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Spectral Analysis of Experimental Ultrasonic NDT Signals

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Abstract: Non Destructive Testing (NDT) plays an important role in different fields. It allows materials control or structures to check their condition, as well as detect defects without damaging inspected parts. The practical difficulty of extracting information to characterize materials led to use different methods of signal processing. Real ultrasonic signals considered in this paper are collected from Steel plate with defect and Aluminum cubic sample without defects prepared in LEND laboratory of Jijel University in Algeria. Two experiments are used: pulse-echo by contact and immersion techniques wherein ultrasonic energy is transmitted by piezoelectric transducer. The reflected signals are received by the same transducer where the energy is converted into an electrical signal. Signals are treated by three techniques adapted for nonstationary signals, and based on energy distribution in time-frequency plan; namely: Continuous Wavelet Transform (CWT), Wigner Ville (WVD) and Choi-Williams (CWD) distributions. This energy distribution allows an easy flight of time's measurement of different echoes, and thereafter velocity's calculation and defect's localization. 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 characterization (Velocity and Young's modulus).

Keywords: Ultrasonic, NDT, Wigner-Ville, Choi-Williams, Wavelet

Introduction

Non-destructive testing (NDT) has become a field of continuous growth. It plays a very important role in various fields, particularly in the pipeline and storage industry, especially in the oil and gas, nuclear, automotive and aeronautics sectors. NDT groups together a set of methods whose general purpose is to control a material without modifying it, either during production or during maintenance. They can be classified according to the physical phenomena involved: acoustic, radiation, material flow or electromagnetic fields. The choice of a method depends on the structure to be examined, the conditions under which the control will be carried out, as well as the time and cost constraints.

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In this work, we are interested in the ultrasound control method, in which ultrasound waves are emitted in the material to be examined. The waves propagate in the medium and retrieved by a receiver allowing in the possible, to identify the defects contained in the material and thus determine nature of material and/or sample size. The same method can be applied to characterize it, ie to estimate the physical parameters proper. Ultrasonic testing is frequently used because 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. In addition, the existence of relationships between the ultrasonic propagation material and the characteristics of the material allows its characterization. Signal processing is the discipline that develops and studies signal analysis techniques (Malik & Saniie, 1996), (Dib, Djerfi, Merdjana, & Bouden, 2017). In this paper, we focus on the separation of near echoes and the localization of ultrasound echoes. This analysis will be done using some signal processing methods based on energy distribution in Time-Frequency plan, namely: WVD, CWD and CWT and test their feasibility on experimental ultrasonic signals.

The remainder of this paper is organized as follows: the selected time-frequency techniques which can be applied to ultrasonic NDT of materials are first presented. Then results and discussion are expressed. The paper is closed by conclusions highlighting the main advantages and disadvantages of each considered method.

Time-frequency methods

Wigner Ville Distribution (WVD)

The WVD is a method of describing the energy distribution of a signal in the time-frequency plan. It provides time-frequency decomposition without any restriction on temporal and frequency resolutions. It appears perfectly suited to the analysis of nonstationary signals. The DWV is defined as

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

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. In practice, a smoothed version of the DVW is often preferred. It is named the Wigner-Ville Smoothed distribution and is defined by

$$WVD_{x}(t,f) = \int_{-\infty}^{+\infty} p(t)x\left(t+\frac{t}{2}\right)x^{*}\left(t-\frac{t}{2}\right)e^{-j2\pi f x}\,dt \tag{2}$$

where *p (t)* is the smoothing window that reduces the amplitude of the interference terms (Gaohui, Jun, Dezhi, Huasong, Wulan, & Yan, 2008).
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 locate the defect in specimens.

Choi-Williams Distribution (CWD)

The CWD was first proposed by H.I. Choi and J. Williams in 1989. It is a transformation that represents the spectral content of the nonstationary 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 (Choi & Williams, 1989).
The mathematical representation of the CWD is given by the following equations

$$CWD_{x}(t,f) = \iint_{-\omega}^{\omega} A_{x}(\eta,\tau)\Phi(\eta,\tau)\exp\left(2j\pi(\eta.t-\tau.f)\right)d\eta d\tau \tag{3}$$

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

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

$\Phi_{x}(\eta,\tau)$ 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 will 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 which allowing to insulate, at the same time of the pure frequencies and the impulses (Djerfi, 2017).

