Time Frequency Analysis of Experimental Ultrasonic NDT Signals

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Abstract - In order to evaluate the properties of a material or detect defects / discontinuities, non-destructive testing (NDT) is carried out by the industry without damaging the original part. To extract these informations, different signal processing methods are used.The experimental ultrasonic signals considered in this paper are collected from steel plate and mortar with flaws; as well as flawless aluminum and cement paste samples prepared at the LEND laboratory of the University of Jijel in Algeria. Two experiments are realized: contact pulse-echo and immersion techniques in which ultrasonic energy is transmitted through a piezoelectric transducer. Received signals are treated by three techniques based on energy distribution in time-frequency plan; namely: Continuous Wavelet Transform (CWT), Wigner Ville (WVD) and Choi-Williams (CWD) distributions. The flight of time is easily calculated according to the energy distribution. This makes it easier to extract the positions of different echoes which allows the defect's localization and material's characterization. Advantages and limits of each method are as follows: WVD achieves good resolution of interfaces; however, its capacity remains limited by the appearance of non-desirable terms which may limit results readings. CWD avoids interferences phenomenon. It allows exactly extraction and clearly representation of signal components in time/frequency. Application of CWT clearly shows that temporal resolution is improved by contrast frequency resolution is degraded for high frequency terms. Also the disadvantage of this method comes from the absence of criterion of mother wavelet choice. Comparative study shows that CWD makes it possible to have a velocity closer to that given in theory. While the CWT and WVD give more accurate results regarding the defect's position. This justifies the use of these efficient methods for non-destructive ultrasonic testing for defect localization and material.

Keywords–Choi-Williams, NDT, Signal processing, Time-frequency, Ultrasonic, Wavelet, Wigner-Ville.

I. INTRODUCTION

Nondestructive testing (NDT) is an important method for performance control and condition monitoring. In recent years, many techniques have been proposed to perform nondestructive inspection and maintenance operations of structures.

NDT has been extensively utilized in a wide range of applications including healthcare, agriculture, defense, manufacturing, fisheries, quality control, cleaning, and many more. Its methods are quite numerous and result from the implementation of principles and physical techniques. The selection of an appropriate method is guided by the need to recognize the defects considered dangerous that the object may contain, and also depends on the structure to be examined, the conditions under which the control will be carried out, as well as the time and cost.

Different physical phenomena allow these controls by their penetrating nature in objects (electromagnetic waves, acoustic waves, magnetic field, etc.), leading to different control modes [1-4] such as radiographic testing, ultrasonic testing, electromagnetic testing, etc.

In this work, we are interested at the ultrasonic testing where the principle is based on detection and analysis of received ultrasonic waves. These latter, reflected or diffracted from flaws or boundaries, can give valuable data on its integrity. The basic structure of ultrasonic measurement system is shown in Fig. 1. In fact, waves propagating recovered by the ultrasonic sensor, allow, as far as possible, to detect and identify the defects contained in the material and/or to characterize the materials.

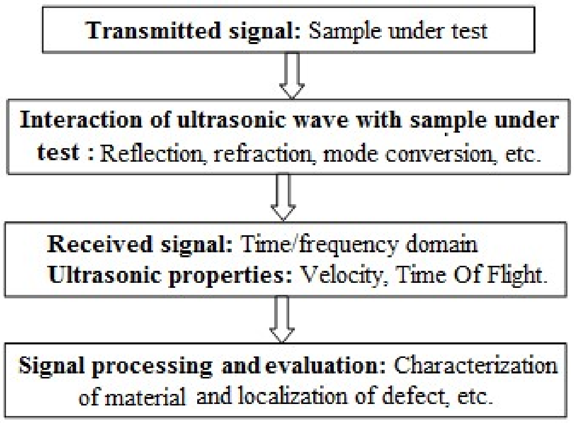


Fig. 1. Basic structure of ultrasonic measurement system.

In particular, ultrasonic techniques have shown to be very promising and privileged means of investigation in the study of the mechanical behavior of materials, as well as analysis and characterization of their mechanical properties, estimation of the size and location of defects.

Ultrasonic testing is frequently used because it makes it possible to detect shortages or discontinuities of the material in products in the rough or finished state, whatever the method of preparation thereof. In addition it has many advantages such as the ease of implementation, the ability to work on one side of the part to be controlled (no need for access to the second side), and the ability to cross large thicknesses of material depending on the working frequency.

