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Application of RMS for damage detection by guided elastic waves

M Radzieński^{1,2}, Ł Doliński¹, M Krawczuk^{1,2}, A Żak² and W Ostachowicz^{2,3}

¹Gdansk University of Technology, Faculty of Electrical and Control Engineering,
Narutowicza 11/12, 80-952 Gdańsk, Poland

²The Szewalski Institute of Fluid-Flow Machinery, Polish Academy of Sciences,
Fiszera 14, 80-952 Gdańsk, Poland

³Gdynia Maritime University, Faculty of Navigation, Al. Zjednoczenia 3, 81-345
Gdynia, Poland

E-mail: Maciej.Radzienski@gmail.com

Abstract. This paper presents certain results of an experimental study related with a damage detection in structural elements based on deviations in guided elastic wave propagation patterns. In order to excite guided elastic waves within specimens tested piezoelectric transducers have been applied. As excitation signals 5 sine cycles modulated by Hanning window have been used. Propagation of guided elastic waves has been monitored by a scanning Doppler laser vibrometer. The time signals recorded during measurement have been utilised to calculate the values of RMS. It has turned out that the values of RMS differed significantly in damaged areas from the values calculated for the healthy ones. In this way it has become possible to pinpoint precisely the locations of damage over the entire measured surface. All experimental investigations have been carried out for thin aluminium or composite plates. Damage has been simulated by a small additional mass attached on the plate surface or by a narrow notch cut. It has been shown that proposed method allows one to localise damage of various shapes and sizes within structural elements over the whole area under investigation.

1. Introduction

Lamb waves are special type of elastic waves which propagate between two parallel surfaces and may travel relatively long distance with small amplitude decrease. In real structures this phenomenon is also called guided Lamb waves or guided elastic waves, due to finite dimension of test object. Employing this phenomenon in construction elements allows for its technical state assessment and it has been investigated by many researchers as a tool for damage detection and localization.

Classical approach in Structural Health Monitoring (SHM) is based mostly on employment of actuators and PZT sensors [1-3]. Placing them (so introducing additional mass and changing local stiffness) on the surface of a specimen may negatively influence measurements conditions. Additionally it is unrealizable to observe whole the surface of tested structure. This problem could be overcome by using Scanning Laser Vibrometer. In 1999 Eudeline et. al. [5] presented Lamb wave

generated in a duralumin plate immersed in water. The experiment was taken using laser vibrometer positioned that its beam was perpendicular to measured surface. Changes of measure points were performed by moving laser head. M. Kehlenbach et. al. [6] in 2003 shown numerical results of Lamb wave propagation in aluminium plate which were confirmed by experimental results using scanning laser vibrometer afterward. They made a visualization of a propagating waves in damaged region. The conclusion was that the effectiveness of a damage detection depends of defect size. In articles [7-9] experimental results of damage detection using Lamb waves in aluminium plate were presented. The surface around the damage was scanned using laser vibrometer. Damage was detected by finding area with maximum signals values. Staszewski et. al. [11] propose a method of Lamb waves measurements in aluminium plate using 3D laser vibrometry. Authors highlighted that this approach allows to separate in-plane (A_0 mode predominance) and out-of-plane (S_0 mode predominance) components. Both A_0 and S_0 modes may be utilized for damage detection. In [12] composite plates damage detection using Lamb waves was studied. Authors showed that it is possible to detect and assessed its size of a delamination.

This paper demonstrates damage detection method based on measurements of guided elastic wave propagation phenomenon by scanning laser vibrometer. Proposed method utilize changes in energy caused by waves reflection from the discontinuities.

2. Experimental measurement

The investigations have been carried out for two types of thin plates (aluminium and composite) with dimensions of 1000mm by 1000mm and 1mm thickness. The plates were placed on 2 cm thick polyurethane foam to reduce the influence of an external vibration on the measurement results and to simulate free vibration conditions. All measurements have been carried out using a PSV- 400 Laser Scanning Vibrometer. Piezoelectric element and linear amplifier (provided by PIEZO SYSTEMS, INC) were used to generate guided elastic waves.

2.1. Aluminium and composite plates

The first object of research was made of pure aluminium (99.5%). Figure 1a schematically illustrates the test object with location of measurement grid, the position of the actuator (guided elastic waves source), and arrangement of damages. The measurement grid consisted of 331 vertical lines and 281 horizontal lines - a rectangle 0.555x0.490m (93011 points). The intersection point of the rectangle diagonals coincides with the plate centre and the source of guided elastic waves. Piezoelectric transducers have been fixed to the plate by electrical conductive adhesive (plate has been used as the negative electrode) and epoxy glue (figure 1b).

