

CHARACTERIZATION AND EVALUATION OF NON-DESTRUCTIVE TESTING USING ULTRASONIC LAMB WAVES

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ABSTRACT

Composite materials are widely used in modern technologies. Their applications are very diverse - from everyday products to high-tech applications. Composite materials created using various innovative materials (mica, carbon structures, nanostructures, glass, etc.). This is a heterogeneous material and has a complex material structure. The application of ultrasonic guided Lamb waves allows for better detection and characterization of various materials and the existing structure. Ultrasonic guided waves allow for the detection and characterization of not only surface micro-damages of composite structures, but also various types of defects (delamination's, cracks, thickness variations) inside the structure. The excitation of higher-order ultrasonic guided Lamb waves modes faces many problems, especially when using the air-bonding technique, and has not been sufficiently studied. This is relevant for paper, high-density polyethylene (HDPE), membranes, GFRP, GLARE, CFRP and other composite structures. The aim of the work is to study the excitation and reception of guided Lamb wave modes in high-density polyethylene and composite materials. To aim of this paper, it is appropriate to apply existing and develop new contact ultrasonic measurement methods based on the excitation and reception of guided waves. The obtained results clearly demonstrated the possibility of effectively exciting and receiving different guided Lamb wave modes with very different phase velocities. Comparison of experimental results with simulation results showed good agreement.

Keywords: Lamb waves; elastic properties; composite materials.

Introduction

Ultrasonic guided wave inspection is a very promising method for non-destructive testing (NDT) [1] and structural health monitoring (SHM). It is a fundamental method for detecting and characterizing defects in a wide range of simple and complex structures over long distances [2]. Various types of guided waves can propagate in any confined medium and include the well-known Rayleigh (surface) waves in a half-space and Lamb waves in plates. Similar types of waves can propagate in rods, cylinders, and elongated structures that are not axisymmetric, such as railway tracks. The use of guided waves in NDE has been discussed for over 40 years, and Worlton [3] was one of the first to recognize their potential. Rose's textbook [3] provides an introduction to the theory and applications of guided waves, and the same author has recently discussed the history and possibilities of such inspection [4]. Guided waves can be distinguished in three different variants, each of which has been extensively studied and described: short-range (<1 m), medium-range (up to about 5 m), and long-range (up to 100 m). The first method, short-range, which involves high-frequency surface wave scanning (for example, the use of Rayleigh waves discussed by Thompson to detect small surface defects in artillery shells), leaky Lamb wave inspection of composite materials [5], and acoustic microscopy [6], in which a lens generates a leaky surface wave. The second method, medium-range testing, typically uses frequencies in the 250 kHz–1 MHz range and has been applied to flat structures, pipes and tubes [5, 7–9], welds [10], aircraft joints, and even ice detection on aircraft [11]. There are cases where guided ultrasound waves should be excited only by non-contact, that is, the third option, e.g. with air-coupled

techniques: hygroscopic materials such as paper, thin films, thin flexible materials such as plastic films or samples moving at high speed [12–17].

The antisymmetric A_0 Lamb wave mode is most commonly used for non-destructive testing. This wave mode is sensitive to defects that are characteristic of composite materials. This mode is dispersive and its phase velocity decreases with decreasing frequency. When the speed of the A_0 mode is higher than the ultrasonic speed in air, a leaky wave is emitted into the surrounding air. A different situation occurs when the speed of the A_0 mode becomes slower than the ultrasonic speed in air. The propagation of such waves is not accompanied by leaky waves into the surrounding air; therefore, there should be no losses due to this phenomenon. When exciting or receiving ultrasonic Lamb waves, the main problems are encountered: first, not one, but several different ultrasonic waves are excited, the solution to this problem requires identifying which UG waves are excited. Second, due to various environmental and structural properties, attenuation of UG waves occurs. To solve this problem, it is necessary to use new, innovative materials when creating transducers or gratings. and here is the main problem, when exciting through the air gap, an air wave also propagates along with the UG waves, which has a negative effect on the UG waves. Therefore, it is necessary to perform wave filtering and eliminate the air wave and other external disturbances.

