

ULTRASONIC SPECTROSCOPY BASED ON WAVELETS TRANSFORM FOR MATERIALS CHARACTERIZATION*

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In this paper, experimental results have been presented to evaluate the effect of wavelet transform (WT) filtering on ultrasonic spectral analysis. In particular we proved that applying the WT, it has been possible to compress and filtered the ultrasonic signal buried in noise, without any loss of accuracy in the time measurement. However, we make a large amount of research, including examinations of the relationship between the location, amount and amplitude of the spectral peaks and the quantificational microstructure, using classical technique and also using wavelets.

The experimental measurements presented here were obtained by the direct contact method using silicon gel as the coupling medium with the pulse-echo technique. The instrumentation consisted of a IPR-100 signal generator, an A/D-90 converter and an SMC-4 of the Physical Acoustic Corporation a sampler and a spectral analyzer.

The results have indicated the potential feasibility of the ultrasonic method and wavelets for ascertaining structural differences in austenitic stainless steel.

Key words: ultrasounds; velocity; peak attenuation; wavelets; power spectrum.

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1. INTRODUCTION

Ultrasonic methodologies are the most practically feasible NDT applications in the area of material characterization. Ultrasonic spectroscopy is the study of ultrasonic waves resolved into their Fourier frequency components. The purpose of ultrasonic spectroscopy is to determine the frequency dependent properties of materials like attenuation, velocity and TOF.

The two major parameters measured with ultrasonic spectroscopy are the attenuation and the velocity of the waves. Attenuation is determined by the energy losses in compressions and decompressions in ultrasonic waves, which include absorption and scattering contributions. Pulse-echo or through transmission techniques were employed with direct contact or immersion modes [1,2].

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After ultrasound traveled through the sample the transducer received the ultrasonic response in the time domain. A spectrum analyzer converted the ultrasonic pulse from the time domain to the frequency domain *via* Fourier transforms.

The technique performs two consecutive FFT on the ultrasonic response signal to find the fundamental resonant frequencies or spectrum resonance spacing domains. Amplitude and frequency changes in the spectrum resonance spacing domains were tested from the ultrasonic responses of the samples.

2. ULTRASONIC SPECTROSCOPY

Resonance is the result of constructive and destructive interference of stading waves into an ultrasonic medium that can be locally modeled as a sample. The fundamental resonant frequency occurs when the wavelength of the transmitted frequency is twice the thickness of the sample. The fundamental resonant frequency f_0 is determined from the relation [3]:

$$f_0 = v/2d \quad (1)$$

where v is the acoustic velocity of the material and d is the thickness of the material.

This relation (1) can be used to relate the frequency of each peak that appeared in the spectrum resonance spacing domain to locations within the sample.

In ultrasonic testing the frequency dependence of the attenuation in some materials can also be regarded as a filtering effect. The transform function of the material is used to evaluate physical and geometrical properties of the medium.

The Fourier transform $F(f)$ in the frequency domain is computed from $f(t)$ in the time domain by the direct integration of the relation:

$$F(f) = \int_{-\infty}^{+\infty} f(t) e^{-j2\pi ft} dt \quad (2)$$

The power spectrum function $G(f)$ is linked with $F(f)$ by the following relation:

$$G(f) = \frac{2}{T} |F(f)|^2 \quad (3)$$

The power spectrum shows the energy distribution in the frequency domain and highlights the main frequency in the signal [4–7].

3. WAVELET TRANSFORM (WT)

In the analysis of transient non-stationary ultrasonic signals, it is important to determine the time-frequency evolution of the signal, with as little distortion

as possible. This is commonly achieved using signal processing techniques such as the Short Time Fourier Transform (STFT), which provides accurate information about the signal simultaneously in the time domain and the frequency domain.