The purpose of the user is to visualize the echoes and to deduce spatial information on the inspected object. Various signal processing techniques are available to improve the accuracy of the defect detection and characterization in ultrasonic testing. These can be categorized as cross-correlation, Hilbert transform (HT), autoregressive analysis, split spectrum processing (SSP), Short- Time Fourier Transform (STFT), Wigner-Ville Distribution (WVD), wavelet transform (WT), Hilbert–Huang Transform (HHT), Empirical Mode Decomposition (EMD) and some of its extensions, etc. There are a few merits and limitations associated with each of the mentioned signal processing methods [5-26].

In this research, the emphasis was focused on Cohen's Class Distribution [9-18]. They are applied on the experimentally obtained data in order to improve defect analysis. Signals were obtained using a pulse-echo technique and processed in Matlab environment. The reflected signals are received by the same transducer where the energy is converted into an electrical signal. The image collected may show the relative thickness (depth) or defects [1-4].

The remainder of this paper is organized as follows: the selected time-frequency techniques are presented in Section II. Experimental measurement systems are described in Section III. Results and discussion are expressed in Section IV. Conclusions are given in Section V highlighting the main advantages and disadvantages of each considered method.

II. TIME-FREQUENCY METHODS

A) Wigner Ville Distribution (WVD)

The square of the Fourier transform is called power spectrum. It characterizes the energy distribution of a signal in the frequency field. One also uses the square of the transform of short-term Fourier (spectrogram) to describe the energy distribution of a signal in the time-frequency field [11]. The resolution of the spectrogram depends on the selection of the analyzed function. To overcome these problems, Wigner Ville Distribution (WVD) was proposed [12]. The WVD provides time-frequency decomposition without any restriction on temporal and frequency resolutions. It appears perfectly suited to the analysis of non stationary signals. It is given by

$$WVD_x(t,f) = \int_{-\infty}^{+\infty} x\left(t+\frac{\tau}{2}\right) x^*\left(t-\frac{\tau}{2}\right) e^{-j2\pi f\tau}\, dt \quad (1)$$

The WVD plays an important role in the theory and the practice of the time/frequency analysis. In our work, one will seek the temporal positions of maxima of the WVD which indicate the positions of the echoes in order to characterize and/or detect the defect in specimens. Furthermore, to allow an implementation on the current computers, it is necessary to define versions in discrete time, discrete frequency or even in both.

Unfortunately, the non-linearity of this transform has disastrous consequences manifested by the appearance of interference and negative energies in the time-frequency distribution of the signal energy [13].

B) Choi-Williams Distribution (CWD)

The CWD was first proposed by H.I. Choi and J. Williams in 1989[18]. It is a transformation that represents the spectral content of the non-stationary signal as a two-dimensional time-frequency map. It largely avoids one of the main problems of the WVD: the presence of interference limits in areas where one would expect values of zero power. CWD employs an exponential grain in the generalized class of time-frequency bilinear distributions to achieve a reduction in cross-boundary components of the distribution.

The mathematical representation of the CWD is given by the following equations [18]

$$CWD_x(t,f) = \iint_{-\omega}^{\omega} A_x(\eta,\tau)\Phi(\eta,\tau)\exp\big(2j\pi(\eta.t-\tau.f)\big)\,d\eta d\tau \quad (3)$$

$$A_x(\eta,\tau) = \int_{-\omega}^{\omega} z(t+\tau).z^{*}t-\tau)\exp\,(-2j\pi t\eta)dt \quad (4)$$

$$\Phi(\eta,\tau) = exp[-\alpha(\eta\tau)^2] \quad (5)$$

$\Phi_x(\eta,\tau)$ is the kernel function which is usually a low-pass function. Choi and Williams have shown that there is a trade-off between the auto term resolution and the cross-term suppression.

The main objective to minimize the interferences terms results in choosing a kernel function which depends with the type of analyzed signal to make it smooth. Smoothing time-frequency have to include very few samples on the frequency axis and many on the temporal axis in order to estimate the reasons for signal as well as possible. Indeed, in the case of real signals, the reasons time frequency are often varied and it is difficult, to find optimal characteristics of the core allowing to insulate, at the same time of the pure frequencies and the pulses [15-18].