The aim of the work is to investigate the excitation and reception of ultrasonic guided Lamb wave modes in high-density polyethylene and composite materials. To achieve this aim, we used existing methods, and we updated and adapted those methods to several different materials.

The first method measures the elastic properties of selected samples. Knowing the exact properties, dispersion curves were calculated using a semi-analytical method. The next important method, using ultrasonic transducers, is to obtain images of the material, from which the structure of the material can be described. Using the methods of filtering and transformation, defects in the structure of the material are identified.

The paper is organized as follows. **Section 1** reviews the properties of ultrasonic guided Lamb waves modes and presents the theoretical background. The experimental investigations performed by contacts methods are reported in **Section 2**. Conclusions and discussion can be found in **Section 3**.

Properties of ultrasonic guided Lamb wave modes

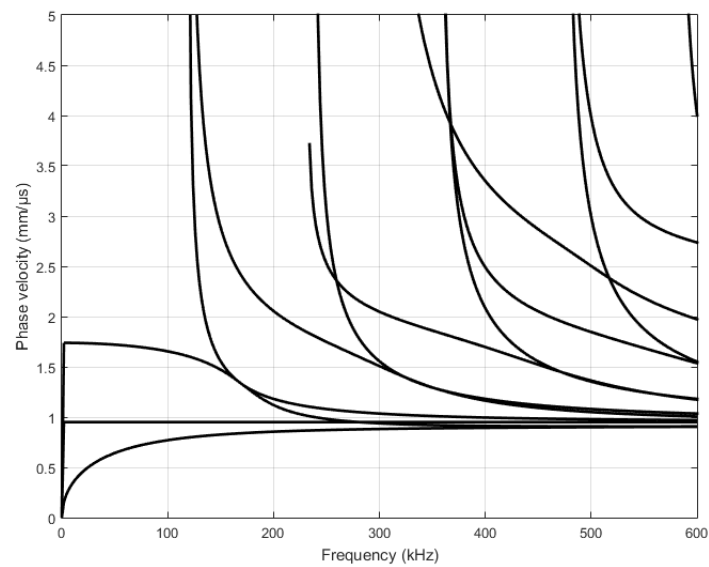
HDPE (high-density polyethylene) is one of the most durable and versatile thermoplastics in today's market. HDPE is made under controlled conditions by applying intense heat to petroleum. This process, also known as "cracking," helps create ethylene gas. During its production, the gas molecules will attach to form polymers, which then produce polyethylene. After this process, the polyethylene will have a sludgy appearance, but after it's put through a series of molds, it forms into granules. Once the moulding process is complete, it will be a strong polymer material. Because HDPE is a versatile material, there are a number of uses for it. Using its chemical properties, HDPE materials are resistant to temperature, pollution, moisture, scratches, dents and is highly resistant to corrosion. Due to its durable construction and recyclability, it's one of the most sought-after materials for liquid containers, used to house hazardous materials and agrochemicals. Another material of choice is GFRP. Pultruded glass fibre reinforced polymer (GFRP) has light weight, good

strength, and excellent resistance to corrosion. The provided GFRP samples were assumed to have anisotropic elastic properties because the main part of the plates was made of CFM material. The thickness of GFRP plate is 4 mm. To generate guided waves, the elastic properties are essential to determine which mode is feasible to generate and how to generate a specific mode. To know the distribution of ultrasonic waves in these materials, it is first necessary to know their exact viscoelastic properties, which were measured at the Department of Physical Acoustics (APY), Bordeaux, France. The sample dimensions chosen for the measurements were 200 × 200 mm. The experimental equipment and setup are given in the article [18].

