KAUNAS UNIVERSITY OF TECHNOLOGY

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APPLICATION OF ULTRASONIC METHODS FOR INVESTIGATION OF STRONGLY ABSORBING INHOMOGENEOUS MULTILAYER STRUCTURES

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KAUNO TECHNOLOGIJOS UNIVERSITETAS

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ULTRAGARSINIŲ METODŲ TAIKYMAS STIPRIAI SLOPINANČIŲ DAUGIASLUOKSNIŲ NEHOMOGENINIŲ STRUKTŪRŲ TYRIMAMS

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Introduction

Ultrasonic non-destructive testing (NDT) techniques are successfully used for detection of defects in various metallic constructions and inspection of quality of welded joints.

Recently, the ultrasonic NDT methods have been used in a field of testing of different synthetic products. Ultrasound has found numerous applications in characterization of various polymers. A novel problem arising in this field is non-destructive testing and evaluation of multi-layer plastic pipes. The purpose of such a testing is detection and sizing of various defects, which may appear during the manufacturing process.

Ultrasonic NDT of composite materials or multi-layer plastic pipes meets serious problems. An important issue in ultrasonic non-destructive testing of composite fiber-reinforced materials is the detection of flaw echoes in the presence of structural noise due to scattering of ultrasonic waves and high attenuation of the ultrasonic signal. The named problems show that testing of composite materials requires a special care in signal processing. As a solution of this problem in presented work we propose a new method for detection of the defects in multilayer composite materials.

Aim of the work

The aim of the present work is to find out a method for ultrasonic testing of composite fiber-reinforced multilayer polymer materials.

Scientific novelty

In this thesis a new method for detection of defects in homogeneous and inhomogeneous multilayer structures is proposed. For the detection of defects in homogeneous structures the Hilbert-Huang signal processing method was adopted. The non-destructive testing of inhomogeneous structures in the thesis is based on the wavelet transform method. The efficiency of the proposed algorithm has been verified using computer simulation and experiments.

Practical results of research

1. The experimental results of ultrasonic testing of multi-layer composite materials with artificial defects and the results of analysis of their parameters.
2. The method for ultrasonic detection of defects in homogeneous multilayer structures based on the Hilbert-Huang signal processing method.

3. The adaptation of the wavelet transform method for detection and sizing of defects in strongly absorbing inhomogeneous structures.
4. Analysis of influence of the proposed method to the accuracy of defect sizing.

Structure of thesis

The thesis composed of introduction, four chapters, conclusions and list of references. The dissertation consists of 106 pages, among them 81 figures and 9 tables. List of references include 84 references.

Content of the dissertation

The introduction of the work covers actuality of detection of ultrasonic defects in composite polymer materials. The goal and the tasks of the thesis are formulated and the practical results are described.

Chapter 1 covers the problem analysis of ultrasonic testing in polymer materials and the overview of ultrasonic visualization and signal processing methods used for detection of defect.

The problem analysis showed that ultrasonic testing of polymer materials is an important issue. Flaw echoes in composite fiber-reinforced materials are observed in presence of a structural noise caused by scattering of ultrasonic waves. The named problem shows us that testing of composite materials is possible only if special signal processing procedures are applied.

For detection and characterization of defects various signal-processing techniques are already used. During the last decade time-frequency signal analysis became a popular tool in signal and image processing. The techniques from the point of their suitability for detection of reflected echoes in composite materials with a high attenuation of ultrasonic waves caused by scattering in this chapter were analysed.

The analysis of various ultrasonic imaging methods was performed and the ultrasonic immersion pulse-echo method in the presented work is chosen. The distances to defects in the test object in this method are determined from the time-of-flight between the initial pulse and the echo produced by a defect.

In **Chapter 2** the theoretical acoustical model of ultrasonic testing of composite polymer material is proposed and experimental results of defects detection in multi-layered plastic pipes are presented.

The proposed acoustical model describes an ultrasonic testing of three-layer polymer material with two homogeneous layers and internal inhomogeneous layer (Fig.1).

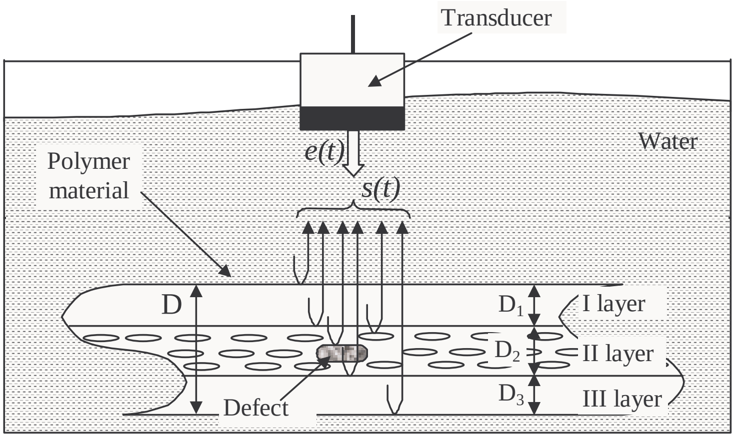


Fig. 1. The acoustical model of ultrasonic non-destructive testing of three-layer polymer material

Let us assume that the transmitted ultrasonic signal is denoted by $e(t)$ in the time domain and the sample under evaluation consists of three layers immersed into the water. The echo signal $s_a(t)$ can be described as the sum of the reflected signals:

$$s_a(t) = s_v(t) + s_1(t) + s_2(t) + s_3(t)\,, \tag{1}$$

where $s_v(t)$, $s_1(t)$, $s_2(t)$, and $s_3(t)$ are the reflected signals from the surfaces of I, II, III layers and bottom of the III layer, respectively. The reflections from the transducer and the sample $s_v(t)$, the bottom of the I layer $s_1(t)$, the bottom of the II layer $s_2(t)$ and the bottom of the III layer $s_3(t)$ are given by:

$$s_v(t) = R_{v1} \cdot \left(e(t) * h_v(t) * h_v(t)\right), \tag{2}$$

$$s_1(t) = \left(1 - R_{v1}\right)\left(1 - R_{1v}\right)\frac{R_{12}}{R_{v1}}\left(s_v(t) * h_1(t) * h_1(t)\right), \tag{3}$$

$$s_2(t) = \left(1 - R_{12}\right)\left(1 - R_{21}\right)\frac{R_{23}}{R_{12}}\left(s_1(t) * h_2(t) * h_2(t)\right), \tag{4}$$

$$s_3(t) = \left(1 - R_{23}\right)\left(1 - R_{32}\right)\frac{R_{3v}}{R_{23}}\left(s_2(t) * h_3(t) * h_3(t)\right), \tag{5}$$

where * denotes convolution; h_v(t), $h1(t)$, $h_2(t)$ and $h_3(t)$ are the impulse responses of the water layer between the transducer and the sample, the layers I, II and III, respectively; R_i are the reflection coefficients between the indicated media.