C) Continuous Wavelet Transform (CWT)

General expression of the CWT is given by:

$$T_x(a,b) = \frac{1}{\sqrt{a}}\int_R x(t)\Psi^{*}\left(\frac{t-b}{a}\right)dt \quad (6)$$

$|T_x(a,b)|^2$ represents the scalogram [15].

The CWT is a multi-resolution representation of a signal. It has become a very powerful tool for filtering the signal, and also, it allows to locate and detect the main components of the signal.

The CWT is a plot on which the abscissa axis represents the temporal variations and the ordinate axis those of the scale (inversely proportional to the frequency). The pronounced color at each point (x, y) represents the importance of the amplitude of the coefficients. Thus, we obtain the coefficients produced at different scales for different sections of the analyzed signal. The contours provide a very clear frequency-temporal representation.

We apply the CWT on measured ultrasonic signals, with a choice of an analysis wavelet and an adapted scaling factor. This adaptation is done by calculating the most powerful coefficients, ie classification of the local maxima.

$$Echo_i = Max(C_i) \quad (7)$$

Once we find the high coefficients, we can deduce the temporal positions corresponding to each echo which composes the ultrasonic wave. This knowledge facilitates the characterization, detection and/or localization of defects by calculating the time of flight [20].

III. EXPERIMENTAL INVESTIGATION

We have realized two experiments based on the pulse-echo transmission. The transducer emits an ultrasonic wave at a normal incidence on the face of the sample so that the received echoes are longitudinal waves.

A) Description of experiment 01

This experiment is based on pulse-echo immersion technique. The measurement system, illustrated inFig.2, consists of a vessel with the sample holder and immersion transducers of 0.5 MHz, 1 MHz and 2.25 MHz. The emitted (or received) pulses are generated by an ultrasonic transmitter/receiver (Panametrics 5077PR, 606V) connected with a digital oscilloscope (Tektronics TDS 1002). The latter is connected to a computer menu of data acquisition software (WaveStar).

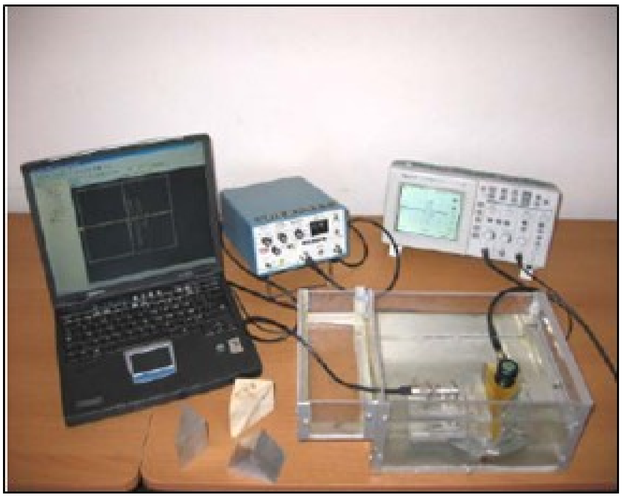


Fig. 2. Measurement device of immersion technique.

Experimental signals analyzed in this paper are collected from three material samples, namely: Aluminum (2017A) without defects (signal 01) realized as a cube of (6x6) cm placed at 4 cm from the transducer; Paste cement without defects (signal 02), realized as a prism of thickness$d_2 = 2.5\ cm$, lenght $L_2 = 6\ cm$ and height $H_2 = 7.5\ cm$; Mortar material with asynthetic defect (signal 03), with $d_3 = 2.8\ cm$, $L_3 = 6.5\ cm$ and $H_3 = 7.5\ cm$. The sampling time is $T_e = 4.10^{-8}\ s$.

B) Description of experiment 02

This experiment is based on pulse-echo contact technique. The transducer is directly placed on the part to be controlled and the acoustic connection is provided by a special gel. The piece under test is a steel plate of dimension *(1x5)cm* with a defect inserted at the depth of *0.5cm*. The measurement system (Fig.3) is the same as that of experiment 01 except that the transducer has a contact of *2.25MHz* placed directly on the part to be controlled.

