Composite Structures 184 (2018) 1156–1164

Contents lists available at ScienceDirect

Composite Structures

journal homepage: www.elsevier.com/locate/compstruct

The Lamb waves phase velocity dispersion evaluation using an hybrid measurement technique

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ARTICLE INFO

Keywords:
Lamb waves
Phase velocity
Dispersion
Composite plate

ABSTRACT

In this paper two techniques: the zero-crossing and the spectrum decomposition are implemented together to obtain the guided waves phase velocity and their dispersion properties. This proposed hybrid technique has been investigated in two different mediums: an homogenous using signals obtain by 2D finite element modeling and experimental investigation and a non-homogenous environment using 3D finite element model. The results are compared with those obtained by the semi-analytical finite element method (SAFE). It was demonstrated that in the case of correctly selected filters the dispersion curves are reconstructed in approximately 90% for the Lamb wave A_0 mode, for the non – dispersive S_0 mode up to 81% of the incident signal frequency bandwidth in a homogeneous medium. In the case of non-homogenous CFRP plate the phase velocity dispersion curve of the A_0 mode can be reconstructed even up to 96% incident frequency bandwidth.

1. Introduction

Nowadays composite structures are used in the most industries fields due to their high strength and stiffness to light weight ratio. However, undesirable issues such as delamination, impact damage, ply gap, ply waviness, porosity, surface notches and others can appear in composite structure during the manufacturing process or during exploitation [1,2]. Therefore, reliable inspection techniques need to be used for structural safety. Non-destructive techniques (NDT) such as radiography, visual inspection, ultrasonic testing, thermography, shearography, tap testing, eddy currents, and others [1–3] are used for inspection of composites. The main requirements are simplicity, rapidity and reliability to identify, locate and characterize changes in the composite structures [3,4]. One of the most versatile, directly related to mechanical properties, sensitive to any changes, enabling to extract detailed information and leading to certification is the ultrasonic testing (UT) [1,2]. Already in 1990, Bar-Cohen has reported that ultrasonic is one of the most adaptable NDT method to extract comprehensive information [1] and to detect easily and accurately alterations [2]. Lately, (UT) methods based on application of Ultrasonic Guided Waves (UGW) have been able to provide more emphasis and wider knowledge to be one of the most encouraging tools for quantitative identification of damage in large composite structures [5,6]. The main advantages of the Lamb waves are their long distances propagation with high sensitivity to small changes [7–9] and their ability to scan large area of objects or structures under investigation [5,9]. Guided waves enable not only to cover large object but they are also sufficiently sensitive to concentrated damage. However the task extracting informations about the defect features is not easy due to complex properties of the guided waves and this requires advanced signal processing techniques. The velocity of the guided waves is one of the main parameter to estimate the deviation or variation of the material properties. However, the guided waves have an infinite number of dispersive modes and each of them is described by two frequency dependent velocities: phase and group. The dispersion curves are used to show the variations of the velocities c as a function of frequency f. The variations of the guided wave velocity can indicate the location and size of the defect [8]. Therefore, a signal processing technique enabling to reconstruct the dispersion curves of the guided waves propagating in a given structure is of a very important issue. Recently, many different techniques were analyzed and their algorithms have been adapted to reconstruct the group and phase velocity dispersion curves of guided waves [5]. However, most of them run into difficulties to assess the time dependent changes of the frequency spectrum of the signal [10]. Therefore, new methods are required to offer an enhanced time frequency analysis of the guided wave signals.

The Ultrasonic Lamb waves are one type of the guided waves propagating in thin plates with parallel free boundaries [5]. The phase velocity dispersion curves of the Lamb waves provide information about dependency of the phase velocity c_{ph} on the product of the

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http://dx.doi.org/10.1016/j.compstruct.2017.10.060
Received 13 October 2017; Accepted 17 October 2017
Available online 20 October 2017

frequency f and the thickness of the plate d. In general, the dispersion curves are different for different wave modes. Except for the horizontal shear $S_{H,}$ all the others (the asymmetrical A_n and the symmetrical S_n) are strongly frequency dependent. As the phase velocity is defined for any particular frequency, the wavelength λ of the mode can be estimated also [11,12]. The wavelength λ of the Lamb wave is very important since it defines the sensitivity to the size and the geometry of the detect [13]. A great number of new or/and adapted methods in various forms [5,14] have shown that the phase velocity dispersion curve is an important parameter to identify the non-uniformity of elastic properties or/and to locate the defects in unknown material objects under testing.

This work presents an hybrid signal processing method that uses the spectrum decomposition and the zero-crossing techniques for analysing non-stationary signals. The proposed technique involves the analysis of the wideband signals, the characterization of the dispersion, the reconstruction of the phase velocity dispersion curve segments of both lowest fundamental modes of the Lamb waves. The aim of work is to investigate the suitability of the proposed signal processing algorithm in a dispersive media for the estimation of dispersive phase velocity and for the reconstruction of this velocity dispersion curve segments in as much as possible wider frequency ranges.

2. The proposed method

The zero-crossing technique was adapted and proposed to the measurement of the Lamb wave phase velocity [15,16]. The advantage of the proposed method is that parameters both in time and frequency domains are calculated and related to each other as the segment of the phase velocity dispersion curve. The results presented in [15–17] have demonstrated that the proposed zero-crossing technique gives several advantages such as the identification of the fundamental A_0 and S_0 modes, operating in low or high dispersion zones, the possibility to reconstruct segments of the phase velocity dispersion curves of A_0 and S_0 modes in the case of Lamb waves.

The physical mechanism of the phase velocity dispersion curve measurement [16] according to the proposed zero-crossing technique is based on at least two signals recorded by two receivers situated at two different and relatively close positions x_i and x_{i+1} (Fig. 1a). The transmitter is attached at a fixed position and excited by a broadband burst $s(t)$. In general, these signals contains information about the phase velocity $c_{ph}(f)$ which needs to be extracted by signal processing.

The Lamb waves signal $u_i(t)$ at distance x_i is defined by the out-of-plane particle velocity on the surface of the plate [18]

$$u_i(t) = \mathrm{FT}^{-1}[S(f)\cdot H(f)], \tag{1}$$

where FT^{-1} denotes the inverse Fourier transform, $S(f)$ is the Fourier transform of the incident pulse $s(t)$, $H(f) = e^{-j\frac{2\pi f x_i}{c_{ph}(f)}}$ is the transfer function determining propagation of Lamb waves.