As the ultrasonic focal spot moves to the defect in the II layer, the echo signal $s_2(t)$ can be written as:

$$s_2(t) = (1 - R_{v1})(1 - R_{12})(1 - R_{21})(1 - R_{1v})R_{2d} \begin{pmatrix} e(t) * h_v(t) * h_1(t) * h_2(t) * \\ * h_2(t) * h_1(t) * h_v(t) \end{pmatrix}. \qquad (6)$$

The presence of a structural noise $h_{tr}(t)$ arises the problem to find the impulse response of II layer $h_2(t)$ and to detect the defects in this layer :

$$h_{2tr}(t) = h_2(t) + h_{tr}(t). \qquad (7)$$

The impulse response of the structural noise can be represented by the sum of delta functions with random delays:

$$h_{tr}(t) = \sum_{k=1}^{M_0} \sigma_{sk} e^{-\alpha_2 \tau_k} \delta(t - \tau_k), \qquad (8)$$

where M_0 represent the total number of scatterers; σ_{sk} is the reflection coefficient of the kth scatterer; α_2 is the attenuation coefficient of the II layer; τ_k is the delay associated with the kth scatterer.

Let us assume that the II layer is a medium with scatterers, which may be modeled as ellipsoidal bodies (fiberglass scatterers) (Fig.2.).

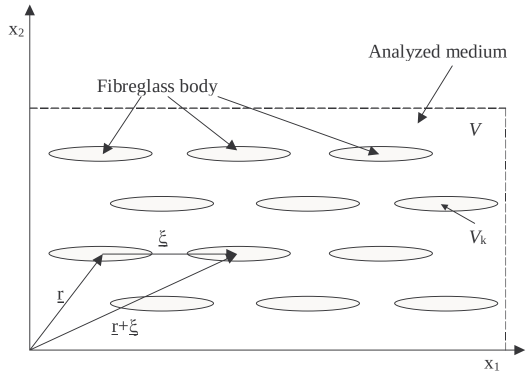


Fig. 2. Illustration of analyzed inhomogeneous medium (V) with fiberglass body (V_k)

The analysed medium (inhomogeneous II layer) occupies a spatial volume V and each scatterer – V_k. The resulting autocorrelation function $F_{11}(\underline{\xi})$ for the ellipsoidal bodies with a fixed shape, size and orientation becomes:

$$F_{11}(\underline{\xi}) = \chi(1 - \chi)R_v(|S^{-1}\underline{\xi}|) + \chi^2, \qquad (9)$$

$$R_v(\xi) = 1 - 3|\xi|/4 + |\xi|^3/16, \ |\xi| < 2, \qquad (10)$$

where χ is the relative volume fractions $\chi = M_0 V_k / V$; R_v is the correlation function for unit sphere; S is the square root matrix of coordinate system matrix; $\underline{\xi}$ is the spatial 3D displacement vector in the correlation analysis. For analysis of the auto correlation function in a two coordinates plane we define the variables S and ξ as:

$$\xi^2 = x_{2k}^2 + x_{3k}^2 , \tag{11}$$

$$S^2 = \frac{x_{2k}^2 l_2^2 l_3^2}{x_{2k}^2 l_3^2 + x_{3k}^2 l_2^2}\left(1 - \frac{l_3^2}{l_2^2}\right) + l_3^2 . \tag{12}$$

The experimental investigation of plastic pipe defects was carried out by the imaging system “Izograf”, developed in Ultrasound institute of the Kaunas University of Technology. The experimental set-up used for investigation of defects in plastic pipes is presented in Fig.3.

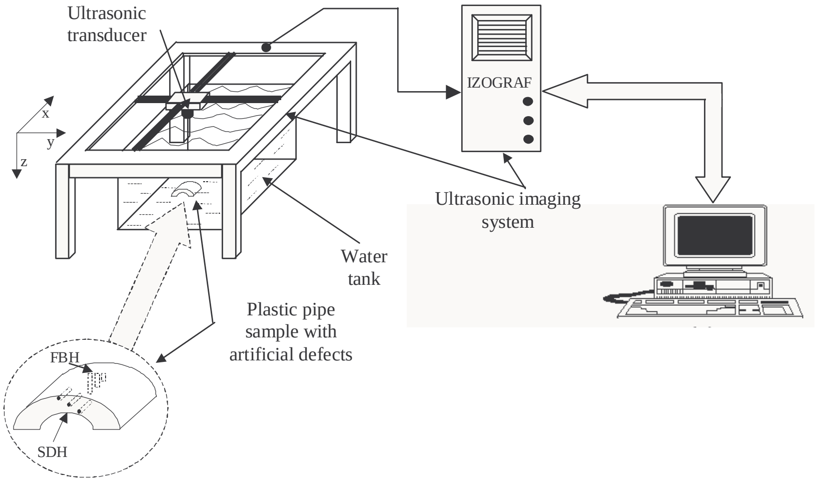
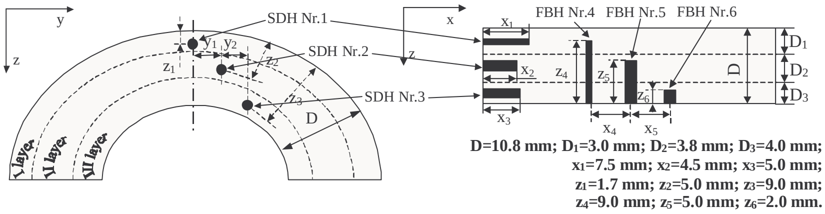


Fig.3. Experimental set-up for detection of defects in plastic pipes by the ultrasonic NDT system “Izograf”

As an ultrasonic transmitting/receiving transducer the Panametrics transducer V308 (frequency 5 MHz, aperture 19 mm) was used. The transducer was excited by the 140 V amplitude and 80 ns duration electrical pulse.

The experimental investigations of plastic pipes were performed with one, two and three layer plastic pipe samples. The pipe samples were made with internal artificial defects – side-drilled holes (SDH) and flat bottom holes (FBH). The holes in pipe samples were at known positions, determined using mechanical measurement means. The results of ultrasonic measurements were compared with the known coordinates of the artificial defects.

