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# Reduction of a structural noise by application of the wavelet transform with level-dependent thresholds

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**Abstract**

In this study de-noising results of the ultrasonic echo-signals using the discrete wavelet transform with level-dependent thresholds is presented. The proposed technique has been applied for simulated and measured ultrasonic signals, obtained from austenitic steel sample and glass fiber reinforced plastic composite pipe. It was obtained, that "Symlet-10" mother wavelet using "Minimax" threshold selection rule provides significant improvement for ultrasonic grain noise reduction in the case of detection of intergranular stress corrosion cracks in austenitic steel samples (in the case of numerical simulation). However, the detection of the defects in composite plastic pipe using the proposed technique for de-noising experimentally obtained signals is enough complicated. The signals reflected by regular discontinuities, like interfaces between adjacent layers of the multilayered structure covers the useful signals from the internal defects (like side drilled holes (SDH)). In order solve these problems, the different type of signal processing technique should be used, for example like the proposed by authors in [17].

**Keywords:** Structural noise, signal processing, wavelet transform, level-dependent threshold.

## Introduction

Imaging of the internal defects in various constructions is widely used in many applications of non-destructive testing (NDT) with ultrasound. This imaging can be often complicated by the presence of a noise during testing. Electrical, pulse, ringing and structure noises are the most commonly encountered noises, which reduces the signal-to-noise ratio (SNR). Some of the noise sources can be reduced by time or spatial averaging methods [1]. Presence of the additive structural noise from grain boundaries and other microstructures limit detection of small cracks, flaws or other defects. If these additive noises are described as a zero-mean Gaussian white noise, than for de-noising of the signal various signal-processing methods is proposed (split spectrum processing, adaptive time-frequency decomposition, Wigner-Ville distribution, wavelet, Hilbert-Huang transforms and other). Many of them process the signals in the time and the frequency domains simultaneously.

If the structural noise due to scattering by the small reflectors is time invariant and slightly correlated with a signal, that this type of noise possess a frequency band very similar to that of the echoes issuing from the defects being detected. Therefore, classical methods do not reduce this type of noise essentially. Therefore, specific de-noising methods have been proposed for processing of these signals, which are based on either spatial or frequency diversity.

The most popular signal processing technique is the Discrete Wavelet Transform (DWT) [2-5]. The wavelet transform decompose the original signal by computing its correlation with a short-duration wave called the mother wavelet, which is flexible in both time and frequency domains. Wavelet de-noising methods usually employ a thresholding operation and/or pruning of the wavelet coefficients in the transformed domain. The efficiency of a structural noise reduction has been evaluated by enhancement of the signal-to-noise ratio.

This paper demonstrates the de-noising capabilities of the DWT using level-dependent thresholds. The proposed method has been employed to several experimental pulse-echo ultrasonic signals, obtained from glass fiber reinforced plastic composite pipe and for simulated reflections from the austenitic steels sample also.

## Reduction of the structural noise by wavelet transform

The DWT may be intuitively considered as a decomposition of a original signal $s(n)$ following hierarchical steps (levels) of different resolution. At the each step the signal is decomposed into low and high frequency coefficients [6]:

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

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

where $j$ indexes the scale or the resolution of the analysis; $k$ indexes the spatial location of the reflection being analyzed; $h(n)$ and $g(n)$ are the impulse response of a low and high-pass filter respectively. The ultrasonic signal has been decomposed into separate frequency bands (scales). Thus the original signal can be represented as the finite summation of the coefficients calculated of the shifted and dilated mother wavelet:

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

where $J$ is the maximal decomposition level, $\varphi(n)$ is the low-pass scaling function, $\psi(n)$ is the band-pass wavelet function.

De-noising of the ultrasonic signals by the wavelet transform is motivated by the different ways in which the wavelet coefficients are calculated according to the appropriate threshold or extraction procedures. The signal having a lower noise level can be reconstructed by selecting the large coefficients which essentially contain the signal information and rejecting the small coefficients, which are dominated by noise. This process can be carried out by hard or soft thresholding rules [7].