The proposed method presented in Ref. [16] is based on the delay times t_{im} and $t_{(i+1)m}$ of propagating waves estimated using the signals recorded at different position x_i and x_{i+1} and calculated according to zero-crossing algorithm (Fig. 1,b). The number of measured zero-crossing instants $m = 1,2,\ldots,M$, where M is the total number of zero-crossing instants under analysis. Subsequently, the phase velocity c_{phm} of the propagating wave at a given distance can be estimated according to

$$c_{phm} = \frac{\Delta x_i}{\Delta t_{im}} = \frac{x_{i+1} - x_i}{t_{(i+1)m} - t_{im}}, \tag{2}$$

where Δx_i is the distance between two neighboring positions, Δt_{im} is the delay time difference defined between instants corresponding to the same phase points in two signals measured at different positions. The delay time differences Δt_{im} calculated according to zero-crossing delay times t_{im} and $t_{(i+1)m}$. The frequencies f_m to which correspond the

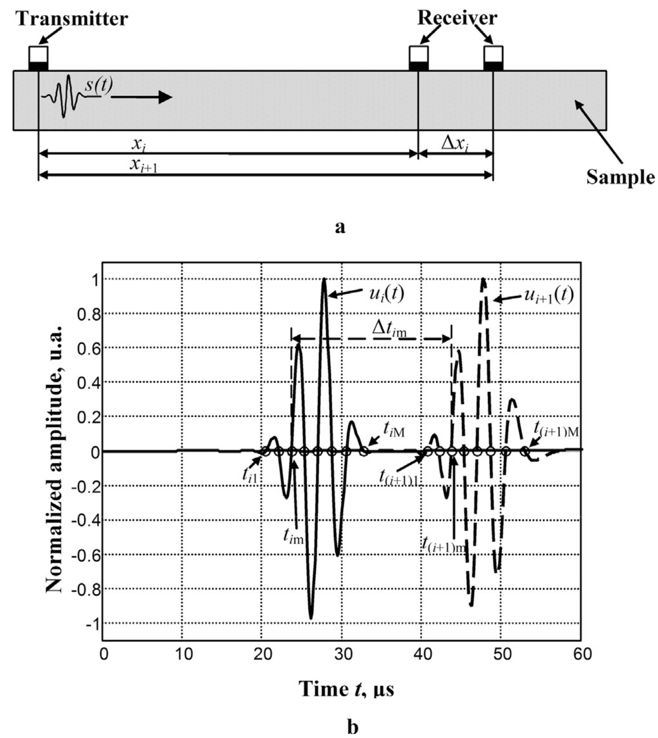

Fig. 1. The set-up of signal acquisition (a) and the waveform of received signals $u_i(t)$ and $u_{i+1}(t)$ (b).

estimated phase velocities c_{phm} are calculated at a half period duration between two neighboring zero-crossing points m and $m + 1$ as reported in Ref. [16]:

$$f_m = \frac{1}{2(t_{i(m+1)} - t_{im})}. \tag{3}$$

The $D(f_m, c_{phm})$ set of phase velocity and frequency pairs represents the segment of the dispersion curve [17]. The number of studies were conducted using this proposed measurement method including modelled signals propagating in different environments, experimental investigation [15,16] and assessment of the quantitative and the qualitative characteristics of this technique [17]. However, in all investigations, it has been showed that the proposed measured method has one basic limitation. The phase velocity dispersion curves are reconstructed only in a relatively limited bandwidth around the central frequency of the signal. This means that not all signal frequency spectra have been exploited and a part of the information has been lost. To solve this limitation and to reconstruct the guided waves phase velocity dispersion curves in as much as possible wider frequency ranges use of the spectra decomposition technique has been proposed.

In general, any investigated signal $s(t)$ can be broken down by trigonometric functions using the Fourier integral [5]:

$$S(j\omega) = \int_{-\infty}^{\infty} s(t)e^{-j\omega t}dt = S(\omega)e^{-j\phi(\omega)}. \tag{4}$$

where $\omega = 2\pi f$ – angular frequency, f – frequency, $j = \sqrt{-1}$, $e^{j\omega t} = \cos\omega t + j\sin\omega t$, $S(\omega)$ – amplitude frequency response, $\varphi(\omega)$ – phase frequency response. The result of such decomposition is the frequency characteristic (spectrum) of the signal. The modulus of the complex spectrum represents the amplitudes of the different frequency components. In general, such spectrum means that the dominant frequency components are concentrated in frequency bandwidth around the maximum of the spectrum. Therefore, in the case of the analysis without filtering the phase velocity dispersion curve will be reconstructed in the narrow bandwidth around the central frequency. So, in order to increase the sensitivity of the signal processing technique to the frequency components with small amplitudes the frequency

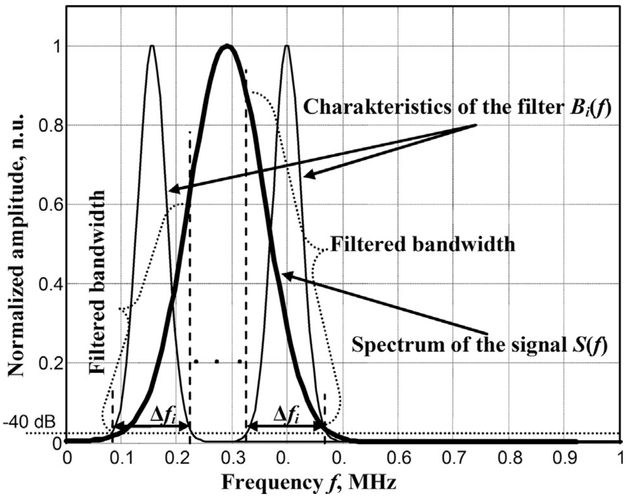

Fig. 2. Frequency spectrum of the Lamb wave signal and of the band pass filters used in the analysis.

components corresponding the higher amplitudes need to be filtered out (Fig. 2).

So, the main idea of the modified zero-crossing algorithm is to decompose the measured signals $u_i(t)$ at the different distances into a set of the band-limited signals $u_{ik}(t)$. This decomposition is obtained by filtering the signals $u_i(t)$ using bandpass filters with narrower band comparing to the incident spectrum bandwidth. Then according to zero-crossing algorithm the delay times t_{imk} and $t_{(i+1)mk}$ are estimated for each filtered signal $u_{ik}(t)$. In this way, the phase velocities c_{phmk} and the frequencies f_{mk} are calculated and the obtained sets (f_{mk}, c_{phmk}) can be presented as segments of the phase velocity dispersion curve. It can be assumed that segment of dispersion curve obtained using one of the filters will be reconstructed in relatively narrow bandwidth however by scanning the central frequency of the filter in wide frequency ranges will enable to cover big part of incident spectrum.

The main steps of the phase velocity dispersion curve reconstruction algorithm can be presented as follows:

- The frequency spectrum of two neighbouring signals are calculated:

$$U_i(f) = \mathrm{FT}[u_i(t)]\,U_{i+1}(f) = \mathrm{FT}[u_{i+1}(t)], \tag{5}$$

where $u_i(t)$ and $u_{i+1}(t)$ are the signals measured at two distances $x_i(t)$ and $x_{i+1}(t)$; FT denotes the Fourier transform.

