Guided Waves-Based Damage Detection in Aircraft Component

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ABSTRACT

In this paper the investigation of a structural health monitoring method for thin-walled aircraft part is presented. The concept is based on the guided elastic wave propagation phenomena. This type of waves can be used in order to obtain information about structure condition and possibly damaged areas. In reported investigation piezoelectric transducer was used to excite guided waves in chosen structural element. Specimen was a riveted panel from an aircraft structure. Dispersive nature of guided waves results in changes of velocity with the wave frequency, therefore a narrowband signal was used to minimize the dispersion phenomenon. The generated signal was amplified before applying it to the transducer in order to ensure measurable amplitude of excited guided wave. Measurement of the wave field was realized using laser scanning vibrometer that registered the velocity responses at a points belonging to a defined mesh. This non-contact tool allowed to investigate phenomena related to wave propagation in considered aircraft element. Due to high complexity of the element baseline measurements were taken before measurements for component with the introduced discontinuity. Signal processing procedures were developed in order to visualize the interaction of elastic waves with specimens components (rivets, etc.). In the second stage of research the signals gather by laser vibrometry method were input to the damage detection algorithms. Signal processing methods for features extraction from signals were proposed. These features were applied in order to detect and localize the presence of damage. In the first step damage detection was based on full wavefield measurements. In this way it was possible to obtain amplitude contrast between region with discontinuities and without them. In the second step a point-wise damage detection was conducted. It was based on several laser measurement points treated as sensors. The signal processing was conducted in MATLAB with the procedures developed by authors. The results of damage detection were compared with each other and conclusions were drawn.

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INTRODUCTION

Elastic wave propagation phenomenon is more and more used in order to assess the state of various structures. Elastic wave propagation method is based on the fact that any kind of discontinuities existing in structures cause changes in elastic wave propagation. Based on these changes damage can be detected, localized or even identified. The main advantage of mentioned method is possibility of detection of damage in early stage of development. Besides this, mentioned method can be easily used in real-time Structural Health Monitoring SHM systems that working online.

Most often elastic waves are excited and sensed through piezoelectric transducers that are placed on investigated structures and creating a network with different configurations. In literature three types of network can be distinguished taking into account the manner of transducer placement: concentrated, distributed, and mixed. However elastic waves can be also excited and registered using noncontact laser based techniques. Excitation of elastic waves can be realized using photo-thermal method and Nd:YAG laser sources [1]. In the purpose of elastic waves registration laser vibrometers are utilized [2]. Scanning laser vibrometers allow to visualise elastic wave propagation in the structure what is very useful during the research. Application of noncontact measurement techniques are rather related to laboratory conditions.

In SHM for thin walled structures most often so called Lamb wave are utilized. The name of these elastic waves comes from the name of Horace Lamb who as first described this type of waves. These waves propagate as symmetric and antisymmetric modes and number of propagating modes strictly depend on product of excitation frequency and element in which waves are excited. However Lamb waves propagate only in thin unlimited solid media such a waves cannot propagate in structural elements which dimensions are limited. Therefore elastic waves propagating in the structural elements are called guided waves. These waves are very similar to the Lamb waves therefore in literature those names are used interchangeably what is not a valid.

Guided waves are utilized for damage detection and localization in simple structural element like beams, plates or shells made out of metal or composite material. Furthermore guided wave are also utilized in order to localize damage in pipes, rails or pressure vessels. Some papers can be found that describe utilization of guided waves for damage localization in more complicated structures like plate with stiffeners or riveted joints. For example in [3] guided waves are utilized for damage detection in riveted aluminium panel. Elastic waves can also be applied in order to localize damage in more complicated structures. In [4] possibility of damage localization in aluminium structures with various shape stiffeners and riveted joints is investigated. Interesting application of elastic wave propagation method can be found in [5] where problem of crack of monitoring in riveted aluminium structure during the fatigue test are conducted. Damage detection and localization in complicated riveted structures (e.g. aircraft structures) is possible however very laborious due to multiple wave reflection from structure discontinuity. In order to develop SHM system for such a structure it is very important to know how the elastic waves propagate in these structures. In this paper this is realized by application of scanning laser vibrometer that allow to visualize elastic wave behavior in the structure.

SCENARIO OF INVESTIGATION

A part of an aircraft structure was investigated. It was an aluminium riveted panel (thickness: 0.7 mm) that is a part of PZL-101 "Gawron" wing (Figure 1). A piezoelectric sensor (material: SONOX P502, diameter: 10 mm, thickness: 0.5 mm) was placed at the middle of one of the sections. The sensors was used to excite elastic waves. The excitation signal was a tone burst with 5 cycles of sine (100 kHz, 100 V). Measurements were divided into three cases. Firstly, a reference panel (without additional mass) was considered. Secondly, additional mass – a coin (diameter: 15.5 mm, weight: 1.5 g) was placed before the rivet lines 80 mm from the piezoelectric sensor (position 1 in Fig. 2). Thirdly, the mass was placed behind the rivet line 145 mm from the piezoelectric sensor (position 2 in Fig. 2). The placement of sensor and additional mass was schematically presented in Figure 2.