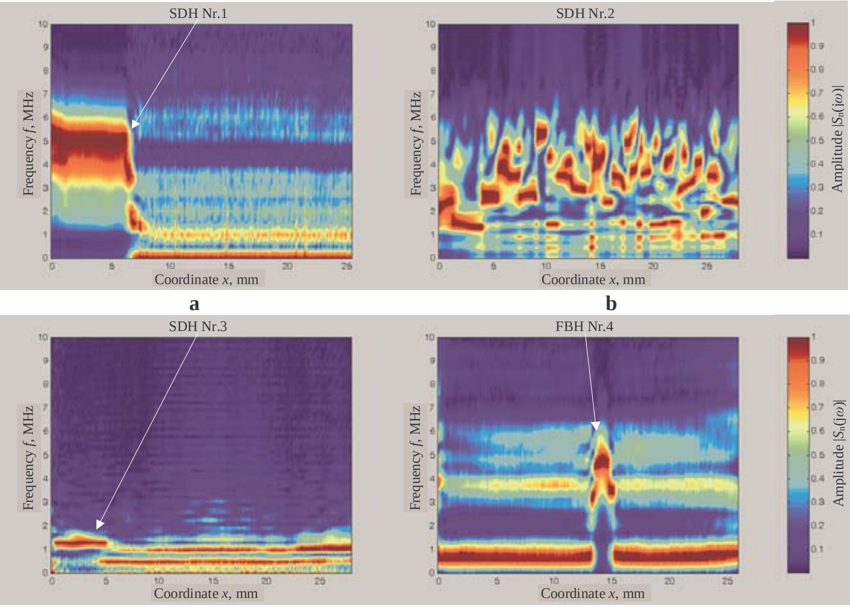
The experiments carried out proved that it is possible to detect reliably SDH and FBH in one and two layer plastic pipes. Detection of holes in the fibre-reinforced layer and under this layer is a serious problem. To solve this problem the second step of experimental investigation was carried out. In the three-layer plastic pipe sample standardized artificial defects were made (Fig.4.). For ultrasonic signal analysis A- and B-scans of the described pipe sample were used. These scans were obtained by scanning the transducer along the coordinate *x* (Fig.4.).



D=10.8 mm; D_1=3.0 mm; D_2=3.8 mm; D_3=4.0 mm;
x_1=7.5 mm; x_2=4.5 mm; x_3=5.0 mm;
z_1=1.7 mm; z_2=5.0 mm; z_3=9.0 mm;
z_4=9.0 mm; z_5=5.0 mm; z_6=2.0 mm.

Fig.4. Artificial defects (side-drilled holes (SDH) and flat bottom holes (FBH)) in a plastic pipe sample

The A- and B-scans were analyzed in the frequency domain to exploit the power density spectrum of ultrasonic signals. The spatial amplitude-frequency response of B-scans signals various layers and defects along the pipe are presented in Fig.5.



a **b**

c **d**

Fig.5. The amplitude-frequency response of ultrasonic signals of various layers: a – I layer with SDH defect; b – II layer with SDH defect; c – III layer with SDH defect; d – I layer with FBH defect

As it is seen from Fig.5 the echoes due to defects SDH Nr.1, Nr.2 and FBH Nr.4 differ in spectral content from the echoes caused by background without defects.

Analysis of the obtained A- and B-scans shows that the correlation functions of echoes caused by the defects SDH Nr1 and FBH Nr.4 are different from the background echoes.

The analysis of spectral and correlation functions has showed that the detection of artificial defects in an inhomogeneous layer is complicated. Therefore, to solve this problem we propose to use a new algorithm based on ultrasonic signal processing.

In **Chapter 3** the new algorithm for detection of defects in homogeneous and inhomogeneous plastic structures is described.

Ultrasonic signals were analyzed in the time-frequency domain using the proposed algorithm. All methods used for the time-frequency signal analysis decompose the signal into components and then analyze each of them by conventional methods. Signal decomposition can be implemented in many ways. The new algorithm combines two signal-processing methods – Hilbert-Huang and wavelet transform.

For defects detection in homogeneous plastic structures we propose the new method based on the Hilbert-Huang signal processing. The Hilbert-Huang technique is based on direct extraction of the energy associated with the intrinsic time scales in the signal. This process generates a set of components, called the intrinsic modes functions (IMF). The algorithm to create IMFs requires to detect local maxima and minima of the time series of the signal $s(t)$. The local maxima $s_{\max}(t)$ and minima $s_{\min}(t)$ are connected by a cubic spline line to produce respectively upper envelope $u_s(t)$ and lower envelope $l_s(t)$. Their mean is denoted as m_1(t) and is given by:

$$m_1(t) = \frac{u_s(t) + l_s(t)}{2} . \tag{13}$$

The difference between the original signal $s(t)$ and the mean m_1(t) is the first component $h_1(t)$:

$$h_1(t) = s(t) - m_1(t) . \tag{14}$$

The sifting process has to be repeated up to k times, as it is required to reduce the extracted signal to an IMF:

$$h_{1k}(t) = h_{1(k-1)}(t) - m_{1k}(t) , \tag{15}$$

where the subsequent component $h_{1(k-1)}(t)$ is treated as the original signal. The resulting time series is the first IMF: $c_1(t)=h_{1k}(t)$.

The first IMF $c_1(t)$ is subtracted from the original signal:

$$r_1(t) = s(t) - c_1(t) , \tag{16}$$

and this difference is called as residue r_1(t). He is treated as the new signal and subjected to the same sifting process.

The process of finding intrinsic modes c_j continues until the final residue r_n(t) will be a constant or a monotonic function. Then decomposition of the original signal into n-empirical modes and a residue is achieved:

$$s(t) = \sum_{j=1}^{n} c_j + r_n \,. \tag{17}$$

In Fig.6 are presented the *A-scan* signal and four IMF modes of this original signal with artificial defect. The number of intrinsic modes is selected according to the criterium how well this mode represents the location of an artificial defect in the time domain. It is seen that the first three modes represent the information about the upper and bottom surfaces of the pipe samples or artificial defects.

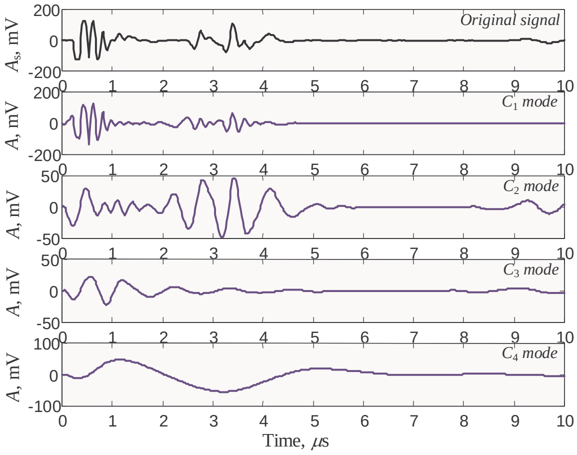


Fig.6. Decomposition by the sifting method of the ultrasonic signals of three layers pipe samples into four intrinsic modes

The second step is to apply the Hilbert transform to the decomposed intrinsic modes functions (IMF). With this definition the analytic signal is defined as

$$z_j(t) = c_j(t) + iy_j(t) = a(t)e^{i\theta(t)} \,, \tag{18}$$

in which $a_j(t) = \sqrt{c_j^2(t) + y_j^2(t)}$ is the magnitude; $\theta_j(t) = \arctan\left(y_j(t)/c_j(t)\right)$ is the phase of the analytic signal.

To analyse the analytic signal $z_j(t)$ the Hilbert amplitude spectrum $H(\omega,\ t)$ is used. Therefore one can define an instantaneous frequency ω_j, given by:

$$\omega_j(t) = \frac{d\theta_j(t)}{dt} \,. \tag{19}$$

Thus the original signal is given by:

$$s(t) = \mathrm{Re}\left[\sum_{j=1}^{n} a_j(t) \cdot e^{\left(i\int \omega_j(t)dt\right)}\right]. \tag{20}$$

This equation enables us to represent the amplitude (or the energy) and the instantaneous frequency in a three-dimensional plot.