- This pair of frequency spectra are filtered by k bandpass Gaussian filters with predefined parameters:

$$U_{ik}(f) = U_i(f)\cdot B_k(f)\,U_{(i+1)k}(f) = U_{i+1}(f)\cdot B_k(f) \tag{6}$$

where $B_k(f) = e^{4\ln(0.5)\left(\frac{f-f_L-(k-1)df}{\Delta B}\right)^2}$ represents the frequency response of k-th bandpass filter, $k = 1,2,\ldots K$, K is the total number of filters, f_L and f_H defines the frequency ranges in which the central frequencies of the filters are varied; ΔB is the filter bandwidth; $df = \frac{f_H - f_L}{K-1}$ is the step in frequency domain between central frequencies of two neighbouring filters [19].

- The filtered signals are reconstructed using inverse Fourier transform:

$$u_{ik}(t) = FT^{-1}[U_{ik}(f)]\,u_{(i+1)k}(t) = FT^{-1}[U_{(i+1)k}(f)]; \tag{7}$$

- The zero-crossing instants timk and t(i + 1)mk for each filtered

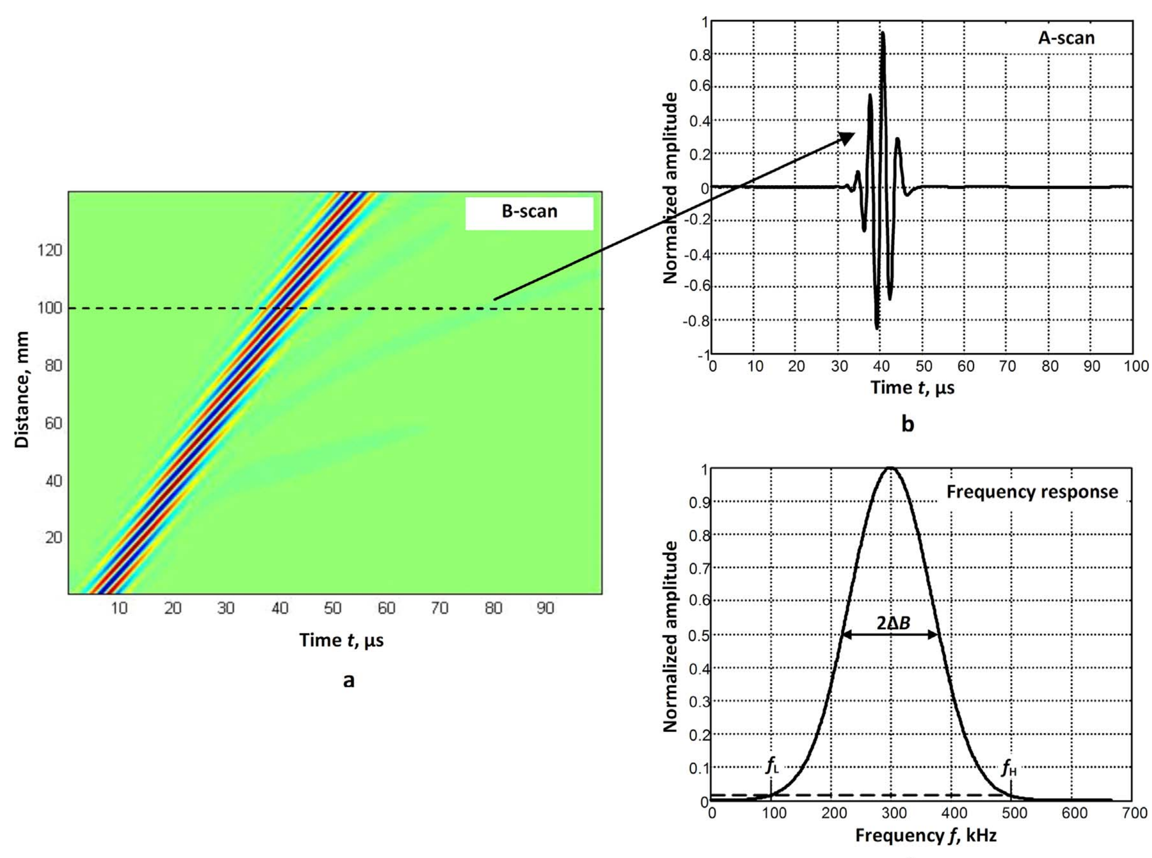

Fig. 3. The B–scan image of the A_0 mode of Lamb wave signals propagating in the 2 mm thickness aluminium plate (a), the waveform of the signal at the 100 mm distance (b) and the frequency response of this signal (c) (f_L = 100 kHz, f_H = 500kHz, ΔB = 80 kHz).