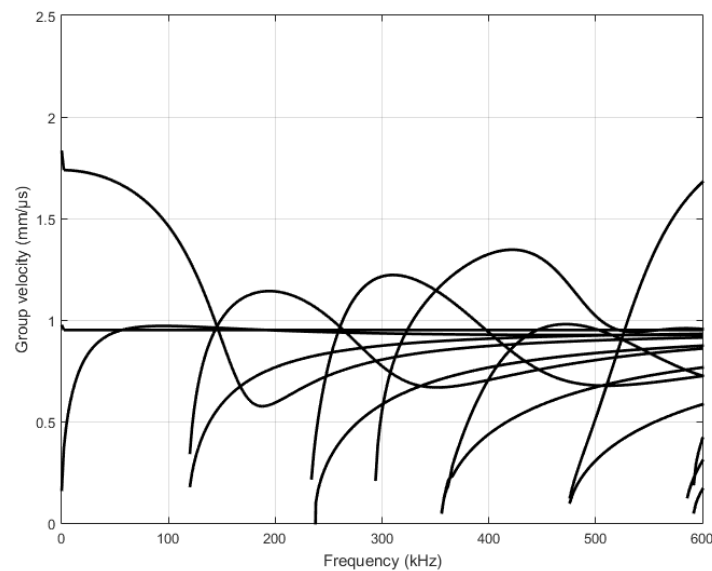
Table 1. *Calculated elastic properties in the HDPE and GFRP materials.*

HDPE	
Parameter	Value
Density	$\rho = 941 \text{ kg/m}^3$
Young's modulus	$E = 2.3839 \text{ GPa}$
Poisson's coefficient	$\nu = 0.4023$
GFRP	
Parameter	Value
Density	$\rho = 2309 \text{ kg/m}^3$
	$E_1 = 24.5928 \text{ GPa}$
	$E_2 = 12.5821 \text{ GPa}$
	$E_3 = 24.5044 \text{ GPa}$
	$\nu_{12} = 0.3833$
	$\nu_{31} = 0.1961$
	$\nu_{13} = 0.2063$
	$\nu_{31} = 0.2056$
	$\nu_{23} = 0.1618$
	$\nu_{32} = 0.3151$
	$G_{12} = 4.00 \text{ GPa}$
	$G_{13} = 3.81 \text{ GPa}$
	$G_{23} = 4.52 \text{ GPa}$

The calculations were performed using two different methods: the first, the semi-analytical finite element (SAFE) method [19] and the 2D Fourier transform [16, 18]. The SAFE method can be used not only for isotropic but also for layered anisotropic materials. The simulated phase and group velocity dispersion curves of the 4 mm HDPE (isotropic material) and GFRP plates (anisotropic material) are shown in Figures 1 and 2. Figures 1a and 2a show the phase velocities for various ultrasonic Lamb wave modes, and Figures 1b and 2b show the group velocities.

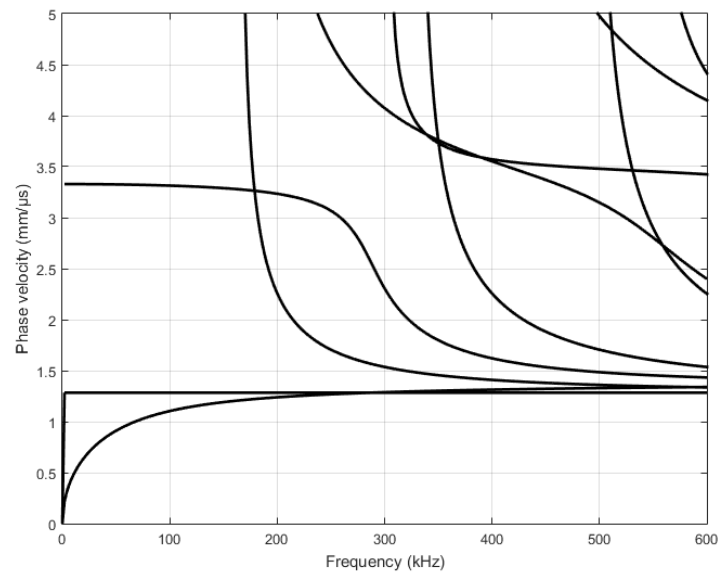


(a)

