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Ultrasonic method for detection and location of defects in three-layer plastic pipe based on the wavelet transform

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Introduction

In aeronautical and automotive fields are increasingly fibre-reinforced polymer composites used, because of their good mechanical strength and light weight. However, during the extrusion of polymer materials various flaws may occur which have a negative impact on a polymer composite quality. To minimize risk of possible mechanical damage of polymer composite 0.5-1.0 mm size flaws should be taken into account. To detect manufacturing defects ultrasonic immersion technique has been used [1, 2]. The automated ultrasonic system measures the time-of-flight (TOF) and the amplitude of the received pulse after transmission through the measured polymer structure. The internal structure can be analyzed using various signal processing methods of the received ultrasonic signals [3]. During the last decade has been the various time-frequency signal analysis methods were used: The Gabor or the Short Time Fourier transform (STFT), the Wigner-Ville distribution, the Split Spectrum Processing (SSP) technique, the Wavelet Transform (WT), the Hilbert-Huang transform and others [4-6].

In this paper the use of digital signal-processing method, based on the Discrete Wavelet Transform (DWT), is suggested. The method was optimized and implemented for detection of defects in three-layer plastic pipes with an internal inhomogeneous layer.

Problem statement

In the past years plastic pipe designers have begun using a fibre-reinforced internal layer in order to achieve high performance of the construction. Ultrasonic non-destructive testing (NDT) of this pipes meets serious problems. An important issue in ultrasonic NDT of composite fibre-reinforced pipes is detection of flaw echoes in the presence of structural noise due to scattering of ultrasonic waves, high attenuation of the ultrasonic signal and multiple reflections inside the pipes, caused by different acoustic impedances of the layers. Usually the received ultrasonic signals consist of signal components and an additive Gaussian noise. However, the ultrasonic structural noise due to scattering by the small reflectors (fibres) is time invariant and slightly correlated with useful signal. Thus, the defects can not be detected reliably and the structural noise can not be cancelled by classical methods.

The wavelet processing is well established as a technique for removing noise from signals [7]. The WT is a new method of processing of transient non-stationary signals simultaneously in the time and frequency domains. This method decomposes the ultrasonic signal into a sum of elementary contributions called wavelets [8]. The WT is the correlation between the signal and a set of basic wavelets. The wavelet coefficients in the time-frequency domain represent the signal and the noise. The manipulation of the wavelet coefficients enables reduce influence of noise and is based on coefficient shrinking. Then the inverse wavelet transform is used to reconstruct the denoised signal.

The main questions to employ the wavelet transform for detection of defects in an inhomogeneous layer of the plastic pipe are:

- what wavelet transform to use – continues (CWT) or discrete (DWT)?
- what mother wavelet to choose?
- what denoising algorithm to wavelet coefficients to use?

The comparison of CWT and DWT shows that the information about the signal what provides the continuous wavelet transform is highly redundant and requires a significant amount of computation time and resources [9]. The discrete wavelet transform provides information both for analysis and synthesis of the original signal. The DWT is considerably easier to implement when compared to the CWT. Therefore we choose the discrete wavelet transform for processing of ultrasonic echo-signals.

The DWT represents the original signal $s(n)$ in terms of the shifted version of a low-pass scaling function $\varphi(n)$ and shifted and dilated versions of the prototype bandpass wavelet function $\psi(n)$ [10]. The low and high-pass wavelet coefficients are defined as:

$$\lambda_{j+1}(k)=\sum_n h(n-2k)\lambda_j(n)\,, \tag{1}$$

$$\gamma_{j+1}(k)=\sum_n g(n-2k)\lambda_j(n)\,, \tag{2}$$

where j indexes the scale or the resolution of analysis; k indexes the spatial location of analysis; $h(n)$ and $g(n)$ are the impulse response of a low and high-pass filter respectively. Thus the original signal can be represented as the finite summation of the coefficients calculated of the shifted and dilated mother wavelets:

$$s(n)=\sum_{j=1}^{J}\sum_k \gamma_{j,k}\psi_{j,k}(n)+\sum_k \lambda_{J,k}\varphi_{J,k}(n)\,, \tag{3}$$

where J is the maximal decomposition level.