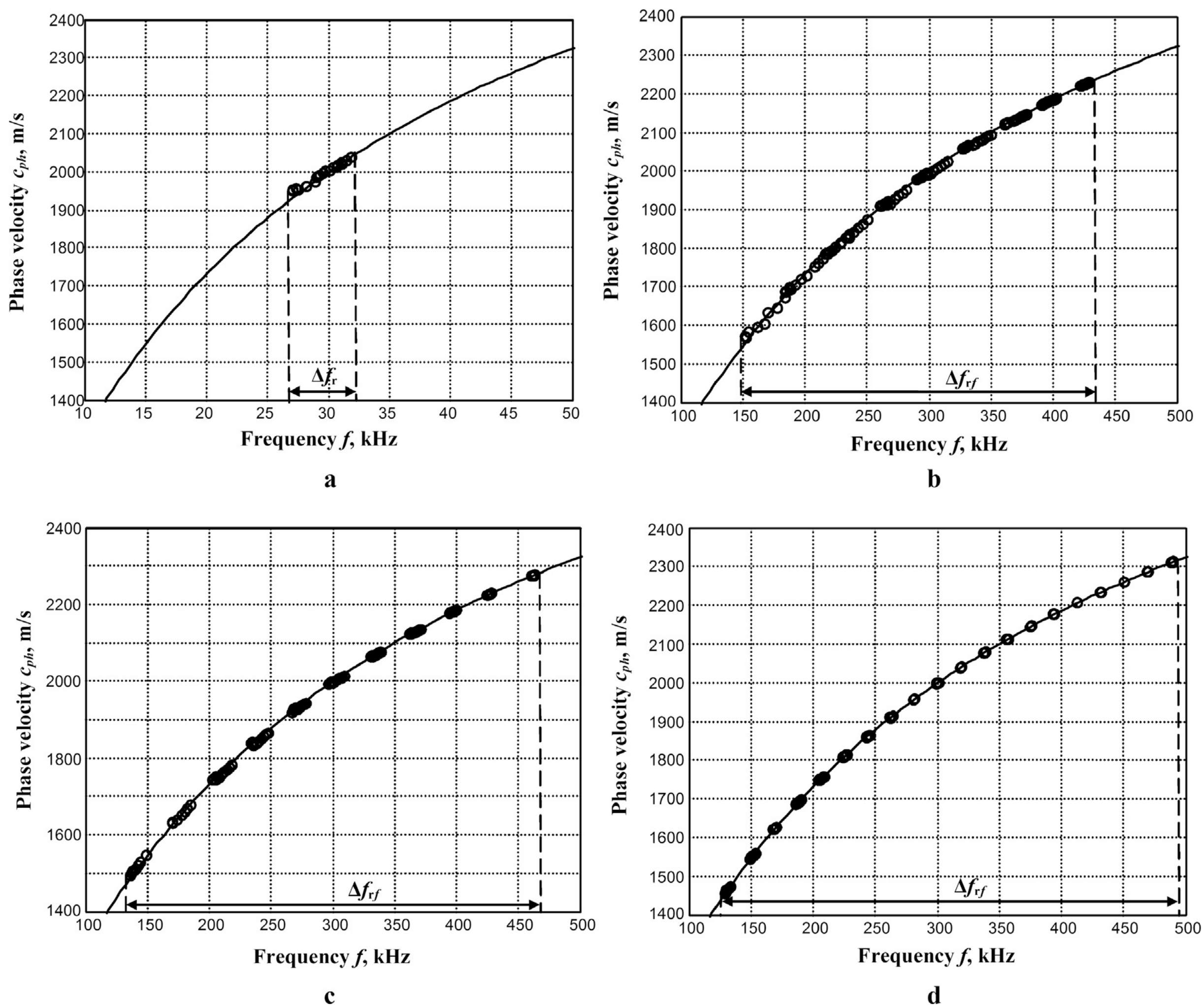

Fig. 4. The reconstructed phase velocities dispersion curves of the Lamb wave A_0 mode: the theoretical dispersion curve (*solid line*) calculated using SAFE method, the measured values (*dots*): a – using zero-crossing method; b – obtained with hybrid algorithm using 9 bandpass Gaussian filters (the bandwidth of the each filter ΔB = 120 kHz); c – obtained with proposed algorithm using 11 filters (ΔB = 80 kHz); d – obtained with proposed algorithm using 21 filters (ΔB=40 kHz).

Table 1
Bandwidth of the frequencies covered by of the reconstructed phase velocity dispersion curves (case of A_0 mode in an aluminium).

Method	Filter bandwidth, kHz	Frequency, kHz		
		Frequency ranges, kHz	Bandwidths, kHz	Bandwidths, %
Reference	Unfiltered	286–319	33	8
Hybrid	120	152–430	278	70
Hybrid	80	136–463	327	82
Hybrid	40	130–490	360	90

signal uik(t) and u(i + 1)k(t), are measured accordingly technique defined in [16,17], where $m = 1 \div M$ is the number of the zero-crossing instants in the signal and M is the total number of zero-crossing instants under analysis.

- The phase velocity is calculated using the expression

$$c_{phmk} = \frac{x_{i+1} - x_i}{t_{(i+1)mk} - t_{imk}}; \quad (8)$$

- The equivalent frequencies to which the estimated phase velocity values should be related are calculated according to the durations of the half- periods of the first signal

$$f_{imk} = \frac{0.5}{t_{i(m+1)k} - t_{imk}}. \quad (9)$$

Usually this frequency does not coincide with the central frequency of the used filter.

- The dispersion curve is defined as the set of velocities related to the frequencies and it is obtained according Eqs. (8) and (9) (f_{mk}, c_{phmk}).

The proposed measurement technique has been verified on two different media. In the first stage, the investigation was performed on an homogenous medium using signals obtain by 2D finite element model of aluminium and experimental investigation. In the second stage, on a non – homogenous medium using signals obtained by 3D finite element model of carbon fibber reinforced plastic plate. In both cases, the obtained phase velocity dispersion curve segments are compared with those calculated when using the semi-analytical finite element SAFE method [20]. The SAFE method is selected as a reference technique because when the elastic properties of the investigate material are know it enables to estimate the dispersion curves for both isotropic and anisotropic materials.

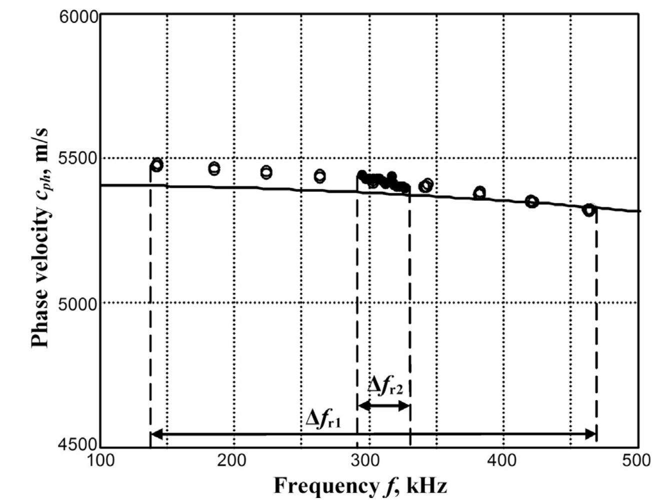

Fig. 5. Theoretical dispersion curve (*solid line*) calculated using the SAFE method, measurement values of the hybrid method (*circles*) and measurement values of zero-crossings (*dots*) in the case of modelled signal analysis of the Lamb waves S_0 mode propagating in 2 mm thickness aluminium.

3. Demonstration of the hybrid method on different objects

3.1. Investigation of the proposed method using simulated signals

At first, the performance of the proposed technique was investigated on modelled signals of the Lamb waves A_0 mode propagating in 2 mm thickness aluminium plate. The signals have been calculated according Eq. (1) and the phase velocity dispersion curve calculated using SAFE method.

The parameters of the homogenous aluminium alloy plate used estimate the dispersion curve are: Density (ρ = 2780 kg/m^3), Young modulus (E = 71.78 GPa), Poisson‘s ratio (ν = 0.3435) [16]. The 3 – period (300 kHz) harmonic bursts with Gaussian envelop was used as the incident signal. Such frequency was selected because A_0 mode posses strong dispersion. The signals of the Lamb waves A_0 mode are calculated at distances starting from 0 mm up to 140 mm with 0.1 mm step. Totally, 1401 signals are obtained and used for the phase velocity dispersion analysis. All these Lamb wave signals are presented in Fig. 3a in the form of the B – scan image. A signal at the distance 100 mm and it‘s frequency spectrum are presented in Figs. 3b and 3c.