Various authors operate with different wavelet signal de-noising methods and DWT is being used across a variety of fields showing its universality. Legendre *et al* [8] proposed a wavelet-based method to perform the analysis of NDE ultrasonic signals received during the inspection of reinforced composite materials. They proposed a selection process of the wavelet coefficients, followed by an interpretation procedure based on a windowing process in the time-frequency domains. Yan *et al* [9] studied damage detection of local and tiny delamination in a laminated composite plate using the piezoelectric patches embedded in a composite plate and the energy distribution of structural dynamic responses has been decomposed in various frequency bands by wavelet packet analysis. Oruklu *et al* [10] analyzed signal decomposition properties of the discrete wavelet transform for enhanced ultrasonic flaw detection. They have presented the performance analysis of different wavelet kernels with respect to ultrasonic NDE applications and the wavelet selection criteria for optimal flaw detection have been developed. Fan *et al* [11] applied stationary wavelet transform with kurtosis and universal de-noising to analyze ultrasonic signals in an attempt to identify the weak signals obtained during testing of metallic materials.

For more general situations, Johnstone *et al* [12] introduced the idea of level-dependent thresholds, which are more adaptive to noise and signal characteristics.

In the case of the noise coefficients correlations, thresholds have been estimated for each decomposition level from the computed wavelet coefficients by different threshold selection rules, like Universal, Minimax and SURE [13].

The approach for de-noising of the ultrasonic signals covered by a grain noise is also presented in this work.

## Simulation and experimental study

Synthetic ultrasonic grain noise signals have been used for the evaluation of wavelet de-noising procedures. These signals have been simulated according to the NDT simulation algorithm presented in [14]. In this algorithm the numerical simulation of the inspection of an austenitic steel structure with an intergranular stress corrosion crack has been performed. The algorithm is based on an extended diffraction model of the ultrasonic transducer. To simulate a vertically oriented intergranular stress corrosion crack, a fractal theory has been applied [15]. The wedge-type shear wave transducer with a radius 4 mm and frequency 4MHz has been used for the simulation. During simulation the sampling frequency has been assumed to be 50 MHz and the ultrasound velocity of the shear waves to be 3120 m/s. The thickness of the object has been 25 mm and the scanning length over the object has been 50 mm. The contact scanning technique has been simulated. The simulated *B-scan* image is presented in Fig.1. In this figure skip reflected (corner effect) and multiple crack edge (tip) diffraction signals can be seen.

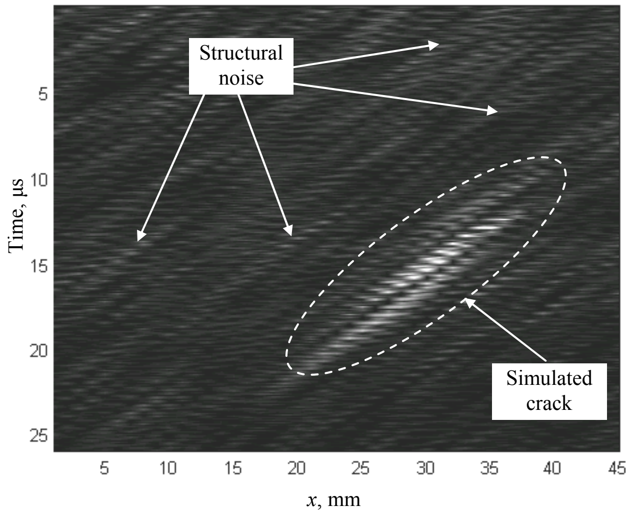


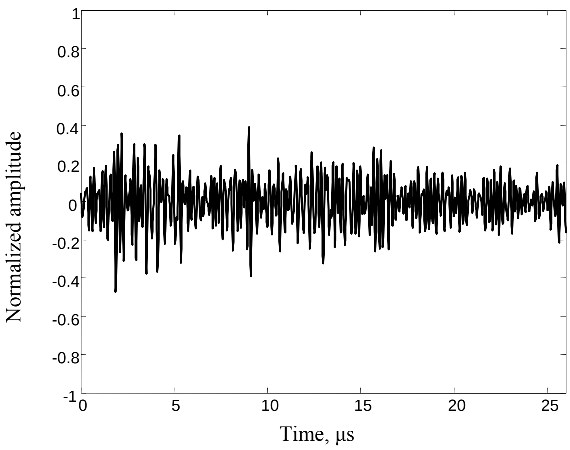

Fig.1. **Simulated *B-scan* image of the intergranular stress corrosion crack, which is covered by the background of the structural noise**