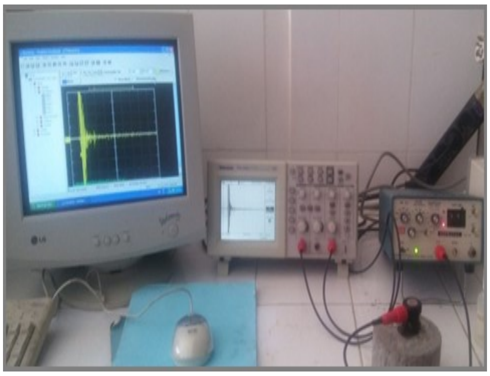
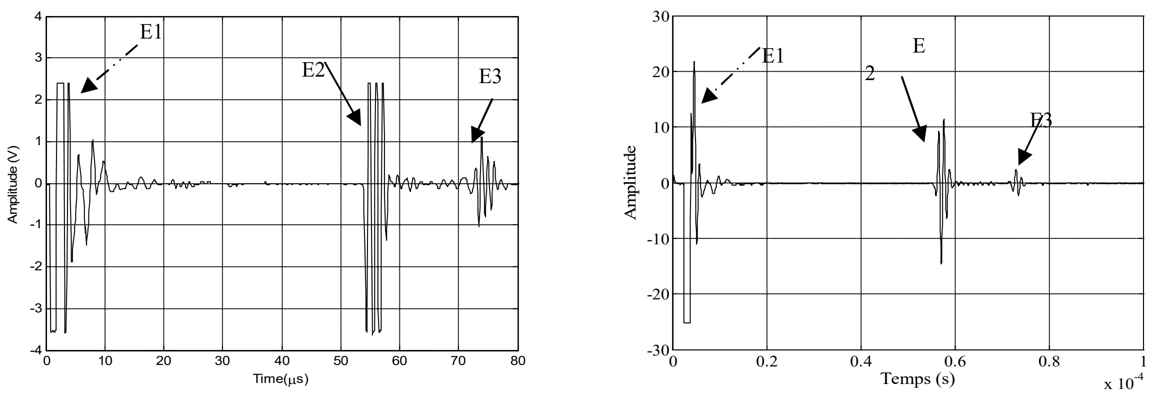
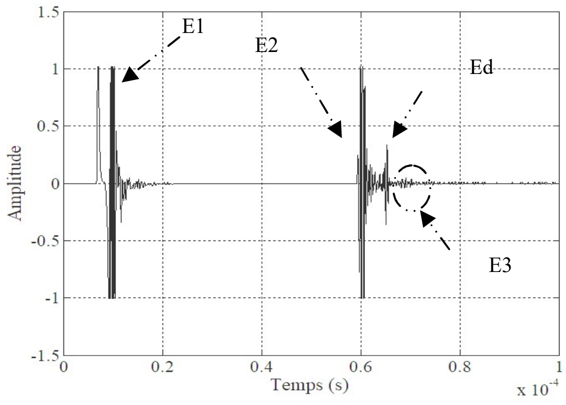


Fig. 3. Measurement device of contact technique.

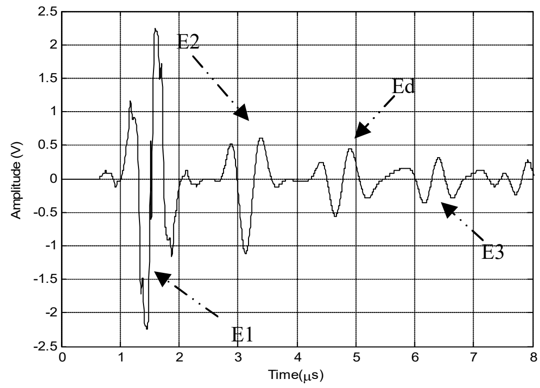
On the reflected signals, Fig. 4, appeared echoes are respectively: emitted signal (E1), front echo (E2), depth echo (E3) and defect echo (Ed). It’s possible to determine the propagation velocity in the material if it is unknown. It has checked on this case and found the propagation velocities in different mediums.



(a) (b)



(c)



(d)

Fig. 4. Emitted and received signals from samples of : (a) aluminum; (b) Cement paste; (c) Mortar and (d) Steel.

IV. RESULTS AND DISCUSSION

A) Characterization of the materials

The equation used to calculate the propagation velocity, v, in a specific medium and the sample thickness (e_p) is based on the time of flight: $\boldsymbol{T_v = 2.e_p/v}$.

From Fig. 4, we can read positions of different interfaces.

The second peak is offset from the first by:$t_{v0} = (56 - 1.9) \times 10^{-6} = 54.1\mu s$.