Continuous Wavelet Transform (CWT)

General expression of the CWT is given by

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

$|T_x(a,b)|^2$ represents the scalogram of $x(t)$ (Ding, 2007).

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 (locate defect and characterize material in our case).

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 .

$$Echo_i = Max(C_i) \tag{7}$$

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 (Djerfi, 2017).

Results and Discussion

Experimental signals analyzed in this paper are collected from samples of Steel with a defect (*signal 01*) and Alluminum without defects (*signal 02*) prepared in the NDT laboratory of Jijel University in Algeria. The main objective is to detect reflected echoes from different interfaces (E1: face-echo, E2: defect-echo and E3: Depth-echo) and improve their visibility. Thus, we have to calculate the velocity of propagation in the Alluminum (the thickness of the piece is $e_p = 6\ cm$) and detect the defect in the Steel ($v_2 = 6082\ m/s$)). The equation used to calculate the propagation velocity and the defect thickness is based on the knowledge of time of flight:
$T_v = 2.e_p/v$.

Experiment 1

This experiment is based on pulse-echo contact technique. The transducer is placed directly on the part to be controlled and the acoustic connection is ensured by a special gel. The piece under test is a steel plate of dimension (1x5) cm with a defect inserted at the depth of 0.5 cm. The defect is an empty crack or internal porosity. This experiment requires only one transducer to emit the ultrasonic signal and receive the echoes of the interfaces.

The measurement system consists essentially of a contact transducer of 2.25 MHz placed directly on the part to be controlled; it represents the generating source of the ultrasonic wave beam. It allows the transmission and reception of pulses. The pulses emitted (received) by the transducer are generated by an ultrasonic transmitter / receiver (Panametrics 5077PR, 606V) connected with a digital oscilloscope (Tektronics TDS 1002) to visualize echoes (ultrasound waves) emitted and reflected which is connected to a computer with data acquisition software (WaveStar) in turn, Figure 1(a). Notice that velocity in steel is equal to 5950 m/s.

Experiment 2

The experiment is based on the pulse echo by immersion technique. It consists essentially of a vessel comprising the sample holder. It includes the same devices as illustrated in Figure 1(b). The transducer works at 1MHz. We use a sample of Aluminum (2017A) realized as a cube of (6x6) cm placed at 4 cm from the transducer. Notice that velocity in alluminum is 6700 m/s and in water is 1480 m/s.

During the two experiments, the ultrasonic waves undergo a normal incidence. Indeed, they fall vertically on the face of the sample so that the echoes received are longitudinal waves. (Bouden, Nibouche, Djerfi , & Dib, 2012) (Dib, Djerfi, Merdjana, & Bouden, 2017).

Figure 2 shows the two received signals. In the Signal 01 providing from the steel plate, the first peak represents the first face of the sample (E1); the following echoes are peaks that represent the interior of the material : the defect echo (Ed) and the bottom echo (E2). In Signal 02, provided from the alluminum sample, the first peak represents the emitted signal; appeared echoes are consecutively face-echo (Face.E) and depth-echo (Depth. E). 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 velocity in water, aluminium and steel.

(a) (b)

Figure 1. General view of measurement systems: (a) Experiment 1 and (b) Experiment 2