There are many mother wavelets of the discrete wavelet transform, which have different properties: Meyer, Haar, "Mexican hat", Symlet, Coiflet, Daubechies and other. For signal processing can be used those mother wavelets whose performance presents better the original signal. The selection of the proper mother wavelet depends on the chosen criterion. The different mother wavelets present differently the original signal. The example of the ultrasonic echo-signal from a defect processed with different wavelets is presented in Fig.1. It can seen "Haar" and "Mexican Hat" that the wavelet coefficients at the level *j* are different.

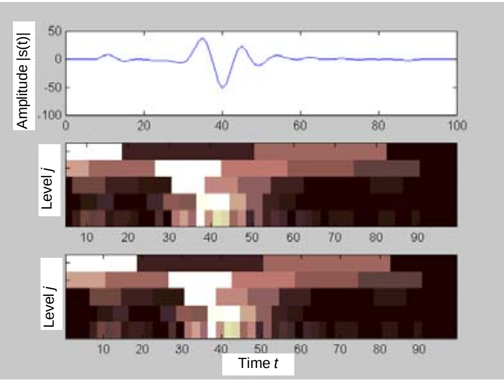


Fig.1. **Example of decomposition of an ultrasonic echo-signal from defect by different mother wavelets**

The second problem is the manipulation of the wavelet coefficients. There are two procedures known for the manipulation with wavelet coefficients: coefficient shrinkage [11] and coefficient selection from the region of interest [12].

There are two shrinkage methods – hard and soft threshold. We have processed experimental echo-signals from artificial defects in an inhomogeneous layer with universal, heuristic, SURE and minimax threshold methods [13]. In this paper it is shown that the standard signal processing procedures of the wavelet transform can not determine defects in a porous inhomogeneous layer.

Experimental setup

In order to optimize the wavelet method pipe we have performed experimental investigations. As the object for investigation we selected the three-layer plastic pipe sample with an internal inhomogeneous layer [14]. All three layers were of polypropylene, the internal layer was with fiberglass infusion. The wall thickness of this pipe sample was D=10.8 mm. In the pipe sample artificial defects – side-drilled holes (SDH) – at known positions were drilled (Fig.2).

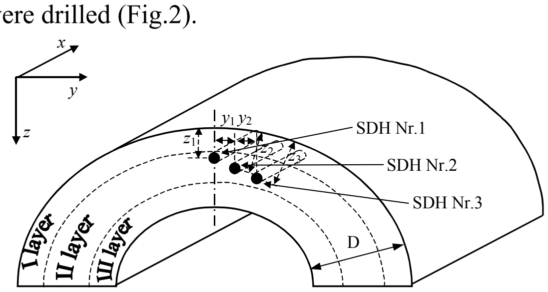


Fig.2. **Artificial defects (side-drilled holes (SDH)) in a internal layer of the three layer plastic pipe**

The distances of the holes from the front surfaces were z_1=5.0 mm, z_2=5.9 mm, z_3=6.7 mm. The distance between the holes SDH Nr.1 and Nr.2 was y_1=3.0 mm, between the holes SDH Nr.2 and Nr.3 was y_2=2.5 mm. The lengths of the holes were the following: x_1=6.3 mm, x_2=5.1 mm, x_3=4.4 mm. The diameter of all holes was 0.7 mm.

The plastic pipe sample was tested using the ultrasonic pulse-echo method by the imaging system "IZOGRAF", developed at the Ultrasound institute of the Kaunas University of Technology. 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. This transducer is spherical in shape and is focused at the distance of 48 mm from the centre of the emitting surface. The pipe sample was tested along the coordinates *x*. The reflected signals are presented on the graphical screen in the form of *A-scans* and *B-scans*.

For ultrasonic signal processing by the wavelet transform we have used *B-scans* of the internal layer of in the three-layer pipe. These *B-scans* obtained by scanning of the transducer along the coordinate *x* are presented in Fig.3.