The *A-scans* without and with simulated crack at the fixed points of the raw *B-scan* image are presented in Fig.2. It can be seen from the Fig.2, b, that the simulated crack has been covered by the structural noise of the granular structure of the austenitic steel. The signal-to-noise ratio for a single *A-scan* signal has been calculated in the selected time window (a rectangularly shaped) equal to the position of the reflection from the crack (Fig.2, b) by expression [16]:

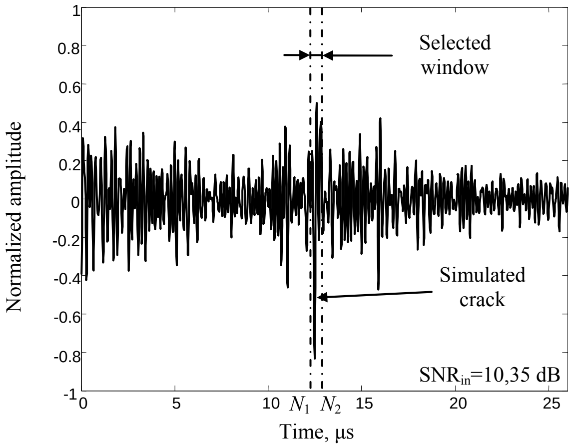
$$SNR = 10\lg\left(\frac{\sum_{n=N_1}^{N_2}\left(\frac{s^2(n)}{(N_2-N_1+1)}\right)}{\sum_{n=1}^{N_1-1}\left(\frac{s^2(n)}{N_1-1}\right)+\sum_{n=N_2+1}^{N}\left(\frac{s^2(n)}{N-N_2}\right)}\right) \quad (4)$$

where $N$ is the total length of the signal $s(n)$ ($N$=1024), $N_1$ and $N_2$ are the time window points around the zone of the crack (Fig.2,b). The $SNR_{in}$ of the presented *A-scan* is 10.35 dB. The proposed NDT simulation algorithm [14] enables to change artificially the SNR in a wide dynamic range. In order to improve the SNR of these ultrasonic signals, the signal processing technique based on the discrete wavelet transform with level-dependent thresholds has been used.

The signal processing technique, based on the wavelet transform with level-dependent thresholds, has been applied for analysis of the experimental signals also. These signals have been obtained from three-layer plastic pipe sample with an internal inhomogeneous layer [17]. All three layers were made of polypropylene, however the middle layer was with a fiberglass infusion. The wall thickness of the multi-layered pipe sample was $d$=10.8 mm. In the internal fibre-reinforced layer side-drilled holes (SDH) were machined. The measurements were taken with ultrasonic imaging system "IZOGRAF", developed at the Ultrasound institute of the Kaunas University of Technology. As an ultrasonic transmitting/receiving transducer the panametrics transducer V308 (the frequency 5 MHz, the aperture 19 mm) was used.




a




b

Fig.2. **The simulated *A-scans* at the fixed points of the simulated *B-scan* image (Fig.1.) without (a) and with presence of the reflection from the intergranular stress corrosion crack (b)**

This transducer is spherical in shape and is focused at the distance of 48 mm away from the centre of the emitting surface. The signals have been sampled at 50 MHz and the total length of the signals as $N$=512 samples. The pipe sample was tested along its length. The *B-scan* image obtained by scanning of the transducer along the pipe axis is presented in Fig.3. It is clearly seen, that strong ultrasonic signals reflected by the front surface exist. In order to eliminate these signals the rectangularly shaped window has been used in the time and the spatial domains for selection of the appropriate reflections (Fig.3).

The measured data show the effect in the echo-signal of the structural noise related to the inhomogeneous II layer of the plastic pipe (Fig.4). The *A-scan* with artificial defect (Fig.4, a) shows, that the SNR is low and detection of the artificial defects is complicated. In *A-scan* signal without defects (Fig.4, b) the structural noise of the II layer can be clearly seen.