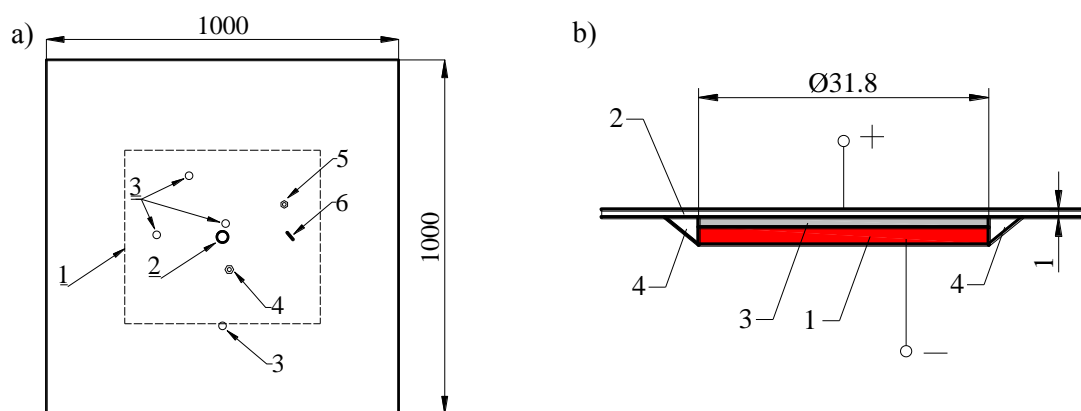


Figure 1. a) Aluminium plate: 1 – measurement area, 2 – PZT actuator, 3, 4 and 5 – additional mass (damages), 6 – notch cut; b) attachment of the active element: 1 – PZT actuator, 2 – aluminium plate, 3 – electrical conductive adhesive, 4 – epoxy glue, +/- – electrodes.

Damage has been simulated by a small additional mass fixed on the plate surface (metal discs with a diameter of about 15 mm) and by a narrow notch cut (25 millimetres length, a millimetre width and depth of 0.5 millimetres). The experiment involved three value of the additional masses: 1.6 grams (Figure 1a, position 3), 2.5grams (position 4) and 9.8 grams (position 5).

The fibreglass cloth woven roving and the epoxy resin have been used as the laminate components of the second object. Reinforced fibers of four layers have been symmetrically arranged ($0^\circ/90^\circ$). In this case the measurement grid consisted of 90475 which formed a rectangle with dimensions 0.6 by 0.5m (331 vertical lines and 281 horizontal lines). The location of PZT element, measured area and arrangement of the damages for composite plate is showed at the figure 2a. Measurements have been carried out at four positions for different values of the additional mass. Positions 1 and 2 were additional masses with a value of 3.2 grams placed according to direction of the laminate fibers. In the position 3 and 4 the damages were placed on the diagonal of the plate (45 degrees to the fibers) on both sides of the piezoelectric element (3.2 grams of additional weight for position 3 and 1.6 grams of additional weight for position 4). In the composite the piezoelectric transducer has been placed between layers of woven roving during the lamination process (figure 2b).

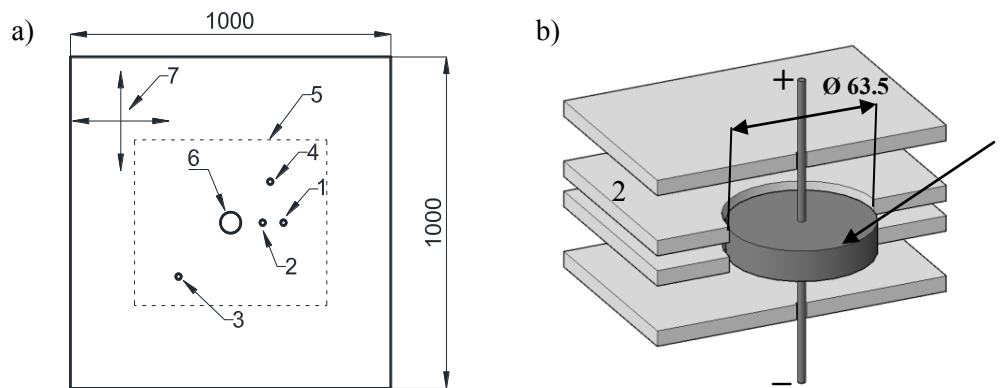


Figure 2. a) composite plate: 1 to 4 – additional mass (damages); 5 – measurement area, 6 – PZT actuator, 7 – direction of fibers, b) attachment of the active element: 1 – PZT actuator, 2 – laminate layers, +/- – electrodes.

Table 1 shows the basic parameters of the piezoelectric transducers used in the experiments [13].

Table 1. Characteristic features of PZT element

	Aluminium plate	Composite plate
Type	T216-A4NO-373X	T216-A4NO-573X
Diameter [mm]	31,8	63.5
Rated Voltage [Vp]	± 180	± 180
Resonant Frequency [Hz]	1170	290
Free Deflection [μm]	± 119	± 476

2.2. Laser Scanning Vibrometer

Experiment has been carried out using PSV- 400 Laser Scanning Vibrometer. The most important part of PSV system is sensor head with laser Doppler vibrometer which enables one to make fast, accurate and non-contact vibration measurements of whole tested surface. Hence, the influence of undesirable effects which could distort the results has been eliminated. The main advantages are automatic, high sensitivity and non-contact measurement capabilities. Entire surfaces can be rapidly scanned and automatically probed with flexible and interactively created measurement grids. The vibrometer

automatically moves to each point on the scan grid, measures the response and validates the measurement by checking the signal-to-noise ratio [4].