Figure 1. Investigated aircraft panel.

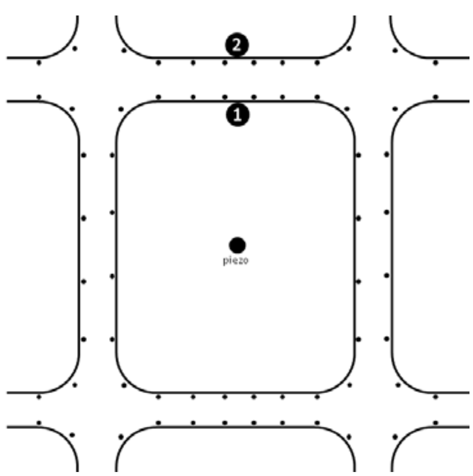

Figure 2. Schematic drawing of sensor and additional mass placement within the investigated panel.

The measurements were conducted using scanning laser vibrometer (Polytec PSV400). The measured surface was covered with retroreflective tape in order to enhance the signal level. The measured surface was the other than this shown in Figure 1. This means, that neither the presence of sensor nor additional mass influenced the measurements. For each case 94149 measurement points were used. The mean distance between two neighboring points were 1.6 mm, ensuring high spatial sampling of the wave field.

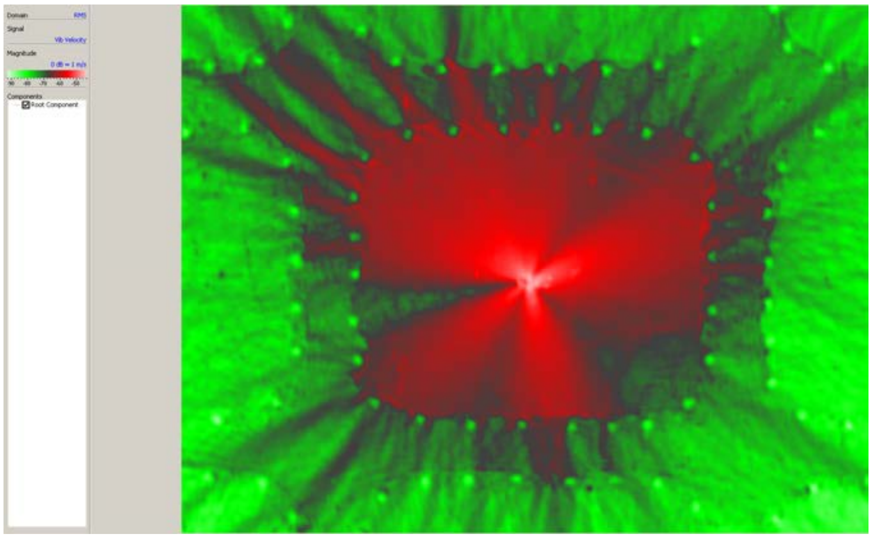

Figure 3. Reference measurement.

VISUALISATION

In the first approach the registered signals were mapped into surface of the panel by calculating the signal energy (the RMS index [6]) using the vibrometer software.
The result for reference case is presented in Figure 3. Logarithmic scale was chosen for plotting. One can easily notice the highest energy is at the middle of the panel section where the piezoelectric sensor was placed. Some imperfections in wave excitation can be noticed because the energy is not distributed equally around the sensor. The rivets can be clearly noticed due to a contrast in relation to neighboring areas. Another important observation is that the wave energy do penetrate the first and second rivet line but after the second rivet line the energy level is rather low.

DAMAGE LOCALIZATION RESULTS

In this section the two measurement cases with additional mass are investigated. Using the RMS index one can clearly distinguish the presence of the additional mass before the rivet lines (Figure 4). As one can see the mass shadows the area behind it. In the case of the additional mass behind the rivet lines, the location of the mass cannot be indicated (Figure 5).