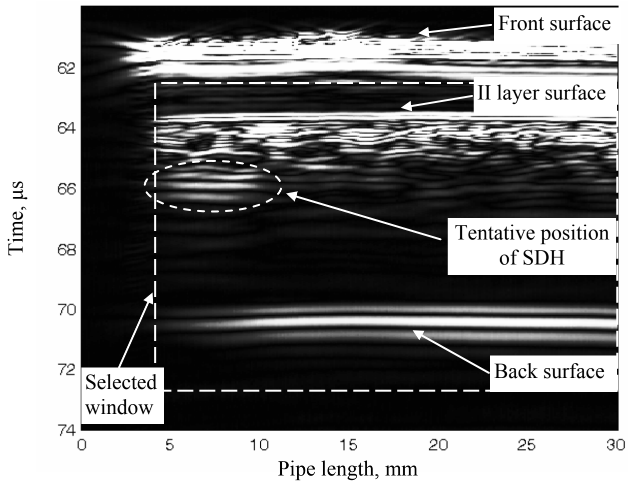
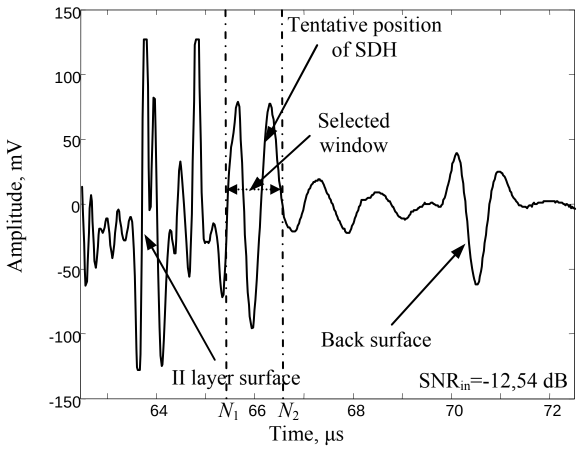
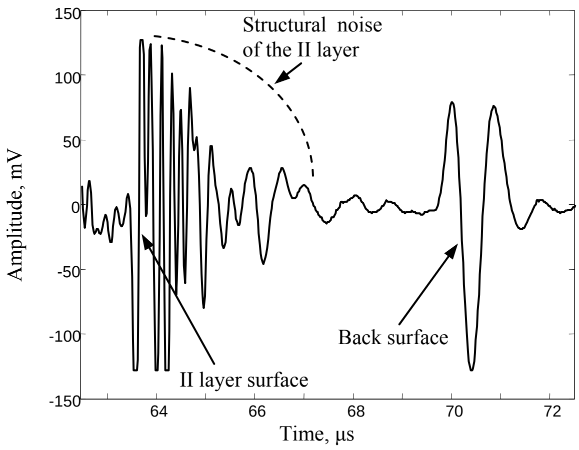



Fig.3. ***B-scan* image along pipe length with the side-drilled hole SDH in an internal layer of the three layers plastic pipe**




a




b

Fig.4. ***A-scans* obtained at fixed points of the *B-scan*, which indicate the presence of the artificial defect in an internal layer (a) and without defects (b)**

## Results of the signal processing

The performance of the used DWT procedures with level-dependent thresholds and different threshold selection rules has been determined using interdependence between the SNR before ($SNR_{in}$) and after ($SNR_{out}$) signal processing. The signal-to-noise ratio for a single *A-scan* before (or after) processing has been calculated by Eq.4.

The each analyzed *A-scan* has been decomposed into a sum of elementary contributions called wavelets. Such wavelets included in the presented study belong to the following families: Daubechies (Haar, Db2-20), Symlets (Sym2-20) and Coiflets (Coif1-5). Wavelets coefficients have been set, which depends on the used mother wavelet. For each combination of the mother wavelet the soft thresholding operation with Universal, Minimax and SURE threshold estimators at each resolution level has been used. The maximal level $J$ of decomposition (Eq.3) has been calculated according to the length of the signal in samples [18]:

$$J = \log_2 N - 1. \quad (5)$$

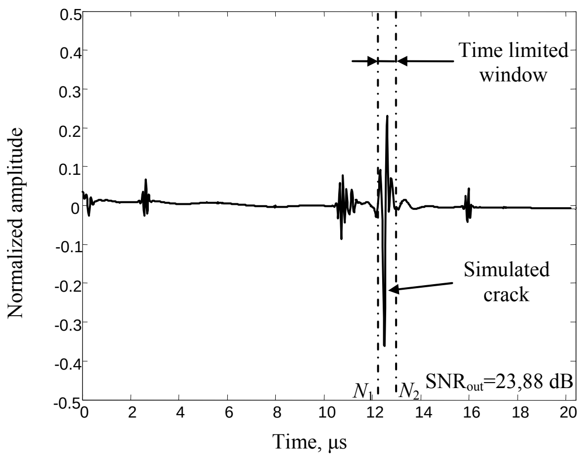
The analysis of the ultrasonic signals de-noising by application of the level-dependent thresholds wavelet procedure has been performed according the criterion $max(SNR_{out})$ and the optimal mother wavelet has been chosen.

The analysis of various mother wavelets indicates, that the optimal mother wavelet for simulated ultrasonic echo-signal from an intergranular stress corrosion crack (Fig.2, b) is "Symlet-10" with Minimax threshold selection rules (Table 1). The improvement of the SNR with this procedure is about 13.5 dB (from 10.35 dB up to 23.88 dB).

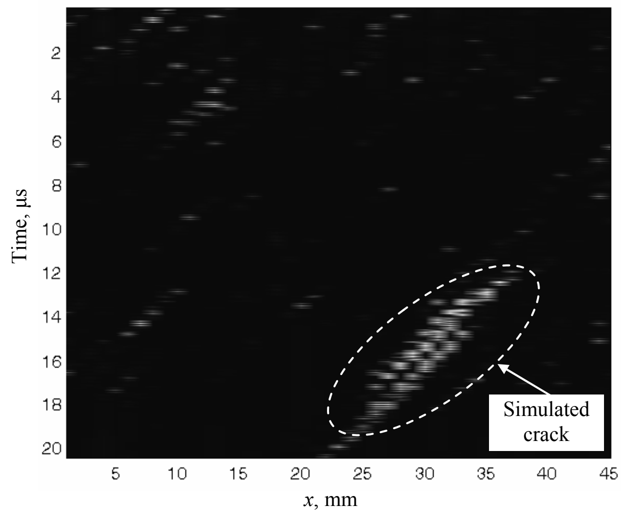
Table 1. **The $SNR_{out}$(dB) of the processed ultrasonic signals, which are reflected from the intergranular stress corrosion crack ($SNR_{in}$=10.35 dB)**

| Mother wavelet | Universal threshold | Minimax threshold | SURE threshold |
|---|---|---|---|
| Db4 | 14.84 | 18.83 | 16.23 |
| Db5 | 13.71 | 19.01 | 16.26 |
| Db10 | 14.08 | 17.15 | 16.46 |
| Db13 | 7.28 | 17.81 | 14.26 |
| Db14 | 12.34 | 17.02 | 15.78 |
| Sym6 | 19.42 | 20.11 | 17.49 |
| Sym7 | 14.35 | 20.15 | 16.96 |
| Sym8 | 18.73 | 20.89 | 17.67 |
| Sym9 | 19.58 | 20.16 | 18.29 |
| Sym10 | 16.97 | 23.88 | 18.91 |
| Sym11 | 17.02 | 20.67 | 16.18 |
| Sym13 | 18.56 | 22.95 | 22.81 |
| Sym15 | 15.29 | 23.29 | 18.38 |
| Sym17 | 19.89 | 22.16 | 18.59 |
| Sym20 | 18.68 | 21.33 | 15.60 |
| Coif3 | 8.99 | 19.79 | 15.57 |
| Coif5 | 11.95 | 19.66 | 15.25 |

The *A-scan* and the *B-scan* images after application of the de-noising procedure, which has been based on the threshold dependent "Symlet-10" wavelet, are presented in Fig.5. The "Minimax" rules have been used for selection of the appropriate threshold for de-noising of the simulated *B-scan* and *A-scan* images (Fig.1).




a




b

Fig.5. **Processed simulated data after the level-dependent threshold estimation by "Minimax" threshold selection rules of the "Symlet-10" mother wavelet: a - *A-scan*, b – *B-scan***

