Improving Hilbert Huang and Wavelet Transforms for Ultrasonic Signals Characterisation

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***Abstract*— In Non Destructive Testing, defect detection is affected by noise and/or overlapping of reflected signals in thin samples. Thus, it is necessary to enhance visibility and resolution of defects echoes by signal processing techniques. The proposed methods are Wavelet and Wiener-Ville Transforms. They are tested on real ultrasound signals, collected from an experimentation using the technique pulse-echo immersion in longitudinal direction, for cement paste and mortar.**

Good results are obtained confirming the robustness of the proposed methods on detection/localization of defects in materials and demonstrating the feasibility, simplicity and effectiveness of these methods.

Keywords-Detection of defects; NDT; ultrasonic signals.

I. INTRODUCTION

The Non Destructive Testing (NDT) plays a very important role in the economy and becomes the essential tool for evaluating the mechanical properties of materials and detecting their defects. NDT techniques, as impact echo, are used for ultrasonic flaw detection in most commercial instruments [l]. In some materials, there are many scattering centers, such as grain boundaries, which can generate echoes that at first approximation seem randomly distributed in time. The ensemble of these echoes is usually defined as background noise and it limits the detection of small cracks, flaws, or other metallurgical defects [2]. Various techniques for the enhancement of detected echoes using signal processing techniques have been utilized [3-8].

In all cited techniques, the signal is analyzed either in the time domain or in the frequency one. In ultrasonic flaw detection, the ultrasonic signal is usually a broadband pulse modulated at the center frequency of the transducer; therefore the transient signal is usually limited in time and frequency. For this reason, the utilization of 2-dimensional analysis can be more appropriate. Time-frequency representation of ultrasonic signals is thus a useful tool for ultrasonic signals, in particular for detecting and characterizing dispersive effects and flaw echoes in high scattering materials [l-11].

Recently, many time-frequency analysis methods have been developed namely the Gabor or Short Time Fourier transform (STFT) [9], the Wigner-Ville distribution, and the Choi-William distribution [10] as well as the wavelet-based approaches. Generally the frequency of ultrasonic signals is often rather high, and according to the Shannon sampling theory, large size samples are needed for detecting the defect and/or characterizing the material in question. Additionally, due to the limitations of the Heisenberg-Gabor inequality, wavelet transform cannot achieve fine resolutions simultaneously in both time and frequency domain. So, we use another time-frequency analysis method called Hilbert-Huang transform (HHT) [1-3], [12-15].

In this paper, we apply these two methods in the ultrasound NDT to enhance signals qualities for characterizing materials and locating the imperfections present in the used materials using the impact echo technique. We compute the relative thickness (depth), or detect and localize defects and compute the material velocity which allow to determine the nature of the material if the latter is unknown and the position of different interfaces, so the size of the sample [13][16,17]. We use paste cement sample, with no flaws in its internal structure, and mortar sample, with defects. Tests are conducted in the NDT laboratory of Jijel University in Algeria. In Section 2, the HHT is briefly introduced and its application in ultrasonic is presented. Description of the Wavelet Transform is given in Section 3. Numerical and experimental results are presented and discussed in Section 4. A conclusion is given in Section 5 highlighting the main results obtained.

II. HILBERT HUANG TRANSFORM FOR ULTRASONIC SIGNAL PROCESSIG (HHT-SP)

The HHT, proposed by Hilbert-Huang, combines Hilbert transform and EMD decomposition. The algorithm is based on the decomposition of the studied ultrasonic signal in several sub-band by the EMD and the application of HT of each obtained sub-band to obtain the Hilbert amplitude spectrum and the instantaneous frequency using the following equations

$$H_i(t) = abs(hilbert(c_i(t))) \quad (1)$$

$$a_i(t) = \sqrt{c_i(t)^2 + H_i(t)^2} \quad (2)$$

$$\varphi_i(t) = \arctan\left(\frac{H_i(t)}{c_i(t)}\right) \quad (3)$$

Equations (2) and (3) represent the amplitude and phase of each sub-band. $w_i(t) = \frac{d\varphi_i(t)}{dt}$ is the instantaneous frequency. In order to use the instantaneous frequency mentioned above, we have to reduce an arbitrary signal into Intrinsic Mode Functions (IMF) components from which an instantaneous frequency value can be assigned to each IMF component. Consequently, for complicated signal, we can have more than one instantaneous frequency at a time locally. We will introduce the empirical mode decomposition method to reduce the signal into the needed IMFs

