Structural health monitoring by means of elastic wave propagation

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Abstract. This paper presents numerical and experimental approach for damage detection in structures. Presented methods are based on the phenomenon of elastic wave propagation. The results are provided for isotropic and anisotropic plates with damage in form of fixed mass or notch cut.

1. Introduction
The scope of Structural Health Monitoring (SHM) includes constant monitoring of the structure's material condition (in real–time), for the elements of the structure as well as for the whole structure during its useful lifetime. The main goal of the SHM technique is to conduct research aimed at developing advanced non–destructive diagnostic methods of assessing integrity of diverse composite structures. Determining location, size and type of damage together with estimating the remaining operational lifespan of investigated structures is very important for assessing technical condition of many safety–critical machines and devices, as well as of means of transport (e.g. aircraft, helicopters, land and sea engineering structures).

Developing such methods and then applying them during construction and operation of composite structures allows for evaluating degradation, and therefore remaining life, of such structures. Application of the SHM methods is doubtlessly enable avoiding dangerous situations, and even more importantly, serious catastrophic scenarios.

Among various techniques available, a health monitoring system based on piezoelectric transducers and Lamb wave propagation seems to be a promising method for inspection of metallic and composite plate-like structures.

Guided waves induced by piezoelectric transducers are extensively used for damage detection purpose. A numerical model based on time–domain spectral element method has been developed to simulate elastic wave propagation in metallic and composite structures induced by the piezoelectric transducers. Moreover, numerical models constitute the foundation for developing perfect tools for designing and verifying new concepts of signal processing and testing methodology. Visualisations of elastic waves excited by the piezoelectric actuator in selected structures have been performed. Apart from visualisation of propagating waves also the interaction of guided waves with various types of damage have been investigated.
Wide range of numerical simulations and experimental validations of analysed structures provide helpful information about dispersion, mode conversion, thermo-mechanical processes and wave scattering from stiffeners and boundaries. It can allow one to optimise excitation signal parameters and sensor placement, as well as enable analysis of signals reflected from damage.

2. Lamb Waves
Lamb waves are specific type of elastic waves that propagate in solid media bounded by two parallel surfaces. They were discovered and formulated by Horace Lamb in 1917 [1]. In non-destructive testing or SHM those waves are often called guided Lamb waves or just guided waves, because of finite dimensions of a real test structure.

Two forms of Lamb waves exist in infinite solutions: symmetric (S0,S1,...) and anti-symmetric (A0,A1,...) which depends on the product of excited frequency and plate thickness. For an aluminium alloy structure only two basic modes coexist up to 1.8 MHz·mm which is presented by the means of dispersion curves in figure 1 and figure 2. Those fundamental modes are found to be used in damage detection methods.

![Figure 1: Phase velocities of symmetric (blue) and anti-symmetric (green) modes of Lamb waves.](image1)

![Figure 2: Group velocities of symmetric (blue) and anti-symmetric (green) modes of Lamb waves.](image2)

In comparison to isotropic plates, dispersive relations in composite material are more complex. The solution must satisfy Christofel’s equation for each layer, the continuity condition at the interfaces and the traction–free boundary conditions at the plate surfaces [2]. Base on Mindlin’s plate theory approximate solution can be found [3]. This approach shows that group velocity of the transverse wave (which approximates A0 Lamb wave mode) is a function of a direction of propagation and relative volume fraction of fibres. Some examples for GFRC and GFRC are presented in figure 3, where green line stands for 0% and 100% volume fraction of fibres and blue line stands for 20, 40, 60, 80% volume fraction of fibres composite material.
Modelling guided waves propagation in real structures is a challenging task. An efficient method was proposed by Doyle [4] in the form of FFT-based Spectral Element Method. However, it cannot be applied for 3D geometry. Both Finite Element Method and Finite Difference Method may be used for complex geometries [5] but they are not efficient enough for elastic wave propagation phenomenon modelling.

Spectral Element Method developed by IFFM research group overcame those problems [3, 6]. Additionally, authors propose spectral elements for electromechanical coupling [7] which is important in case of piezoelectric transducer modelling. Some exemplary results for guided wave propagation in 2 mm thick aluminium alloy halfpipe are presented in figure 4.

Figure 3: Group velocities surfaces a) glass-epoxy composite, b) graphite epoxy composite.

3. Wave propagation modelling
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Figure 4: Guided wave propagation in halfpipe structure at three consecutive time steps.

4. Damage imaging techniques
Due to different approaches to guide wave registration two main groups of damage detection methods may be defined. First one of them is based on number of sensors mounted on the specimen surface to excite and/or register time signals. Second group utilizes full wavefield of propagating guided waves which may be obtained by shearography or Doppler vibrometry.

4.1. Fixed sensors
Registered signals by the piezoelectric transducer may be used for damage localization by various inverse techniques. However, this approach is very computationally intense. Utilizing information about wave propagation velocity and the position of the sensors, direct methods may be applied in order to create damage maps. Among direct damage detection methods two main approaches may be
distinguished: pulse-echo or pitch-catch. The former is based on assumption that discontinuity of a structure is causing elastic wave reflections. Additional wave packages in registered signal allow one to determine the distance between excitation, damage and sensor. The latter group utilized information about direct patch of elastic wave between excitation and receivers. Any changes due to damage within amplitude, velocity, type of mode may be recognized as a material discontinuity [8, 9, 10].