In order to provide optimal conditions for measuring a large dispersion of the laser beam reflected from the measurement surface should be avoided. Small amount of light returning to the sensor head would cause noisy measurement. To overcome this effect, the measured area was taped with reflective film. Characteristic feature of this film is that it is reflecting light in the direction of its source.

2.3. Excitation

Generated wave packages for measurements were composed of 5 or 4 sinus periods multiplied by Hanning window for aluminium and composite plate respectively. For each point measurements were repeated 20 times and a recorded time signal was averaged to improve signal-to-noise ratio. Between measurements 50ms time interval was used assuring that previously generated waves faded out. Frequency of the excitation signal for aluminium plate was 35kHz and for composite specimen 10kHz. Sampling frequency was set up at 512kHz for the aluminium plate and 256kHz for the composite plate. Both cases 1024 time samples were registered (4ms and 8ms).

3. Results – guided elastic wave propagation

It is typical for scanning laser measurements that a small amount of points have lower signal-to-noise ratio caused by the fact that not enough reflected light returned to the scanning head. Those points have much bigger Root Mean Squared (RMS) values. To reduce this effect a median filtering in space domain with 3x3 points window was applied. Examples of registered guided elastic wave propagation in the aluminium plate were presented in form of 6 arbitrary chosen time snapshots. Figure 3 shows guided elastic waves propagation in the aluminium plate with attached an additional mass.

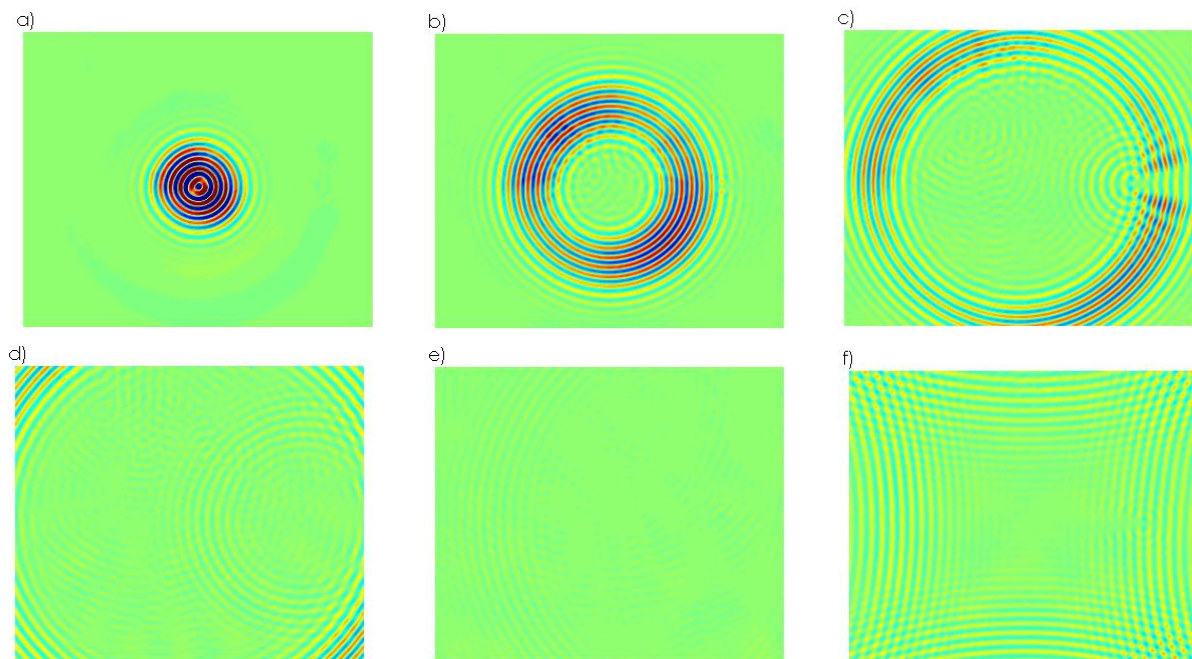


Figure 3. Propagation of elastic wave in the aluminium plate with one damage at time a) 97.66 μ s b) 195.31 μ s c) 292.97 μ s d) 390.62 μ s e) 585.93 μ s f) 781.25 μ s

Due to the fact that the additional mass introduce discontinuity, propagating waves are reflected and the damage became a source of new waves. This effect is clearly visible in figure 3c. This phenomenon may be used for damage detection. However, it could be hard to recognize all defects when there are more of them like in figure 4. For more accurate damages pattern recognition the RMS-based damage detection method is proposed.

