Investigation of the zero-crossing technique in measurement of phase velocities of the guided wave in thin CFRP composite plate

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Abstract

One of the main areas for application of the guided waves is inspection of composite materials. These materials usually possess anisotropy of elastic properties. In order to investigate the possibilities of the developed phase velocity measurement technique based on accurate measurements of the zero crossing points of ultrasonic signals the numerical modelling of a thin CFRP plate was carried out. The finite element model of the CFRP plate with thickness 0.2 mm, length 100 mm and width 40 mm was created and used in order to obtain the signals for analysis. The A_0 mode was excited by attaching tangential force and the S_0 mode by attaching normal force to the one edge of the plate. The width of the excitation zone was 10 mm and it was situated in the center of the plate. The waveform of the excitation signal was 3 period, 400 kHz burst with the Gaussian envelope. In general, the investigations demonstrated the same regularities as were obtained on non-homogeneous material and enable to identify different modes in the signals and to reconstruct the segment of the phase velocity dispersion curve.

Keywords: Lamb wave, mode, dispersion curves, phase velocity, zero-crossing technique, non-homogeneous material.

Introduction

In previous our articles [1-4] the phase velocity method based on the analysis of zero-crossing point in the signals of the guided waves was presented. It was shown that such technique enables to identify at least fundamental Lamb wave modes and to reconstruct the segment of the dispersion curve. As the phase velocity is related to the elastic properties of the materials it can be used for investigation of different composite structures. The previous investigations [1-4] were carried out on the aluminium plate which is homogenous material. However the composite materials are more complicated and usually possess the anisotropic acoustic properties. So, the objective of the work presented was to investigate the proposed method for analysis of the properties of the guided waves propagating in the composite materials with strong anisotropic properties.

Object of the investigation

As the object for investigation a thin CFRP (carbon fibres and epoxy) plate with one directional orientation of fibbers was selected. Such plates are used to manufacture various components for aerospace or ground transport applications by gluing them together at different angles. It is known that the ultrasound velocity of the guided waves along and across the fibbers differs more then twice [5]. In order to obtain signals for analysis the propagation of the A_0 and the S_0 modes the 3D finite element model of the CFRP plate was created. The length of the plate was 100 mm, width 40 mm and the thickness 0.2 mm. The dispersion curves of the guided waves propagating along fibbers direction in plate were calculated using the SAFE method [6-8] and are presented in Fig.1.

As can be see the asymmetric A_0 mode has dispersion in all frequency ranges under analysis. The symmetric S_0 mode in the same frequency bandwidth possesses very small dispersion which starts slightly to increase approximately from 300 kHz. The an other difference between A_0 and S_0 modes is that the phase and the group velocities of the S_0 mode are almost the same. At the frequency 400 kHz the phase velocity is 9510 m/s and the group velocity is 9511 m/s. The group velocity of A_0 mode is bigger then the phase velocity. At the frequency 400 kHz the phase velocity of the A_0 mode is 1040 m/s and the group velocity is 1687 m/s. Both of them increase with a frequency. In Fig.1 the non-dispersive shear horizontal S_H mode can be observed also.

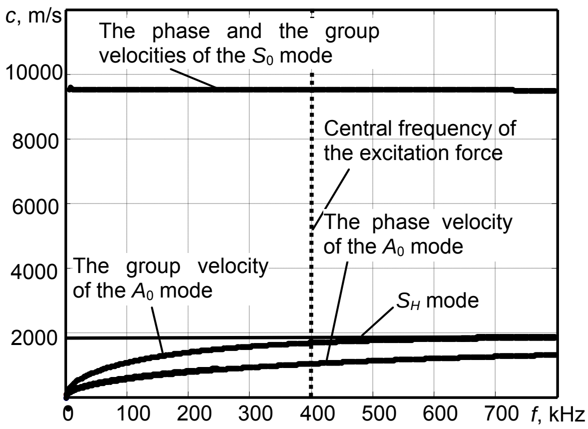

Fig.1. **The dispersion curves A_0, S_0 and S_H modes propagating in the thin 0,2 mm thickness and 100 mm length CFRP plate**

