations:

- Acquisition of wave propagation images at each sampling interval t_i
- For each wave propagation image 2D Discrete Fourier Transform is performed
- Determining wave propagation pattern in wavenumber domain

- Filtering applied in the wavenumber domain
- Reconstructing filtered propagation image with 2D Inverse Fourier Transform

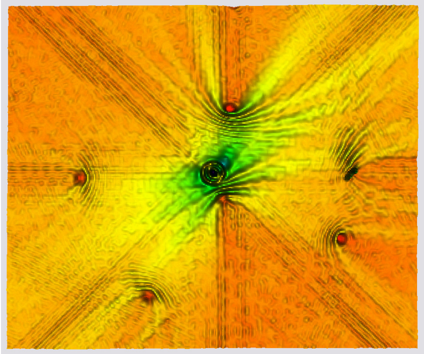


Figure 10(a): Additional masses detection.

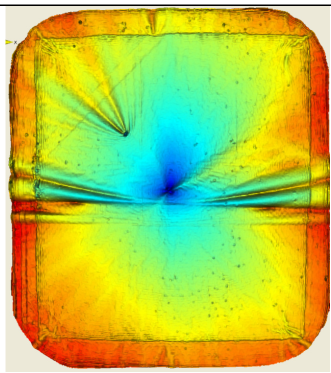


Figure 10(b): Notch detection.

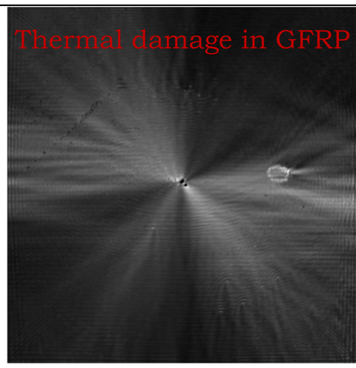


Figure 10(c): Thermal damage detection.

First step consists in measurements of excited guided wavefield images at a rectangular grid of points covering inspected area. As to the sequence shown in Figure 11 the second step is to transform obtained images to wavenumber domain using 2D DFFT (Discrete Fast Fourier Transform). The next step is to create a wavenumber domain pattern of propagating guided wave based on a defined number of wavefield images. Successively this pattern is removed from the whole data and 2D Inverse Fast Fourier Transform is applied. This operation removes the main component of guided waves leaving only information about changes in wavefield pattern caused by specimen's discontinuities.

In this way all structural features as well as damage locations may be easily recognized. As a final damage index these filtered guided wavefield images are used for creating RMS map.

3.2 Terahertz Technology

The second global method for damage localization and characterization is based on terahertz technique (Figure 12). THz spectrometer is designed for non–destructive testing of materials. It works according to the method of time–domain spectroscopy. THz spectroscopy method uses a band of electromagnetic radiation in the terahertz range. The waves propagate through the specimen and have lengths in the range of 1 mm to 30 microns. Terahertz waves have a number of characteristics that indicate broad possibilities of their application to the measurement of thin layer properties.

Terahertz radiation is relatively easy to penetrate through most polymeric materials. Metals and other conductive materials (i.e. carbon fiber) are not transparent and cause reflection of terahertz waves. Terahertz radiation also exhibits greater contrast to the infrared, visible and X–ray. Its lower permeability allows materials with lower density to be analysed. An important feature of terahertz radiation is its non – ionization character (no harmful effects on the human body), which increases operating safety performing the tests. Figure 13 provides an example of the images retrieved when applying the terahertz technique to a PZT-equipped SHM system described in the chapter before of this book.

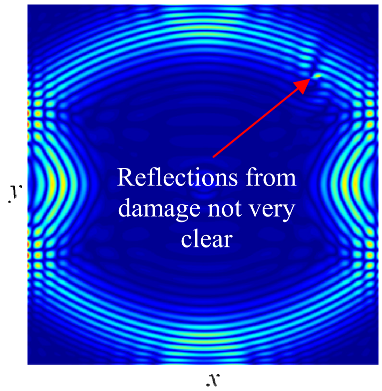


Figure 11(a): Acquisition of wave propagation images at each sampling interval t_i [5].

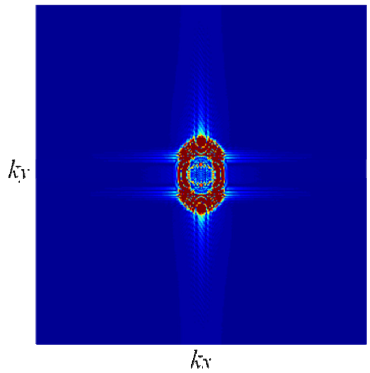


Figure 11(b): For each wave propagation image 2D Discrete Fourier Transform is performed [5].

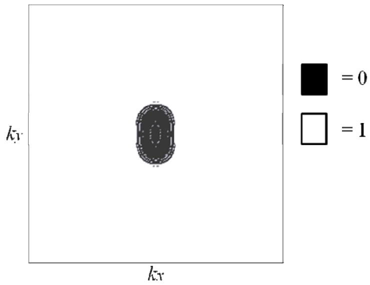


Figure 11(c): Determining wave propagation pattern in wavenumber domain [5].

