Investigations on guided wave interaction with various discontinuities

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ABSTRACT: In this paper results of investigation of elastic wave mode conversion due to different discontinuity types in thin aluminum panel was presented. The concept is based on the guided elastic wave propagation phenomenon. Guided waves are widely utilized in Structural Health Monitoring. In research presented in this paper piezoelectric transducer was utilized in order to excite guided waves in aluminum panel. 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 specimen. Different types of discontinuities (notch, through-thickness cut, drilled hole, riveted stiffener) were introduced to the panel during the research. Signal processing procedures were developed in order to visualize the interaction of guided elastic waves with introduced discontinuities. Research was focused on problem of guided waves mode conversion. Three commonly know fundamental modes of guided wave were noticed during the research: symmetric S₀, anti-symmetric A₀ and shear horizontal SH₀.

KEY WORDS: Guided waves; Mode conversion; Laser vibrometry.

1 INTRODUCTION

The research towards creating a Structural Health Monitoring (SHM) systems is more and more popular due to numerous possible advantages of SHM applications. Such a systems can significantly increase the safety of various structures due to the fact that diagnostic process can be conducted in real time during normal structure operations. Moreover SHM system allows to reduce structure operation costs which are directly linked to operations. SHM systems allows to reduce these costs by directly linking expensive application of classic non-destructive testing methods. In Structural Health Monitoring very often elastic waves propagation method is utilized in order to assess the state of structure [1],[2]. Principle of operation utilize fact that any discontinuities existing in the structure change elastic wave propagation. These discontinuities can be in the form of structural element boundary, thickness change, stiffeners, joints or damage like notch, crack or delamination.

Generally elastic wave propagating in solid media with discontinuity can reflect, scatter and transmit due to this discontinuity. During elastic wave reflection one type of wave mode can convert to another [3],[4]. In the case of guided elastic waves in thin panels three types of modes of these waves propagate: symmetric (S), antisymmetric (A) and shear horizontal (SH) [1]. Mode reflection or conversion occurs at boundaries, discontinuities or structural defects, resulting in complicated multimode wave signals. After the wave mode conversion, the converted A₀ mode and the fundamental horizontal shear wave SH₀, are two candidates for indication of a crack [5]. In [6] the scattering problem was treated with two different approaches. The first approach was based on 3D theory, expressing the wave fields as superposition of Lamb modes and SH modes, both propagating and evanescent modes. The second approach is based on a combination of Kirchhoff plate theory for flexural motion and elementary Poisson theory for extensional motion. These theories are only valid for very low frequencies and/or very thin plates. Thus, accurate results can only be expected for very low frequencies using the plate theory approach. For instance, at a moderately low frequency equal one-third of the cut-off frequency of the second flexural mode, a total of nine Lamb modes were required in the calculations. For higher frequencies, more terms would be needed in the expansions which would result in a slower convergence rate. Due to this, a computationally more efficient method is required for inverse solutions. In [7] hybrid Boundary Element Method for simulation of Lamb wave propagation was utilized. In the case of the plate the incident A₀ wave mode from one edge propagates and then interacts with the notch, undergoing mode conversion. If the notch spans over the full depth, then the A₀ wave is fully reflected with no conversion. If notch does not span over the full depth, the incident A₀ wave will undergo mode conversion, partially transmitted and partially reflected containing both A₀ and S₀ components. For surface cracks deeper than 1/7 wavelength, the reflection coefficients of A₀ wave may be used to characterize the presence of a notch as it increases with notch depth. If S₀ mode is input, a similar phenomenon can be observed where mode conversion is maximum when notch depth is about half through the plate thickness. Unlike A₀, S₀ exhibits good sensitivity even for a shallow notch. The existence of surface crack destroys the symmetry of the wave, resulting in mode conversion.
general, the reflection increases with increase in notch depth. The depth of the notch is shallow when both reflection and mode conversion coefficients are both low, close to mid-depth when reflection coefficient is of intermediate value and mode conversion coefficient is relatively high and deep when the reflection coefficient is high and mode conversion is low. In [8] crack detection using PZTs was realized. The working frequency is controlled to that below the first cut-off frequency of the Lamb modes to allow only the two fundamental modes, $A_0$ and $S_0$, to be generated. Each mode will undergo mode conversion and result in multiple wave packages when reflected from cracks or boundaries. In the [9] mode conversion phenomenon due to the fatigue crack was investigated. When Lamb waves propagate through a crack, mode conversion occurs. Because of this mode conversion, a single Lamb wave mode is divided into multiple modes at the discontinuity point such as a crack. The uniqueness of the proposed crack detection technique is that this mode conversion due to a crack is instantly identified without using prior baseline data. Mode conversion of Lamb waves occurs if Lamb waves propagating along a thin plate with a uniform thickness encounter a discontinuity such as a sudden thickness variation of the plate. When a $S_0$ mode arrives at the discontinuity, the transmitted wave is separated into $S_0$ and $A_0$ modes (denoted as $S_0/A_0$ and $A_0/S_0$, respectively). In a similar manner, an $A_0$ mode is also divided into $S_0$ and $A_0$ modes ($S_0/A_0$ and $A_0/A_0$). In this section, the polarization characteristic of the PZT material is utilized to detect this mode conversion due to crack formation without using any prior baseline data. Note that a notch was simulated in the numerical model while a fatigue crack was introduced in the subsequent experimental study. As long as a notch or a crack produces sudden reduction in thickness, it is expected that they do produce mode conversion. However, the characteristics of a breathing crack can be different from those of a notch because the breathing crack can produce crack opening and closing while the notch remains open. Therefore, the amplitude of the mode conversion may decrease for the crack when the crack is closed. Therefore, the applicability of the proposed technique to fatigue crack detection was investigated in the following experimental study. In [10] three kinds of discontinuities that enable mode conversions are considered: steps down, steps up and asymmetrical notches. The paper presents firstly, a numerical study of the fundamental Lamb waves interaction with the step down (DAA), the step up (IAA) and asymmetrical notches (AN). These discontinuities enable mode conversions from the incident mode $A_0$ to the converted mode $S_0$ and inversely. In [11] the interaction of the fundamental Lamb waves with symmetrical discontinuities has been investigated by the authors. It is well known that this kind of discontinuities does not produce any mode conversion in the case of the $A_0$ or the $S_0$ Lamb mode. In [12] authors concluded that experimental data of guided wave scattering and particularly mode conversion at non-symmetric defects is scarce. Moreover authors proposed to use Mindlin plate theory, which is a commonly accepted better model of the $A_0$ mode instead of Kirchhoff plate theory for flexural waves. Mindlin model is still numerically easy and fast to solve while it also shows an increased range of validity. Due to mode conversion the pure incident mode will be scattered into all three fundamental guided wave modes. In this paper a model for guided wave scattering from non-symmetric blind holes in isotropic plates using Poisson and Mindlin plate wave theories for in-plane and flexural wave modes, respectively, is presented. It makes use of the wave function expansion technique and coupling conditions at the defect boundary in order to evaluate the scattered far fields of the three fundamental guided wave modes. The results were compared to other analytical models as well as experimental measurements for mode conversion from $S_0$ to $A_0$. Results show that the mode conversion from $S_0$ to $A_0$ at the defect is a convenient way to measure the scattered $A_0$ field directly since the incident mode is barely received by the laser vibrometer (1D) while it is very sensitive.