Thus, equations (2) and (3) allow reconstructing the signal decomposed by the EMD using

$$x(t) = \mathrm{Re}\sum_{j=1}^{m} a_j(t).\exp(i\varphi_j(t)) = \mathrm{Re}\sum_{j=1}^{m} a_j(t).\exp\left(i\int w_i(t)dt\right) \quad (4)$$

Equation (4) is called the Hilbert spectrum. We can deduce the instantaneous frequency IF of each MFI as

$$IF_i(t) = \frac{1}{2.\pi}\frac{d\varphi(t)}{dt} = \frac{1}{2.\pi} w_i(t) \quad (6)$$

The above equation is a distribution in time and frequency of the amplitude. This is called the Hilbert-Huang spectrum of HHT which can be considered as a generalized form of the Fourier transform.

III. Wavelet Transform

We have high time resolution when observing the high frequency signal component and high frequency resolution when observing the low frequency signal component. Wavelet transform is one of the solutions to the above problem: by changing the location and scaling of the mother wavelet, we can implement the multi-resolution concept. When using a window with variable width, Wavelet transform can capture both the short duration, high frequency and the long duration, low frequency information simultaneously.

The Continuous Wavelet Transform (CWT) can be defined by the coefficient of similarity between the signal and the wavelet used defined as follows

$$WT_x(a,b) = \frac{1}{\sqrt{|a|}}\int_{-\infty}^{+\infty} x(t)\psi^*\left(\frac{t-b}{a}\right)dt = \langle x(t), \psi_{a,b}(t)\rangle \quad (7)$$

$$\psi_{a,b}(t) = \frac{1}{\sqrt{|a|}}\psi^*\left(\frac{t-b}{a}\right) \quad a,b \in R \ and \ a \neq 0 \quad (8)$$

$\Psi^*(t)$ the mother wavelet or the basic wavelet function that satisfies certain conditions, a is the dilation factor and b is the translation of the origin. An intuitive physical explanation of equation (7) is very simple: $WT_x(a,b)$ is the 'energy' of the signal $x(t)$ of scale a at $t = b$ and $\psi_{a,b}(t)$ the wavelets girls.

The computation of the wavelet transform, a and b should be discredited; this is called the discrete wavelet transform (DWT). Obtaining bases discrete wavelet based on the theory of analysis multiresolution (AMR) which consists of a signal in its decomposition at different scales, approximations and details [18, 19]. The scalogram is expressed from the CWT and is defined as

$$|WT_x(a,b)|^2 = \left|\frac{1}{\sqrt{|a|}}\int_{-\infty}^{+\infty} x(t)\psi^*\left(\frac{t-b}{a}\right)dt\right|^2 = |\langle x(t), \psi_{a,b}(t)\rangle|^2 \quad (9)$$

The approximation is the low frequency component of the signal and the detail is the high frequency component.

The proposed method is based on a choice of a wavelet analysis and a scale factor suitable. It will be possible to estimate the delay of the ultrasound wave and detect echoes. According to this, we can deduce the temporal and frequency positions corresponding to each echo that makes up the ultrasonic wave. Knowledge of time and frequency coordinates of each echo makes the estimation of the Time Of Flight (TOF) very easy [2, 3], [20]-[24]

$$E_i = Max(C_i) \quad (10)$$

C_i are the wavelet coefficients.

IV. Results and Discussion

The real signals used in this paper are collected from prismatic samples of paste cement without defects and the mortar material with a synthetic defect prepared in the NDT laboratory of the University of Jijel. Noticing that determining the position of a defect is in the same manner as that of one side of the cube.

4.1. Description of experience and process

We use the pulse echo technique with two environments liquid/solid interface separated by size (6x6) cm.

The device includes a transmitter/receiver ultrasonic (Panametrics 5077PR, 606V), a transducer 1MHz immersion, a digital oscilloscope (Tektronix TDS 1002) and a computer with data acquisition software (WaveStar). During the experiment, the incident wave ultrasonic immersion transducer is normally intended to infringe on both sides of the used prism sample. Indeed, the transducer emits ultrasonic wave in a way that it falls vertically on the face of the sample to eliminate the effect of conversion of modes, so the echoes are received longitudinal waves. Distance between the transducer and the sample is 4cm.

4.2. HHT and experimental results

We apply the HHT, in order to calculate the relative thickness of the defect in the sample 02 (mortar) and the propagation velocity of ultrasound in the sample 01 (cement paste).