The third peak is offset from the second by:$\boldsymbol{t_{v2} = (73.9 - 56) \times 10^{-6} = 17.9\mu s}$.

Thus we obtain two interfaces situated respectively at the distances $e_{p1} = (v_1 \times t_{v1})/2 = 4.0034\ cmande_{p2} = (v_2 \times t_{v2})/2 = 5.9965\ cm$so the first peak represents the first face of the sample.

The calculation results confirm that the material is of 5.99 cm thick placed at a distance of 4.00 cm from the transducer. In addition, it contains no defects.

If the longitudinal propagation velocities were unknown, we can calculate them as follows:

The longitudinal wave propagates in the water between the transducer and the first interface of the sample for a time $t_1$with: $v_1 = \frac{2d_1}{t_1}$; d_1 the distance between the transducer and the first face of the sample.

The velocity in aluminum can be calculated by the relation: $\mathrm{v_2} = \frac{2\mathrm{d_2}}{\mathrm{t_2}}$ with $\mathrm{d_2}$ the distance separating the two faces of the specimen.

From Fig. 4, we can read: $t_1 = 54.1$ μs, and $t_2 = 17.9$ μs and knowing that : $d_1 = 4$ cm and $d_2 = 6$ cm, we can deduce the propagation velocities of the longitudinal wave in water and in aluminium respectively equal to: $v_0 = 1478.74\ m/s$ and $v_1 = 6703.91\ m/s$.

The same procedure is followed for all the measured signals when using different methods.The results are gathered in Table 1.

B) Interpretation of results

Results are illustrated by Fig. 5 to 16. The objective is to compare the performances of the considered techniques applied on the two samples of materials.

We applied in the first, the Wigner Ville distribution on the real ultrasound signals in order to detect and locate the exact position of the echoes. The problem of attenuation is quite clear in this application. Indeed, the visualization of the emitted pulse, having a great power, will not allow the detection of other bottom echoes or defects. To remedy this problem, only the backscattered echoes are traced in the appropriate scale.

Figures 5 to 8 show that the Wigner Ville distribution is an effective tool for the time-frequency analysis, because it has a good joint resolution. Thus it enables to locate the time-frequency positions of each echo. Unfortunately, one notices clearly the appearance of interferences which can harm the legibility of the time-frequency. Also, they are responsible with the false readings for the results.

A solution to avoid these problems would be to apply the Choi-William distribution and the wavelet transform.