In this paper influence of different discontinuities on elastic wave mode conversion is investigated. Research is related to simple thin square aluminum panel and panel with riveted stiffeners coming from aircraft wing. In the research 3D scanning laser vibrometer working in 1D mode was utilized. Moreover full-field measurements were conducted that allow to visualize elastic wave modes propagation. Application of full-filed measurements using laser vibrometer in order to analyse elastic wave mode conversion is new in the literature.

2 MEASUREMENT SET-UP

Research presented in this paper was conducted for two metallic specimens. First specimen was in the form of simple aluminum panel with dimensions 1 m x 1 m x 0.001 m (Figure 1a). Surface of this panel was divided in four square parts. In one of the parts aluminum stiffener with dimensions 0.33 m x 0.02 m x 0.002 were attached using five rivets (Figure 1b). The rest three parts was without any stiffeners. In each part one type of discontinuities simulating damage was introduced: notch and through-thickness cut (as one type), drilled hole, one rivet loss and thickness change. The last one simulated corrosion however it did not cause any significant changes in elastic wave propagation. Piezoelectric transducer (material: SONOX P502, diameter: 10 mm, thickness: 0.5 mm) was placed in the middle of the panel on the same side where stiffener was placed. Piezoelectric transducer was used to excite elastic waves. Laser vibrometry measurements were taken from the second panel face.