For ultrasonic signal processing by the Hilbert-Huang method we used *B-scans* of the described pipe samples (Fig.4.). To display the Hilbert spectrum distribution along the coordinate *x* we represent the amplitude and the instantaneous frequency as a function of coordinates *x* and *z* in a four-dimensional plot, in which the amplitude is presented as the colour coded maps. To improve the defects visualization we have proposed a new presentation of the Hilbert spectrum, which is based on calculation of the product of the instantaneous frequency ω_j and the amplitude a_j of the analytic signals. The product is displayed in a three-dimensional plot. The best result of this presentation is detection of the defect FBH No.4 in I layer of the analyzed pipe sample (Fig.7).

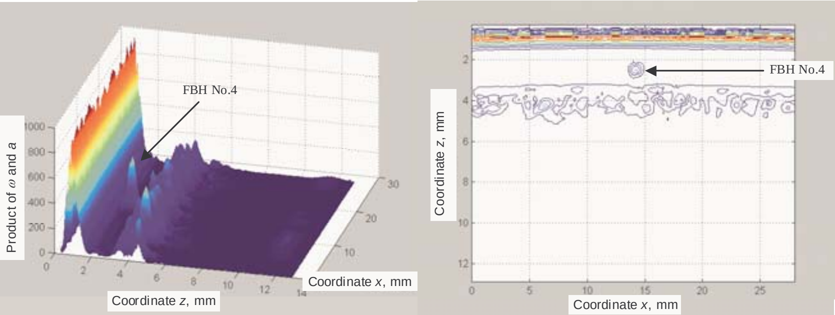


Fig.7. The new presentation of the Hilbert spectrum of the first IMF of the ultrasonic signals of the three layers pipe samples with artificial defects along the coordinates *x* (a). The contour plots of the amplitude of the Hilbert spectrum (b)

Analysis of the ultrasonic signals by the Hilbert-Huang method have shown that the information about defects in a homogeneous plastic pipe sample represents the combination of the first and second modes and for defects visualization gives the best results.

To find the defects in inhomogeneous structures we adopted and optimised the wavelet transform method. The wavelet transform (WT) is a new method of processing of transient non-stationary signals simultaneously in time and frequency domains.

The wavelet transform decomposes the signal $s(t)$ in to a sum of elementary contributions called wavelets. The WT is the correlation between the signal and a set of basic wavelets. The daughter wavelets $\psi_{a,b}(t)$ are generated from the mother wavelet $\psi(t)$ by dilation (a) and shift (b) operations. The WT expansion coefficients $X_{WT}(a,b)$ of the signal $s(t)$ are given by:

$$X_{WT}(a,b)=\int_{-\infty}^{\infty}s(t)\psi_{a,b}^{*}(t)dt\ , \tag{21}$$

where

$$\psi_{a,b}(t)=\frac{1}{\sqrt{|a|}}\psi\left(\frac{t-b}{a}\right). \tag{22}$$

The Fourier transform of the daughter wavelet $\psi_{a,b}(t)$ is given by:

$$\psi_{a,b}(f)=\sqrt{a}\psi(af)\cdot e^{-j2\pi fb}\ , \tag{23}$$

where $\psi(f)$ represents the Fourier transform of the mother wavelet.

If the variables a and b are limited to integer values, the discrete wavelet transform (DWT) is obtained:

$$\psi_{j,k}(n)=2^{-j/2}\psi(2^{-j}n-k)\ ,\qquad j,k\in \mathrm{Z}, \tag{24}$$

where $\psi_{j,k}(n)$ constitute an orthonormals functions family. The discrete wavelet transform of an analogue temporal signal is given by:

$$X_{DWT}(j,k)=\sum_{n=1}^{N}s(n)\psi_{j,k}^{*}(n)\ , \tag{25}$$

where N is the length of the signal in samples; j indexes the scale or the resolution of analysis; k indexes the spatial location of analysis. The example of decomposition of ultrasonic signal by the discrete wavelet transform is presented in Fig.8.

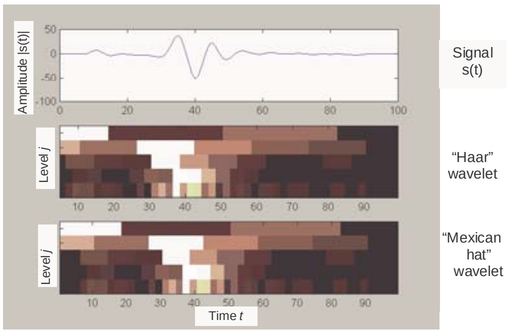


Fig.8. Example of decomposition of an ultrasonic signal by the discrete wavelet transform

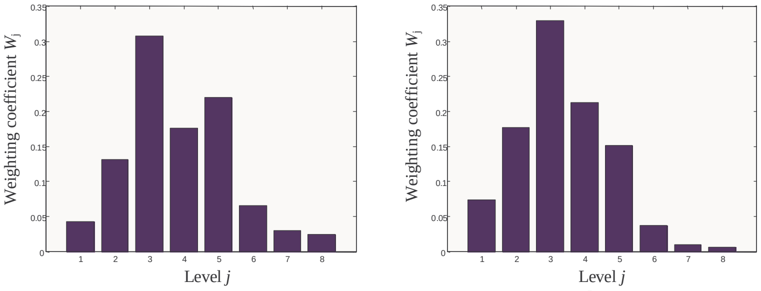
To recover the analyzed signal from its wavelet coefficients can be performed using the formula:

$$s_r(n)=\sum_{j}\sum_{k}X_{DWT}(j,k)\psi_{j,k}(n)\,. \tag{26}$$

A wavelet coefficient shows how much of the corresponding wavelet basis function is presented in the whole signal. This information is localized in the time and frequency domain. To analyse how much the wavelet coefficient of the level *j* presents the ultrasonic signal, we use the weighting coefficient:

$$W_j = \frac{\gamma_{j\Sigma}}{\gamma_\Sigma}, \tag{27}$$

where $\gamma_\Sigma = \sum_{j=1}^{J}\sum_{k}\gamma_{j,k}$; $\gamma_{j\Sigma} = \sum_{k}\gamma_{j,k}$; $\gamma_{j,k}$ are the high pass filter coefficients; *J* is the maximal decomposition level. This analysis shows that the echo signals from the artificial defects in II layer are represented by the level *j*=5 (Fig.9.).



a **b**

Fig.9. The weighting coefficients calculated from the *A*-scans of echo signals with (a) and without defect (b)

As an optimal mother wavelet we have chosen:

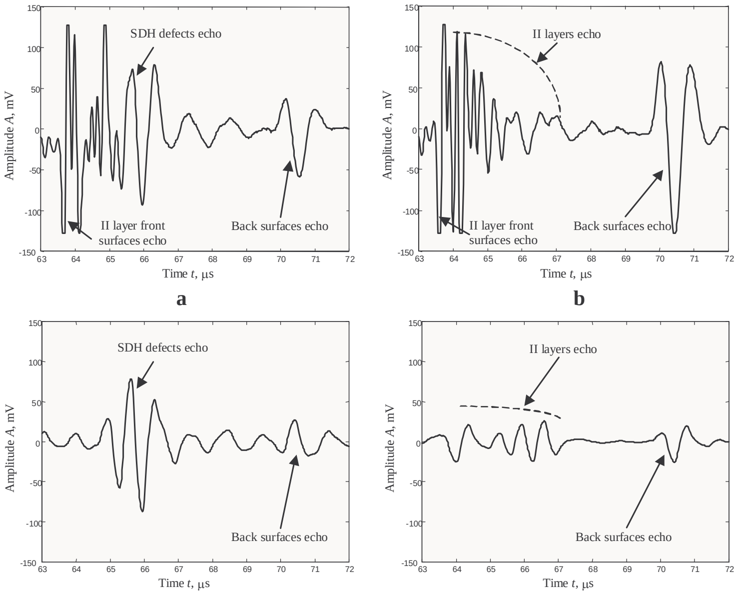
$$\psi(n)_{opt} \Rightarrow \max(W_5). \tag{28}$$

The analysis of various mother wavelets shows us that the optimal mother wavelet for analyzed ultrasonic echo signals is “Coiflet-5” (Table 1).

Table 1. The weighting coefficients W_5 for various mother wavelets

Mother wavelet	Symlet 3	Symlet 4	Symlet 5	Symlet 6
Weighting coefficient W_5	0,2181	0,2265	0,22	0,2176
Mother wavelet	Symlet 7	Symlet 8	Symlet 10	Haar
Weighting coefficient W_5	0,2304	0,2179	0,2270	0,1154
Mother wavelet	Daubechies 3	Daubechies 4	Daubechies 5	Daubechies 6
Weighting coefficient W_5	0,2181	0,1979	0,2450	0,2104
Mother wavelet	Daubechies 10	Coiflet 1	Coiflet 3	Coiflet 5
Weighting coefficient W_5	0,2139	0,1974	0,2151	0,2499

The results of optimization of the wavelet transform for detection of the defects in a inhomogeneous layer of a plastic pipe are presented in Fig.10. This figure shows us the *A*-scans from the II layer of the three-layer pipe with (Fig.10,a) and without the defect (Fig.10,b). The *A*-scans with and without defects, processed by the proposed algorithm are presented in Fig.10,c and d.

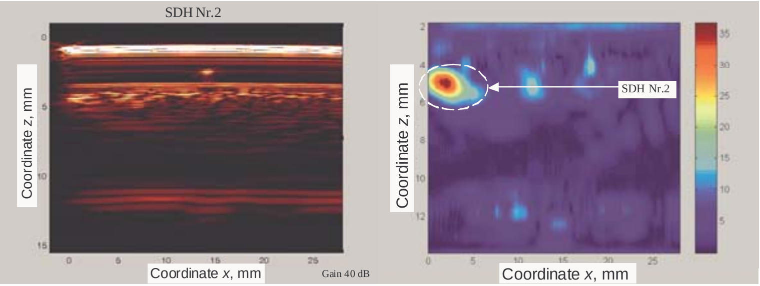


a b

c d

Fig.10. ***A*-scans from II layer of the three-layer pipe with defects (a) and without defects (b) and corresponding *A*-scans (c) and (d) after reconstruction from “Coiflet-5” original wavelet and optimized algorithm**

To estimate the size and coordinates of the artificial defects in the II layer the *B*-scans processed by the proposed algorithm and the Hilbert transform were used. The results of signal processing are presented in Fig.11.



a b

Fig.11. ***B*-scan from II layer of the three-layer pipe with defects (a) and this scan processed with proposed algorithm and Hilbert transform (b)**

In **Chapter 4** the uncertainty components of the defects detection algorithm were analysed.

In the proposed algorithm the acoustic transducer generates an ultrasonic pulse, which propagates through the contacting media and is reflected by interfaces, boundaries and defects (Fig.1). Thus the measured coordinates of defect z_d and x_d can be presented as in Fig.12.

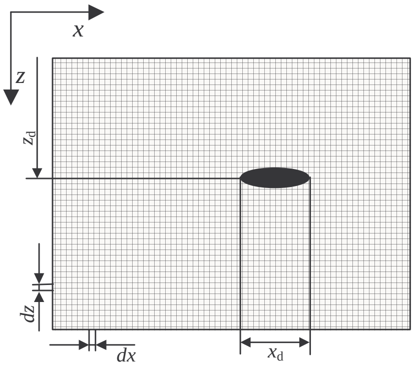


Fig.12. Estimation of coordinates of the defect

The distance between the transducer and the defect in the II layer z_d can be estimated indirectly by the formula:

$$z_d = \frac{1}{2} t_s c_2 - l_w \frac{c_2}{c_w} - D_1 \frac{c_2}{c_1}, \tag{29}$$

where l_w is the distance between the transducer and the surfaces of a pipe sample; D_1 is the thickness of the I layer; c_1, c_2 and c_w are propagation velocities of ultrasonic signals in I and II layers and water, respectively; t_s is the time of flight (TOF) of echoes from the analysed defect. Than the standard uncertainty of the measured coordinate of defect z_d can be estimated as follows:

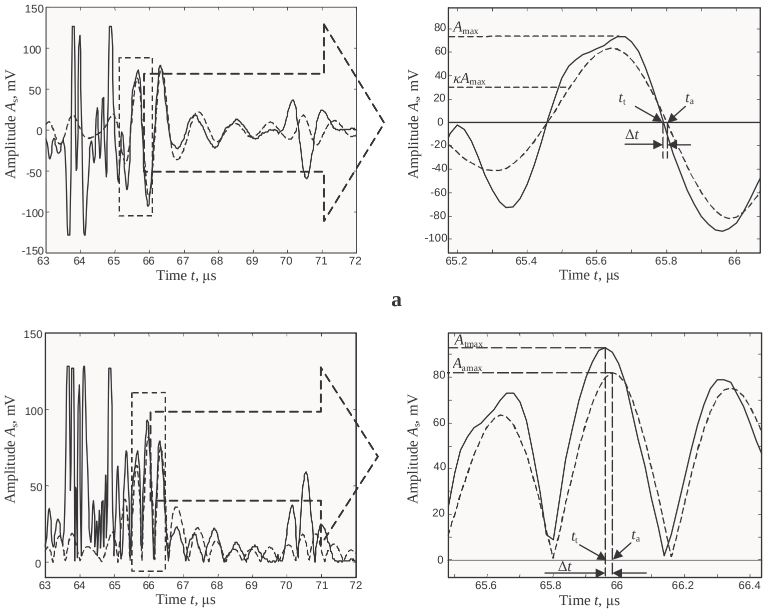
$$\begin{aligned} u^2(z_d) = &\left(\frac{t_s}{2} - \frac{l_w}{c_w} - \frac{D_1}{c_1}\right)^2 u^2(c_2) + \frac{c_2^2}{4} u^2(t_s) + \frac{c_2^2}{c_w^2} u^2(l_w) + \\ &+ \frac{l_w^2 c_2^2}{c_w^2} u^2(c_w) + \frac{c_2^2}{c_1^2} u^2(D_1) + \frac{D_1^2 c_2^2}{c_1^4} u^2(c_1) \end{aligned}, \tag{30}$$

where $u^2(c_1)$, $u^2(c_2)$, $u^2(c_w)$, $u^2(t_s)$, $u^2(l_w)$, $u^2(D_1)$ is the standard measurement uncertainties of the velocities c_1, c_2, c_w, the time of flight t_s, the distance l_w and the thickness of the I layer D_1.

