



Analysis of Guided Wave Propagation in an Aluminium-CFRP Plate

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Abstract

Guided waves cover comparably long distances and thus allow for online structural health monitoring of safety relevant components, *e.g.* lightweight composite overwrapped pressure vessels (COPV) as used for the transportation of pressurised gases.

Reliable non-destructive assessment of COPVs' condition is not available yet due to their complex composite structure comprising a thin metal liner and a fibre reinforced plastics (FRP) overwrap. The conventional overload hydrostatic pressure testing used for the metal vessels is not suitable for the composite vessels, because it may damage the FRP overwrap reducing the service life of the COPV. Therefore, ISO and CEN defined a maximum service life of composite pressure vessels as of 15 to 20 years. To extend the COPVs' service life and to ensure a safer usage a structural health monitoring system based on guided ultrasonic waves is to be developed.

In this contribution first results of guided waves propagation in a flat composite plate consisting of an aluminium layer firmly bonded to a carbon fibre reinforced plastic laminate are presented. Based on experimental results material properties of FRP are reconstructed by means of the Scaled Boundary Finite Element Method (SBFEM).

1. Introduction

Guided waves come into play when a task to assess big portion of a structure with the minimal number of transducers arises. These waves propagate in thin structures, with respect to the wavelength, and have been successfully implemented as a defect screening technique in numerous applications, *e.g.* oil and gas pipelines monitoring [1], corrosion monitoring [2], and rail inspection [3]. However, most of the time guided waves are applied to the components made of either metal or fibre reinforced plastics (FRP). A little research was done to understand guided wave propagation in components comprising both metal and FRP [4].

Currently, lightweight COPVs are used in diverse applications from ultra-compact oxygen equipment to hydrogen fuel storage tanks. One of the issues concerning the use of COPVs is lack of appropriate testing procedures that is why present use of composite vessels is limited to 15 to 20 years. The goal is to develop a structural health monitoring (SHM) system based on guided ultrasonic waves to ensure a safer usage and to extend the COPVs' service life.

In this work the cylindrical part of a pressure vessels is considered neglecting end caps, because in this part critical flaws occur. The guided wave propagation in a plate made of aluminium and a carbon fibre reinforced plastic (CFRP) laminate is analysed with the aim of modelling of more complex structure of a composite pressure vessel (COPV). It was shown by Wilcox [5] that curvature has negligible effect on propagation of lower guided wave modes, when the ratio of radius to thickness is greater than 10:1. It applies to COPVs

starting with 6 to 8 mm of thickness and 80 mm in radius, that is why a cylinder can be approximated to a plate.

2. Materials and methods

2.1 Test specimen

SAERTEX[®] non-crimps fabrics with the total mass per unit area of 603 g/m² were used. Unidirectional fabrics consist of ZOLTEK PANEX 35 50K carbon fibres hold together with glass fibres and polyester sewing threads. Resin MGS[™] RIMR 135 and curing agent MGS[™] RIMH 137 from EPIKOTE[™] were used. A 2 mm thin aluminium plate with dimensions of 600x600 mm² was used as a base plate, on which 6-layered [0/90/0/90/0/90] carbon fibres stack with dimensions of 500x500 mm² was placed. A test sample was produced using vacuum assisted resin transfer moulding process. After the process the sample was cut to the size of 480x480 mm². The overall thickness of the sample is 6 mm – 2 mm of aluminium and 4 mm of a fibre reinforced laminate – resulting in the nominal thickness of 0.67 mm for each unidirectional ply. Material properties were calculated using as initial guesses values for high tenacity carbon fibres and epoxy matrix given in AlfaLam Software from the Technische Universität Darmstadt [6]. Material properties for a single ply in 0° direction (fibre direction) are given in Table 1, where ρ is density, E is Young's modulus, G is shear modulus and ν is Poisson's ratio.

Table 1. Properties of an epoxy carbon ply (E_1 is in the fibre direction)

Property	ρ (kg/m ³)	E_1 (GPa)	E_2 (GPa)	G_{12} (GPa)	ν_{12}
Value	1490	166.6	5.135	2.4	0.27

2.2 Dispersion curves for the aluminium-CFRP plate

Dispersion curves shown in Figure 1 for the aluminium-CFRP plate were calculated by means of the Scaled Boundary Finite Element Method (SBFEM) under a 2D plane strain assumption. The details of the SBFEM implementation for multilayer plate structures can be found in [7, 8].