The presented frequency spectrum determines:

- The limits of the frequency ranges of the dispersion curves expected to be reconstructed;
- The frequency range for spectrum decomposition technique;
- The bandwidth of the filters;

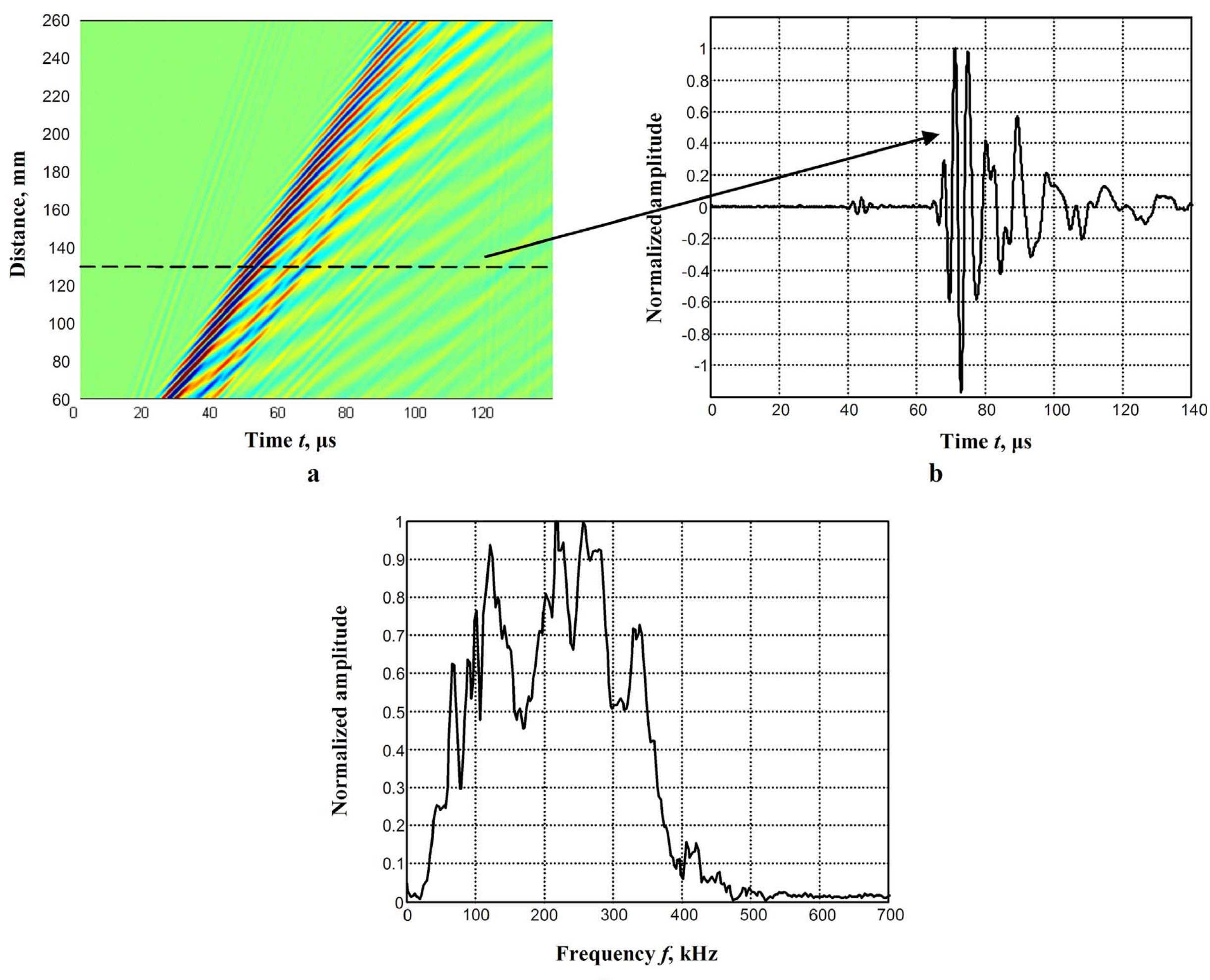

Fig. 6. B–scan image of the A_0 mode of Lamb wave experimental signals propagating in the 2 mm thickness aluminium plate (a), waveform of the signal at the 130 mm distance from the excitation point (b) and frequency response of this signal (c) (f_L = 0 kHz, f_H = 420 kHz, ΔB = 280 kHz).