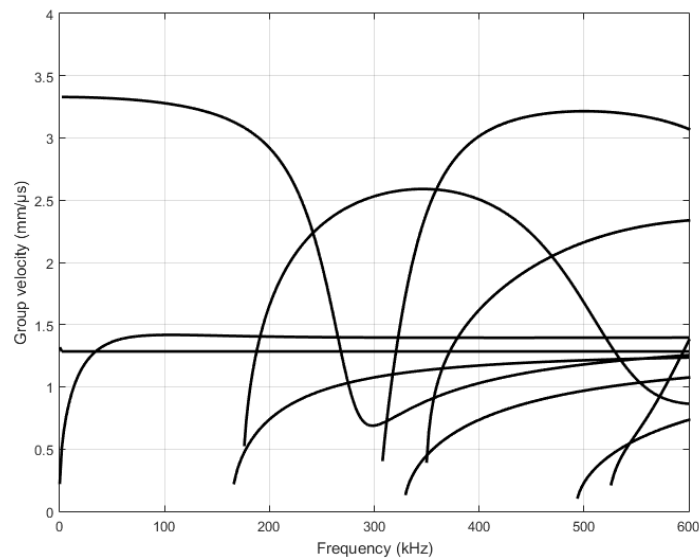


(b)

Figure 1. Simulated dispersion curves of the HDPE 4 mm sample: (a) phase velocities; (b) group velocities.



(a)



(b)

Figure 2. Simulated dispersion curves of the CFRP 4 mm sample: (a) phase velocities; (b) group velocities.

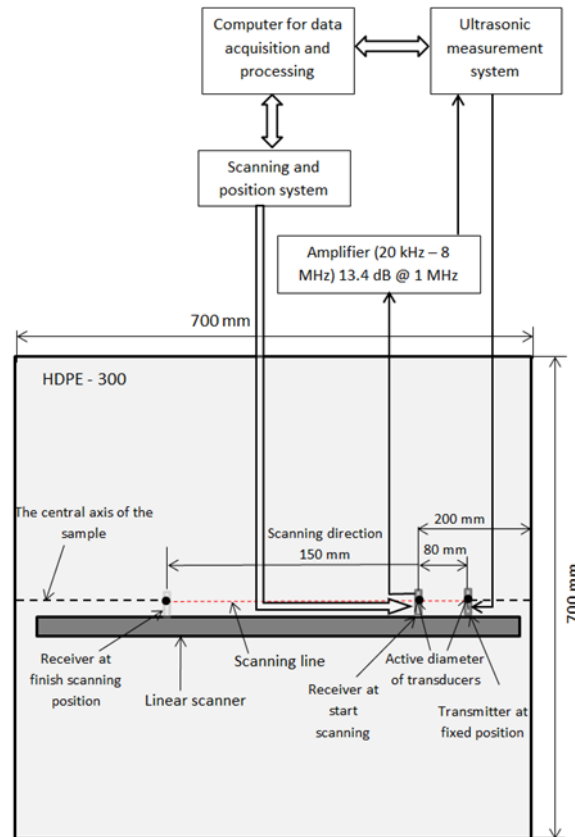
The calculated phase and group velocities versus frequency are shown in the figure above. The semi-analytical simulation results show that even in the frequency range up to 600 kHz, higher-order ultrasonic wave modes can propagate, which means that the structure of the material can be described in more detail. The measurement results are presented in the next section.