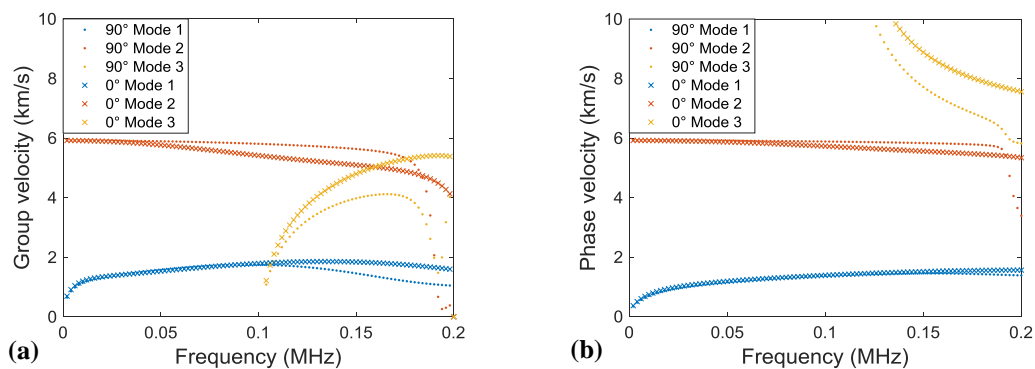


Figure 1. Dispersion curves for: (a) group velocity and (b) phase velocity, calculated for the infinite aluminium-CFRP plate using the Scaled Boundary FEM

Material properties used are listed in Table 1. Each ply is 0.67 mm thin and assumed to be transversally isotropic. A 0° direction corresponds to a $[0/90/0/90/0/90/Al]$ stacking sequence and a 90° direction corresponds to a $[90/0/90/0/90/0/Al]$ stacking sequence. The directions define the main wave propagation direction and can be seen in Figure 2.

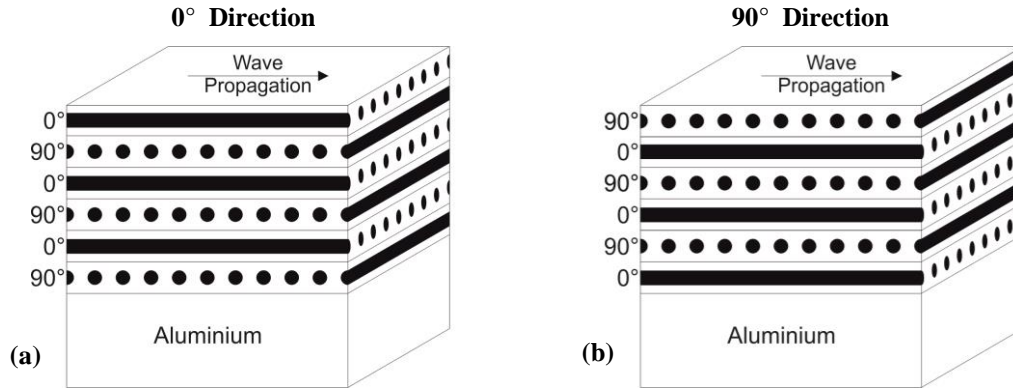


Figure 2. Sketch of stacking sequences of the aluminium-CFRP plate: (a) 0° and (b) 90° wave propagation directions

2.3 Experimental set-up

To verify theoretical dispersion curves and to analyse propagation of guided waves in the aluminium-CFRP plate a Polytec PSV-500-3D Scanning Vibrometer was used. Excitation was performed using a pulse generator connected through an amplifier to a piezoelectric transducer with the central frequency of 100 kHz. The transducer was placed on the aluminium side. The overall experimental set-up is shown in Figure 3. Scans were conducted along four lines, see Fig. 3 (b). Each line has 50 scan points with a spatial resolution of 3 mm. The 0° scanning direction corresponds to the 0° wave propagation direction, see Fig. 2 (a). After this direction was scanned the aluminium-CFRP plate was rotated by 90° and scanning was performed for the 90° wave propagation direction, see Fig. 2 (b). The data obtained were analysed by means of a two-dimensional fast Fourier transform (2D FFT).