4.2. Full wavefield

Another approach for elastic wave-based damage localization utilizes non-contact measurements of full wavefield, which is possible to register using shearography or scanning Doppler vibrometry. Due to information about full wavefield of propagating guided waves new damage detection possibilities arise. One of the first damage detection method incorporating full wavefield obtained by Doppler vibrometer was presented by Ruzzene et al. [11]. This approach was based on visualization of the energy of propagating wave distribution over the measured surface. Any local change in energy maps may be recognized as geometry feature of specimen or damage.

Radzięński et al. [12] developed RMS method by normalizing amplitude of propagating waves spread on surface which facilitate analysis of created damage maps and was called weighted RMS. In paper [13] Ruzzene proposed utilizing 3D Fourier Transform for filtering incident waves leaving only reflections from potential damages. The calculated energy of filtered signal should have the biggest values in the position of damage.

The studies presented in this paper covers comparison between three of those methods (RMS, weighted RMS, incident wave filtering) as well as new method developed by the authors. Proposed approach utilizes 2D Fourier Transform for wave image filtering. Spectral pattern of propagating guided waves in specimen is determined by averaging first few time snapshots in wavenumber domain. By taking advantage of this information it is possible to define specific filter which is successively used for eliminating main component of propagating guided waves from each registered time frame. In results the filtered signals contains mostly information about changes in wave propagation pattern with its positions. Map of distribution of energy of this filtered signal in expected to have highest values in position where propagating guided waves are affected by material discontinuity.

5. Results

First tested structure was 1 x 1 x 0.002 m aluminum alloy plate. One quarter of this specimen was considered in numerical and experimental researches, as indicated by a grey rectangle at figure 5. Simulation of damage in form of fixed 1 g mass was introduced. Exemplary results of abovementioned methods for both numerical and experimental studies are presented in figure 7 and figure 8 respectively.

Second specimen used in investigations was 0.44 x 0.44 x 0.0032 m glass-epoxy composite plate composed of 4 layers of glass fibre mats with vertically oriented fibres. In this specimen damage was introduced in form of narrow notch cuts with length 4 mm in positions indicated at figure 6a and 6b. In numerical model notch cut was simulated by separation of nodes between elements. In experiment notch cuts were about two thirds of the specimen thickness deep. Results obtained for this structure are presented in figures 9 and 10 for numerical and experimental data respectively.

In all numerical and experimental studies burst sine excitation at carrier frequency 35 kHz applied in the geometrical centre of specimens were used.

It should be noted that experimental data was filtered prior to applying damage localization techniques, using median filtering in space domain. This provided elimination of several sparsely distributed measurement points with low signal to noise ratio, which is typical for scanning laser vibrometry measurements.
In case of aluminum alloy plate damage may be localized using all tested methods. The best results were obtained using incident wave filtering. However, it should be stated that signals used for creation of damage maps in this particular approach were limited to time step in which guided waves reached the boundaries of structure. In this manner top right corner was not covered by the signal and may be considered as so called ‘dead zone’. This is only problem in case when investigated area is in proximity or includes specimens boundaries.

In numerical results obtained for composite plate all four tested techniques were able to correctly localize position of damage. Incident wave filtering method was prepared separately for every quarter of specimen and then merged into one map (figure 9c and 10c).

Nevertheless, experimental results were not so encouraging. Top notch cut was barely visible in RMS based methods and incident wave filtering method (figure 10a, 10b, 10c). Second notch cut cannot be pinpointed by those three methods. Due to the fact that this crack was oriented perpendicular to excited wave front, incident wave was almost not affected by damage. However, proposed by the authors method is capable of excluding information about wave pattern changes also from reflected by the structure boundaries guided waves. In case of notch cut of composite plate situated on the left side of excitation, guided waves reflected from the top and the bottom boundaries of specimen were perpendicular to this damage. Therefore localization of both cuts by proposed method was possible, what is presented in figure 10d.
Figure 7: Damage detection maps for numerical aluminium alloy plate with additional mass a) RMS, b) Weighted RMS, c) Incident wave filtering, d) Adaptive wave image filtering.

Figure 8: Damage detection maps for experimental aluminium alloy plate with additional mass a) RMS, b) Weighted RMS, c) Incident wave filtering, d) Adaptive wave image filtering.
Figure 9: Damage detection maps for numerical composite plate with crack a) RMS, b) Weighted RMS, c) Incident wave filtering, d) Adaptive wave image filtering.

Figure 10: Damage detection maps for experimental composite plate with cracks a) RMS, b) Weighted RMS, c) Incident wave filtering, d) Adaptive wave image filtering.
6. Conclusions
Spectral Element Method was found to be very helpful in designing effective Structural Health Monitoring systems. Numerical results verified by the experimental research confirm its capability of modelling and testing damage detection algorithms.

Adaptive wave image filtering method for damage detection was proposed. Numerical and experimental results proved that this technique can be used as an effective tool for localization of cracks in composite plate.

It has been shown that in spite of the fact that guided wave propagation is very complex phenomenon it can be successfully utilized for damage detection and localisation in both isotropic and anisotropic plates. There are many various approaches for this process and depending on the type of structure, implementation possibilities, exploitation environment, accessibility and time constraints one should satisfy its needs. The capability of employing more than one SHM techniques simultaneously in order to improve the overall performance of structure technical condition evaluation should be also considered.

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