However, the signal processing of the experimental pulse-echo ultrasonic reflections from the internal structure of the multi-layered plastic pipe using the proposed technique cannot eliminate the influence of the structural noise significantly (Fig.3). The best result of the $SNR_{out}$, which has been obtained using this procedure, was obtained by "Symlet-20" mother wavelet with "Minimax" threshold selection rules ($SNR_{out}$=12.21 dB). This result is presented in Fig.6. It can be seen, that in the analyzed *A-scan* image the signal reflected by II layer surface exist. This signal having large amplitude partly covers the useful informal signal from the SDH and complicates detection of such defect also. In order to solve this problem, the improved algorithm has been proposed, which eliminates the signals reflected by interfaces of the multilayered pipe [17]. Therefore, the technique presented in [17] clearly indicates possibility for reliable detection of the artificial defects in the presence of a structural noise.

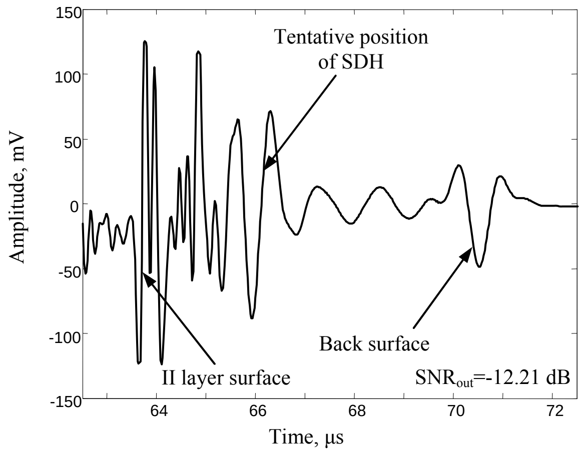



Fig.6. ***A-scan* image after wavelet processing by level-dependent thresholds, which indicates presence of the artificial SDH defect**.

## Conclusions

In this paper the de-noising study of ultrasonic echo-signals using the discrete wavelet transform with level-dependent thresholds is presented. The proposed technique has been applied for simulated and measured ultrasonic signals, obtained from the austenitic steel sample and the carbon fiber reinforced plastic composite pipe. The results presented here indicate, that the proposed technique is suitable to detect the intergranular stress corrosion cracks in austenitic steel. It was obtained, that "Symlet-10" mother wavelet using "Minimax" threshold selection rules provide great improvements for ultrasonic grain noise reduction.

However, the detection of the defects in composite plastic pipe using proposed procedure is complicated. The signals reflected by regular discontinuities, like interfaces between the adjacent layers covers the useful signals from the internal defects (like SDH). The proposed wavelet de-noising procedure cannot eliminate these reflections from the interfaces. In order solve these problems, the different type of signal processing technique should be used, for example like proposed in [17].