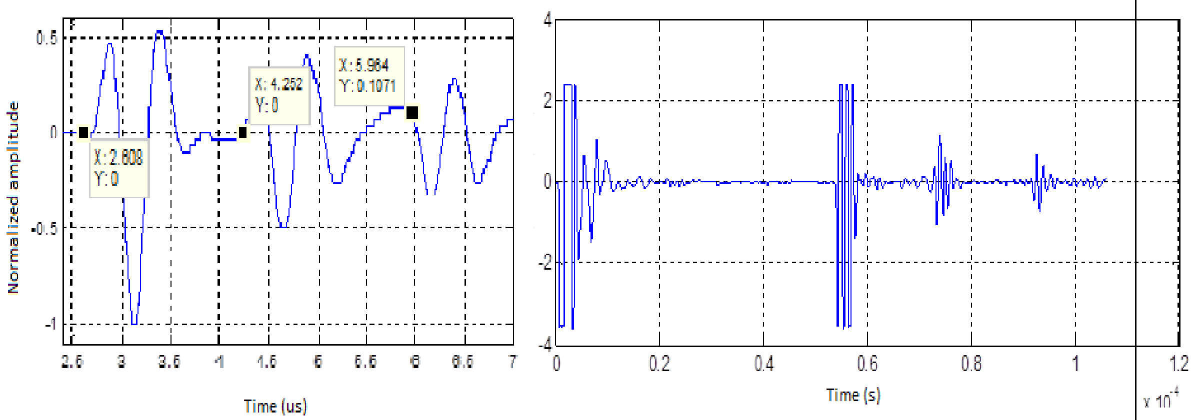


Figure 2. Signal 01 'Real data from the steel plate' at the left and Signal 02 'Real data from the Alluminum sample' at the right

Results are illustrated by Figures 3 to 9. The objective is to compare the performances of the considered techniques applied on the two samples of materials.Figures 3 and 7 show that WVD has a good joint resolution and thus enable 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 representation.

The results obtained when applying Choi-Williams distribution are presented on Figures 4 and 8. 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. Therefore, one can say that it brings a solution to the problem of defects localization.

Figures 5, 6 and 9 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 Signal 01. However, 'Morlet' and 'Meyer' give good results for analyzing Signal 01.

The scalogram allows us to detect the temporal and frequency positions of the echoes in each signal. So CWT has demonstrated its ability to locate defects, since it acts as a "microscope" with which we can observe different parts of the signal.