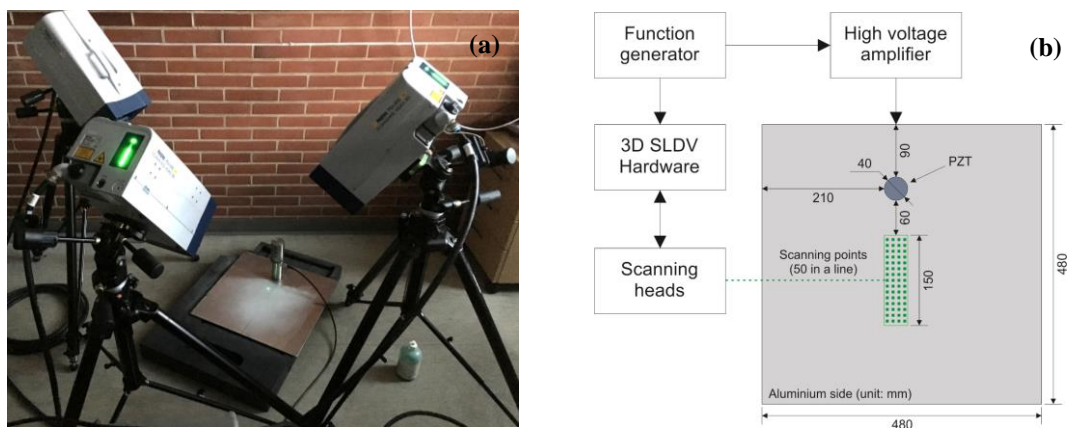


Figure 3. Experimental set-up for measurement of guided waves in the aluminium-CFRP plate. (a) positioning of the scanning heads one to another and to the test specimen, (b) overall experimental set-up

3. Results and discussion

Experimental data analysed by means of 2D FFT for in-plane and out-of-plane velocity components are presented in Figure 4 [(a), (c)] and [(b), (d)] respectively. Data presented in Figure 4 are the average of 4 scanning lines. For the identification of modes propagating in the aluminium-CFRP plate frequency spectra are overlaid with the frequency-wavenumber curves calculated using the SBFEM. Based on the experimental results effective material properties were reconstructed as follows.

During research on the influence of the material properties change it was found that up to the frequency of 0.2 MHz for both 0° and 90° wave propagation directions:

- an increase in Young’s modulus in the fibre direction (E_1) leads to an increase in the phase velocity (a decrease of the wavenumber) of mode 2, with no essential influence on mode 1
- an increase in Young’s modulus in the epoxy matrix direction (E_2) does not have essential influence on the phase velocity of both mode 1 and mode 2
- an increase in shear modulus (G_{12}) leads to an increase in the phase velocity (a decrease in the wavenumber) of mode 1, with no essential influence on mode 2
- a change in Poisson’s ratio does not have essential influence on the phase velocity of both mode 1 and mode 2
- a decrease in density (ρ) by 10 % leads to an increase in the phase velocity of mode 2 by maximum 3 %. No essential influence on mode 1 was observed.

Based on aforementioned observations Young’s modulus in the fibre direction (E_1) and shear modulus (G_{12}) were increased by 50 % and 40 % from initial guesses, respectively. Results are listed in Table 2. A decrease in the density would indicate presence of pores from production process and was not considered in this case.

Table 2. Reconstructed by means of the SBFEM properties of an epoxy carbon ply based on the experimental results (E_1 is in the fibre direction)

Property	ρ (kg/m ³)	E_1 (GPa)	E_2 (GPa)	G_{12} (GPa)	ν_{12}
Value	1490	249.9	5.135	3.36	0.27

In the case of the 0° direction mode 2 has distinct in-plane movement at frequencies of 70 and 95 kHz, see Fig. 4 (a). In contrast mode 1 has pronounced out-of-plane movement with the maximum at the frequency of 62 kHz, see Figure 4 (b). Also, mode 2 has almost double amplitude compared to mode 1. For the 90° direction it is not possible to distinguish propagating modes by analysing the in-plane velocity components, see Fig. 4 (c). Mode 1 has pronounced out-of-plane movement with the maximum at the frequency of 64 kHz, see Fig. 4 (d). Mode 1 for both 0° and 90° direction (Fig. 4 (b), (c)) has the maximum at a lower frequency compared to mode 2 for the 0° direction (Fig. 4 (a)). This may be due to the excitation pulse which has a broadband frequency range, resulting in the excitation of different guided wave modes at most favourable

frequency. Another reason for this maybe the finite size of a piezoelectric crystal. Mode 1 has a wavelength of approximately 20 mm at the frequency of 62 kHz, so that there are two wavelengths of the guided wave mode fit into 40 mm of the diameter of the piezoelectric crystal, allowing for more efficient excitation of this mode.