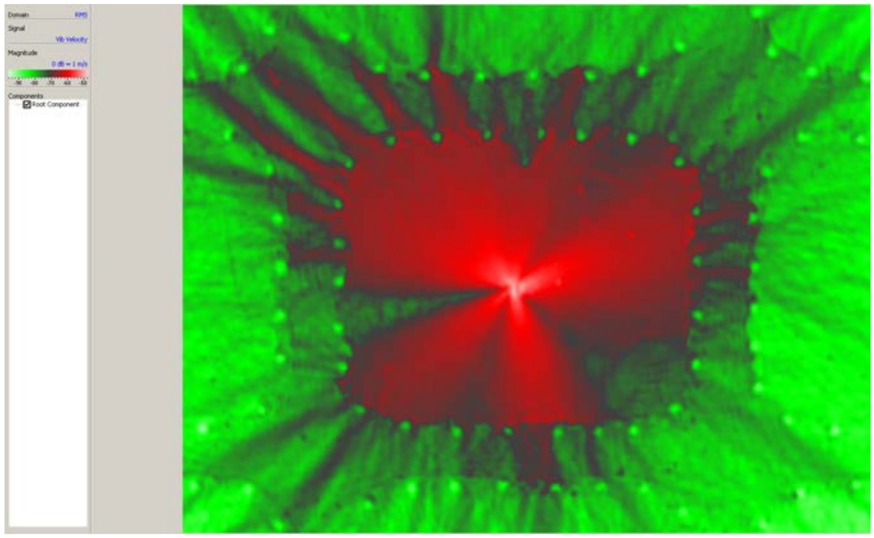

Figure 4. Discontinuity before rivet lines.

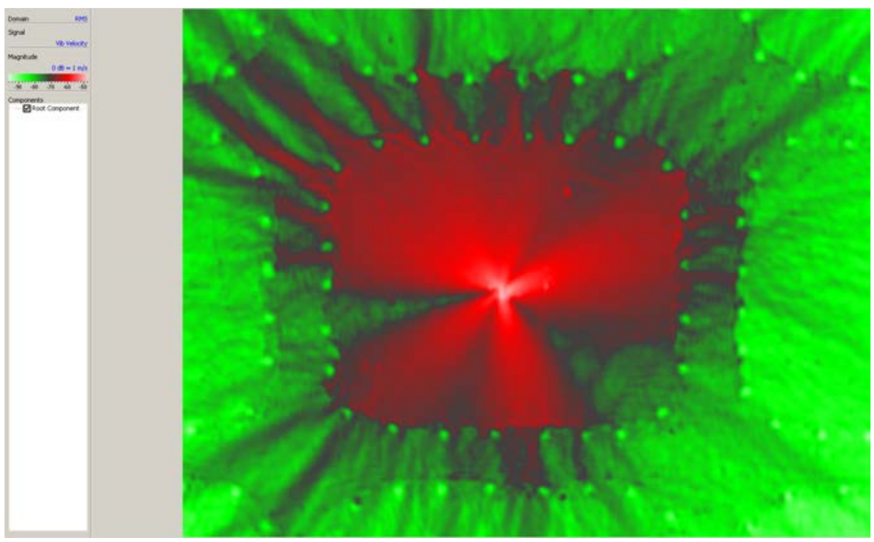

Figure 5. Discontinuity behind rivet lines.

A signal processing algorithm was proposed to further investigate the obtained results. From the registered signals only a part was extracted that represents time necessary for a wave to propagate from the piezoelectric sensor to considered point (t_E in Figure 6). The new index was calculated by formula

$$E_j = \sum_{k=1}^{N} S_{j,k}^2 \tag{1}$$

N was chosen to fulfill the relation: $t(N) = t_E$. The measurement points chosen for investigation were selected to be placed on a horizontal line. In the first step the points lying 50 mm away from the sensor were investigated. These points were lying between the sensors and the upper rivet line. The normalized energy for these point is plotted in Figure 7.

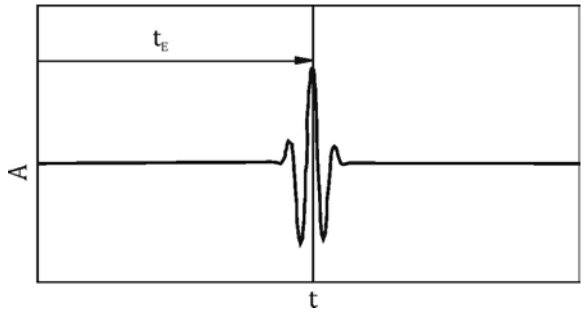

Figure 6. An illustration for signal processing algorithm. The signal part up to t_E is extracted.

As one can notice for both cases (additional mass before and behind the rivet lines) the presence of additional mass did not influence the reading and the result follows the same trend. In the second step the points lying 80 mm away from the sensor were picked. This distance corresponds to the mass placed before the rivet line. This time an energy drop was observed in comparison to the case without the mass (Figure 8). The energy drop is around $x=0$ which correspond to horizontal position of the sensor and the additional mass. The variation in energy is a clear indicator of damage presence. In the third step of investigation the distance corresponding to the mass placed behind rivet lines (150 mm away from the sensor) was considered. In both cases the energy distribution along a horizontal line follows the same trend (Figure 9). It appears that the wave energy after propagating through the rivet lines is too weak to indicate the presence of the discontinuity.