### References

1. **Chen J., Shi Y., Shi S.** Noise analysis of digital ultrasonic nondestructive evaluation system. International Journal of Pressure Vessels and Piping. 1999. Vol.76. P.619-630.
2. **Reda Taha M.M., Noureldin A., Lucero J.L., Baca T.J.** Wavelet transform for structural health monitoring: a compendium of uses and futures. Structural Health Monitoring. 2006. Vol.5(3). P.267-295.
3. **Shou-peng S., Pei-wen Q.** Wavelet based noise suppression technique and its application to ultrasonic flaw detection. Ultrasonics. 2006. Vol.44. P.188-193.
4. **Wawszczak J.** Analysis of geometric features of quasi-brittle profiles of iron fractures with various levels of wavelet filtration in relation to the grain size of the ferritic structure. Materials Characterization. 2006. Vol.56. P.305-309.
5. **Liu F., Ruan X.E.** Wavelet-based diffusion approaches for signal denoising. Signal Processing. 2007. Vol. 87. P.1138-1146.
6. **Mallat S.** A theory for multiresolution signal decomposition: The wavelet representation. IEEE Trans. Patt. Anal. Machine Intell. 1989. Vol.11. No.7. P.674-693.
7. **Abbate A., Koay J., Frankel J., Schroder S.C., Das P.** Signal Detection and Noise Suppression Using a Wavelet Transform Signal Processor: Application to Ultrasonic Flaw Detection. IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control. 1997. Vol.44. No.1. January. P.14-26.
8. **Legendre S., Goyette J., Massicotte D.** Ultrasonic NDE of composite material structures using wavelet coefficients. NDT&E International. 2001. Vol.34. P.31-37.
9. **Yan Y.J., Yam L.M.** Detection of delamination damage in composite plates using energy spectrum of structural dynamic responses decomposed by wavelet analysis. Computers and Structures. 2004. Vol.82. P.347-358.
10. **Oruklu E., Saniie J.** Ultrasonic flaw detection using discrete wavelet transform for NDE applications. 2004 IEEE International Ultrasonics, Ferroelectrics, and Frequency Control Joint 50th Anniversary Conference. P.1054-1057.
11. **Fan X., Zuo M.J., Wang X.** Identification of weak ultrasonic signals in testing of metallic materials using wavelet transform. Smart Materials and Structures. 2006. Vol.15. P.1531-1539.
12. **Johnstone I.M., Silverman B.W.** Wavelet threshold estimators for data with correlated noise. Journal of the Royal Statistical Society. 1997. Vol.59. P.319-351.
13. **San Emeterio J.L., Pardo E., Ramos A., Rodriguez M.A.** Ultrasonic grain noise reduction using wavelet processing. An analysis of threshold selection rules. 2006. Proceedings of the 9th ECNDT, 2006.
14. **Raišutis R.** The simulation of ultrasonic imaging in the case of internal defect. Insight. 2005. Vol.47. No.11, November. P.682-687.
15. **Mažeika L., Kažys R., Šliteris R., Raišutis R.** Application of modelling for ultrasonic non-destructive estimation of cracks caused by intergranular stress corrosion. Proceedings of the 8th ECNDT, 2002.
16. **Lazaro J.C., San Emeterio J.L., Ramos A., Fernandes-Marron J.L.** Influence of thresholding procedures in ultrasonic grain noise reduction using wavelets. Ultrasonics. 2002. Vol.40. P.263-267.
17. **Kažys R., Tumšys O., Pagodinas D.** Ultrasonic method for detection and location of defects in three-layer plastic pipe sample based on the wavelet transform. Ultragarsas (Ultrasound), Kaunas: Technologija. 2005. Nr.1 (54). P.33-38.
18. **Valens C.** A Really Friendly Guide to Wavelets. 1999. 19 p.

O. Tumšys, R. Raišutis

**Struktūrinių triukšmų mažinimas nevienodu bangelių transformacijos koeficientų filtravimu skirtinguose lygiuose**

Reziumė

Nagrinėjamos struktūrinių triukšmų, atsirandančių ultragarsiniu aidoimpulsiniu metodu tiriant nehomogeninį objektą, mažinimo bangelių transformacijos metodu galimybės. Tirti pasirinkti nerūdijančio plieno ir trijų sluoksnių polimerinio vamzdžio su tarpiniu, stiklo pluoštu sutvirtintu, sluoksniu bandiniai. Bangelių transformacijos skaitmeniniu signalų apdorojimo metodu apdoroti, pagal skaitmeninį modelį sukurti ir eksperimentiškai išmatuoti ultragarsinių signalų B vaizdai. Šiems vaizdams apdoroti panaudotas nevienodas bangelių transformacijos koeficientų filtravimas skirtinguose lygiuose. Nustatyta, kad struktūrinius triukšmus, nestipriai koreliuotus su nuo dirbtinio defekto atsispindėjusiais signalais, nerūdijančiame pliene galima sumažinti panaudojus „Symlet-10“ pirminę bangelę ir „Minimax“ bangelių transformacijos koeficientų filtravimo būdą. Tačiau nuo polimerinio vamzdžio tarpinio sluoksnio atsispindėjusių ultragarsinių signalų struktūrinius triukšmus labai sumažinti minėtuoju metodu nepavyko. Nustatyta, kad struktūrinius triukšmus mažinti trukdo didelės amplitudės ultragarsiniai signalai, atsispindėję nuo tarpinio sluoksnio paviršiaus. Šių signalų įtakai mažinti naudotinas skaitmeninis signalų apdorojimo algoritmas, aprašytas [17].

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