The model of the CFRP plate and obtained signals

The geometry of the 3D model of the CREP plate, the dimensions and the position of the excitation zone are presented in Fig.2 and 3. The carbon fibbers were oriented along axis *x*. The parameters of the CFRP plate used in the modelling are: the density ρ =1570 kg/m^3 and the elastic coefficients have been defined by the stiffness matrix

$$\mathbf{C}_{CFRP} = \begin{bmatrix} 13.59 & 6.63 & 5.46 & 0 & 0 & 0 \\ 6.63 & 13.59 & 5.46 & 0 & 0 & 0 \\ 5.46 & 5.46 & 144.9 & 0 & 0 & 0 \\ 0 & 0 & 0 & 7.2 & 0 & 0 \\ 0 & 0 & 0 & 0 & 7.2 & 0 \\ 0 & 0 & 0 & 0 & 0 & 3.48 \end{bmatrix} \cdot GPa \qquad (1)$$

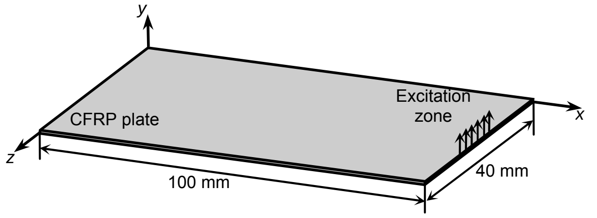

Fig.2. **The finite element model for investigation of the A_0 mode of guided waves propagating in thin CFRP plate**

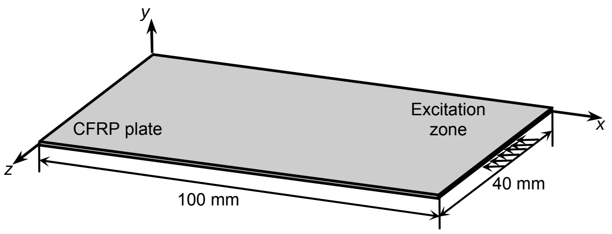

Fig.3. **The finite element model for investigation of the S_0 mode of guided waves propagating in thin CFRP plate**

The sampling step in the spatial domain was dx=0.1mm and dt=0.1 μs in the time domain. The A_0 mode was excited by attaching the tangential force (Fig.2) and the S_0 mode – by attaching the normal force (Fig.3) to the edge of the plate. The length of the excitation zone was 10 mm and it was situated in the centre of the one of the plate edge (Fig.2-3). The waveform of the excitation signal was 3 period, 400 kHz burst with the Gaussian envelope. The waveform of this signal is presented in Fig.4.

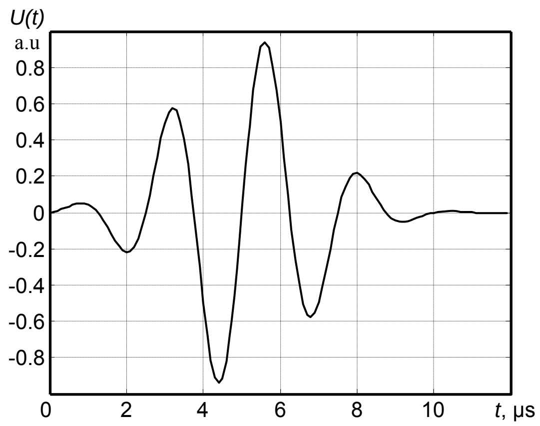

Fig.4. **The waveform of the excitation signal**

The propagation of the A_0 and S_0 modes was modelled during 70 μs time interval. The obtained B-scan images of the normal component of the particle velocity on the top surface of the plate in the case of propagating A_0 mode are presented in Fig.5 and in the case of the S_0 mode - in Fig.6. The pattern of the A_0 mode demonstrates that the phase and the group velocities are different and the phase velocity is smaller than the group velocity. At the distance 40-60 mm small reduction of the amplitude of the A_0 mode can be observed. Probably it can be caused by the diffraction due to a limited length of the excitation zone. The S_0 mode of the Lamb waves is about five times faster than the A_0 mode and during the same modelling time several times reflected by the plate edges. In Fig.6 the B scan is zoomed in order to show only directly propagating waves (without reflections). The reflected waves were filtered using 2D Fourier transform. It can be seen also that together with the S_0 mode some the other much slower mode is generated. It can be assumed that it is the S_H mode (Fig.6).