In the signal processing analysis (SP), the constant bandwidth property of the STFT is used to represent the ultrasonic signal in the time-frequency plane. The split spectrum method is based on the assumption that scattered echoes, which arise from multiple reflections, exhibit a different frequency distribution than true echoes from flaws. The output from the different pass band filters is analyzed by correlation techniques, such as minimization or polarity threshold algorithms, to differentiate between flaws and scattered echoes [8–10].

The Wavelet Transform (WT) is a new method of processing transient non-stationary signals simultaneously in the time domain and in the frequency domain. The WT uses scaling in the time domain to scale a single function in frequency. This function, commonly referred to as the mother wavelet, is used to extract details and information on time and frequency domains from the transient signal under analysis. This approach results in a more natural description of the signal, since the size of the window in the time domain is now a function of scaling.

The WT of a function $f(x)$ corresponds to the decomposition of $f(x)$ on the family of wavelets, $(\Psi_{a,b}(x))_{a \in \mathfrak{R}^+, b \in \mathfrak{R}}$ generated from one single function $\psi(x)$ (namely the mother wavelet) by dilatations and compressions:

$$(W_{\psi}f)(a,b) = \int_{-\infty}^{+\infty} f(x)\psi_{a,b}(x)dx \quad (4)$$

$$\psi_{a,b}(x) = a^{-\frac{1}{2}}\psi\left(\frac{x-b}{a}\right) \quad (5)$$

Of particular interest is the discretization on a dyadic grid ($a = 2^j$, $b = 2^j k$ with $(j, k) \in \mathbb{Z}^2$ for which it is possible to construct functions ψ such that the set $\psi_{j,k}(x) = 2^{-\frac{j}{2}}\psi(2^j x - k)$, $j, k \in \mathbb{Z}$ constitutes an orthonormal basis of square integrable functions over $L^2(\mathbb{R})$. On this discrete grid, the wavelet decomposition of $f(x)$ becomes

$$f(x) = \sum_{j,k=-\infty}^{\infty} c_{j,k}\psi_{j,k}(x) \quad (6)$$

where the wavelet coefficients c_{ijk} are the inner products of the signal with the wavelet basis functions

$$c_{j,k} = \langle f, \psi_{j,k} \rangle \quad (7)$$

The parameter b and a are the time and frequency, respectively, so the relation (7) can be written by replacing both parameters with the time parameter, t and frequency parameter, f .

We must specify that the mother wavelet satisfy the admissibility condition:

$$\sum_{n=-\infty}^{\infty} |c_n|^2 < \infty \quad (8)$$

The signal specific analyzing wavelet is applied to $\Psi(f, t, x)$ [11].

4. SAMPLES

The measurements were performed on two structures of austenitic stainless steel types: P5 and 16Mo3 in European Norm (EN). Their chemical composition is given in Table 1.

Table 1

	P5	16Mo3		P5	16Mo3
Fe	93.48	98.08	Ni	0.029	0.11
C	0.035	0.12	Mo	0.57	0.26
Si	0.34	0.30	Cu	0.15	0.026
Mn	0.47	0.68	Al	0.015	0.018
Cr	4.85	0.085	V	0.002	0.0018

5. EXPERIMENTAL SET-UP

The experimental measurements presented here were obtained by the direct contact method using silicon gel as the coupling medium with the pulse-echo technique [12, 13]. The instrumentation consisted of a IPR-100 signal generator, an A/D90 converter and a SMC-4 of the Physical Acoustic Corporation, a sampler and a spectral analyzer. The signals received by the transducer (echo waveforms) from the sample were sent to an oscilloscope where their amplitude and velocity (TOF) were read directly from the sampler which performs the sampling of the signals. This signal (echo waveforms) was transmitted to the spectral analyzer, where the spectrum of the concerned signal was loaded.

6. RESULTS – DISCUSSIONS

The ultrasonic waveform contains the characteristics of the ultrasound producing source as well as desirable information pertaining to the material

being tested. A Fourier Transform of the reflected signal from the distilled water was used and echo waveforms from the water and their power spectrum are shown in Fig. 1 and Fig. 2.