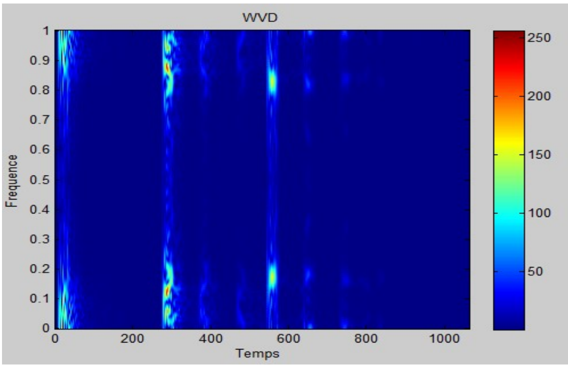


Fig. 5. Analysis of Signal 01 by **WVD**

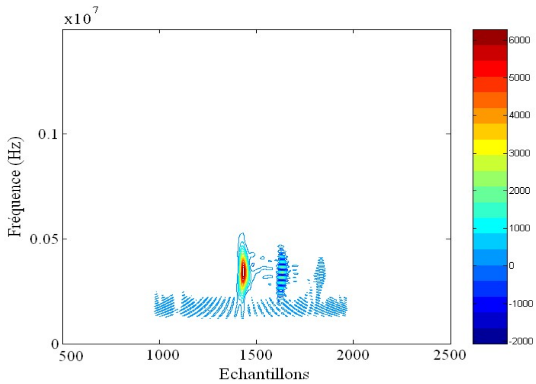


Fig. 6. Analysis of Signal 02 by **WVD**

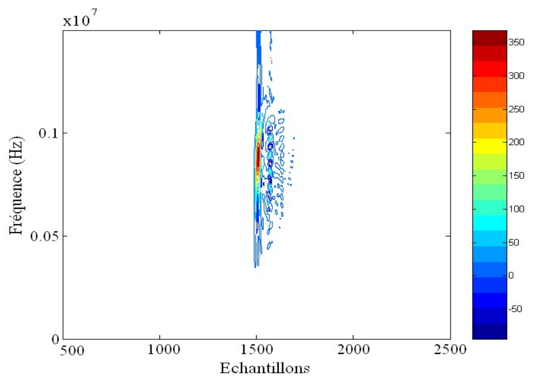


Fig. 7. Analysis of Signal 03 by **WVD**

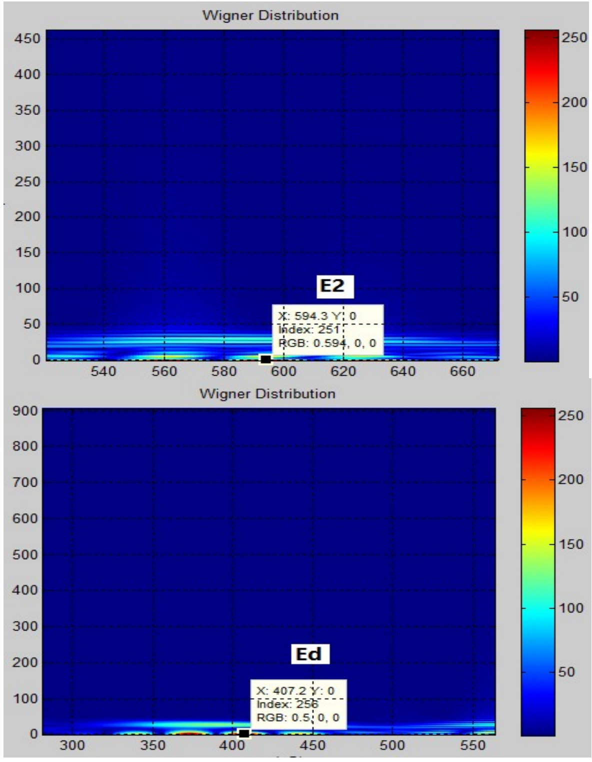


Fig. 8. Analysis of *Signal 04* by **WVD**

The results obtained when applying Choi-Williams distribution are presented on Fig. 9 to12. We notice that the echoes of the external and internal faces appear clearly. We show by this the effectiveness of this method for ultrasonic signals, and give an advantage of eliminating all additional echoes and keeping only the range likely to contain the desired echo.Therefore, we can say that it provides a solution to the problem of detecting defects drowned in noise.