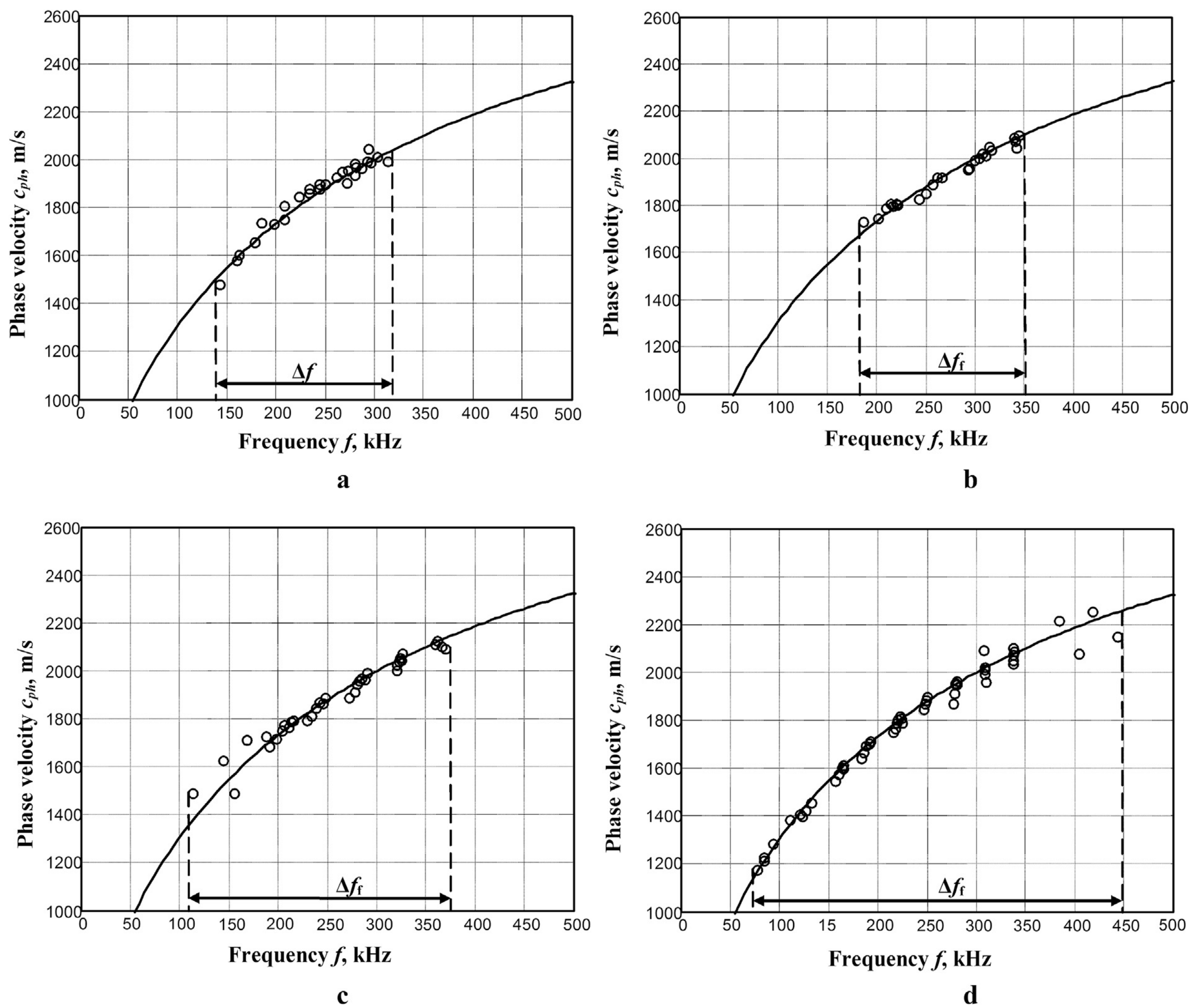

Fig. 7. Reconstructed phase velocities dispersion curves of the Lamb wave A_0 mode: theoretical dispersion curve (*solid line*) calculated using SAFE method, measured values (*dots*): a – using zero-crossing method; b – obtained with hybrid algorithm using 4 bandpass Gaussian filters (the bandwidth of the each filter ΔB = 210 kHz); c – obtained with proposed algorithm using 6 filters (ΔB = 140 kHz); d – obtained with proposed algorithm using 12 filters (ΔB = 70 kHz).

Table 2
Bandwidth of the frequencies covered by of the reconstructed phase velocities dispersion curves of the A_0 mode in an aluminium plate when using experimental signals.

Method	Filter bandwidth, kHz	Frequency, kHz		
		Frequency ranges, kHz	Bandwidths, kHz	Bandwidths, %
Reference	Unfiltered	145–315	170	43
Hybrid	210	187–345	158	40
Hybrid	140	110–370	260	65
Hybrid	70	77–445	368	92

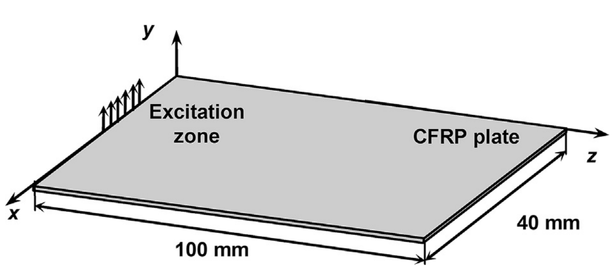

Fig. 8. The 3D finite element model to obtain the signals of the Lamb waves A_0 mode propagating in a thin CFRP plate.

- The number of the filtering operations.

As it can be seen from the spectrum presented in Fig. 3(c), the frequency bandwidth at – 40 dB level is in the range 100–500 kHz. It means that the reconstructed phase velocity dispersion curve should involve all these frequencies and the filtering has to be perform in this range. The frequency bandwidth of the analyzed signal at 6 dB level is $2\Delta B$ = 160 kHz Fig. 3(c). In order to reconstruct the segment of the dispersion curve, in as much as possible wider frequency ranges, filters with three different bandwidth have been selected for analysis: 40 kHz (25%), 80 kHz (50%) and 120 kHz (75%). The selected filter bandwidth determines the number of the filters to be used in the processing. In the case of 40 kHz filter bandwidth the number of filters was 21, using the 80 kHz filter bandwidth 11 and using 120 kHz filter bandwidth only 9 filters. The results obtained using previous zero-crossing technique and spectrum decomposition method with filter possessing in different bandwidths and the dispersion curve obtained by SAFE method are presented in Fig. 4.

The comparison of the results obtained by the proposed hybrid technique and those of a previous version of the reference zero-crossing technique are presented in Table 1. It can be seen that when using zero-crossing technique, the phase velocity dispersion curve is reconstructed in frequency range of 286–319 kHz which is only 8% of signal initial bandwidth. Meanwhile, the proposed spectrum decomposition

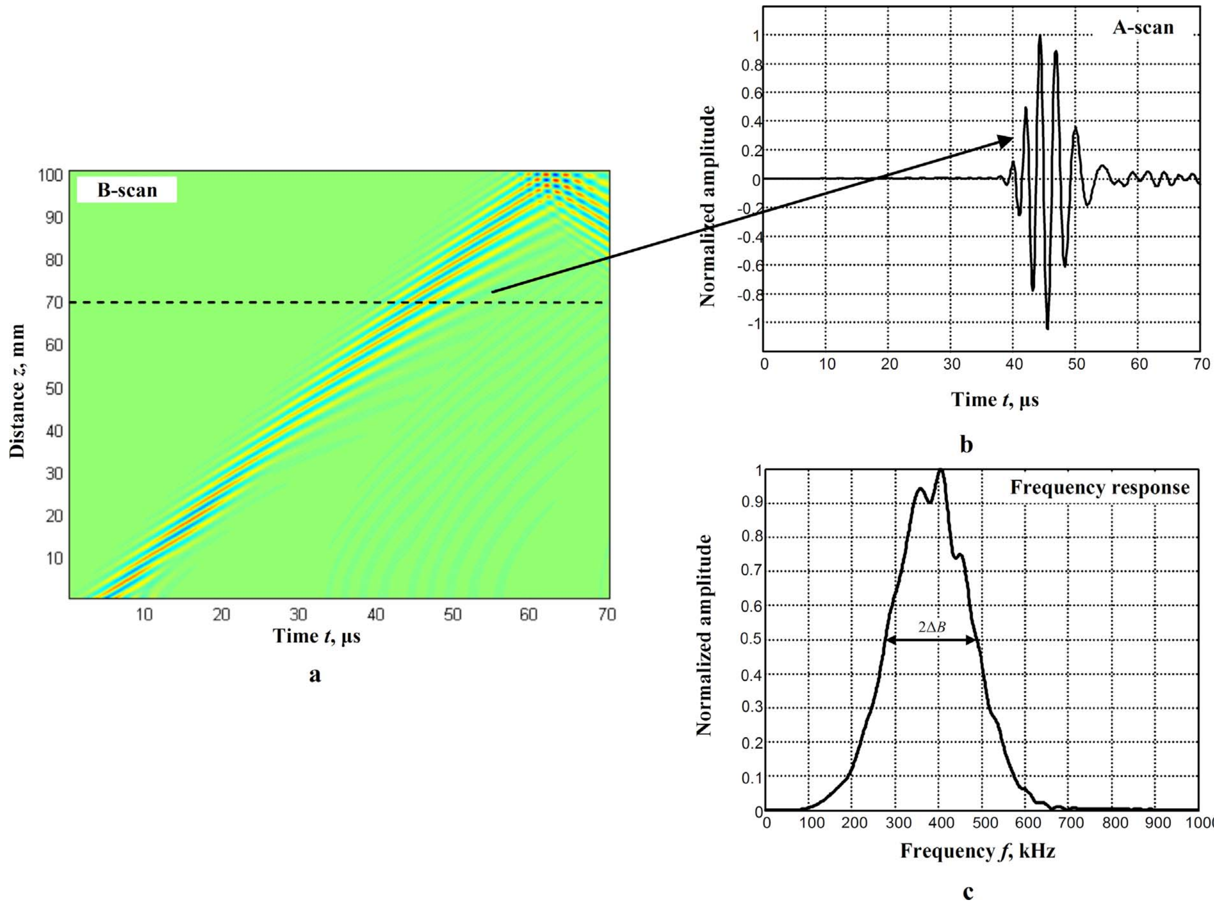

Fig. 9. B–scan image of the A_0 mode signals propagating in CFRP plate (a), waveform of the signal at the 70 mm distance (b) and frequency spectrum of this signal (c) (f_L = 100kHz, f_H = 700kHz, ΔB = kHz).