Experimental investigation

The aim of the experimental study presented in this part was to verify whether the calculated dispersion curves correspond to the experimental ones and how the corresponding ultrasound-controlled Lamb wave modes can be excited and received. Experimental studies were performed by the contact method using contact ultrasonic transducers. Experimental studies were performed using the ultrasonic equipment and setup shown in Figure 3. It consists of an ultrasonic measurement system ULTRALAB with a linear scanner (Kaunas University of Technology Ultrasound Institute), an amplifier and contact ultrasonic transducers. These are low-frequency broadband contact-type ultrasonic transducers (from 50 kHz to 350 kHz). The stability of ultrasonic signals and, accordingly, higher measurement accuracy were achieved by using acoustic contact between the transmitter and receiver using a coupling liquid (glycerol), which was used to obtain a more stable acoustic contact with the ultrasonic transducers during scanning. Let us take a closer look at the HDPE example. The dimensions of the sample selected for measurement were 700×700 mm. The distance between the transmitter and receiver transducers was set to 80 mm. The scanning distance was set to 150 mm from the receiver; the step was 0.1 mm, respectively. Let us analyse one selected ultrasonic wave mode A_1 in more detail. The transmitter transducer was excited by an A_1 mode signal $f_{A_1} = 170$ kHz. The sampling frequency was set to 100 MHz.



(a)



(b)

Figure 3. Equipment of the measurement (a); measurement set-up with linear scanner (b).

In this case, the measured B-scan obtained from the contact excitation of a 4 mm thick high-density polyethylene (HDPE) sample is shown in Figure 4, and the results of the 2D Fourier transform method are shown in Figure 5. The dispersion curves using the semi-analytical finite element method (SAFE) are shown as red and blue lines, and the 2D Fourier transform of the B-scan in the converted frequency-phase velocity domain is shown in Figure 5. Lamb waves propagating at different velocities are indicated in this figure. More information about the 2D Fourier transform and the 2D spatiotemporal spectrum of the measured B-scan methods can be found in our article [16]. The amplitude color scale is shown on the right side of the image; the amplitude values are given in arbitrary units. The antisymmetric higher-order A_1 mode is analyzed in more detail. The filtered and normalized amplitude of the antisymmetric A_1 mode is shown in Figure 6.