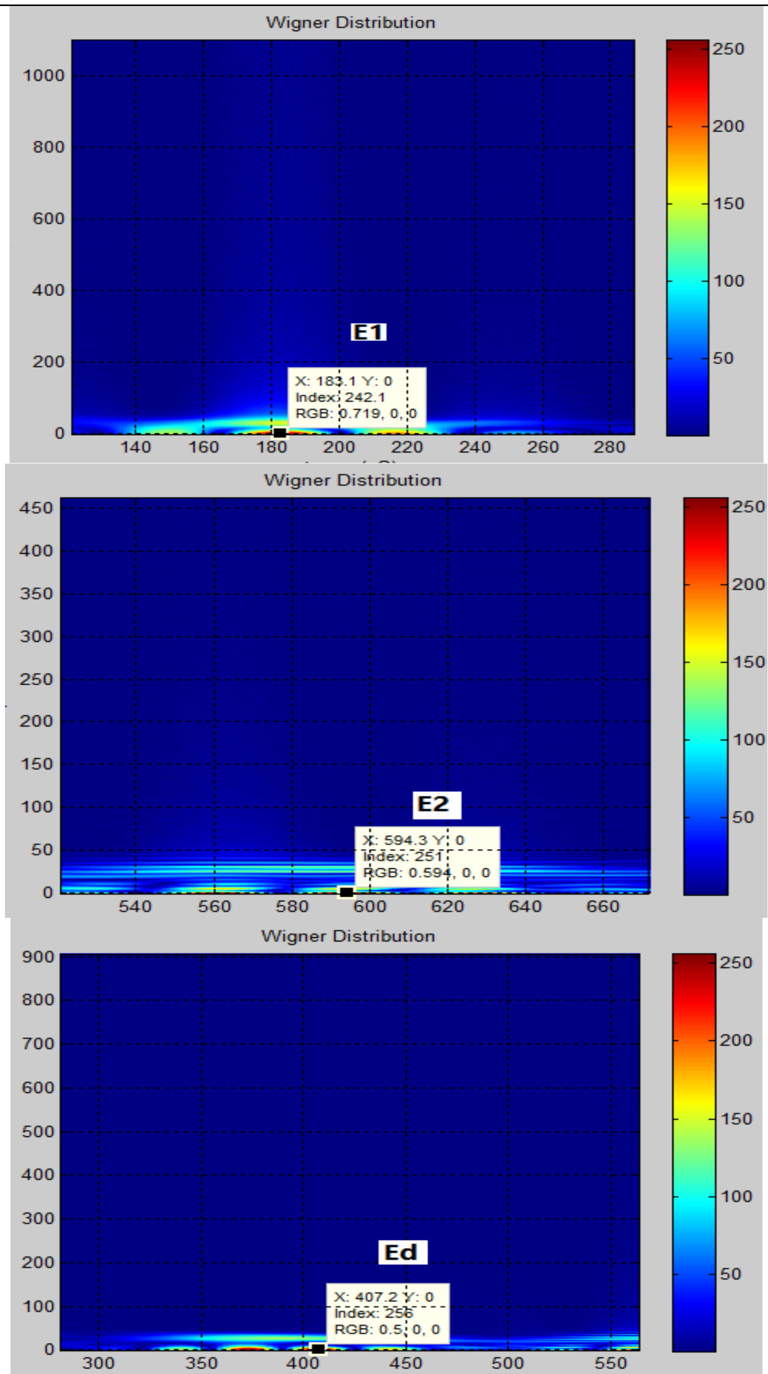
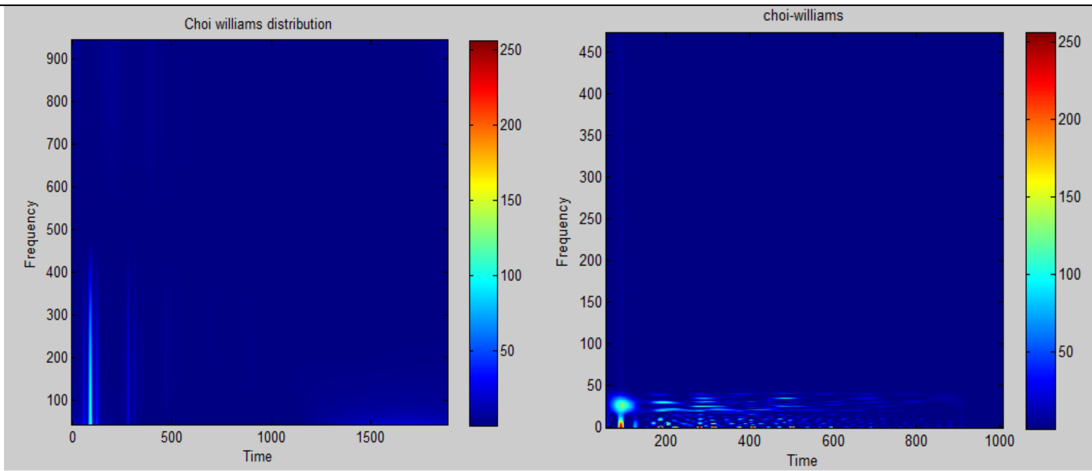
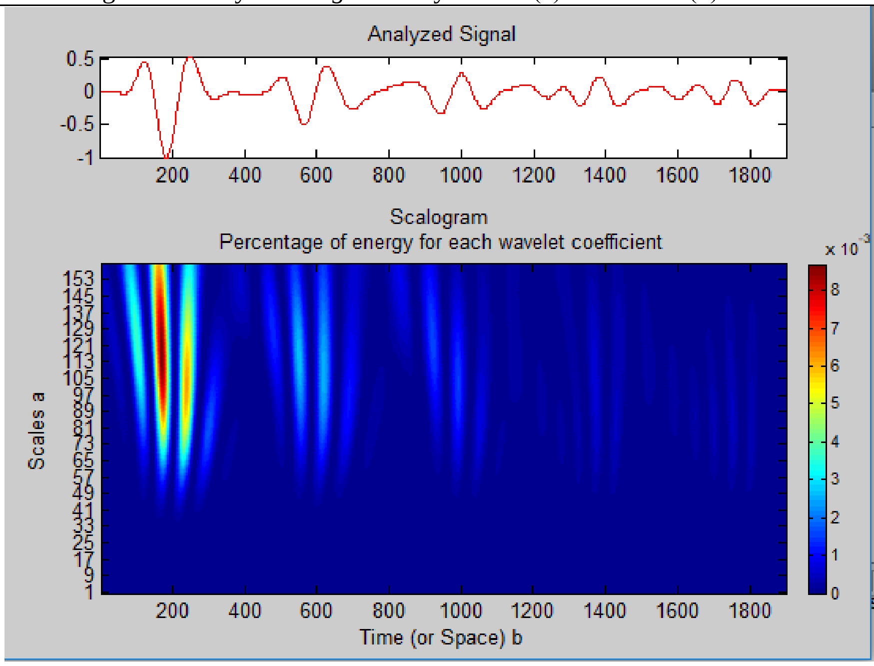