The propagation velocities of ultrasonic signals in water and plastic pipe layers depend on chemical and physical parameters of the corresponding medium. These velocities may be measured in advance with a high accuracy using various techniques.

The critical point of the measurement procedure is estimation of the time of flight. Various methods have been developed to improve the TOF measurement. In the proposed algorithm the digital processing of ultrasonic signals by the wavelet transform and the Hilbert transform can be used and finally the signals can be detected by the zero crossing or the maximum amplitude methods. The uncertainty of the measured TOF is caused by various factors: the signal detection technique, processing methods, non-perpendicularity of the incident wave with respect to the surfaces of the samples layers, and diffractions effects.

For detection of defects using the zero crossing or maximum amplitude methods and the wavelet transform, the TOF measurement error may be presented as $\Delta t = t_t - t_a$, where t_t and t_a are the delay times without and with signal processing, respectively (Fig.13.). The analysis of the TOF measurement error Δt shows that the dispersion of the measurement results obtained by the proposed algorithm is more than 1,5 times smaller than the dispersion of the measurement results of the raw signals. The smaller measurement error is when the position of the signals is detected by the maximum amplitude method.



a

b

Fig.13. The measurement errors of the TOF of signal using the wavelet transform and the zero crossing (a) or the maximum amplitude method (b)

The influence of non-perpendicularity of the incident ultrasonic wave with respect to the surfaces of the samples layers to the TOF measurement error is presented in Fig.14. It is seen that this error depends on the angles α_1, α_2 and α_3 between the wave propagation direction and the normals to the I, II and III layers (Fig.14.).

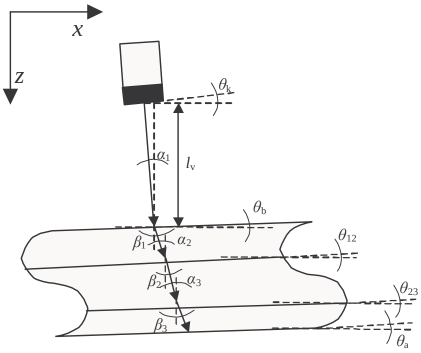


Fig.14. The TOF measurements error depending on non-perpendicularity of the incident ultrasonic wave and the surfaces of the plastic pipe samples

The influence of non-perpendicularity can be estimated as the deviation of the distance between the transducer and the surfaces of a pipe sample (l_r) and the layers thickness (D_{1r}, D_{2r}, D_{3r}):

$$l_r = \frac{\left(l_v - \Delta x \cdot tg\theta_b\right)}{\cos\theta_k}, \tag{31}$$

$$D_{1r} = \frac{D_1 - \Delta x \cdot tg\theta_{12}}{\cos\left(\arcsin\frac{c_1\sin\left(\theta_k - \theta_b\right)}{c_v}\right)}, \tag{32}$$

$$D_{2r} = \frac{D_2 - \Delta x \cdot tg\theta_{23}}{\cos\left(\arcsin\frac{c_2\sin\left(\beta_1 - \theta_{12}\right)}{c_1}\right)}, \tag{33}$$

$$D_{3r} = \frac{D_3 - \Delta x \cdot tg\theta_a}{\cos\left(\arcsin\frac{c_3\sin\left(\beta_2 - \theta_{23}\right)}{c_2}\right)}, \tag{34}$$

where $\beta_1 = \arcsin\left(\frac{c_1\sin\alpha_1}{c_v}\right)$ and $\beta_2 = \arcsin\left(\frac{c_2\sin\left(\beta_1 - \theta_{12}\right)}{c_1}\right)$. (35)

In Eq.31-34 Δx is the distance displacement in x-axis direction (Fig.14.). The calculated deviation of the distance l_v is not bigger than ±1,22% and the layers thickness not bigger than: D_1 - ±3,5 %, D_2 - ±2,9 %, D_1 - ±2,7 %.

The coordinate of the defect x_d (Fig.12) along x-axis direction can be estimated from the echo-signals amplitude (Fig.15). For that we use 3 dB and 6 dB thresholds:

$$x_d^{3dB} = x_2^{3dB} - x_1^{3dB} \text{ or } x_d^{6dB} = x_2^{6dB} - x_1^{6dB}, \tag{36}$$

where x_1^{3dB}, x_2^{3dB}, x_1^{6dB}, x_2^{6dB} are the coordinates estimated using 3 dB and 6 dB thresholds, respectively.

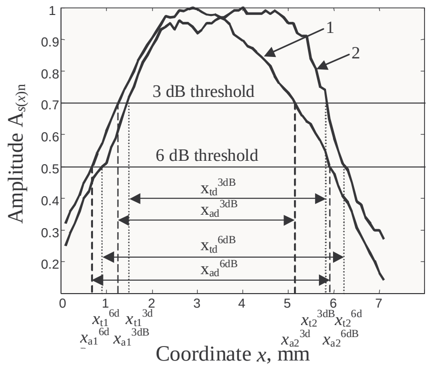


Fig.15. Estimation of coordinates of the defect x_d using processed by the proposed algorithm (1) and raw (2) echo-signals

The analysis of the defects length x_d estimated from the processed by the proposed algorithm and raw signals shows that measurement errors $\Delta x_d^{3dB} = x_{td}^{3dB} - x_{ad}^{3dB} > \Delta x_d^{6dB} = x_{td}^{6dB} - x_{ad}^{6dB}$ and it is obvious advantage to use the proposed algorithm with the 6 dB threshold.

The measurement results of the coordinates of the artificial defects, performed using mechanical measurement means and by means of ultrasonic waves using the proposed algorithm are presented in Table 1. In this table the measurement errors of the coordinates Δz_d and Δx_d are also given.