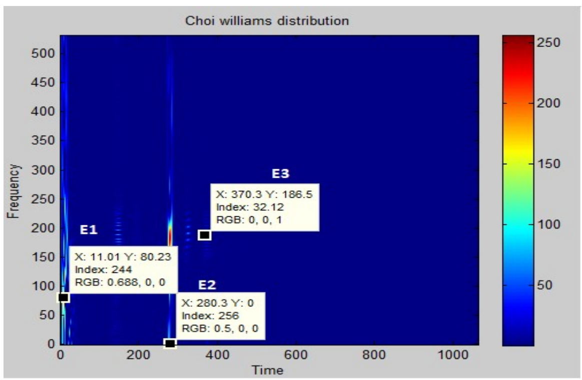


Fig. 9. Analysis of Signal 01by **CWD**

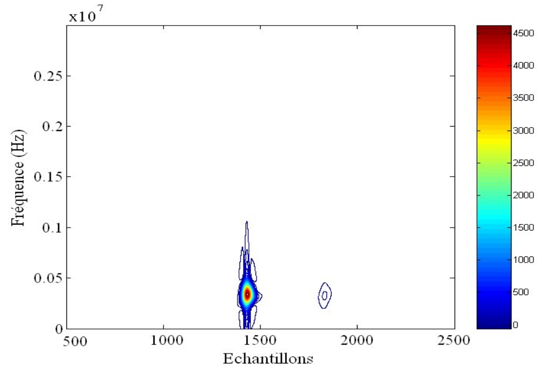


Fig. 10. Analysis of Signal 02by **CWD**

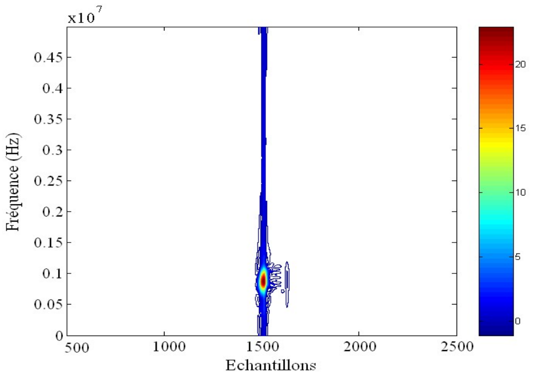


Fig. 11. Analysis of *Signal 03* by **CWD**

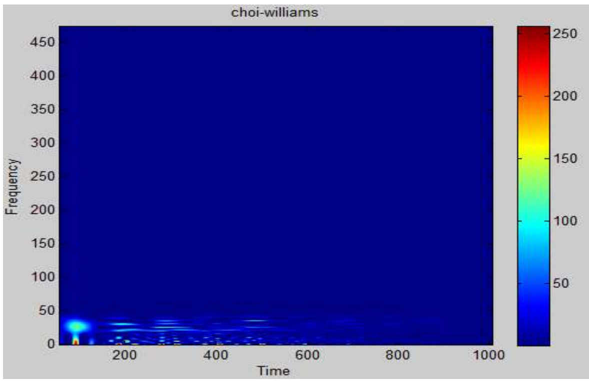


Fig. 12. Analysis of *Signal 04* by **CWD.**

Fig.13 to 16 illustrate the good performances of CWT. In fact, we apply the wavelets with a judicious choice of the mother wavelet and the scale coefficient. The results obtained proved that the wavelet coefficients calculated by the wavelet family 'db4', 'Haar' and 'Meyer' are better than the other families for analyzing Signals 01 and 02. However, 'Morlet' and 'Meyer' give good results for analyzing Signals 03 and 04.

The scalogram allows us to detect the temporal and frequency positions of the echoes in each signal.

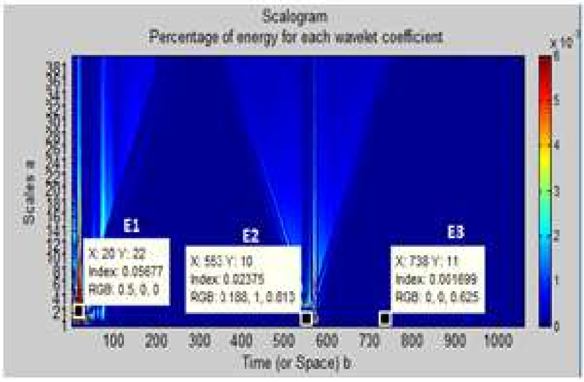


Fig. 13. Analysis of Signal 01 by **CWT**

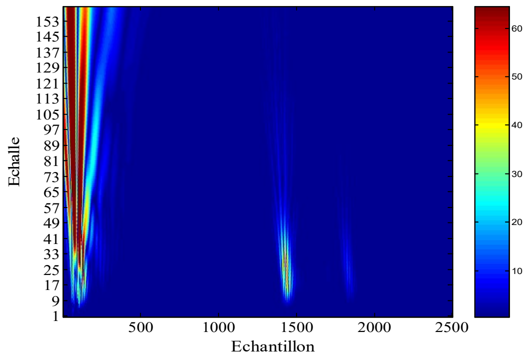


Fig. 14. Analysis of Signal 02 by **CWT**

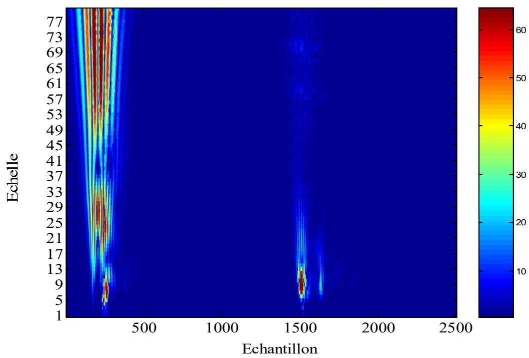


Fig. 15. Analysis of Signal 03 by **CWT**

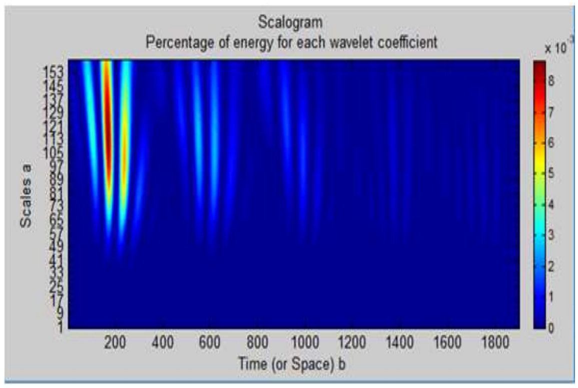


Fig. 16. Analysis of Signal 04 by **CWT**

When calculating the longitudinal velocities using the different methods, we note according to the Figures that each technique showed its capacity to locate the time-frequency positions of each interface. Numerical results are summarized in table 1.