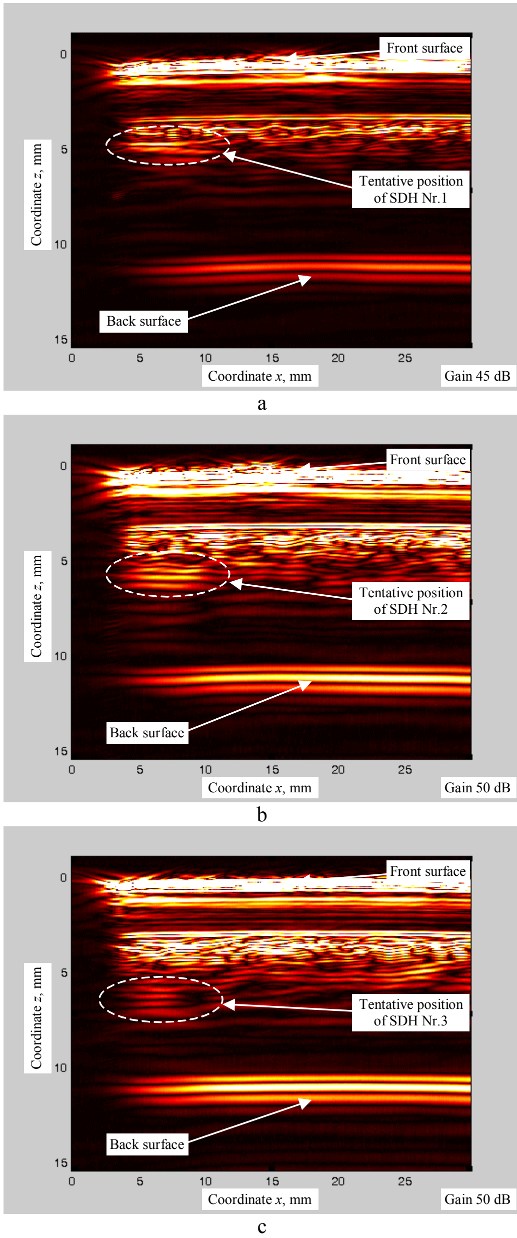


Fig.3. ***B-scans* along coordinate *x* with the artificial defects (side-drilled holes (SDH)) in an internal layer of the three layer plastic pipe: a - SDH Nr.1; b - SDH Nr.2; a - SDH Nr.3**

How it is seen from Fig.3, the artificial defects in the inhomogeneous internal layer are not detected reliably. It is seen the structural noise in the internal layer is caused by in homogeneities in the internal layer. As a solution of this problem we propose a new method for detection and location of defects.

Signal processing method

It can be seen that in the collected B-scans the signals reflected by regular discontinuities like interfaces exist (Fig.3). These signals with a large amplitude complicate detection of defects with a small amplitude and they mask the useful signals. To solve this problem we propose the improved algorithm eliminating the signals reflected by interfaces. For that we use the reference signal obtained as an average of the five signals collected at the fixed points along *x*-axis. These signals are picked-up in the region without defects:

$$s_r(t) = \frac{s_1(t)\big|_{x=x1} + s_2(t)\big|_{x=x2} + s_3(t)\big|_{x=x3} + s_4(t)\big|_{x=x4} + s_5(t)\big|_{x=x5}}{5}. \qquad (4)$$

In order to eliminate strong ultrasonic signals reflected by interfaces, which may be irregular in a spatial domain, we need to find the optimal position and the amplitude of the equivalent signal in the best way describing the signal reflected by a particular interface at different spatial positions. For this purpose for each *A-scan* signal $s_i(t)$ we calculate the difference between this particular signal and the reference signal (Eq.4) changing the delay Δt of the reference signal until this difference obtains minimum:

$$\Delta s(\Delta t)\big|_{\Delta t=\Delta t_{opt}} = \min \sum_{i=1}^{N} \left(s_i(t) - s_r(t+\Delta t)\right)^2, \qquad (5)$$

where N is the length of the signal in the samples.

Further we search for the optimal amplitude of the reference signal at the optimal delay Δt_{opt}:

$$\Delta s(K, \Delta t_{opt})\big|_{K=K_{opt}} = \min \sum_{i=1}^{N} \left(s_i(t) - K \cdot s_r(t+\Delta t_{opt.})\right)^2, \qquad (6)$$

where K is the amplitude coefficient of the reference signal. When this difference obtains minimum, then the optimal value of the coefficient K_{opt} is found.

After that from each *A-scan* signal in the *B-scans* (presented in Fig.6) the signals reflected by interfaces are eliminated:

$$s_{iproc.}(t) = s_i(t) - K_{opt.} s_r(t+\Delta t_{opt.}). \qquad (7)$$

In the next step of the signal processing we use the discrete wavelet transform (DWT). We decompose each *A-scan* into a sum of elementary contributions called wavelets. Then we have the set of wavelets coefficients, which depend on the used mother wavelet. The maximal level J of decomposition (Eq.3) depends on the length of signal in term of samples [15]:

$$J = \log_2 N - 1. \qquad (8)$$

Because we use the *A-scans* with N=512 samples, the maximal level J=8. The each level corresponds to the frequency range depending on the signal sampling frequency. Since the signal is sampled at 50 MHz, the highest frequency component that exists in signal is 25 MHz. Therefore, the first level correspond to (12.5-25) MHz range. The second level corresponds to the frequency range subsampled by two and etc. The illustration of the decomposition of original signal in to 8 level wavelet coefficients is presented in Fig.4.