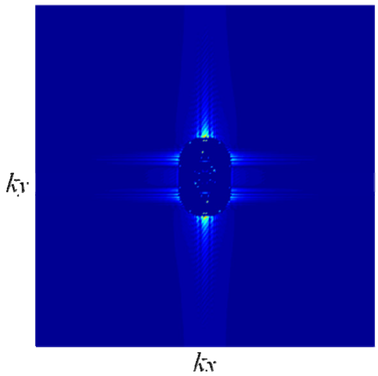


Figure 11(d): Filtering applied in the wavenumber domain [5].

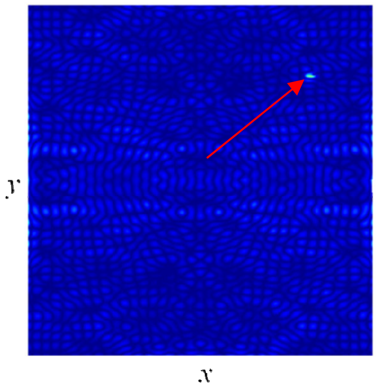


Figure 11(e): Reconstructing filtered propagation image with 2D Inverse Fourier Transform [5].

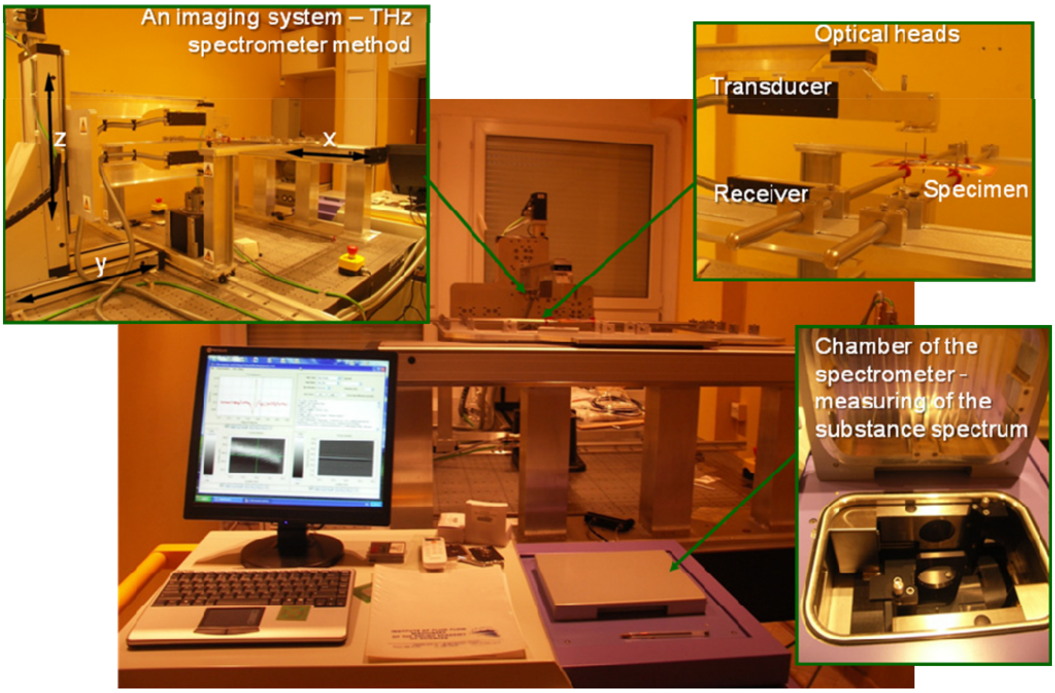


Figure 12: THz spectrometer at the laboratory of the Institute of Fluid Flow Machinery, PAS, Gdansk.

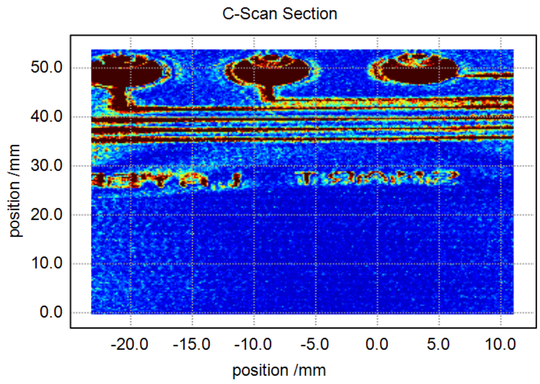


Figure 13(a): PZT matrix – THz imaging (laboratory of the Institute of Fluid Flow Machinery, PAS, Gdansk).

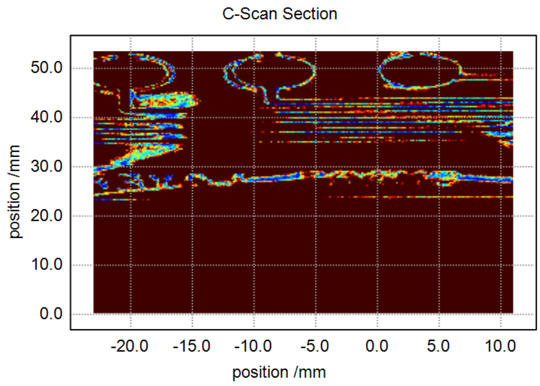


Figure 13(b): PZT matrix – THz imaging (laboratory of the Institute of Fluid Flow Machinery, PAS, Gdansk).

4.0 REFERENCES

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