Second sample comes from the wing of an aircraft structure. It was an aluminium riveted panel (thickness: 0.7 mm) that is a part of PZL-101 "Gawron" aircraft (Figure 2). A piezoelectric transducer was placed at the middle of one of the sections (Figure 2a). Measurements were generally divided into two approach. In the first approach elastic waves were excited in the side of panel with stiffeners (visible in Figure 2a) and measurements of elastic waves were conducted on the second side. This means, that neither the presence of sensor nor additional mass influenced the measurements. In the second approach excitation and sensing processes were realized on the same
side of panel (Figure 2b). Measurements were conducted for the referential state of panel as well as for the panel in damaged state. Damage was simulated as drilled hole and as a removed rivet connecting stiffener with the panel.

In both cases the measurements were conducted using 3D scanning laser vibrometer (Polytec PSV400). The measured surface was covered with retroreflective tape in order to enhance the signal level. It should be underlined that only 1D mode was utilized what allow to measure effectively out-of-plane velocities and displacements related to elastic wave propagation. Excitation signal in the form of five cycle tone burst was applied to the piezoelectric transducers. Two values of excitation frequency were utilized: 100 kHz and 200 kHz.

RESULTS FOR SIMPLE SQUARE ALUMINIUM PANEL

In this section results from square aluminum panel were presented. In the Figure 3a) frame from animation of elastic wave propagation in the quarter of whole panel area as was presented. It should be mentioned that panel was at referential state (without discontinuities). In Figure 3b) signal taken from one scanning point marked in the Figure 3a) was presented.

![Figure 1](image1.png)

**Figure 1** Investigated square aluminum panel with riveted stiffener: a) measured side of panel, b) back side of panel with visible stiffener.

![Figure 2](image2.png)

**Figure 2** Aluminum panel with riveted stiffeners comes from aircraft wing: a) bottom side of panel with visible riveted stiffeners, b) upper side of panel.

**SIGNAL PROCESSING ALGORITHM**

The registered signals were processed in order to create maps that present elastic waves energy distribution in investigated structure. In this purpose signals are mapped into surface of the panel by calculating the signal energy (the RMS index [13]) using the vibrometer software. The index for measurement point \( j \) was calculated from signal \( S \) of length \( N \) using following formula:

\[
RI_j = \sqrt{\frac{1}{N} \sum_{k=1}^{N} S_{j,k}^2}
\]

(1)

Logarithmic scale was chosen for plotting these maps.

Besides, simple analysis of animation of elastic wave propagation were conducted based on single frame.
Figure 4. Mode conversion $S_0$ to $A_0$ due to elastic wave interaction with: a) notch 0.5 mm deep, b) through-thickness cut; excitation frequency 100 kHz.

Figure 5. Mode conversion $S_0$ to $A_0$ due to elastic wave interaction with not through-thickness hole; excitation frequency 100 kHz.

In the second part of the sample firstly half-thickness hole was drilled (diameter 3 mm) and in the next step through-thickness hole was drilled (the same diameter). However in the first case wave mode conversion phenomenon was not observed. Result for the second case was present in Figure 5. However wave mode conversion $S_0$ to $A_0$ is very poorly visible.

In third part of the panel stiffener was attached using five rivets. Measurements were taken firstly for panel with stiffener attached using full set of rivets. In the next step measurements were taken after removing of one rivet. Frames from animation of elastic wave propagation for both cases were presented in Figure 6a) and Figure 6b) respectively. Analyzing results presented in Figure 6a) it can be clearly noticed that $S_0$ mode due to its interaction with rivets is converted to $A_0$ mode.

Wave mode $S_0/A_0$ is created for each rivet. Similar situation can be noticed in Figure 6b). However in the place where one rivet was removed mode conversion phenomenon was not observed. It should be emphasised that rivet was completely removed and after that only through-thickness hole remained. This situation is better visible in Figure 7a) and Figure 7b) where RMS energy maps were presented for the case of full sets of rivets (Figure 7a) and case were one rivet was removed (Figure 7b). After removing of the rivet one do not see the ‘shadow’ behind the rivet. These RMS maps were created for results obtained for excitation frequency 100 kHz. In the fourth part of the panel corrosion was simulated as thickness reduction (approximately few hundredths of millimeter) approximately in the area 10 mm by 10 mm. However it have not caused any significant changes in elastic wave propagation: wave mode reflection as well as mode conversion.

Figure 6. Interaction of symmetric mode $S_0$ with riveted joints in simple aluminum panel: a) full set of rivets, b) second rivet on the left removed; excitation frequency 100 kHz.
RESULTS FOR RIVETED AIRCRAFT PANEL WITH STIFFENERS

In Figure 8 two frames from animation of elastic wave propagation in riveted panel with stiffeners were presented. Excitation frequency was equal 100 kHz. This animation was created in the vibrometer software based on full-field measurements. Analyzing results presented Figure a) it can be easily noticed that two modes of guided waves propagate symmetric (faster with larger wavelength) and antisymmetric (slower with shorter wavelength). In the Figure 8b) frame from the animation taken after propagation of waves through stiffener was presented. In both cases elastic wave mode conversion $S_0/A_0$ can be noticed as a result of interaction of symmetric mode with riveted stiffeners. Mode conversion occurs for each rivet.