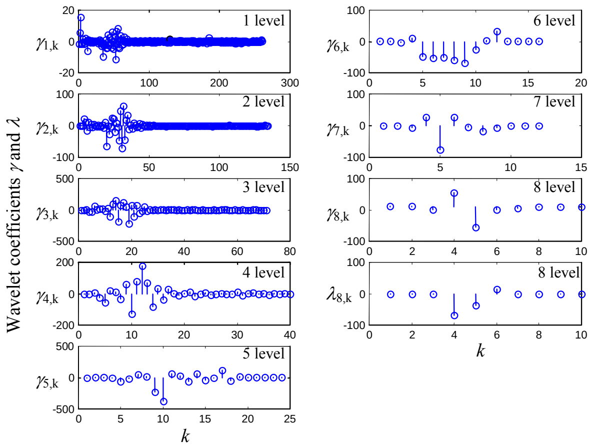


Fig.4. **Original signal decomposition by the "Symlet-5" mother wavelet transform into wavelet coefficients on eight levels**

A wavelet coefficient shows how much of the corresponding wavelet basis function is presented in the whole signal. To analyze how much the wavelet coefficients of the level j present the ultrasonic echo-signal from the artificial defect, we propose to use the weighting coefficient:

$$W_j = \frac{\gamma_{j\Sigma}}{\gamma_\Sigma}, \qquad (9)$$

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.

Obviously that $\sum_j W_j = 1$.

The analysis of the decomposition of the echo-signals from the artificial defects in the internal layer by the wavelet transform shows that the defects are presented by the coefficients of the level j=5. This conclusion is confirmed on by results presented in Fig.5.

According to this criterion we have chosen an optimal mother wavelet:

$$\psi(n)_{opt} \Rightarrow \max(W_5). \qquad (10)$$

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

The optimization of the wavelet transform for detection of defects in an inhomogeneous layer of a plastic pipe we have reconstruct the original signal reconstruction from 5 level wavelet coefficients:

$$s_r(n) = \sum_{j=5} \sum_k \gamma_{j,k} \psi_{j,k}(n). \qquad (11)$$

The results of optimization of the wavelet transform for detection of the defects are presented in Fig.6.

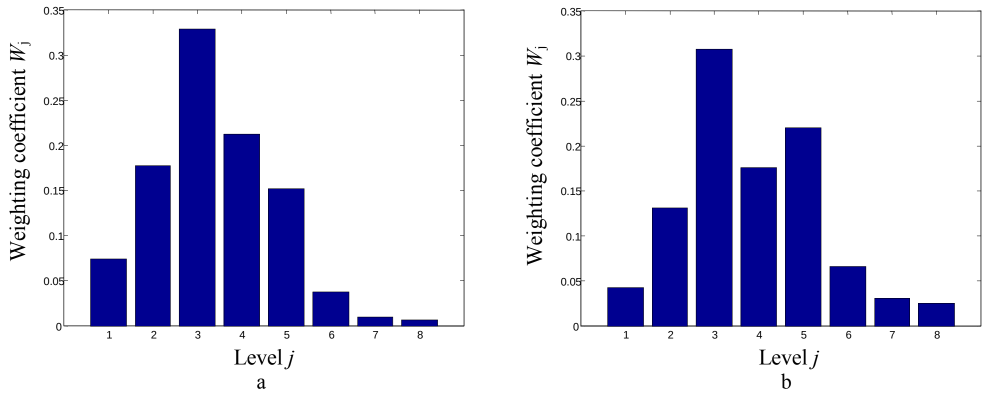


Fig.5. **The weighting coefficients calculated by the “Symlet-5” wavelet from the *A*-scans of echo-signals without (a) and with the artificial defect SDH Nr.2 (b)**