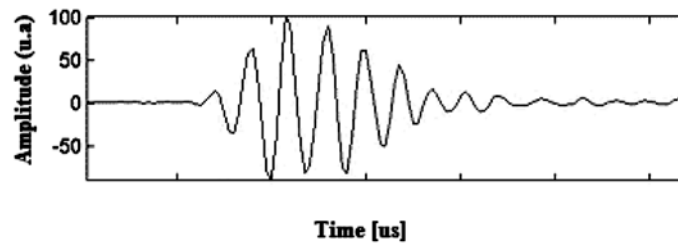


Fig. 1. – Echo waveform water.

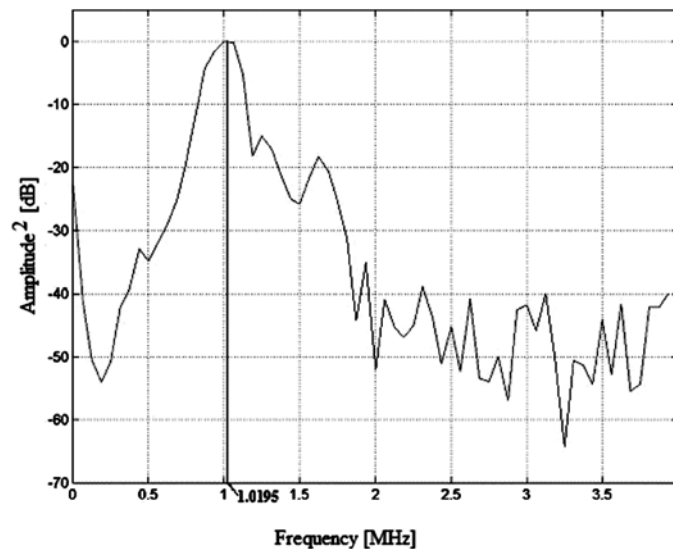


Fig. 2. – Power spectrum of echo in water.

Analyzing peak amplitude we could identify the spectral peak appeared at 1.0195 MHz in the distilled water. This spectral peak corresponds to a normalized frequency of 0.1274 MHz with a 8 MHz sampling frequency.

Amplitude and frequency changes in the spectrum resonance spacing domains were evaluated from the ultrasonic responses (echo waveforms) of the samples.

Applying FFT and WT from the frequency domain to P5 and Mo16 samples we determined typical power spectrum. Thus, in Fig. 3a it is shown the echo waveform (signal filtered with wavelets) and in Fig. 3b it is shown the power spectrum. We obtained the spectral peak at 4.33 MHz from the sample P5. In Fig. 3c there are shown the spectrum resonance spacing domains with the value $f_0 = 0.499$ MHz for the fundamental resonant frequency.