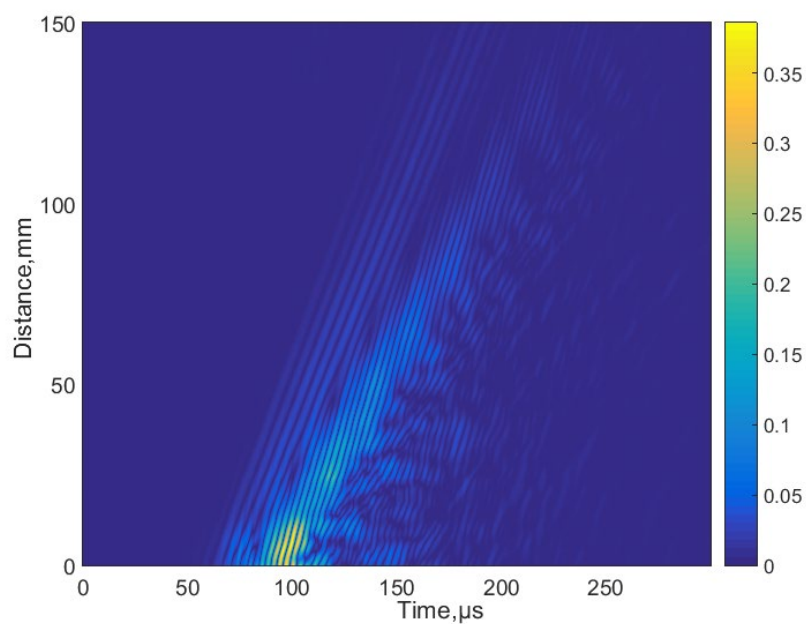


Figure 4. *B-scan of HDPE material.*

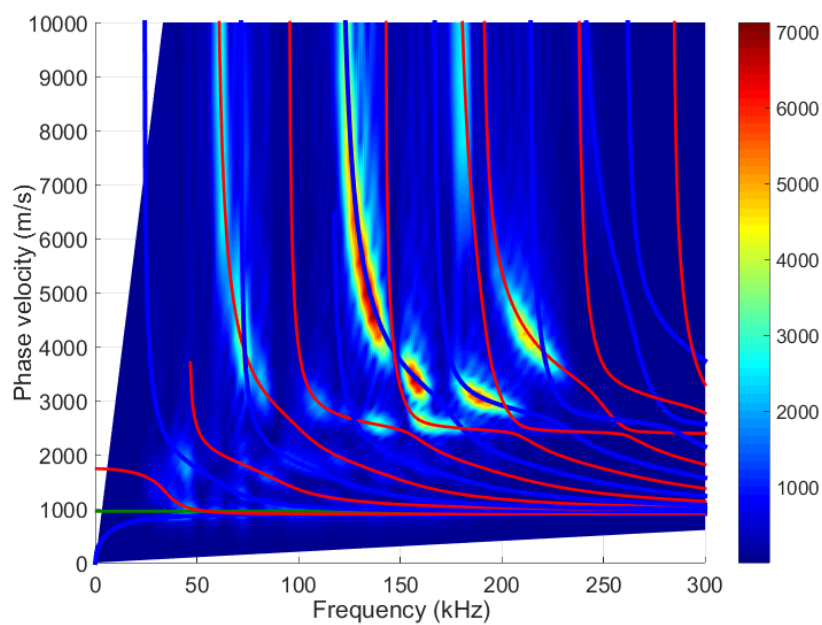
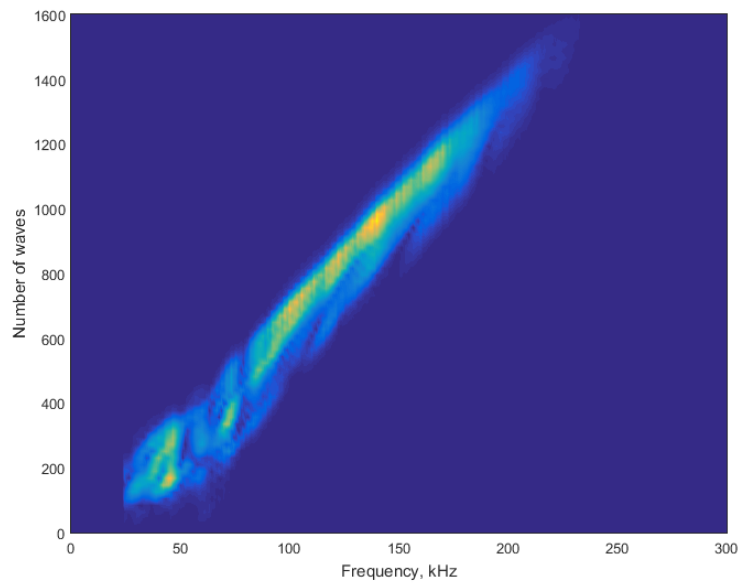
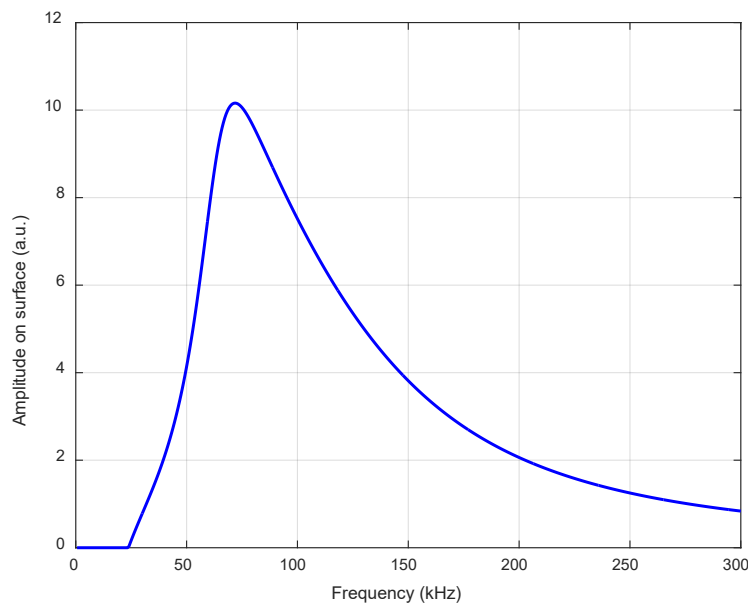