Figure 3. Analysis of *Signal 01* by **WVD** (Separation of the echoes)

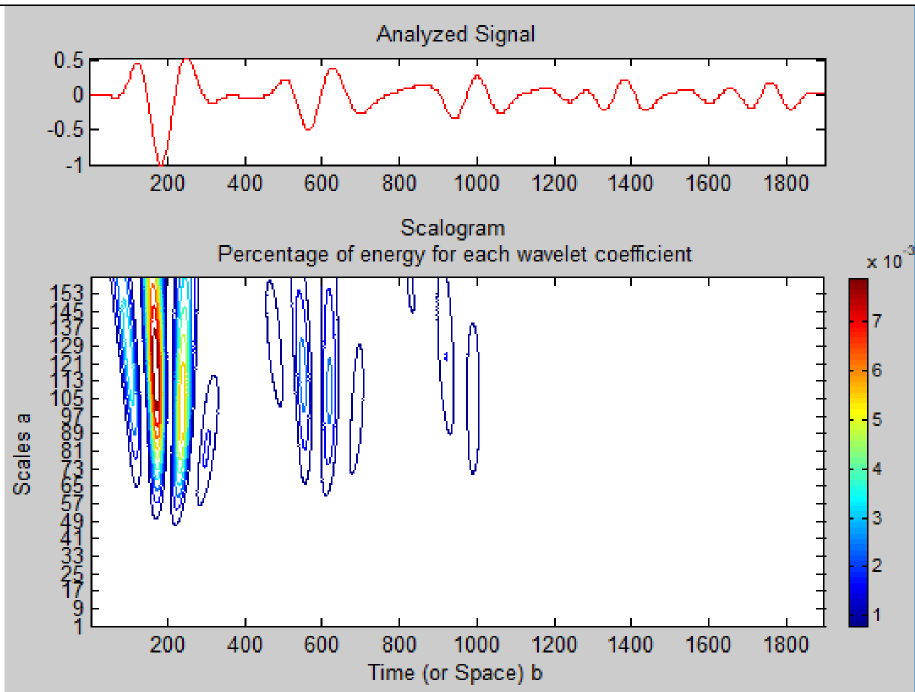


(a) (b)