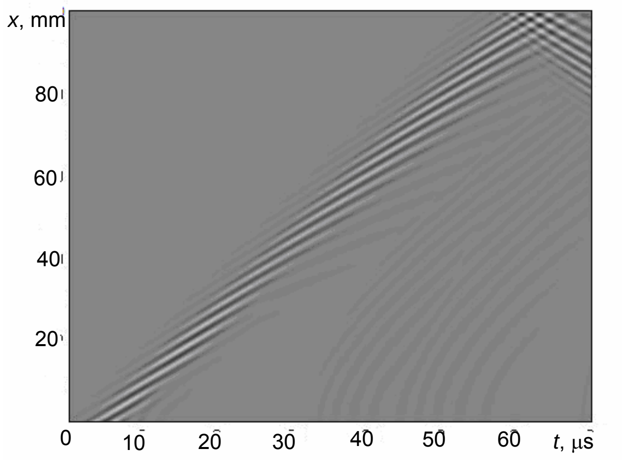

Fig.5. **The B-scan image of the normal component of the particle velocity on the surface of the plate in the case of generated A_0 mode**

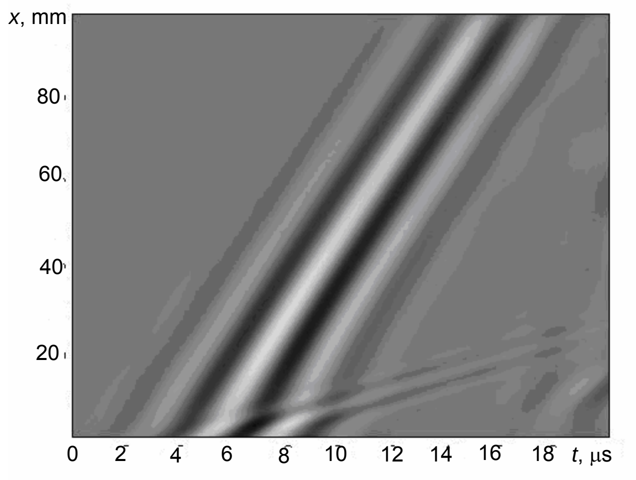

Fig.6. **The B-scan image of the normal component of the particle velocity on the surface of the plate in the case of generated S_0 mode**

Analysis of the signals

The signals obtained by modelling were analysed using the same method based on the zero-crossing technique and described in [1-4]. The obtained phase velocities of the A_0 mode at the different distances are presented in Fig.7. The small increase of the phase velocity with the distance can be observed. It can be seen also that the zero-crossing points with a bigger number give the smaller value of the phase velocity. In order to relate the phase velocity values to the frequency, the equivalent frequencies of the each half period in the signal were estimated. The obtained results are presented in Fig.8. As can be seen the average frequency of the signal increases with the distance and the later half periods in the signal possess lower equivalent frequencies (Fig.9). Such regularity is typical for the A_0 mode in the analysed frequency ranges [1]. A similar regularity was observed in the case of aluminium plate [1, 4] also, so it can be stated that it is related not to the material in which the waves propagates, but to the character of the dispersion curve in the analysed frequency ranges. This feature can be exploited for the identification of the A_0 modes signal in complicated trails of the reflected guided waves. It can be observed also that at the shorter distance the central frequency of the A_0 modes is even slightly lower than the central frequency of the excitations signal (400 kHz) (Fig.10).

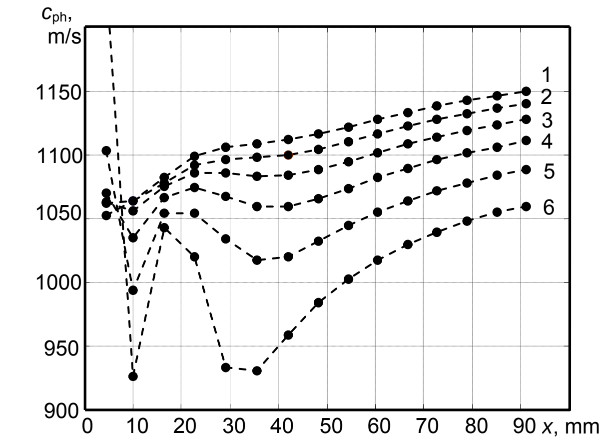

Fig.7. **The phase velocity of the A_0 mode of the Lamb waves measured at different distances: 1-6 are the numbers of zero-crossing point in signal used in the delay time estimation**