Figure 5. *2D Fourier transform FFT of the B-scan data and simulated SAFE dispersion curves of the HDPE 4 mm sample (red colors - symmetric modes; blue - antisymmetric modes).*



(a)



(b)

Figure 6. Filtered A_1 mode (a); the amplitude is normalized with respect to the maximum displacement values of the filtered A_1 mode (b).

The dispersion curves calculated by the semi-analytical finite element method (SAFE), shown by solid red lines, and the 2D Fourier transform of the measured B-scan data are presented in Figure 5. The presented results showed a very good agreement between the results obtained by two different methods: the first simulated by SAFE, and the second

measured and processed by the software-mathematical package FFT_{2D}. We selected and characterized one ultrasonic A_1 mode. From the results, the excitation frequency of the A_1 mode is determined to be 35 - 230 kHz. The ultrasonic component of the A_1 wave mode at the surface has a sufficiently large amplitude, which indicates the possibility of exciting this mode also through the air gap. The possibility of exciting the antisymmetric A_1 guided wave mode by the air connection method will be discussed in the next article.

Conclusions and Discussion

Various guided wave modes are already used for non-destructive testing and evaluation of composite structures. It can be expected that symmetric and antisymmetric guided wave modes can improve the characterization and evaluation of various plastic and composite structures. This is important in both the medical and aviation fields. To evaluate all this, efficient excitation and reception techniques of such modes are necessary. The aim of this work was to adapt existing ultrasonic methods to characterize and evaluate the excitation and reception of various guided Lamb wave modes in plastic and composite panels. To excite such ultrasonic waves, appropriate frequencies must be selected, which depend on the mode type, specimen thickness and elastic properties of the material. When all these factors are known, then the structure of the material can be characterized and evaluated. In most cases, the elastic properties of the material are not known with the required accuracy; therefore, it was proposed at the very beginning to measure the elastic properties and use them to calculate accurate dispersion curves. The dispersion curves were calculated using the semi-analytical finite element (SAFE) method. Theoretical calculations were performed using the semi-analytical finite element method, which allowed us to find out the frequency ranges in which various ultrasonic waves can be excited. One selected higher-order asymmetric A_1 mode was analysed in more detail, and it was determined that its excitation frequency should be from 35 kHz to 230 kHz in the selected sample. Dispersion curves allow us to determine the phase and group velocities of certain modes for the selected frequencies. It should be noted that in the frequency range in which various ultrasonic waves can exist, not one, but several different modes are usually excited. This makes it difficult to determine which modes were actually excited. Therefore, during experimental studies, we checked whether the calculated dispersion curves correspond to the theoretical ones and found a good agreement. Experimental studies were performed by the contact method using point ultrasonic transducers with a 0.1 mm aperture. Ultrasonic phase velocities were determined according to B-scan using 2D spatial and temporal spectrum analysis. Experimental results obtained using the contact method show that it is possible to excite ultrasonic waves of varying degrees in plastic and composite materials.

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NEARDOMŲJŲ BANDYMŲ APIBŪDINIMAS IR VERTINIMAS PANAUDOJIMAS ULTRAGARSINĖS BANGOS