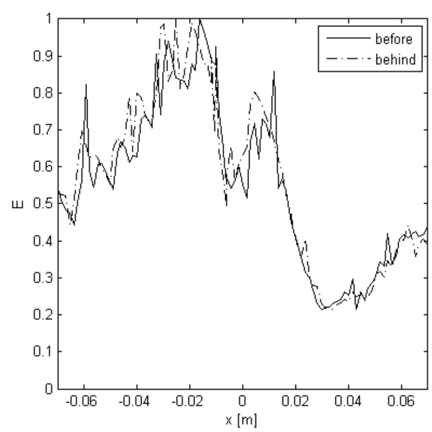

Figure 7. Energy distribution along a horizontal line 50 mm away from the sensor. This distance corresponds to a intact region.

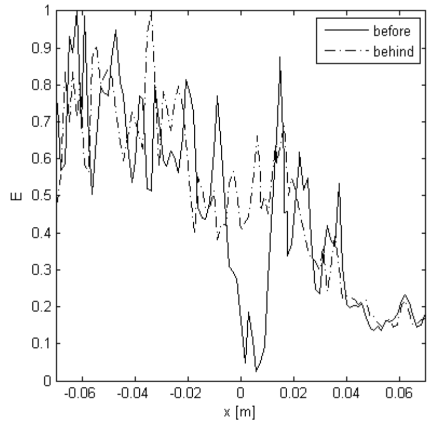

Figure 8. Energy distribution along a horizontal line 80 mm away from the sensor. This distance corresponds to a discontinuity placed before the rivet line.

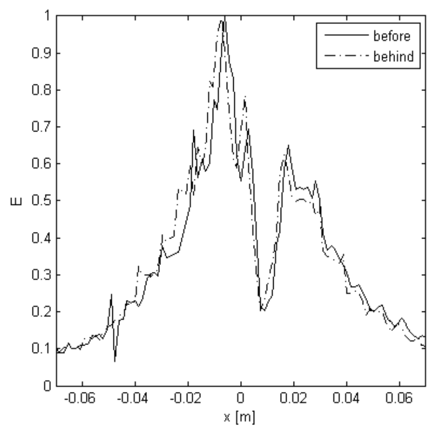

Figure 9. Energy distribution along a horizontal line 150 mm away from the sensor. This distance corresponds to a discontinuity placed behind the rivet lines.

The conducted investigation showed that the presence on discontinuity before the rivet line can be detected using visualization of the wave energy for the whole investigated surface (Figure 4). Analysis of the energy in the region of the mass also indicates the presence of discontinuity (Figure 8). In the last step a method based on point-wise measurements was used. Five points from the measurement grid were chosen. They form a cross shape with spacing 1.5 mm. The algorithm based on triangulation and summation of energy was utilized [7]. The result is presented in Figure 10. The value increase of the damage index value directly corresponds to the position of the additional mass (indicated by x). The theoretical value of the wave velocity (730 m/s) was taken for the calculations.

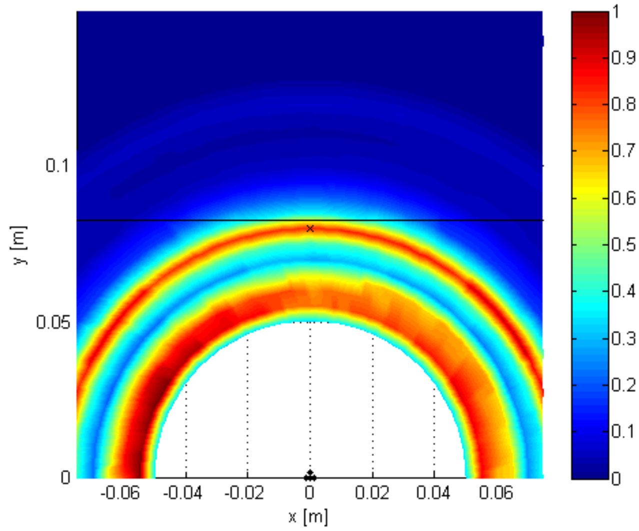

Figure 10. Damage localization result for the experimental case with mass placed before the rivet lines; x denotes the position of the mass; horizontal line indicates the rivet line.

CONCLUSIONS

The investigation showed that the full wave field registration can provide useful information of the discontinuity presence in a riveted aircraft panel. It was also shown that using few measurement points (for example piezoelectric sensors) the indication of discontinuity position can also be obtained.

Using the proposed signal processing one can easily distinguish a panel with and without additional mass. This leads to conclusion that the method can be easily adapted for damage detection and localization.

The presence of riveted sections makes difficult to monitor the condition of other panel sections than these with the attached piezoelectric sensor.

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