Table 1. **The weighting coefficients W_5 for various mother wavelets**

Mother wavelet	Symlet 3	Symlet 4	Symlet 5	Symlet 6	Symlet 7	Symlet 8	Symlet 10	Haar
Weighting coefficient W_5	0.2181	0.2265	0.22	0.2176	0.2304	0.2179	0.2270	0.1154
Mother wavelet	Daubechies 3	Daubechies 4	Daubechies 5	Daubechies 6	Daubechies 10	Coiflet 1	Coiflet 3	**Coiflet 5**
Weighting coefficient W_5	0.2181	0.1979	0.2450	0.2104	0.2139	0.1974	0.2151	**0.2499**

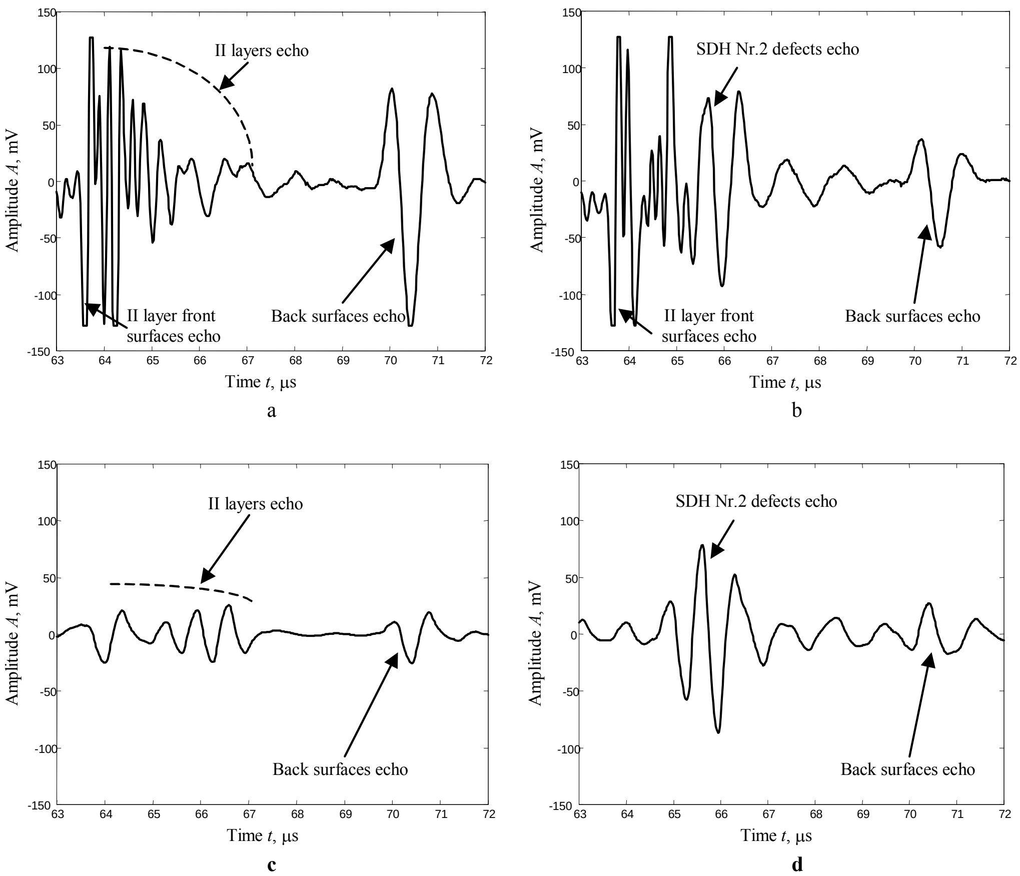
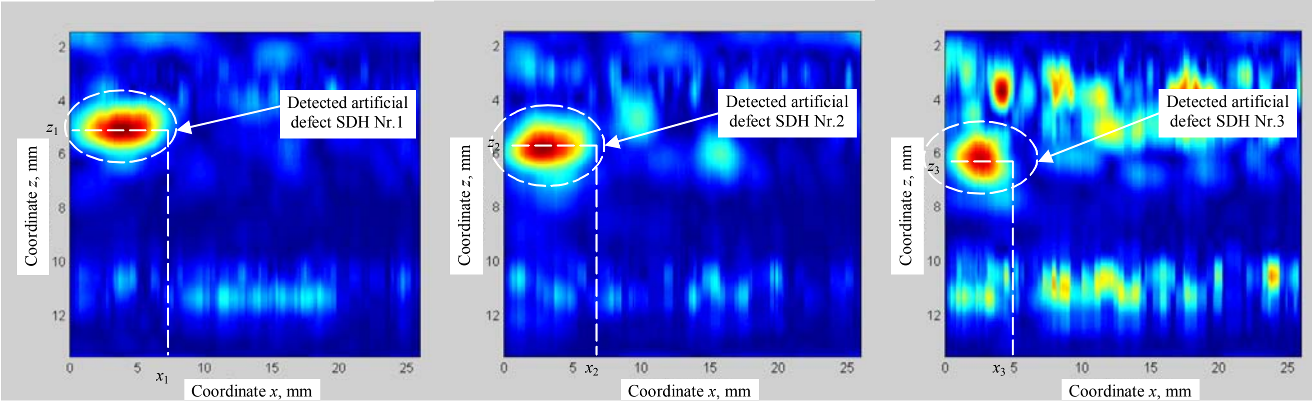