dr. Justina Šestokė

Santrauka

Šiuolaikinėse technologijose plačiai naudojamos kompozicinės medžiagos. Jų pritaikymas yra labai įvairus – nuo kasdienių gaminių iki aukštųjų technologijų taikymo. Kompozitinės medžiagos, sukurtos naudojant įvairias inovatyvias medžiagas (žerutį, anglies struktūras, nano struktūras, stiklą ir kt.). Tai nevienalytė medžiaga ir turi sudėtingą medžiagos struktūrą. Ultragarso valdomų Lembo bangų taikymas leidžia geriau apibūdinti ir įvertinti įvairias medžiagas bei esamą jos struktūrą. Ultragarso valdomos bangos leidžia aptikti ir apibūdinti ne tik kompozitinių konstrukcijų paviršiaus mikro pažeidimus, bet ir įvairaus pobūdžio defektus (atsisluoksniavimą, įtrūkimus, storio pokyčius) konstrukcijos viduje. Aukštesnio laipsnio ultragarso valdomų Lembo bangų režimų sužadinimas susiduria su daugybe problemų, ypač naudojant oro tarpo techniką, ir nėra dar pakankamai ištirta. Tai aktualu popieriui, didelio tankio polietilenui (HDPE), membranoms, GFRP, GLARE, CFRP ir kitoms kompozitinėms struktūroms. Šio darbo tikslas – ištirti valdomų Lembo bangų režimų sužadinimą ir priėmimą didelio tankio polietileno ir kompozitinėse medžiagose. Šio darbo tikslui tikslinga taikyti esamus ir kurti naujus kontaktinio ultragarso matavimo metodus, pagrįstus valdomų bangų sužadinimu ir priėmimu. Ultragarso bangoms sužadinti reikia parinkti atitinkamus dažnius, kurie priklauso nuo režimo tipo, bandinio storio ir medžiagos elastingumo savybių. Kai žinomi visi šie veiksniai, galima apibūdinti ir įvertinti medžiagos struktūrą. Daugeliu atveju medžiagos tamprumo savybės nėra žinomos reikiamu tikslumu; todėl pačioje pradžioje buvo pasiūlyta išmatuoti elastines savybes ir pagal jas apskaičiuoti tikslas sklaidos kreivės. Dispersijos kreivės buvo apskaičiuotos pusiau analitiniu baigtinių elementų (SAFE) metodu.

Teoriniai skaičiavimai atlikti pusiau analitiniu baigtinių elementų metodu, kuris leido išsiaiškinti dažnių diapazonus, kuriuose galima sužadinti įvairias ultragarso bangas. Išsamiau išnagrinėtas vienas pasirinktas aukštesnės eilės asimetrinis A_1 režimas ir nustatyta, kad jo žadinimo dažnis pasirinktoje imtyje turi būti nuo 35 kHz iki 230 kHz. Dispersijos kreivės leidžia nustatyti tam tikrų režimų fazinių ir grupinių ultragarsinius greičius pasirinktiems dažniams.

Pažymima, kad dažnių diapazone, kuriame gali egzistuoti įvairios ultragarso bangos, dažniausiai sužadinamas ne vienas, o keli skirtingi režimai. Dėl to sunku nustatyti, kurie režimai iš tikrųjų buvo sužadinti. Todėl eksperimentinių tyrimų metu patikrinome, ar apskaičiuotos dispersijos kreivės atitinka teorines ir radome gerą sutapimą. Eksperimentiniai tyrimai atlikti kontaktiniu metodu, naudojant taškinius ultragarsinius keitiklius su 0,1 mm diametru. Ultragarsiniai faziniai greičiai buvo nustatyti pagal B-scan, naudojant 2D erdvinio ir laiko spektro analizę. Eksperimentiniai rezultatai, gauti naudojant kontaktinį metodą, rodo, kad plastikinėse ir kompozitinėse medžiagose galima sužadinti įvairaus laipsnio ultragarso bangas.

Gauti rezultatai aiškiai parodė galimybę efektyviai sužadinti ir priimti skirtingus nukreiptųjų Lembo bangų modas su labai skirtingu faziniu ultragarsiniu greičiu. Eksperimentinių rezultatų palyginimas su teoriniu modeliavimo rezultatais parodė gerą suderinamumą.

Raktiniai žodžiai: Lembo bangos, elastinės savybės, kompozitinės medžiagos.