When using EMD, we can extract automatically and exactly the components of the ultrasonic signal (echoes) with the energy of each band, that is to say that the essential information of signal is concentrated in the most energetic

IMF. Fig. 1 shows clearly the appearance of the face echo (E2) from the IMF1 and the depth echo (E3) in IMF2 for ultrasonic signal reflected by paste cement sample (signal 01). So the TOF and the ultrasonic velocity in the paste cement can be calculated from these IMFs and/or from the Hilbert spectrum (Table 1).

Fig. 2 to 5 prove clearly that the face echo (E2) appears in the IMF1 and the depth echo (E3) appear also in IMF1 for the second ultrasonic signal reflected by mortar sample (signal 02). So the TOF and the defect thickness in this case can be calculated from these IMF1 and/or from the Hilbert spectrum (Table 2).This method is a simple, powerful and effective to treat, locate defects and/or characterize ultrasonic signals.

4.3. Wavelet Transform results

We have used the Daubechies wavelet (db4) to decompose the first signal of paste cement (signal 01) into 160 levels and the second signal of mortar (signal 02) which containing synthetic defect into 80 levels.

Fig. 6 to 9 represent the speed factor approximations. We note that variations of the signal after the contents of the original signal, where there is a low coefficient of variation in the non-noisy, and high coefficients of variation in the noise. The time-scale representation shown in Fig. 7 permits to differentiate between low and high frequencies which generally represent noise. Spectrograms, shown in Fig. 8, indicate that the fundamental echoes in the case of:

1) The paste cement signal echoes are concentrated around values given in Table 3. From these values, the paste cement velocity can be computed to be 3263.7 m/s and so we can determine the elastic constants (Young modulus, Poisson's ratio). That allows us to describe the development of properties and mechanical properties of paste cement material.

2) The mortar signal echoes are concentrated around values given in Table 4. The defect thickness in the mortar is equal to 1.55 cm.

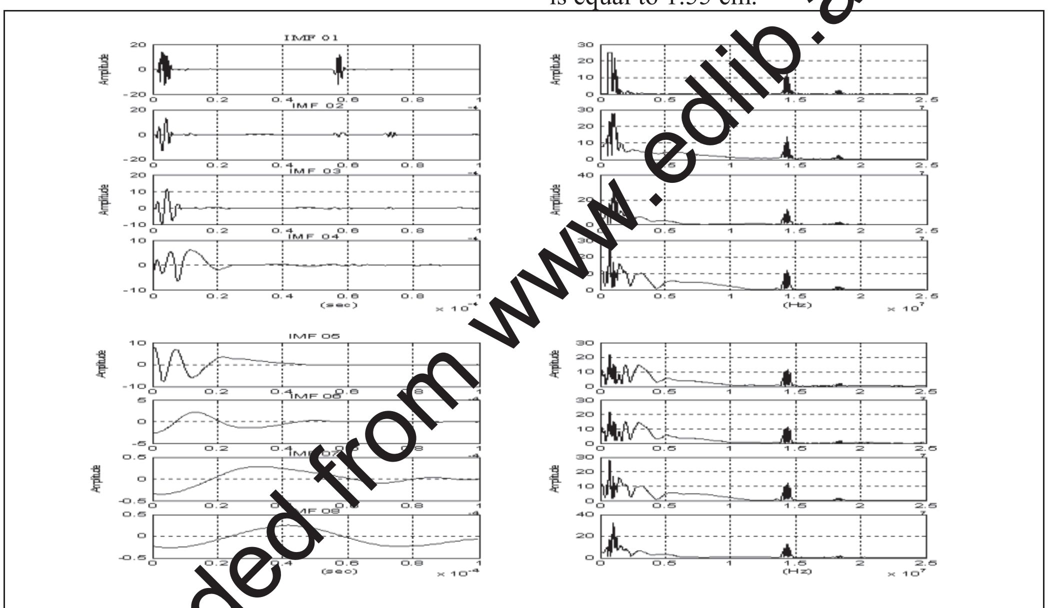

Figure 1. Intrinsic Mode Functions of Signal 01 in the left and their spectrum in the right

TABLE I. CALCULATION OF THE PASTE CEMENT VELOCITY

Echo	Echoes parameters			
	IMFs	Time (μs)	TOF (μs)	Velocity (m/s)
Face E	**1**	57.76	**15.32**	**3263.7**
Depth E	**2**	73.08		

TABLE II. CALCULATION OF THE THICKNESS OF DEFECTS IN THE MORTAR

Echo	Echoes parameters			
	IMFs	Time (μs)	TOF (μs)	Thickness (cm)
Face E	1	50.48	**4.92**	**1.55**
Defect E	1	65.40		