Figure 4. Analysis of *Signal 01* by **CWD**: (a) σ → 1 and (b) σ → ∞

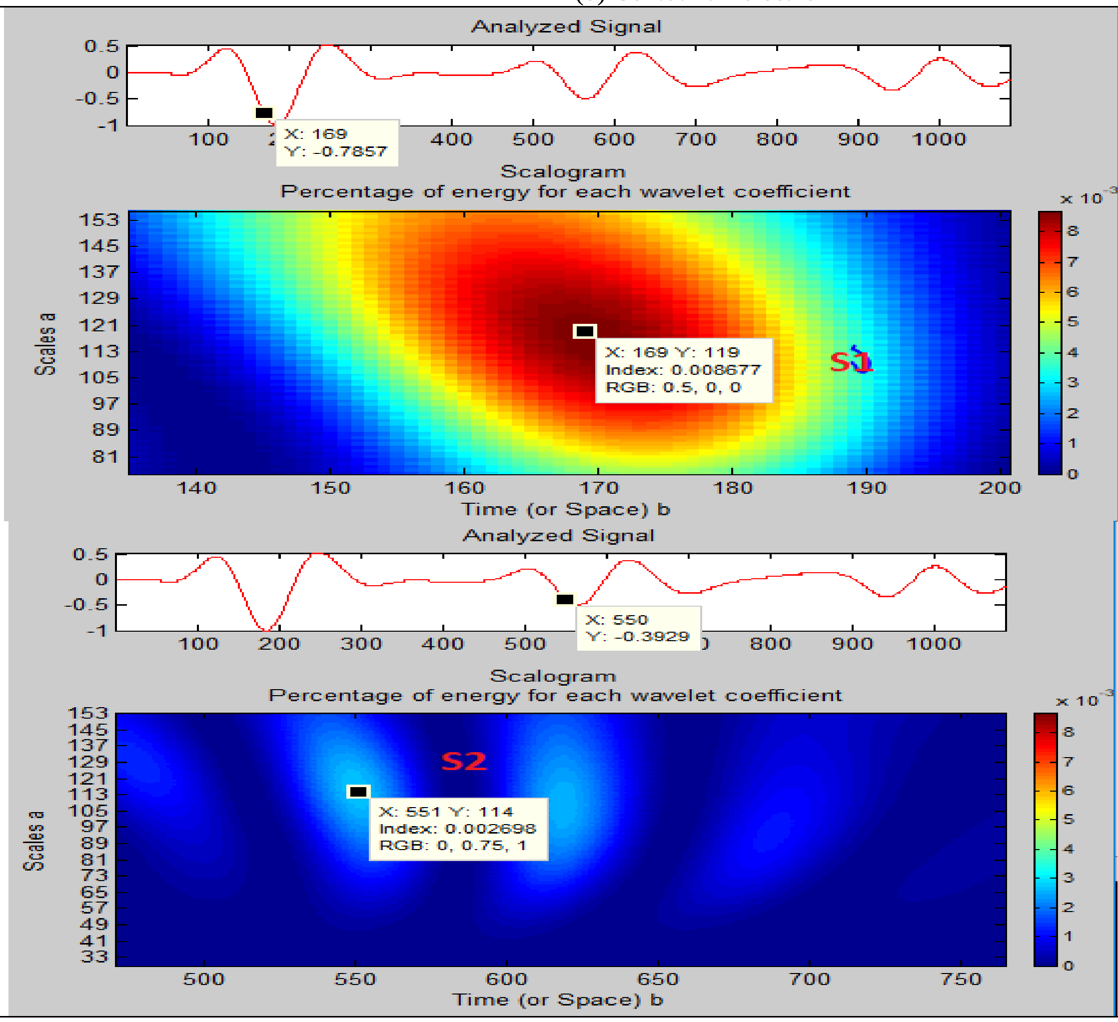


(a)



(b)

Figure 5. Analysis of *Signal 01* by **CWT**: (a) Scalogram of Signal 01 on scale at 160
(b) Contour time-scale



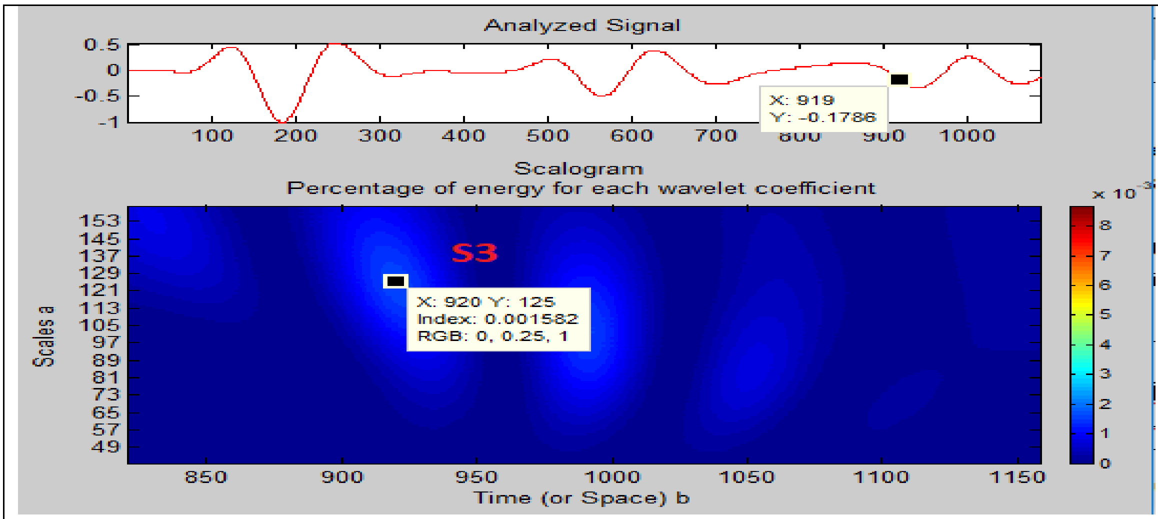


Figure 6. Analysis of *Signal 01* by **CWT**(separation of the echoes)