Fig.6. ***A-scans* from the internal layer of the three-layer pipe without (a) and with the artificial defect SDH Nr.2 (b) and the corresponding *A-scans* (c) and (d) after reconstruction using the “Coiflet-5” mother wavelet and the optimized algorithm**



a b c

Fig.7. **With proposed method processed *B-scans* along coordinate *x* with the artificial defects in an internal layer of the three layer plastic pipe: a - SDH Nr.1; b - SDH Nr.2; a - SDH Nr.3**

Table 2. **The results of measurements of the artificial defects in internal layer of three-layer plastic pipe sample**

Parameters	Defects / Measurement method	Artificial defect SDH Nr.1	Artificial defect SDH Nr.2	Artificial defect SDH Nr.3
z_7, z_8, z_9	Mechanical measurements (mm)	5.0	5.9	6.7
	Detected by proposed method (mm)	5.1	5.9	6.2
Absolute error	(mm)	-0.1	0	0.5
x_7, x_8, x_9	Mechanical measurements (mm)	6.3	5.1	4.4
	Detected by proposed method (mm)	7.3	6.7	4.9
Absolute error	(mm)	-1.0	-0.4	-0.5

Fig. 6 shows us the *A-scans* from the internal layer of the three-layer pipe without (Fig.6 a) and with the SDH Nr.2 defect (Fig.6 b). The *A-scans* without and with defects, processed by the proposed algorithm are presented in Fig.6 c and d.

From the results obtained follows that application of the proposed method enables reliably detect artificial defects in the presence of a structural noise.

To estimate the size and coordinates of the artificial defects SDH Nr.1-3 in the internal layer of a three-layer plastic pipe sample we processed the *B-scans* (Fig. 3) by the proposed method and the Hilbert transform. The processed *B-scans* are presented in Fig.7.

The position of the defects can be measured mechanically and detected by the proposed method. To characterize the position we use two measured coordinates: the distance z_d between the front surface of the plastic pipe and the symmetry axis of the hole; the length of the hole x_d. Mechanical measurement results and detection results by the proposed method are compared in Table 2. From the results presented follows that the absolute error of the defects position is not bigger than 1.0 mm.

Conclusions

In this paper we present the new ultrasonic method for detection and location of defects in an internal inhomogeneous layer of three-layer plastic pipe based on the wavelet transform. This method consists of the improved algorithm eliminating the signals reflected by interfaces and the optimized wavelet analysis. It was shown that in the 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, detection of the artificial defect with the diameter 0,7 mm was obtained. The absolute error of the defects location is not bigger than 1.0 mm.

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Defektų trijų sluoksnių plastikiniuose vamzdžiuose ultragarsinis aptikimas bangelių transformacija

Reziumė

Kad kuriamos naujos polimerinės medžiagos būtų tvirtesnės ir lankstesnės, jos sudaromos iš kelių skirtingų sluoksnių, kartais naudojami įvairūs užpildai. Šie nehomogeniniai sluoksniai sukuria ultragarsinės diagnostikos problemų – didelis akustinių signalų slopinimas bei dideli medžiagos struktūriniai triukšmai tuose sluoksniuose riboja realių defektų aptikimo bei jų dydžio įvertinimo galimybes. Straipsnyje pasiūlytas naujas defektų aptikimo metodas. Čia pirmiausia naudojamas ultragarsinis aido impulsinis tiriamosios struktūros skenavimas, o toliau optimizuotu bangelių transformacijos metodu skaitmeniškai apdorojami atsispindėję signalai. Originaliosios bangelės optimizuojamos pagal svorio koeficientus. 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 nehomogeniniame sluoksnyje, kai defektų matmenys skyrėsi nuo mechaniškai išmatuotų ne daugiau kaip 1 mm.

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