Table 1. The results of measurements of position of the artificial defects

Measurement method	Defects Parameters	Defect SDH Nr.7.	Defect SDH Nr.8.	Defect SDH Nr.9.
Mechanical measurements	z_{md}, mm	5,05	5,85	6,55
Detected by the proposed algorithm	z_{ad}, mm	5,04	5,77	6,13
	$\sigma(z_{ad})$, mm	0,166	0,116	0,156
	$u(z_{ad})$, mm	0,052	0,037	0,049
$\Delta z_d = z_{md} - z_{ad}$, mm		0,01	0,08	0,42
Mechanical measurements	x_{md}, mm	6,3	5,1	4,4
Detected by the proposed algorithm (3 dB level)	x_{ad}^{3dB}, mm	4,26	3,89	2,65
	$\sigma(x_{ad}^{3dB})$, mm	0,117	0,006	0,012
	$u(x_{ad}^{3dB})$, mm	0,037	0,0019	0,0038
$\Delta x_d^{3dB} = x_{md}^{3dB} - x_{ad}^{3dB}$, mm		2,04	1,21	1,75
Detected by the proposed algorithm (6 dB level)	x_{ad}^{6dB}, mm	5,73	5,24	3,557
	$\sigma(x_{ad}^{6dB})$, mm	0,130	0,023	0,083
	$u(x_{ad}^{6dB})$, mm	0,041	0,007	0,026
$\Delta x_d^{6dB} = x_{md}^{6dB} - x_{ad}^{6dB}$, mm		0,57	-0,14	0,84

Conclusions

1. The novel method for detection of defects and evaluation of their dimensions in multi-layered homogeneous and inhomogeneous structures was proposed, investigated and optimized. The method is based on combination of immersion pulse-echo ultrasonic scanning and the Hilbert-Huang and wavelet signal processing methods.
2. The one, two and three-layer plastic samples were experimentally examined. It was found that the pulse-echo method enables to detect the artificial defects in homogeneous one or two-layer plastic samples only. However, in the case of three-layer samples with an internal inhomogeneous layer the use of conventional equipment and signal processing is inefficient.
3. The comparative analysis of the frequency, autocorrelation and power spectrum characteristics of reflected an ultrasonic signal was performed. It was found that some variations of frequency and autocorrelation characteristics in inhomogeneous media do not enable to estimate localization of defects. Nevertheless, the changes in a power spectrum in homogeneous and inhomogeneous media were observed and were exploited in the signal-processing algorithm.
4. For detection of defects in multi-layered homogeneous structures the Hilbert-Huang method was adapted. To improve the defects visualization a new presentation of the Hilbert spectrum was proposed. This visualization is based on calculation of the product of the instantaneous frequency and the amplitude of the analytic signals. The product is displayed in a three-dimensional plot. This method gives us sufficient results of defects detection in homogenous structures.
5. For detection of defects and estimation of dimensions in inhomogeneous internal layer in the three-layer plastic pipe sample the use of the optimized wavelet analysis was proposed. It was shown that in an inhomogeneous layer after choosing the wavelet Coiflet-5, reconstruction of the signal according to the 5-th level coefficients and rejection of the unwanted reflected signals; the detection of the artificial defect with the diameter 0,7 mm was obtained.
6. The uncertainty components of defects detection by the proposed algorithm were analyzed. The dependences of the uncertainty upon the signal processing method were estimated and the dispersion of measurements results of defects position was determined.

List of publications on the theme of dissertation

1. R.Kažys, **D.Pagodinas,** O.Tumšys. Detection of defects in multi-layered plastic cylindrical structures by ultrasonic method // Ultragarsas (Ultrasound). ISSN 1392-2114. Kaunas, Technologija, 2002. Nr.2(43). P. 7-12.
2. **D.Pagodinas.** Ultrasonic signal processing methods for detection of defects in composite materials // Ultragarsas (Ultrasound). ISSN 1392-2114. Kaunas, Technologija, 2002. Nr.4(45). P. 47-53.
3. R.Kažys, **D.Pagodinas,** O.Tumšys. Analysis of ultrasonic determination of defects in polymer materials with porous intermediate layer // Matavimai (Measurements). ISSN 1392-1223. Kaunas, Technologija, 2003. Nr.2(26). P. 24-28.
4. R.Kažys, **D.Pagodinas,** O.Tumšys. Detection of defects in multi-layered plastic cylindrical structures by ultrasonic method. NDT.net July 2003, Vol. 8 No.07.
5. **D.Pagodinas.** Ultrasonic signal processing methods for detection of defects in composite materials. NDT.net July 2003, Vol. 8 No.07.
6. R.Kažys, **D.Pagodinas,** O.Tumšys. Application of the Hilbert-Huang signal processing to ultrasonic nondestructive testing of composite materials // Ultragarsas (Ultrasound). ISSN 1392-2114. Kaunas, Technologija, 2004. Nr.1(50). P.17-22.

Information about author

Darijus Pagodinas was born on the 19-th of July 1968, in Klaipėda, Lithuania.
1986 - graduation from secondary school in Vilkaviškis.
1986 – 1991 he studied in Telecommunications and Electronic department (former Radioelectronics department), Kaunas University of Technology and earned a degree of diploma engineer.
In 1991 he began to work as an engineer later as a lecturer assistant at the same department he had graduated from.
2000 – 2004 - doctoral studies in a branch of Measurement Engineering at Kaunas University of Technology.

REZIUMĖ

Problemos aktualumas

Ultragarsiniai neardomieji bandymai plačiai naudojami įvairiausių gaminių defektų lokalizavimui. Jie ypač paplitę metalinių konstrukcijų kokybės tyrimuose, diagnozuojant įvairius techninių reikalavimų neatitikimus tiek paprastos, tiek sudėtingos konstrukcijos gaminiuose. Tyrimams naudojami įvairiausi metodai, paruošti konkretūs matavimų algoritmai, kalibravimo metodikos, testiniai pavyzdžiai ir t.t. Tiriami ir vienasluoksniai, ir daugiasluoksniai gaminiai. Tuo pat metu šiuolaikinėje pramonėje vis plačiau naudojami įvairių konstrukcijų gaminiai iš polimerinių medžiagų – plastmasių. Šių medžiagų didelis santykinis tvirtumas, mažas tankis, atsparumas susidėvėjimui, agresyvių terpių poveikiui, gamybos technologijos nesudėtingumas sąlygoja vis platesnį jų naudojimą įvairiose pramonės šakose. Kyla akivaizdus tokių medžiagų kokybės vertinimo poreikis, pritaikant šiuolaikinius tyrimų metodus, įskaitant ir ultragarsinius. Ultragarsinių metodų panaudojimas polimerinių medžiagų kokybės tyrimams įgauna vis platesnius užmojus ir skatina mokslininkus bei inžinierius domėtis šių tyrimų taikymu įvairiose polimerinių medžiagų gamybos bei vartojimo srityse. Tai sąlygoja polimerinių medžiagų ultragarsinių tyrimų problematikos analizę plačiame polimerų taikymo diapazone.

Kuriant naujas polimerines medžiagas siekiant papildomo tvirtumo, lankstumo, jos sudaromos iš kelių skirtingų sluoksnių, kai kuriuose iš jų naudojant įvairius užpildus. Šių nehomogeninių sluoksnių naudojimas sukuria papildomas jų ultragarsinės diagnostikos problemas – didelis akustinių signalų slopinimas bei stipriai pasireiškiantys medžiagos struktūriniai triukšmai tuose sluoksniuose riboja realių defektų aptikimo bei jų dydžio įvertinimo galimybes. Naudojant įprastinius šiuolaikinius ultragarsinės diagnostikos metodus nepavyksta patikimai įvertinti šių sluoksnių kokybę - lokalizuoti juose egzistuojančius defektus bei pakankamu tikslumu įvertinti jų geometrinius parametrus. Šių problemų sprendimui ir skirtas pateiktas darbas, aprašantis naują ultragarsinių metodų taikymo algoritmą stipriai slopinančių daugiasluoksnių struktūrų su nehomogeniniu tarpiniu sluoksniu kokybiniams tyrimams.