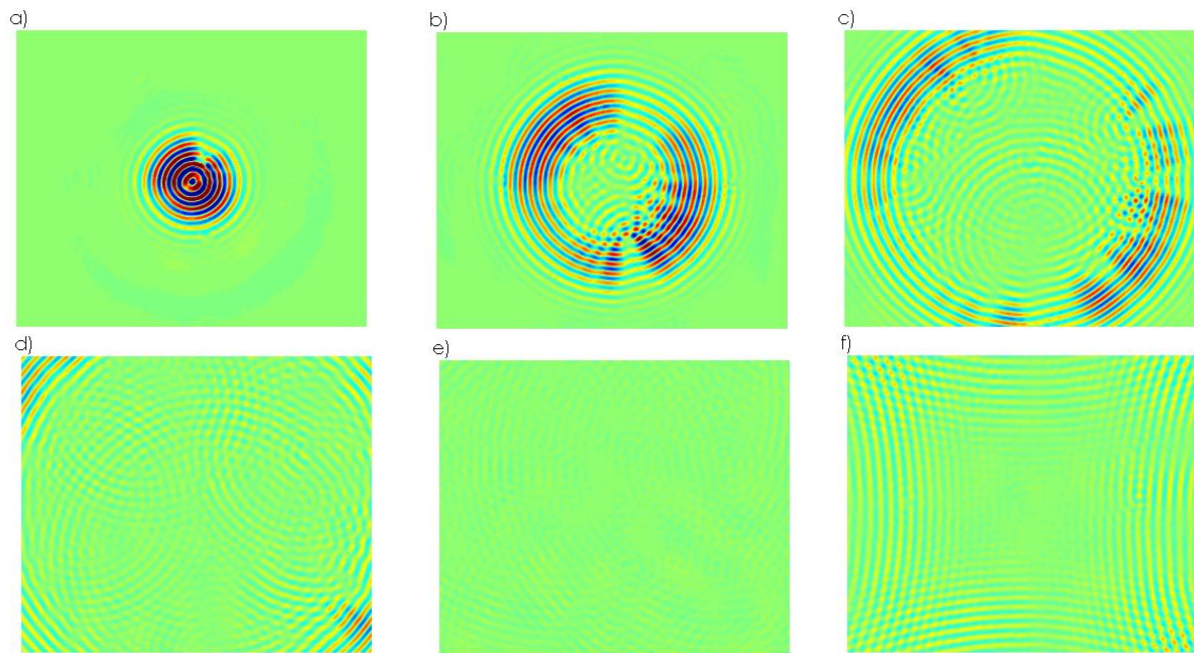


Figure 4. Propagation of guided elastic wave in aluminium plate with 7 failures at a) 97.66 μ s b) 195.31 μ s c) 292.97 μ s d) 390.62 μ s e) 585.93 μ s f) 781.25 μ s

4. RMS-based damage detection method

Registered time signals were used to determine Root Mean Squared (RMS) value for each point as

$$RMS = \left(\sum_{k=1}^N f_k^2 / N \right)^{1/2}, \quad (1)$$

where f_k^2 is a squared vibration magnitude for a sample k , and N is a number of samples used for RMS calculation. Because guided elastic wave is reflected from damages, distribution of the energy is changed. Those changes are represented as changes in the RMS values and could be used for damage detection. Considering this map from excitation point of view behind the damage the RMS has lower values and in front of the damage waves interference pattern appears.

Great values of RMS function in excitation area produce that almost whole range of scale values are spread only on this small area. To overcome this problem authors propose to use logarithmic values of RMS function. This shall ease identification of local energy distribution changes – potential damages. Figures 5, 6 presents RMS and log(RMS) functions for the aluminium plate using all 1024 time samples.

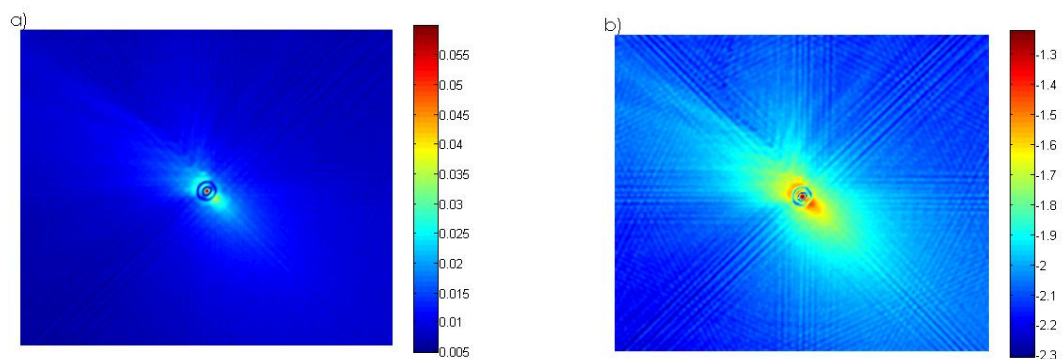


Figure 5. Reference aluminium plate a) RMS b) log(RMS)