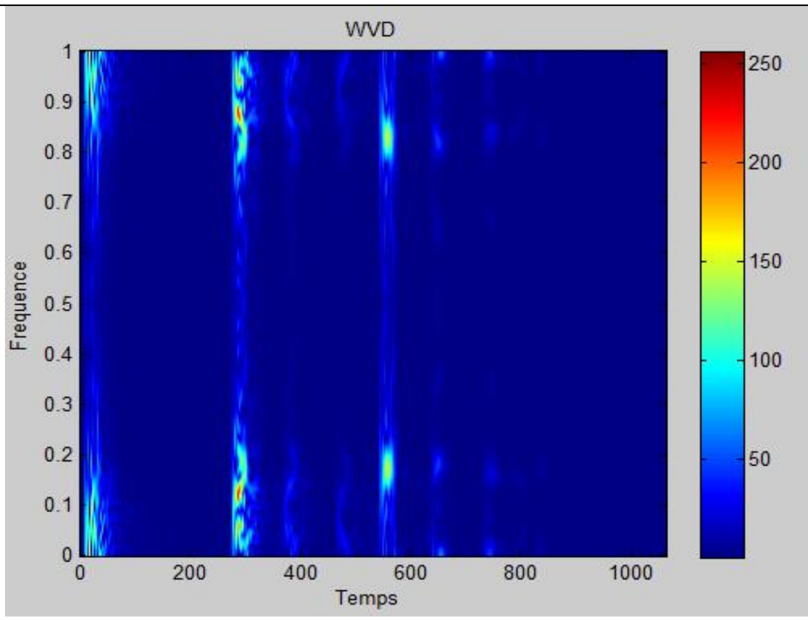


Figure 7. Analysis of *Signal 02* by **WVD**

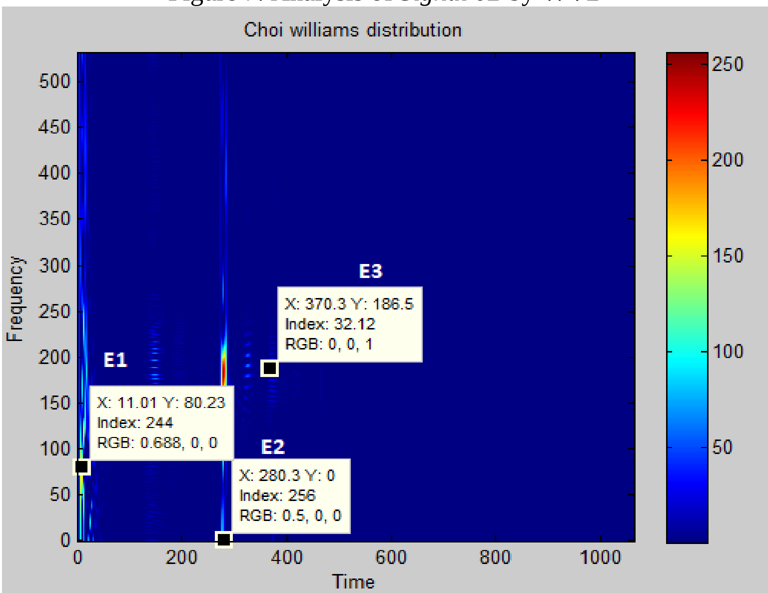


Figure 8. Analysis of ***Signal 02*** by **CWD**

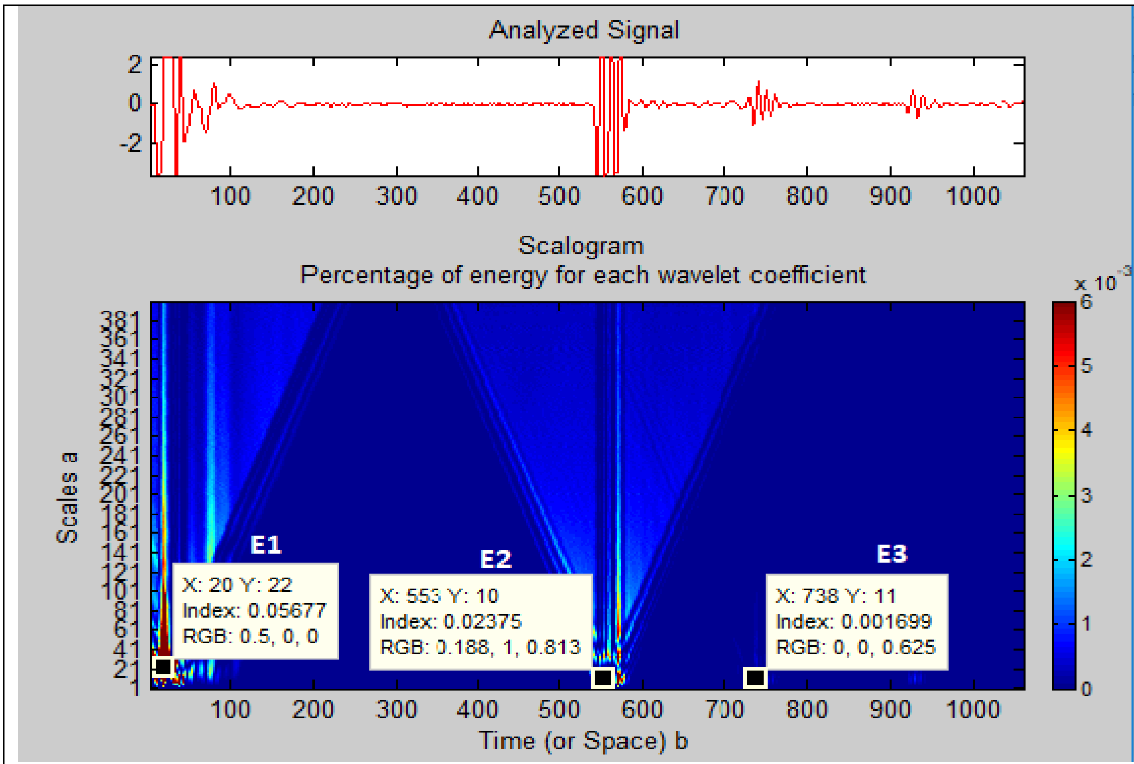


Figure 9. Analysis of ***Signal 02*** by **CWT**

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 tables 1 and II. 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.

Table 1. Propagation velocity, sample thickness and defect position from ***experiment 1***

	Experiment 1		
	Velocity	*Thikness*	*Defect position*
Theoritical	5950 m/s	1 cm	5 mm
WVD	5814 m/s	**0.99 cm**	**5.1 mm**
CWD	6622 m/s	0.97 cm	4.5 mm
CWT	**6025 m/s**	0.9 cm	**4.9 mm**

Table 2. Propagation velocity, sample thickness and transducer position from ***experiment 2***

	Experiment 2		
	Velocity	*Thikness*	*Transducer position*
Theoritical	6700 m/s	6 cm	4 cm
WVD	6350 m/s	6.3 cm	4 cm
CWD	**6666 m/s**	**6 cm**	4 cm
CWT	6486 m/s	6.2 cm	4 cm

Young's modulus determination E

We know that: $V_l = \sqrt{E/\rho}$ $and\ E = V_l^2.\rho.$

Theoretically: ρ=7.85 g/cm³ for steel and ρ=2.79 g/cm³ for aluminum, we obtain results in Table 3.

Table 3.Young modulus determined by different methods

	Theoritical	***WVD***	***CWD***	***CWT***
Steel	278 GPa	**265 GPa**	344 GPa	**285 GPa**
Aluminum	121 GPa	109 GPa	**120 GPa**	113 GPa

Conclusion

In this paper, pulse-echo technique has been used to characterize materials. Two specimens were considered: a steel plate (with crack in the middle) and an aluminum cube (without defect). Longitudinal wave velocities were determined from flight time calculations in the specimens. A comparative 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.

First, we applied these methods on two materials: Steel plate and Aluminum sample. 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, compare 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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