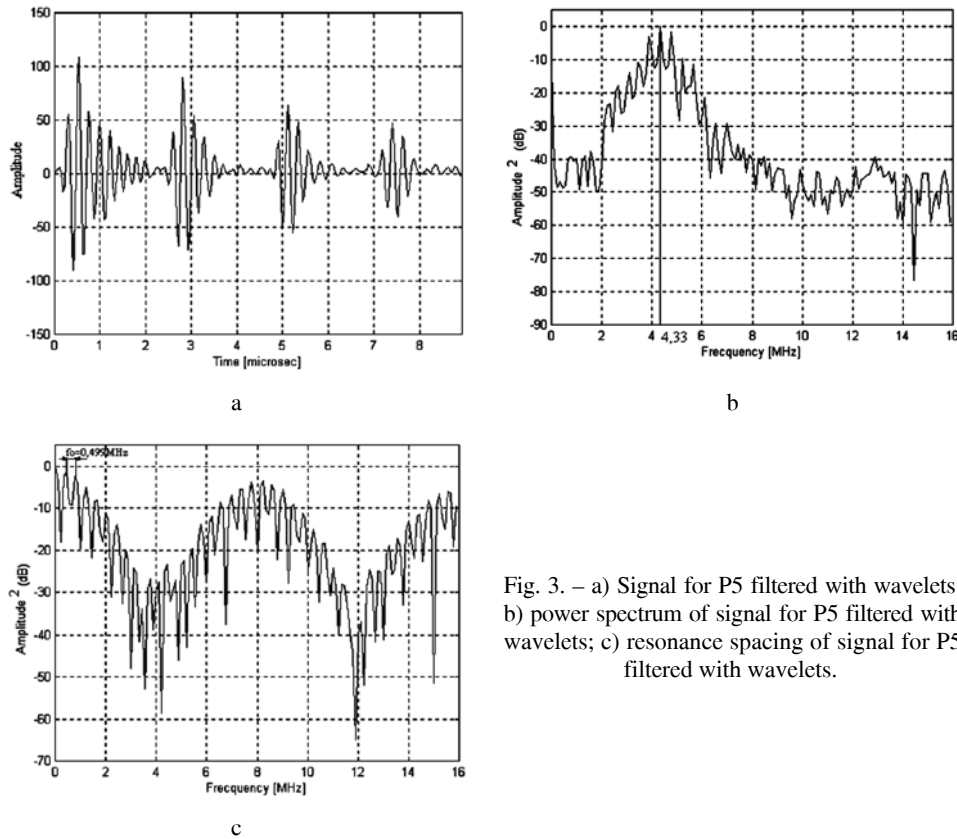


Fig. 3. – a) Signal for P5 filtered with wavelets; b) power spectrum of signal for P5 filtered with wavelets; c) resonance spacing of signal for P5 filtered with wavelets.

Under the same work condition, the results for the Mo16 sample are shown in Fig. 4 as it follows: the waveform in the time domain (signal filtered with wavelets) in Fig. 4a and in Fig. 4b the power spectrum with the spectral peak at 4.11 MHz which can also be distinguished with the frequency content of the signal compressed with the wavelet.

The spectrum resonance spacing domains are shown in Fig. 4c with the value $f_0 = 0.44$ MHz for the fundamental resonant frequency.

The use of FFT and WT in the frequency domain for the distilled water and of the two austenitic stainless steel samples allowed us to find the power spectrum and the spectral peak for each sample.

The spectral peak determined in distilled water has a value closed to the one found by [14] ($f_0 = 1.02$ MHz) which proves that the functions and methods used here are correct.

The values of the spectral peak calculated for the two samples are close enough due to the fact that the chemical composition of both samples is almost the same [15].