approach enables to reconstruct the phase velocity dispersion curve in essentially wider frequency range covering almost the whole bandwidth of the incident signal. However, the frequency ranges in which the dispersion curve is reconstructed depend on the bandwidth of the filters used in the spectrum decomposition approach. For 120 kHz filter, 70% coverage of incident bandwidth was achieved. Foremost results were attained in the case of narrowest filter (40 kHz bandwidth) when the reconstructed dispersion curve covers 90% of the initial bandwidth. So, it follows that the narrow filters are more efficient, but this leads to large number of filters which engender more calculation resources and longer processing time.

Usually non-dispersion signals are easier to measure and to figure out since the waveform does not change during propagation. But the proposed hybrid method exploits the dispersive character of the wave to reconstruct the dispersion curve. The question which can arises is whether the frequency decomposition technique will be effective for the modes having the small dispersion. In order to study the performance of the proposed hybrid method in the case of low dispersion, the propagation of a symmetric mode S_0 was analyzed. The signals have been generated in the same 300 kHz frequency range. In that frequency range, S_0 mode possess very low dispersion [21].

For the reconstruction of the dispersion curve segment, a 80 kHz (50%) filter is selected for analysis. The results obtained for the case of the Lamb waves S_0 mode are presented in Fig. 5.

As it can be seen, similar regularities as in the case of the A_0 mode are obtained. The zero-crossing technique enables to reconstruct the phase velocity dispersion curve only in a very narrow 32 kHz frequency range which represents only 8% of the incident bandwidth. Meanwhile, using the spectrum decomposition technique the reconstruction totally was achieved by filtering the signals frequency spectra the frequency values of the S_0 mode in a 323 kHz frequency range which means 81% of incident bandwidth. So, the proposed hybrid technique has also revealed enhanced performance in low dispersion S_0 mode.

3.2. Investigation of the proposed method using experimental signals

The proposed signal processing algorithm has been confirmed experimentally by carrying measurements on aluminium plate. The experiment set-up, the geometry of the object, the excitation signal are presented in previous works [22]. The signals of the Lamb waves A_0 mode are calculated at distances from 60 mm up to 200 mm with 0.1 mm step from the excitation point. Totally, 1401 signals are obtained and used for the phase velocity dispersion analysis. The B – scan image of all of the Lamb waves A_0 mode signals used in the investigation, the waveform of the signal at 130 mm distance from the excitation point and the frequency spectrum of this signal are presented in Fig. 6.

According to the frequency spectrum of the analyzed A_0 mode signal Fig. 6(c), the bandwidth at – 40 dB levels is in the range of 0–420 kHz, the frequency bandwidth at 6 dB level is $2\Delta B$ = 280 kHz. Similar filters as in the case of modelling were use with bandwidth 70 kHz (25%), 140 kHz (50%) and 210 kHz (75%). According to the selected filter bandwidth, the number of the filters used in processing is different. In the case of 70 kHz filter bandwidth the number of filters was 12, with 140 kHz the number was 6 and with 210 kHz it was only 4 filters. The measurement results using different bandwidths and different sets of the filters are obtained and compared with the dispersion curve obtained by SAFE method (Fig. 7).

The results obtained by the hybrid technique and the previous version of the reference zero-crossing technique are presented in