Darbo tikslas

Darbo tikslas – panaudojant šiuolaikinius ultragarsinių tyrimų metodus sukurti defektų daugiasluoksnėse nehomogeninėse polimerinėse medžiagose aptikimo bei geometrinių matmenų įvertinimo metodiką.

Mokslinis naujumas

1. Ištirtos trijų sluoksnių polimerinės struktūros su tarpiniu nehomogeniniu sluoksniu dažninės, autokoreliacinės, galios spektro charakteristikos, atlikta homogeninio ir nehomogeninio sluoksnių parametrų palyginamoji analizė.
2. Ištirtas, įvertintas ir pritaikytas defektų aptikimui daugiasluoksnėse polimerinėse medžiagose naujas Hilberto-Huango skaitmeninis signalų apdorojimo metodas.
3. Sukurtas, ištirtas ir optimizuotas defektų nehomogeninėse struktūrose lokalizavimo ir geometrinių matmenų įvertinimo algoritmas, naudojantis bangelių transformacijos skaitmeninį signalų apdorojimo metodą.
4. Išnagrinėti sukurtam algoritmui būdingi neapibrėžčių sandai bei įvertinta defektų aptikimo šiuo algoritmu rezultatų sklaida.

Gynimui pateikiami darbo rezultatai

1. Daugiasluoksnių polimerinių medžiagų dirbtinių defektų aptikimo ultragarsiniu imersiniu aido-impulsiniu metodu eksperimentinių tyrimų rezultatai bei šių medžiagų homogeninių ir nehomogeninių sluoksnių su dirbtiniais defektais parametrų palyginamoji analizė.
2. Hilberto-Huango skaitmeninio signalų apdorojimo metodo taikymo defektų aptikimui daugiasluoksnėse homogeninėse medžiagose algoritmas.
3. Defektų nehomogeninėse terpėse su dideliu slopinimu ir išsklaidymu lokalizavimo ir geometrinių matmenų įvertinimo algoritmas, naudojantis bangelių transformacijos signalų apdorojimo metodą.
4. Defektų parametrų įvertinimo neapibrėžčių priklausomybių nuo tiriamos struktūros parametrų, matavimo bei signalų apdorojimo metodų tyrimo rezultatai.

Išvados

1. Sukurta, ištirta ir optimizuota defektų daugiasluoksnėse homogeninėse ir nehomogeninėse struktūrose aptikimo ir geometrinių matmenų įvertinimo metodika, taikant ultragarsinį imersinį aido-impulsinį tiriamos struktūros skenavimo būdą ir apdorojant gautus atsispindėjusius ultragarsinius signalus Hilberto-Huango bei bangelių transformacijos metodais.

2. Eksperimentiškai ištirti vieno, dviejų ir trijų sluoksnių polimerinių medžiagų bandiniai ir nustatyta, kad, detektuojant dirbtinius defektus ultragarsiniu aido-impulsiniu metodu, šie defektai aptinkami ir galima išmatuoti jų matmenis tik vieno ir dviejų sluoksnių bandiniuose. Nustatyta, kad trijų sluoksnių su tarpiniu nehomogeniniu sluoksniu defektų aptikimui nepakanka standartinės įrangos bei naudojamų signalų apdorojimo algoritmų.
3. Atlikta nuo polimerinių struktūrų homogeninių ir nehomogeninių terpių atsispindėjusių ultragarsinių signalų dažninių, autokoreliacinių ir galios spektro charakteristikų palyginamoji analizė. Nustatyta, kad, skirtingai nuo homogeninės terpės, nehomogeninėje terpėje dirbtinių defektų vietoje fiksuojami nedideli dažninių ir autokoreliacinių charakteristikų pokyčiai neįgalina įvertinti šių defektų dislokacijos vietų. Tuo tarpu visų terpių galios spektrai srityse be defektų koncentruoti žemesnių dažnių srityje, o, atsiradus defektui, galios spektrai pasislenka į aukštesnių dažnių sritį. Gauta informacija panaudota homogeninių ir nehomogeninių terpių defektų aptikimo algoritmo kūrimui.
4. Defektų aptikimui daugiasluoksnėse homogeninėse medžiagose modifikuotas ir pritaikytas naujas Hilberto-Huango metodas. Aptiktų defektų išskyrimui panaudota pirmos ir antros modų suma, o šių defektų vizualizacijai pasiūlytas naujas metodas - Hilberto-Huango spektro momentinio dažnio ir amplitudės sandaugos erdvinis vaizdavimas.
5. Trijų sluoksnių tarpinio nehomogeninio sluoksnio defektų aptikimui bei matmenų įvertinimui atliktas bangelių transformacijos metodo originaliųjų bangelių optimizavimas pagal svorio koeficientus 5 lygyje. Parodyta, kad originaliąja bangele parinkus Coiflet-5 bangelę, rekonstravus tiriamą signalą pagal 5 lygio koeficientus bei pritaikius neanalizuojamų atspindžių eliminavimo algoritmą aptikti 0,7 mm skersmens dirbtiniai defektai trijų sluoksnių polimerinio vamzdžio bandinio tarpiniame sluoksnyje, kai defektų gyliai skyrėsi nuo mechaniškai išmatuotų ne daugiau 0,5 mm, o išilginiai matmenys ne daugiau 1 mm.
6. Išnagrinėti trijų sluoksnių struktūros tarpiniame nehomogeniniame sluoksnyje aptiktų sukurtu algoritmu defektų parametrų (defektų gylių tiriamame sluoksnyje bei šių defektų ilgių) įvertinimo charakteringi neapibrėžčių šaltiniai. Nustatytos šių parametrų nuokrypius sąlygojančios komponentės, aprašyta sukurtam algoritmui būdingesnių komponenčių įvertinimo metodika bei ištirta šių komponenčių įvertinimo rezultatų sklaida.

Disertacijos struktūra ir apimtis

Daktaro disertaciją sudaro įvadas, 4 skyriai, išvados ir literatūros sąrašas. Bendra apimtis 106 psl., kuriuose yra 81 paveikslas, 9 lentelės ir 84 pavadinimų literatūros sąrašas.

Rezultatų aprobavimas

Disertacijos tema paskelbti 6 moksliniai straipsniai, 4 iš jų recenzuojamuose Lietuvos moksliniuose leidiniuose, įtrauktuose į Mokslo ir studijų departamento patvirtintą sąrašą, 2 iš jų užsienio mokslo leidiniuose.

Pagrindiniai rezultatai paskelbti 4 pranešimuose respublikinėse mokslo konferencijose.

Trumpa informacija apie disertacijos autorių

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