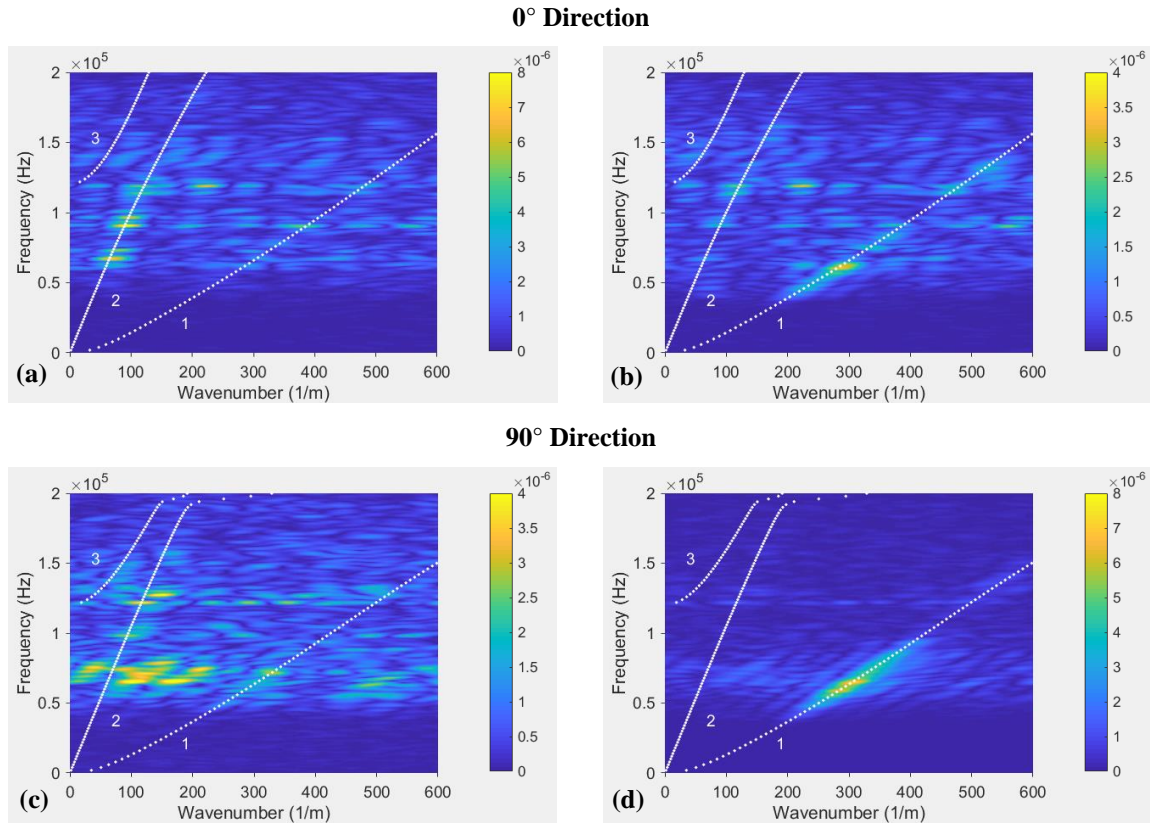


Figure 4. 2D FFT spectra obtained from experimental data overlapped with adjusted frequency-wavenumber curves calculated using the Scaled Boundary FEM. Colour axis corresponds to the velocity (in meter) measured by a 3D Scanning Vibrometer. Excitation from the aluminium side at $f=100$ kHz. For 0° propagation/scanning direction (a) in-plane and (b) out-of-plane components. For 90° propagation/scanning direction (c) in-plane and (d) out-of-plane components

From the experimental results it seems that there is a correlation between the stacking sequence, amplitude and behaviour of the excited guided wave modes. For the 0° direction mode 2 – in-plane movement, symmetric behaviour – has the highest amplitude, see Fig. 4 (a), whereas for the 90° direction mode 1 – out-of-plane movement, antisymmetric behaviour – has the highest amplitude, see Fig. 4 (d).

4. Conclusions

In this contribution first results of guided waves propagation in a composite plate consisting of an aluminium layer firmly bonded to a carbon fibre reinforced plastic laminate are presented. Based on experimental results material properties of CFRP are reconstructed by means of the Scaled Boundary Finite Element Method. Dependence between phase velocities of the modes and material properties is analysed using the SBFEM. The phase velocity of mode 2 (symmetric behaviour) is dominated by Young’s modulus in fibre directions, whereas the phase velocity of mode 1 (antisymmetric

behaviour) is dominated by shear modulus. Poisson's ratio and Young's modulus in the epoxy matrix direction have no essential influence on the phase velocities of both modes.

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