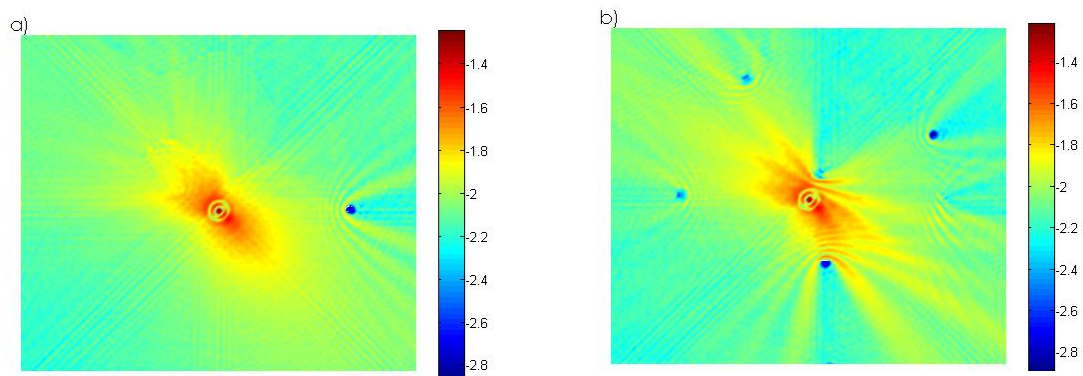


Figure 6. $\log(\text{RMS})$ function of the aluminium plate with a) 1 damage b) 7 damages

The magnitude of propagation wave decreases with travelled distance from the excitation point. In RMS function it produce bigger values near to the excitation. This cause effect that the further the damage the harder is to identify it. To equalize RMS function in whole area subsequent time samples are multiplied by a weight factor as

$$\text{RMS_}W^k = \left[\sum_{i=1}^N (f_i^2 \cdot t^k) / N \right]^{1/2} \quad (2)$$

where $\text{RMS_}W^k$ is proposed weighted RMS function and k is a power of the weight factor. Comparisons of $\text{RMS_}W^k$ and $\log(\text{RMS_}W^k)$ calculated using first 256 time samples (1ms) for different k values are showed in figures 7 and 8 correspondingly.

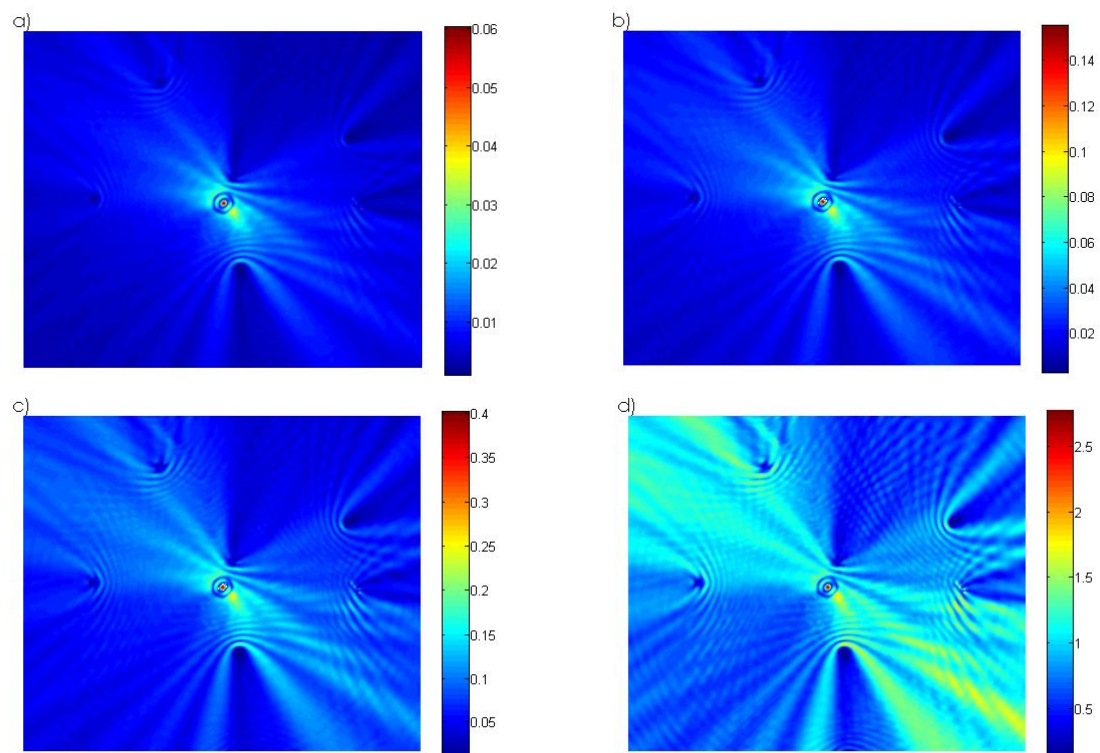


Figure 7. $\text{RMS_}W^k$ function for aluminium plate with 7 damages a) $k = 0$ b) $k = 0.5$ c) $k = 1$ d) $k = 2$