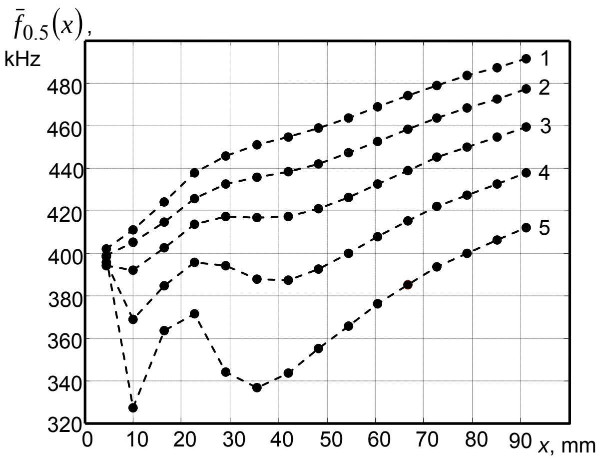

Fig.8. **The equivalent frequencies of different half periods of the signal versus distance: 1-5 are the numbers of the half period**

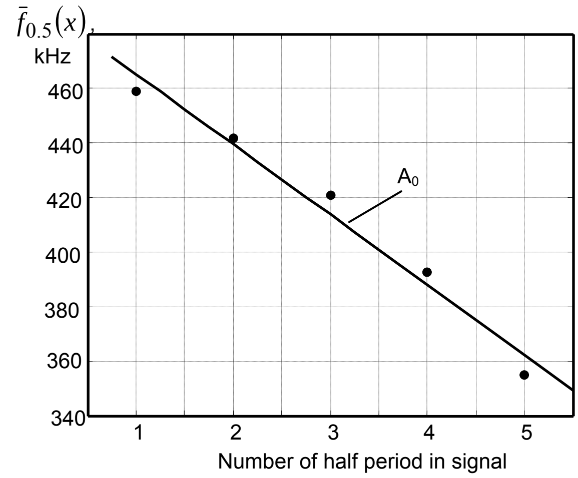

Fig.9. **Variations of the equivalent frequency of the different half periods in the case of the A_0 mode signals at the distance 50 mm**

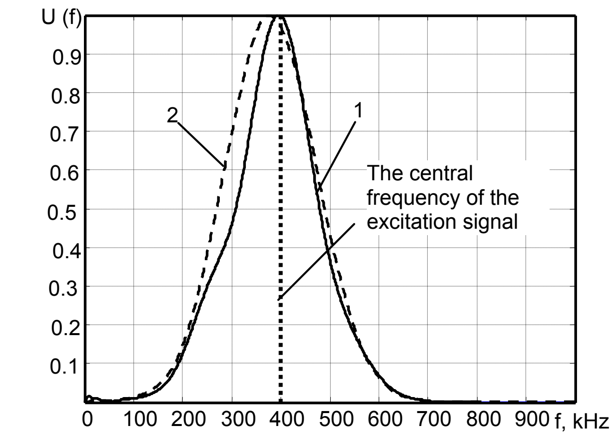

Fig.10**. The frequency spectrum of the A_0 mode: the solid line (1) the signal is on the 1 mm distance and the dotted line (2) the signal is on the 50 mm distance**

This regularity can be observed in various modelling and experimental investigations – the A_0 mode is generated at slightly lower frequency ranges comparing to the bandwidth of the excitation signal or transmitter.

The combination of the measured phased velocities and the measured equivalent frequencies gives the segment of the dispersion curve (Fig.11.) As can be seen it fits relatively well to the theoretical one, obtained by the SAFE technique, only some systematic shift can be observed.

The symmetric S_0 mode gives different regularities. The phase velocities obtained from the signals measured at the different distances and using different zero-crossing points demonstrate some scattering of results at the beginning and at the end of the plate (Fig.12). The scattering of the results can be explained by the interference of the several waves in these zones. At the beginning of the plate the S_0 mode is interfering with the assumed S_H mode and at the plate end with the reflected S_0 mode wave. In the middle zone a small reduction of the phase velocity versus distance can be observed.