It should be mentioned that due to the fact that 1D scanning mode is used (sensing of out-of-plane velocities and displacements) sensitivity to symmetric mode (mainly in-plane displacements) is much lower than for antisymmetric mode (mainly out-of-plane displacements).

In the next step RMS map was created based on full-field measurements for referential state panel. This map was presented in Figure logarithmic scale was chosen for plotting. One can easily notice the highest energy is at the middle of the panel section where the piezoelectric transducer was placed. Some imperfections in wave excitation can be noticed because the energy is not distributed equally around the sensor.

In Figure 9 frames from animation of elastic wave propagation behind the stiffener were presented. This time in the part of panel behind the stiffener through-thickness hole (diameter 5 mm) was drilled. In the Figure 9a) frame from animation illustrating $S_0$ mode integration with drilled...
hole is presented. In this case mode reflection as well as mode conversion was not observed. On the other hand in the Figure 10b) frame from animation illustrating $A_0$ mode interaction with drilled hole is presented. This time $A_0$ mode reflection from drilled hole can be noticed. Wave mode $A_0$ conversion to $S_0$ mode was not observed. This can be caused by much smaller sensitivity of laser vibrometer working in 1D mode to the in-plane velocities related with $S_0$ mode. Even when the $S_0$ mode would be created as result of mode conversion probably it will not be visible if amplitude of new mode will be very small. In order to investigated this phenomenon 3D scanning mode need to be utilized. However this approach is much more time consuming and was not utilized in research presented in this paper.

![Figure 8 Interaction of elastic wave modes with drilled hole in riveted panel, propagation of: a) mode $S_0$, b) mode $A_0$; excitation frequency 200 kHz.](image)

In Figure 8 interaction of elastic wave modes with drilled hole in riveted panel, propagation of: a) mode $S_0$, b) mode $A_0$; excitation frequency 200 kHz.

In Figure 10 one frame from animation presenting $S_0$ mode propagation and interaction with drilled through-thickness hole (diameter 5 mm). Now this hole is located before stiffener and $S_0$ mode has larger amplitude because does not propagate through the stiffener like in previous case. However this time also mode conversion from $S_0$ to $A_0$ was not observed.

![Figure 9 Lack of interaction of symmetric mode $S_0$ with drilled hole in riveted panel; excitation frequency 200 kHz.](image)

Figure 9 Lack of interaction of symmetric mode $S_0$ with drilled hole in riveted panel; excitation frequency 200 kHz.

In the next step elastic wave propagation measurements were taken for the panel with stiffener mounted by full sets of rivets and for the case where one rivet was removed. Chosen frames from elastic wave animation for both cases were presented in Figure 12a) and Figure 12b) respectively. In Figure 12a) mode conversion $S_0$ to $A_0$ is clearly visible in the location of every rivet. On the other hand, in Figure 12b) mode conversion was not observed for location where the rivet was removed (first rivet on the left). It should be emphasised that also this time rivet was completely removed and after that only through-thickness hole remained.

![Figure 10 Interaction of symmetric mode $S_0$ with riveted joint: a) full set of rivets, b) first rivet on the left removed; excitation frequency 200 kHz.](image)

Figure 10 Interaction of symmetric mode $S_0$ with riveted joint: a) full set of rivets, b) first rivet on the left removed; excitation frequency 200 kHz.

CONCLUSIONS
The results of investigations show that the full wave field registration can provide useful information of the elastic wave interaction with discontinues in structures. This approach is very useful especially for structure with complicated geometry.

During research influence of different type of discontinuities on mode conversion from $S_0$ to $A_0$ was investigated. It can be summarized that discontinuities in the form of notch, through-thickness cut, not through-thickness drilled hole and rivet caused $S_0$ to $A_0$ mode conversion. Each rivet causes mode conversion of elastic waves - symmetric mode is converted into antisymmetric mode ($S_0$ to $A_0$). However, after removing a rivet, mode conversion on remain hole was not observed.

In the case of discontinuity in the form of drilled through-thickness hole wave mode conversion phenomenon was not observed. This needs to be investigated deeper in the further investigations.

Further research will be also focused on application of mode conversion phenomenon for damage detection.

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REFERENCES