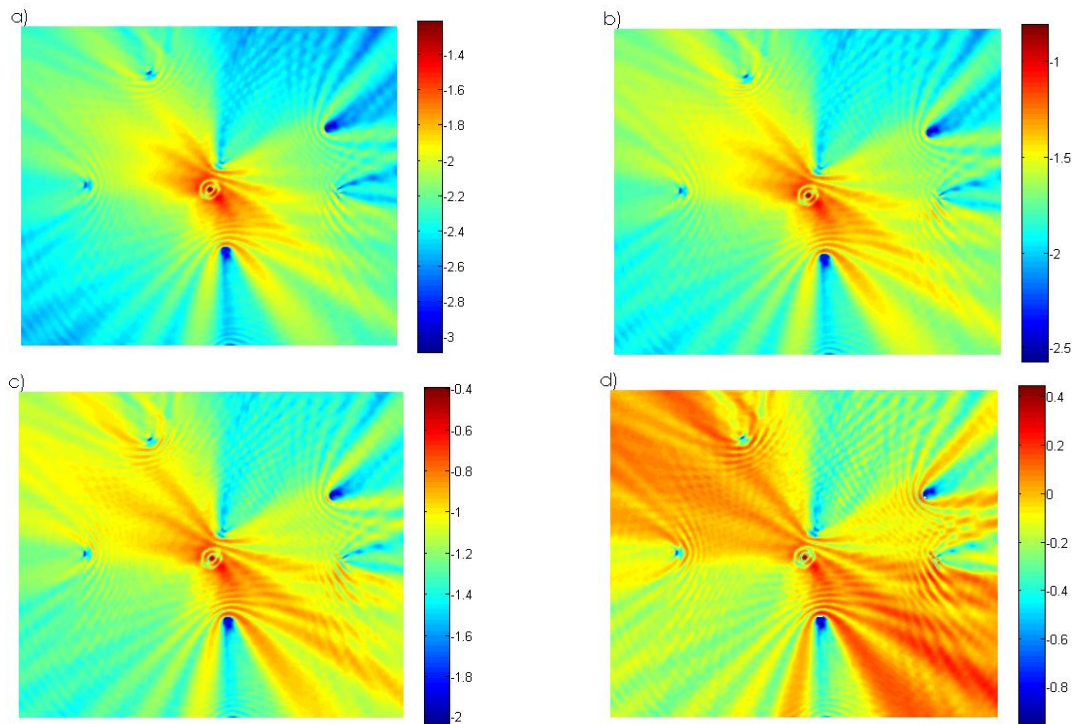


Figure 8. $\log(RMS_W^k)$ for aluminium plate with 7 damages a) $k = 0$, b) $k = 0.5$, c) $k = 1$, d) $k = 2$

It is worth to notice that the higher k factor is the more influence on the RMS function time period used for calculation has. Figure 9 presents comparison of $\log(RMS_W^2)$ function when different number of time samples were used.

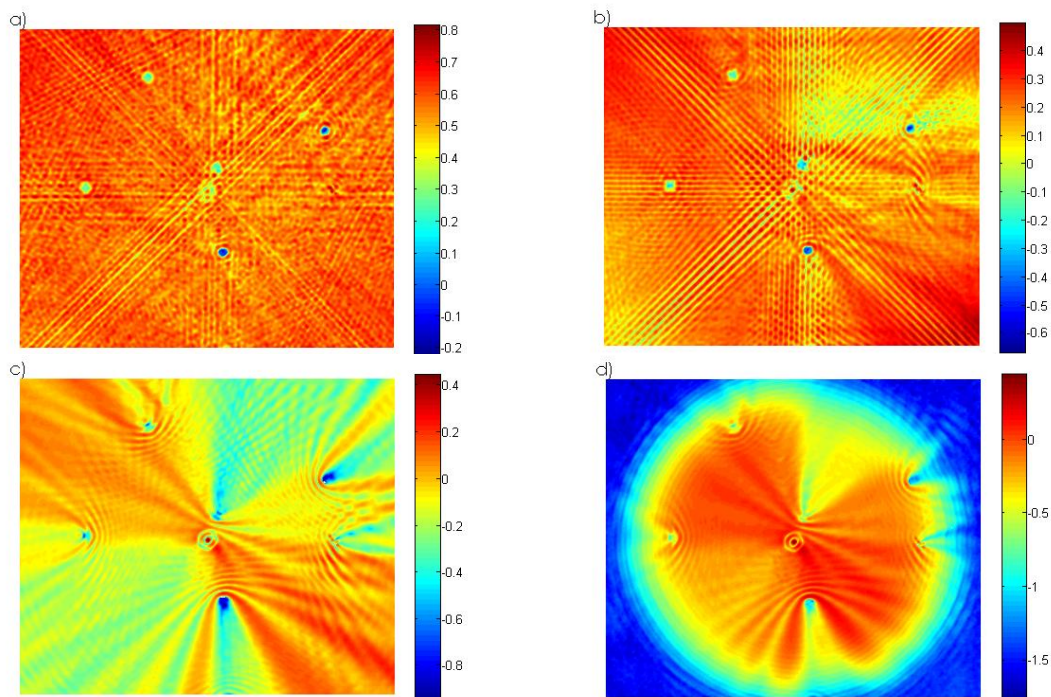


Figure 9. $\log(RMS_W^2)$ function for aluminium plate with 7 damages when using a) 1024 first time samples, b) 512 first time samples, c) 256 first time samples, d) 128 first time samples.