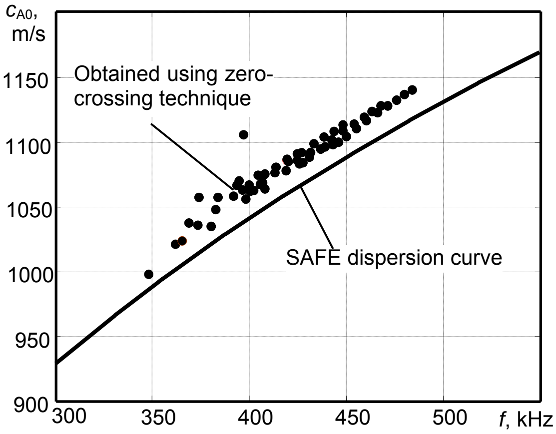

Fig.11. **The phase velocities of the A_0 mode Lamb wave in 0.2mm thickness CFRP plate obtained using simulated signals and SAFE dispersion curve**

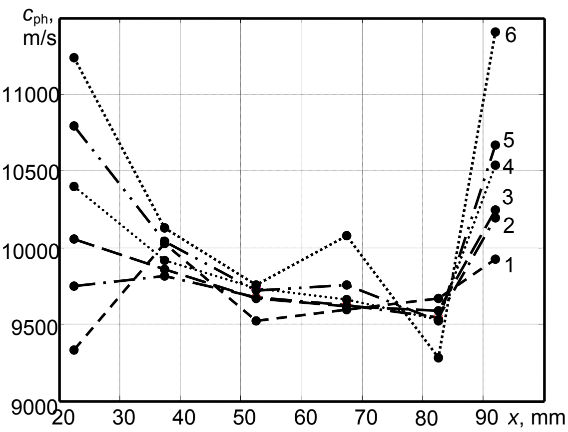

Fig.12. **The phase velocity of the S_0 mode of Lamb wave measured at different distances using different zero-crossing points: 1-6 are the numbers of zero-crossing point in the signal used for the delay time estimation**

The estimated equivalent frequencies of the S_0 mode demonstrate increase versus distance also (Fig.13). However, comparing with the A_0 mode this dependency is different, not so linear. On the other hand the variation of the equivalent frequency in the signal demonstrates opposite dependency with respect to with the A_0 mode - the equivalent frequency increases for the later half periods of the signal (Fig.14). Of course this dependency is not so strongly expressed due to the very small dispersion of the S_0 mode in the frequency ranges under analysis. The small increase of the central frequency of the signal with the distance can be observed also (Fig.15). The combination of the measured phase velocities and the equivalent frequencies in one figure (Fig.16) gives the segment of dispersion curve. In the case of the S_0 mode some systematic shift can be observed also – the measured values of the phase velocity are higher then the phased velocities obtained using the SAFE method. However the results are distributed in more narrow frequency ranges comparing to the A_0 mode due to the week dispersion of the S_0 mode phase velocity.

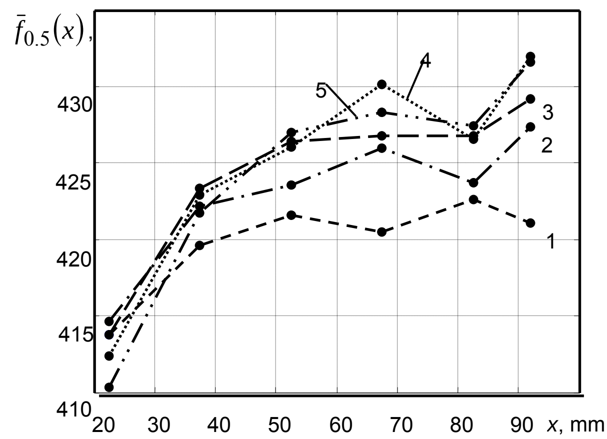

Fig.13. **The equivalent frequencies of different half periods of the signal: 1-5 are the numbers of the half period**

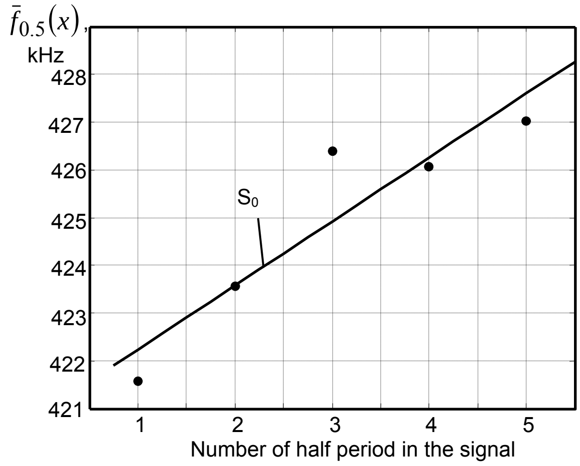

Fig.14. **Variations of the equivalent frequency of the different half periods in the case of the S_0 mode signal at the distance 50mm obtained using modelling signals.**