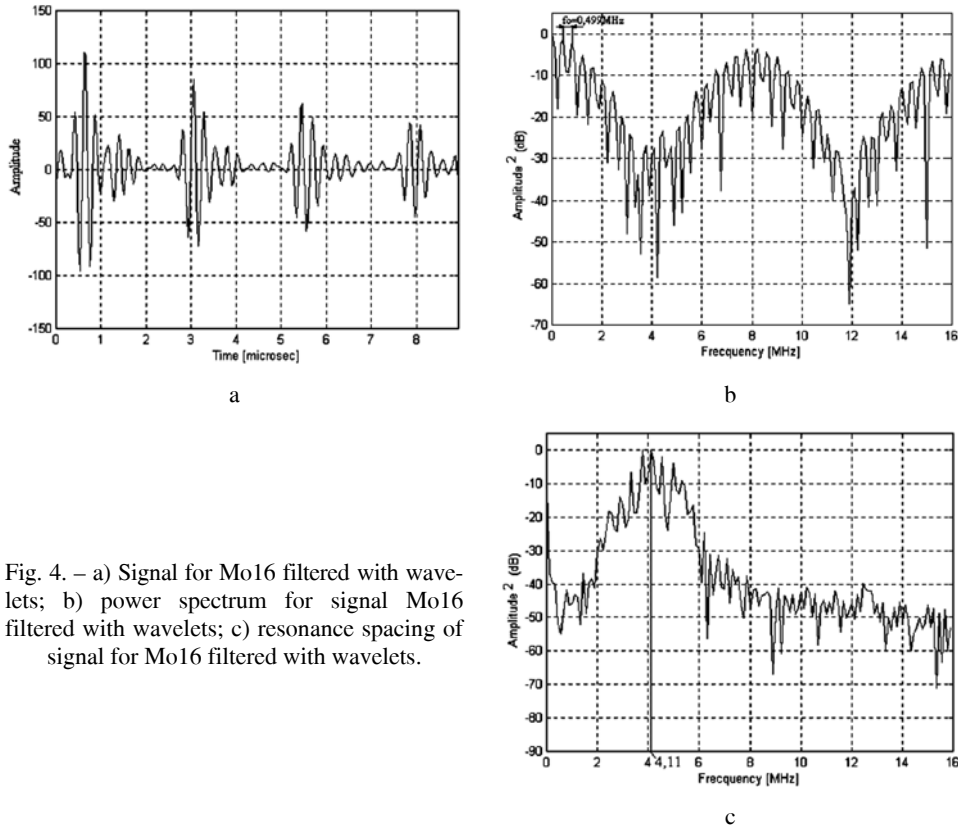


Fig. 4. – a) Signal for Mo16 filtered with wavelets; b) power spectrum for signal Mo16 filtered with wavelets; c) resonance spacing of signal for Mo16 filtered with wavelets.

Another method for the spectral analysis to confirm our results is power spectral density (PSD). This method includes both power spectral density (PSD) and spectrum resonance spacing domains (SRSD) having a higher frequency spectrum. Thus, in Fig. 5 are given the frequency values for sample P2, namely: 3.04 MHz; 3.52 MHz; 4.00 MHz; 4.32 MHz; 4.79 MHz; in this spectrum one can notice the frequency of 4.33 MHz determined by the power spectrum method (see Fig. 3b). The values obtained for SRSD are shown in the same Fig. 5 having the following values: 0.488 MHz; 0.488 MHz; 0.322 MHz and 0.488 MHz, whereas the frequency of 0.499 MHz was determined by the first method (see Fig. 3c). Amplitude values corresponding to spectrum frequencies for the same sample P5 were determined in the same time and were: 0.04 dB; 0.12 dB; 0.29 dB; 0.89 dB; 0.74 dB (see Fig. 5). By the same PSD method, for the Mo16 sample one could find a spectrum composed by 6 frequencies having the values: 3.333 MHz; 3.777 MHz; 4.111 MHz, 4.555 MHz; 5.000 MHz, 5.333 MHz; in this spectrum one can notice the frequency of 4.111 MHz, determined by the power spectrum method. The values for spectrum resonance spacing domains were:

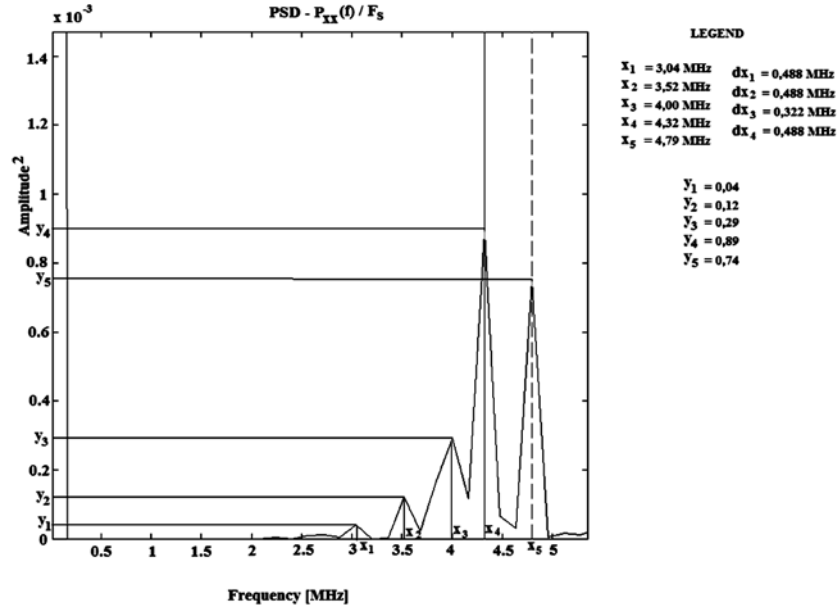


Fig. 5. – Power spectral density of signal for P5 filtered with wavelets.

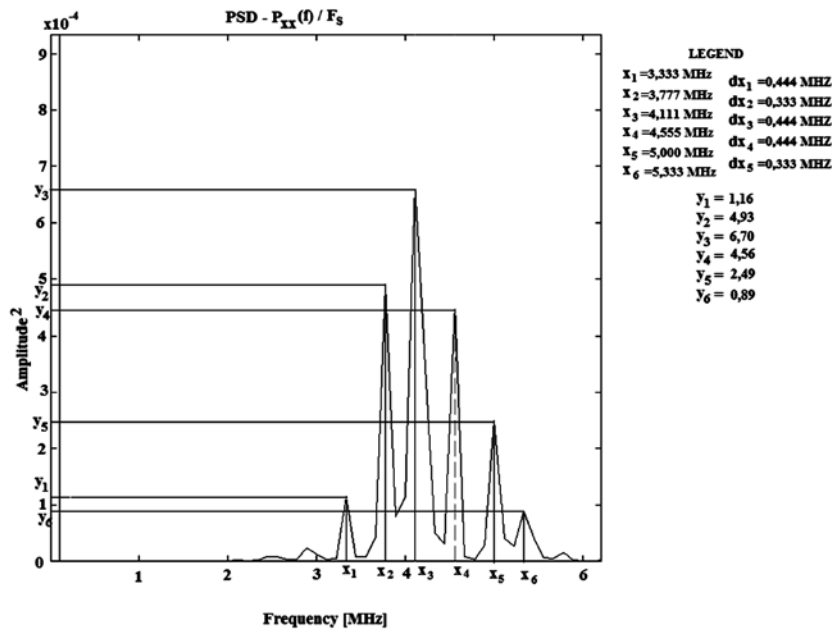


Fig. 6. – Power spectral density of signal Mo16 filtered with wavelets.

0.444 MHz; 0.333 MHz; 0.444 MHz; 0.444 MHz; 0.333 MHz whereas the frequency of 0.44 MHz was determined by the PS method (see Fig. 4c).

Amplitudes were also determined and had the values: 1.16 dB; 4.93 dB; 6.70 dB; 4.56 dB; 2.49 dB; 0.89 dB (see Fig. 6). We have calculated the thickness of the sample by applying two methods SRSD (PS) and PSD and using relation (1). The obtained values are shown in the Table 2.

Table 2

	SRSD(PS)	PSD	Micrometer
P5(mm)	6.33	6.47	6.84
Mo16(mm)	7.00	6.94	7.19

The acoustic velocities for the P5 sample and for the Mo16 sample calculated with USIS program [16] were $v = 6.320$ m/s and $v = 6.160$ m/s, respectively. The values for the thickness are comparable with the ones measured with the micrometer.

7. CONCLUSIONS

When an ultrasound propagates through a material, the frequency components of the initial signal are modified. This is shown more clearly in the frequency domain than in the time domain. In order to obtain the information in the frequency domain, FFT and WT were used. After analyzing the frequency of the reflected signals, it is possible to compare their effects on the material properties.