In figure 10 six chosen time samples of propagating guided elastic waves in composite material are presented. It is visible that this material is anisotropic, and the wave travels faster in horizontal and vertical directions. The reflections of the simulated damage is also visible (fig. 10d) but it is hard to recognize that there were two masses attached.

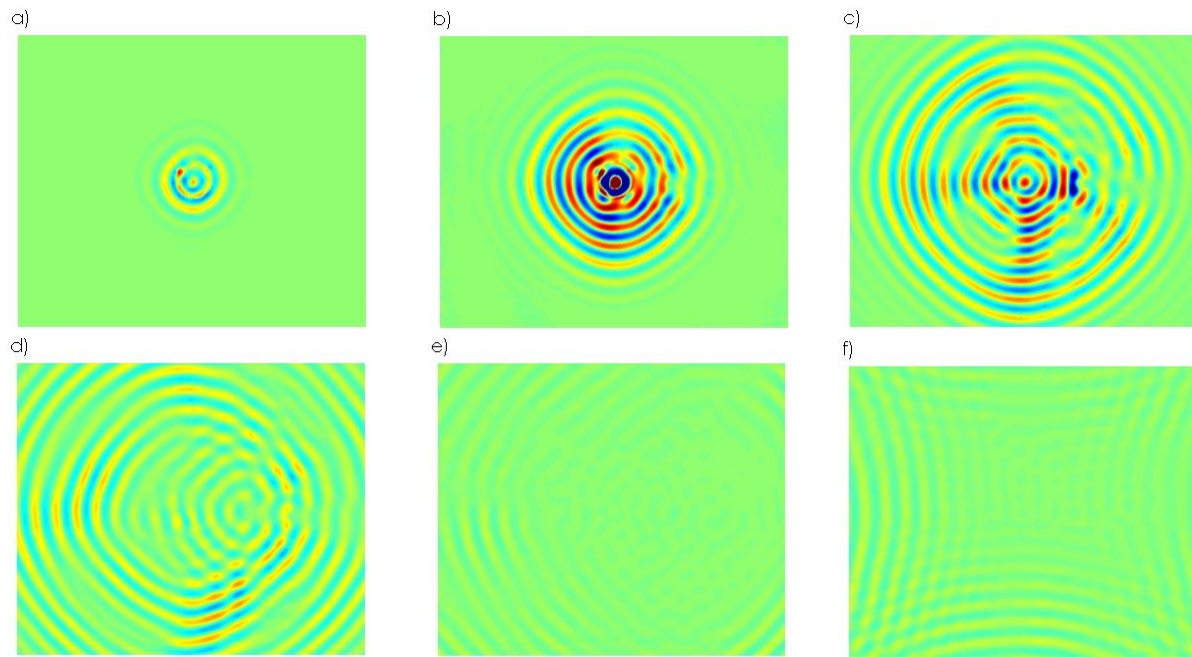


Figure 10. Propagation of guided elastic wave in composite plate with 2 damages v2 at a) $195.31\mu\text{s}$ b) $390.62\mu\text{s}$ c) $585.94\mu\text{s}$ d) $781.25\mu\text{s}$ e) $1172\mu\text{s}$ f) $1562\mu\text{s}$

The RMS functions presented in figure 11a may be used for determining both damages. Another example of RMS-based function for the composite plate with two damages positioned elsewhere are showed in figure 11b. Both cases 256 first samples (2ms) were used.