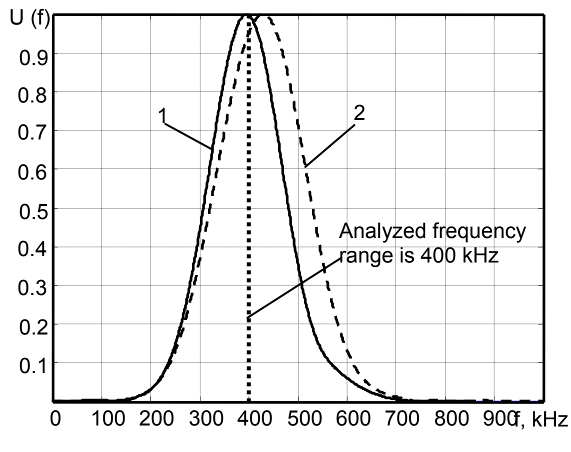

Fig.15. **The frequency spectrum of the S_0 mode: the solid line (1) the signal is on the 1 mm distance and the dotted line (2) the signal is on the 50 mm distance**

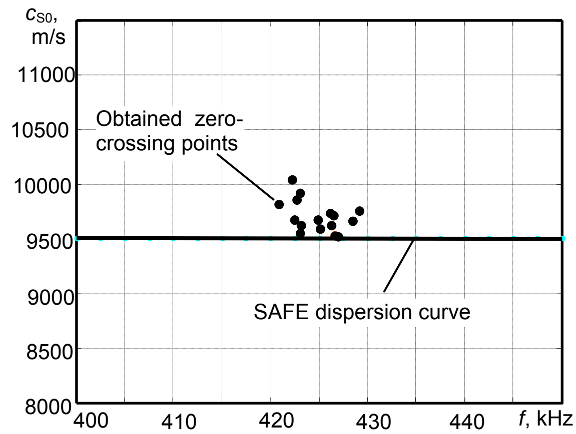

Fig.16. **The phase velocities of S_0 mode Lamb wave in 0.2mm thickness CFRP plate obtained using simulated signals and SAFE dispersion curve**

Conclusions

In general the application of the phase velocity measurement technique applied for the anisotropic CFRP plate demonstrated similar regularities as were obtained on the isotropic aluminium plate. In both cases some systematic mismatch between results obtained using the proposed technique and the results obtained using SAFE method was observed.

The most reliable property which enables to identify different modes is distribution of the equivalent frequencies in the signal.

The results demonstrated also that the phase velocity dispersion curve is reconstructed in wider frequency ranges if the mode under analysis possesses stronger dispersion in that frequency ranges. So, contrarily to other techniques the proposed method is more suitable for measurements in the frequency ranges with a stronger dispersion.

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Perėjimo per nulį matavimo metodo tyrimas matuojant nukreiptųjų bangų fazinį greitį, signalui sklindant plona anglies pluošto (CFRP) plokštele

Reziumė

Viena iš pagrindinių sričių, kurioje nukreiptosios bangos gali būti taikomos, yra kompozicinės medžiagos. Jos dažniausiai turi anizotropinių savybių. Siekiant įvertinti fazinio greičio matavimo metodo, pagrįsto signalo perėjimo per nulį laiko momento nustatymu, galimybes tokioms medžiagoms tirti, buvo atlikti matavimai. Tam naudoti baigtinių elementų metodu gauti kompozicine medžiaga sklindančios bangos signalai. Tyrimo metu buvo modeliuojamas nukreiptųjų bangų A_0 ir S_0 modų sklidimas 100 x 40 mm matmenų, 0,2 mm storio anglies pluošto (CFRP) plokštele. Bangoms žadinti buvo naudojamas įprastas ultragarsinių neardomųjų bandymų 400 kHz Gauso gaubtinės signalas. Tyrimai parodė, kad nukreiptųjų bangų fazinio greičio matavimo duomenų analizės metodas įgalina atkurti skirtingų modų dispersinių kreivių segmentus nagrinėjamame dažnių diapazone ir identifikuoti sklindančių Lembo bangų modas.

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