In this paper, we have used two methods, power spectrum (PS) and power spectral density (PSD) for the determination of the frequency values of the spectrum and the resonance spacing domains. In the same time, we have calculated the thickness of the samples by the two methods knowing the acoustic velocities of the samples.

Experimental results obtained by the second method (PSD) present more frequencies in the spectrum. SRSD (PSD) are in concordance with the one determined by the first method. The disaccord between the resonance frequencies (SRSD) the ones determined by relation (1) are due to the imprecision in measuring the sample thickness (d) with micrometer because the velocity was determined correctly with USIS program. Using both methods one can determine the resonance frequency (f_0) and then, by relation (1), knowing the propagation velocity, one can determine precisely the sample thickness even making an averaging. Therefore, we can consider that the spectral analyze gives an ultrasound "signature" which is usually specific to a type of microstructure. Thus, we can conclude that the values found by us for the two samples reflect their microstructure and composition.

REFERENCES

1. P. Petculescu, R. Ciocan, V. Bokas, "Investigation of the austenitic structures by ultrasonic spectral analysis" 7th ECNDT Copenhaga, 1998 and in Journal of Nondestructive Testing and Ultrasonic vol. 3, nr. 11, 1998 ISSN 1435-4934.
2. R. Zăgan, P. Petculescu, I. Lungu, Gh. Mihăieși, "Comparative study A – scan and wavelets analysis through ultrasonic signals", MEET 2002 First International Congress on Mechanical and Electrical Engineering and Technology and MARIND 2002, Technical University of Varna, 07–11 october 2002, Varna, Bulgaria, vol. 1, ISBN 954-20-0211-4, pp. 229–234.
3. J. and H. Krautkramer, "Ultrasonic testing of materials" Second ed. Springer-Verlag, NewYork 1977.
4. L. Cohen, *Time-Frequency Distributions: A Review – Proc. IEEE*, pp. 941–981, 1989.
5. Signal Processing User's Guide, Mathworks, (1996).
6. R. Zăgan, Contributions at optimization and identification of vibrating systems with application to the naval mechanical equipments, Ph. D. thesis, Iași, March 2000.
7. A. Abbate, J. Koay, J. Frankel, S. C. Schoeder, "Signal detection and noise suppression using a wavelet transform signal processor: application to ultrasonic flaw detection", IEEE Trans. Ultrason., Ferroelect., and Freq. Contr. Vol. 44, no. 1, pp. 14–25, 1997.
8. C. K. Chui, 1994, Wavelets: Theory, Algorithms and Applications, Academic Press, San Diego.
9. Wavelets Toolbox User's Guide, Mathworks, (1996).
10. K. Kaya, N. M. Bilgutay and R. Murthy, "Flaw detection in stainless steel samples using wavelet decomposition", Proc. 1994, Ultrasonic Symp., vol. 94CH3468-6, pp. 1271–1274.
11. P. M. Gammell, „Analogue implementation of analytic signal processing for pulse-echo systems", Ultrasonics, pp. 279–283, November 1981.
12. R. Zagan, P. Petculescu, G. Prodan, N. Peride, "Comparison between ultrasonic and wavelets analysis for characterization stainless steel alloys" Word Congress Ultrasonic Paris 2003.
13. P. Petculescu, R. Ciocan, D. Ciobanu, "Automated system and automated method by ultrasonic investigation" patent no. 118612B, RO.
14. L. Lin, X. M. Li and J. S. Zhang, „Nondestructive differentiation of three transformation products in low alloy steel using two ultrasonic methods", Material Evaluation, april 2003, pp. 512–516.
15. L. M. Cosgriff, G. Y. Baaklini, "Ultrasonic spectroscopy of composite rings for space station flywheel rotors" Materials Evaluation sept. 1013–1019, 2003.
16. R. Ciocan, P. Petculescu, D. Ciobanu, D. J. Roth, "The use of the neural networks in the recognition of the austenitic steel types", NDT&E International vol. 33, 85–89, 2000.