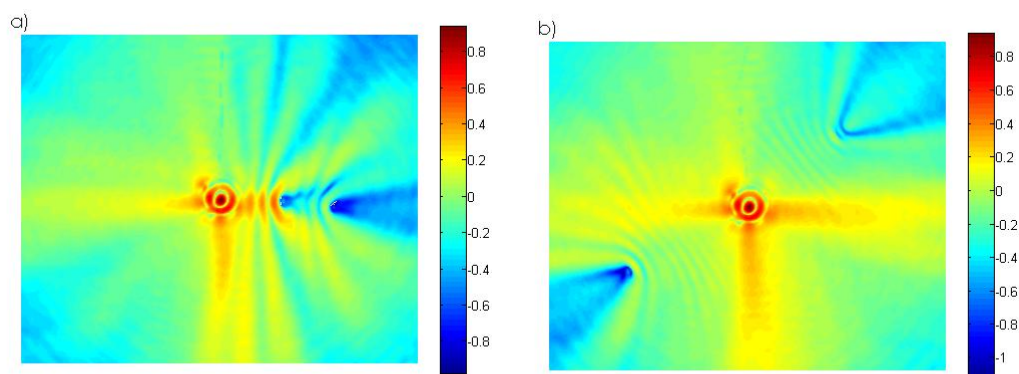


Figure 11. Composite plate with two attached masses a) case 1 b) case 2

The results presented above were obtained from very precise measurements but each of the experiments took about 14 hours. This time is unacceptable from a practical point of view. Thus authors examined shorter testing by reducing number of points from over 90,000 to 9,000 and skipped signal averaging. Hence 200 times less signal registrations were made and therefore the time was reduced to 5 minutes. To improve results (for easier damage pattern recognition) linear and spline interpolation in space domain were tested. Firstly calculated RMS function was interpolated with

linear (fig. 12b) and spline (fig. 12c) functions. This approach do not ease damages pattern recognition. However, when every time sample is interpolated in space domain by spline functions (fig 12d) calculated RMS afterwards is improved. Obtain RMS map is very similar to high resolution results (fig 8d).

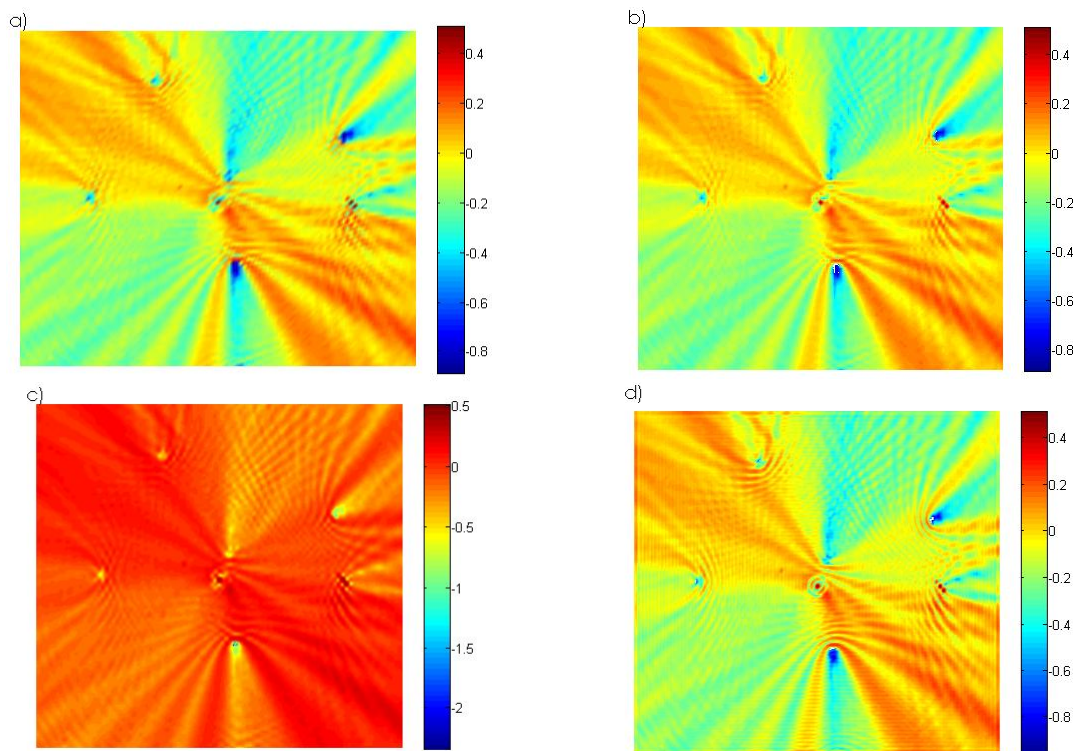


Figure 12. $\log(RMS_W^2)$ function for the aluminium plate with 7 damages a) RMS without postprocessing, b) linear interpolated RMS c) spline interpolated RMS, d) RMS calculated from spline interpolated samples in space domain

Those shorter time measurements of RMS-based function may be successfully used for damage detection and localization. In presented case for the aluminium plate with multiple damages only one of them which was outside the scanned area was impossible to recognize.

5. Conclusions

Obtained results leads to following conclusions:

- Scanning Laser Vibrometer allows very precise measurements of guided elastic waves propagation phenomenon
- RMS-based function is very sensitive tool for damage detection in aluminium or composite plates and allows to pinpoint location of multiple damages like small addition mass (1.6g) or narrow notch cut (0.5mm deep) in the whole measured area.
- Logarithmic values of RMS-based functions ease damage recognition
- Proposed weight factor in RMS-based function improve this method
- It is important to use proper time period for RMS_W^k calculation
- The best results were obtained using 256 time samples, $k = 2$ and logarithmic value of RMS-based function
- The measurement time were shorten by using coarser measuring grid and skipping averaging, still being possible to detect damages

- To improve low resolution RMS spline interpolation in space domain of all time samples should be used.

Acknowledgements

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