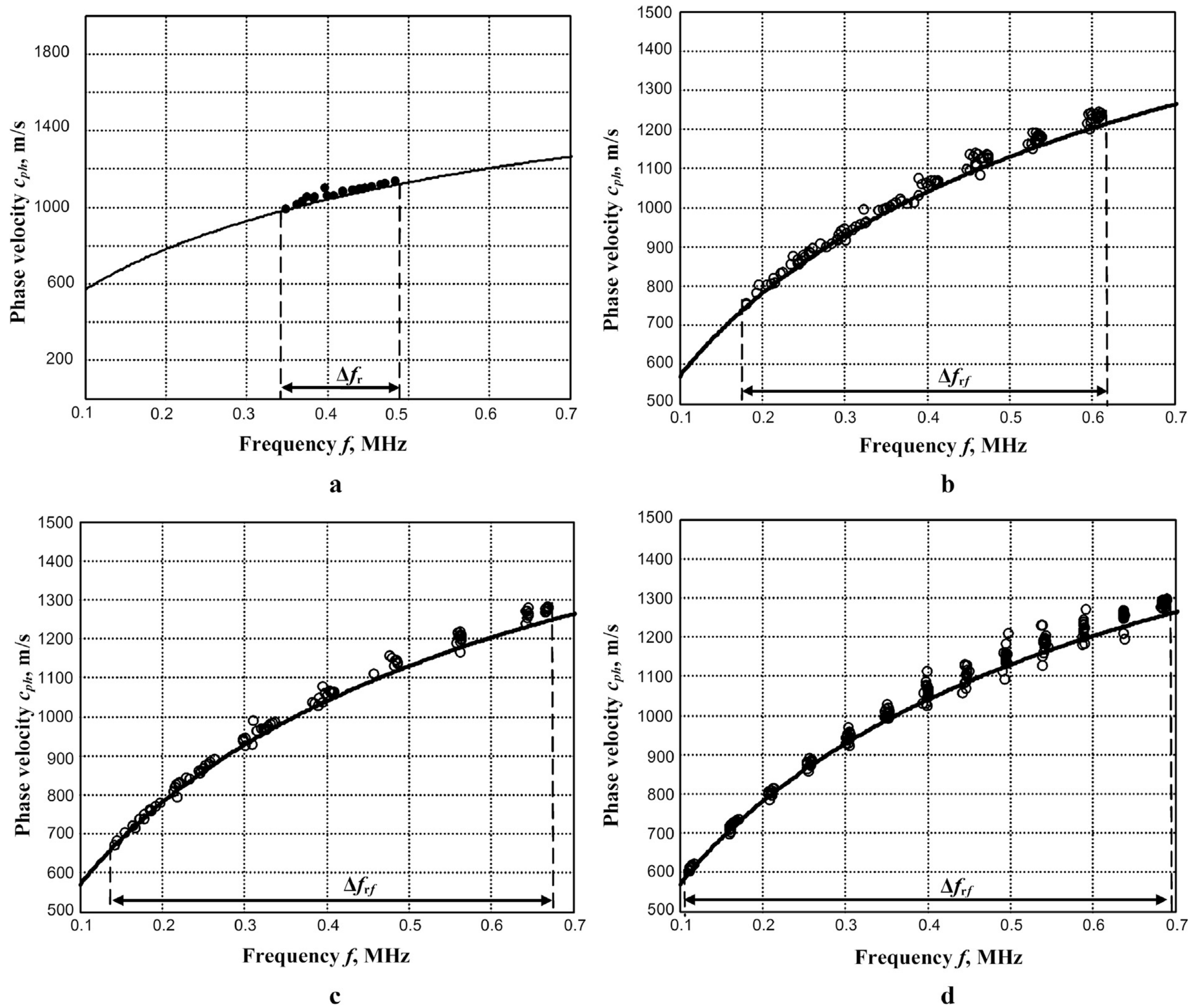

Fig. 10. Reconstructed phase velocities dispersion curves of the Lamb wave A_0 mode: theoretical dispersion curve (*solid line*) calculated using SAFE method, measured values (*dots*): a – using zero-crossing method; b – obtained with hybrid algorithm, bandwidth of the each filter ΔB = 150 kHz; c – ΔB = 100 kHz; d – ΔB = 50 kHz.

Table 3
Bandwidth of the frequencies covered by of the reconstructed phase velocities dispersion curves of the A_0 mode in a CFRP plate.

Method	Filter bandwidth, kHz	Frequency, kHz		
		Frequency ranges, kHz	Bandwidths, kHz	Bandwidths, %
Reference	Unfiltered	348 – 484	136	23
Hybrid	150	181 – 611	430	72
Hybrid	100	122 – 670	548	91
Hybrid	50	111 – 689	578	96

Table 2. The table has outstood that when using zero-crossing technique the phase velocity dispersion curve is reconstructed in frequency range of 145–315 kHz, 43% of initial bandwith of the signal. Meanwhile, the spectrum decomposition approach enables to reconstruct the phase velocity dispersion curve in essentially wider frequency range – in the case of 70 kHz filter which means 92% of incident bandwidth was achieved. Foremost results were achieved when using narrowest filter bandwidth, so the results demonstrate the same regularities as those obtained with modelled signals.

3.3. Investigation of the proposed method using the modelled signals propagating in CFRP plate

In the second stage, the method was completed on an anisotropic material. In order to obtain signals a 3D finite element model of the Carbon Fibber Reinforced Plastic (CFRP) have been created [23]. In general, such plates are widely used as a base material for manufacturing of components with complicated geometry by gluing several plates in layers and shaping them to required geometry [23]. The numerical models give signals relatively close to the experimental ones including presence of several modes and influence of component boundaries. Using the developed model the propagation of the Lamb waves A_0 mode was investigated. The geometry of the 3D model of the CFRP plate and the position of the excitation zone are shown in Fig. 8.

The carbon fibres were oriented along axis *z*. The density of the CFRP plate was assumed to be 1570 kg/m^3. The elastic coefficients have been defined by the following stiffness matrix

$$C_{CFRP} = \begin{bmatrix} 13.49 & 6.67 & 6.42 & 0 & 0 & 0 \\ 6.67 & 13.39 & 6.42 & 0 & 0 & 0 \\ 6.42 & 6.42 & 145.1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 5.3 & 0 & 0 \\ 0 & 0 & 0 & 0 & 5.3 & 0 \\ 0 & 0 & 0 & 0 & 0 & 3.36 \end{bmatrix} \cdot GPa. \quad (10)$$

In order to excite the A_0 mode signals, a tangential force was applied to one of the plate edges. The excitation zone was situated in the centre of one of the plate edges and it was 10 mm in length along *x* axis (Fig. 8). The waveform of the excitation signal was the 3 periods, 400 kHz burst with the Gaussian envelop.

The sampling in the spatial domain was $dx = 0.1$ mm and the guided waves were modelled during 70 μs time interval recorded at distances starting from 0 mm up to 70 mm. The B – scan image of the normal component of particle velocity of the Lamb wave A_0 mode on the top surface of the plate along central line is presented in Fig. 9.

Totally 701 signals were used in the analysis. The waveform of the signal at 70 mm distance from the exitation point is presented in Fig. 9b and the frequency spectra of this signal are presented in Fig. 9c.

The frequency bandwidth of A_0 mode signal at – 6 dB level is approximately $2\Delta B = 200$ kHz, The frequency ranges at – 40 dB level are from 100 kHz up to 700 kHz. As in previous analysis filters with three different bandwidths were used: 50 kHz (25% of incident spectrum), 100 kHz (50%) and 150 kHz (75%). The obtained results are presented in Fig. 10. For comparison, the theoretical dispersion curve calculated using SAFE method is showed also. The frequency ranges in which the dispersion curves were reconstructed are recorded in Table 3.

In general, similar regularities to those obtained by the analytical model and experimental investigation can be observed. At first, the dispersion curves in the case of any used filters have been reconstructed in basically wider frequency bandwidth comparing to the reference method. The second, is that narrower filters enable to achieve better coverage of frequency bandwidth. In the case of filter with 150 kHz bandwidth the coverage was achieved 72% of incident spectrum and in the case of 50 kHz – even 96%. It can be noticed also that at higher frequency some systematic error can be observed between reconstructed and theoretical phase velocity values. Since such error was not observed in the case of the signals obtained by the analytical model it can be assumed that these errors are consequence of numerical dispersion caused by integration scheme used in the finite element model [24].

4. Conclusions

The new tool is based on two techniques: the zero-crossing and the spectrum decomposition that are combined together. This hybrid method extends the possibilities of the previously presented zero-crossing technique for the reconstruction of the Lamb wave phase velocity dispersion curve segments. The presented signal processing algorithm is verified in two different mediums: isotropic-homogenious aluminium plate using modelled and experimental signals and anisotropic-non-homogenious CFRP plate using modelled signals. It was shown that the developed method enables to evaluate the dispersion and to reconstruct the phase velocity dispersion curve segments both in the case of strong and weak dispersion. Furthermore, it permits to reconstruct the dispersion curve in approximately 96% of the whole incident signal frequency bandwith. The comparison of the proposed spectrum decomposition technique with zero-crossing as reference method have shown that the new method enables to reconstruct the dispersion curve in essentialy wider frequency ranges by covering even frequencies represented in frequency spectrum by very low amplitudes. In the case of the non-dispersive Lamb waves symmetric S_0 mode the phase velocity dispersion curve was reconstructed in ten times wider frequency range comparing to the reference method.

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