For the first experiment, CWT give relatively good measures for the characterization (velocity mesurement) and defect localization.

For the second experiment, CWD is much better than WVD and CWT for the characterization (velocity mesurement).

This justifies the use of these efficient methods for non-destructive ultrasonic testing.

Young's modulus determination E

It is known that: $E = {V_l}^2 . \rho$.

Theoretically: ρ = 7.85 g/cm³ for steel; ρ = 2.70 g/cm³ for aluminum and ρ =2.16 g/cm³ for mortar, we obtain results in Table 2.

Table 1. Calculation of velocities and position of defects for different samples

Signals Methods	WVD	CWD	CWT	Theoritical
Signal 01 " Aluminum "				
T.E2 (μs)	55.4	56	55.3	-
T.E3 (μs)	74 .3	74	73.8	-
Tv (μs)	18. 9	18	18.50	-
Velocity (m/s)	6350	**6666**	6486	6700
Signal 02 " Paste Cement "				
T.E2 (s)	$37.32\ 10^{-4}$	$37.36\ 10^{-4}$	$57.68\ 10^{-4}$	-
T.E3 (s)	$53.04\ 10^{-4}$	$53.32\ 10^{-4}$	$72.96\ 10^{-4}$	-
Tv (s)	$15.72\ 10^{-4}$	$15.96\ 10^{-4}$	$15.28\ 10^{-4}$	-
Velocity (m/s)	3180.66	3132.83	3272.25	-
Signal 03 " Mortar "				
T.E2 (s)	$40.40\ 10^{-4}$	$40.40\ 10^{-4}$	$60.52\ 10^{-4}$	-
T.Ed (s)	$45.32\ 10^{-4}$	$45.28\ 10^{-4}$	$65.44\ 10^{-4}$	-
Tv (s)	$4.92\ 10^{-4}$	$4.88\ 10^{-4}$	$4.92\ 10^{-4}$	-
Defect (cm)	**0.97**	**0.97**	**0.97**	1
Velocity (m/s)	**4065**	4098.36	**4065**	3960
Signal 04 " Steel "				
T.E2 (μs)	3.05	2.76	3.05	-
T.Ed (μs)	4.77	4.27	4.71	-
Tv (μs)	1.72	1.51	1.66	-
Defect (cm)	**0.51**	0.45	**0.49**	0.5
Velocity (m/s)	5814	6622	**6025**	5950

Table 2. Young modulus in GPa determined by different methods

	Aluminum	*Mortar*	*Steel*
Theoritical	121.20	33.87	277.91
WVD	108.87	**35.69**	265.35
CWD	**119.98**	36.28	344.23
CWT	113.58	**35.69**	**284.96**

V. CONCLUSION

In this paper, pulse-echo technique has been used to characterize materials. Acomparative study of different methods used for material characterization and defects localization via ultrasonic NDT, was carried out inside the class of Cohen and wavelet. We used three tools of signal processing: Wigner Ville distribution, Choi-Williams distribution and Wavelet.

Four specimens were considered: a steel plate (with crack in the middle), a mortar sample with defect, paste cement sample and and an aluminum samples (without defect). Longitudinal wave velocities were determined from timeof flight calculations in the specimens.

The simulation results showed advantages and limits of each method. In fact, the implementation of the WVD is adequate to achieve good resolution of interfaces. However, its capacity remains limited by the appearance of interferences which can harm the legibility of the representation time- frequency. The CWD allowed the exactly extraction and clearly representation of the various components of the signal in time and frequency. Finally, compared to the Wigner Distribution Function, the Cohen's class distribution may avoid the cross term. The application of CWT performs the localization of the defect especially when making judicious choice of the analysis wavelet and the scale factor.

We can conclude that CWD and CWT are approved for their superiorities in the detection and localization of echoes and the exact calculation of propagation velocities.

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