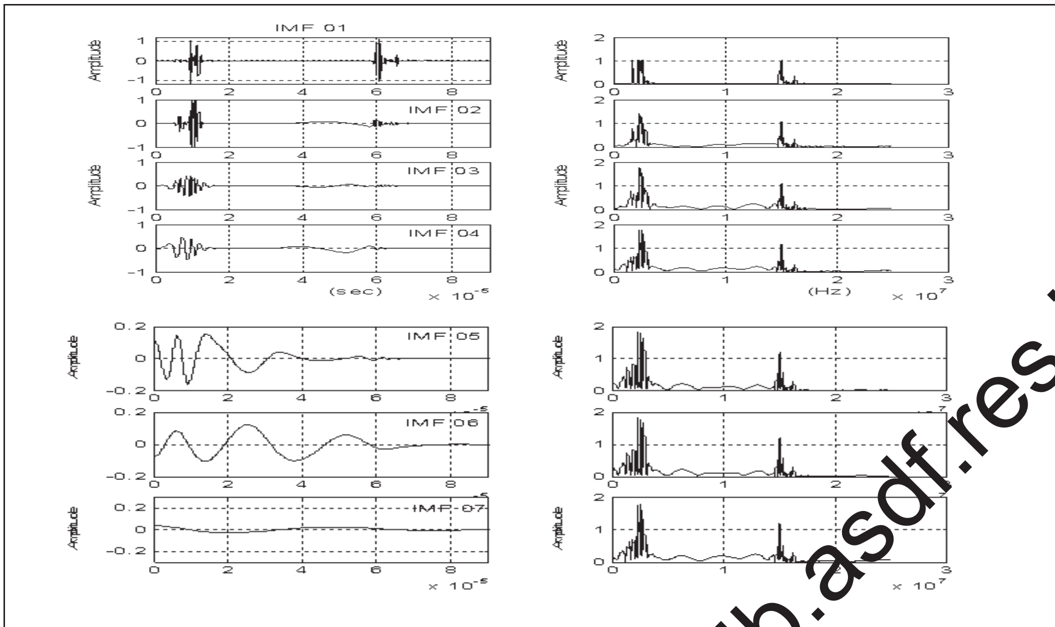

Figure 2. Intrinsic Mode Functions of Signal 02 in the left and their spectrum in the right

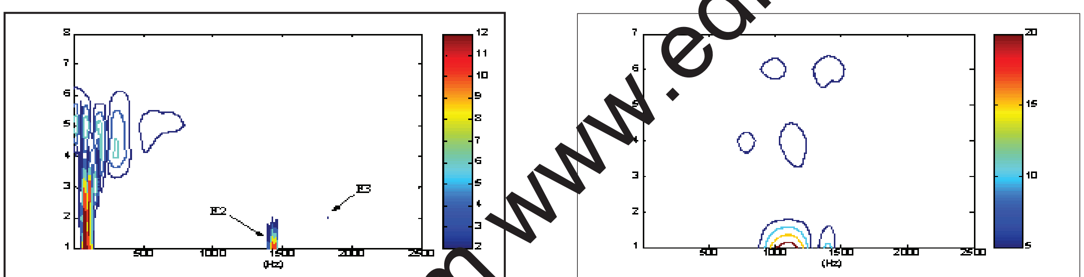

Figure 3. 2D Hilbert Huang Spectrum for Signal 01 in the left and for signal 02 in the right (Times-IMFs)

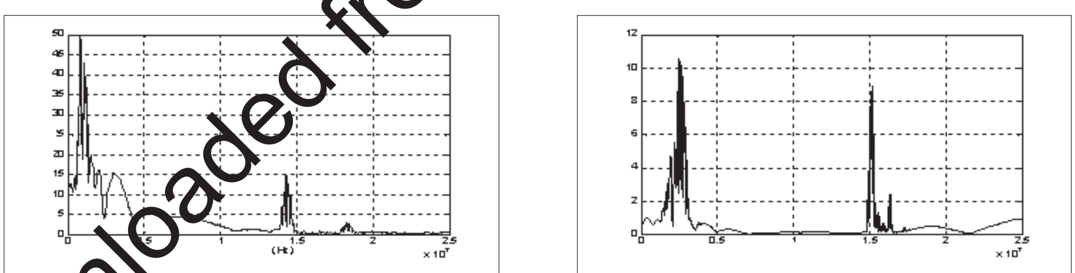

Figure 4. Hilbert Huang Spectrum for Signal 01 in the left and for signal 02 in the right

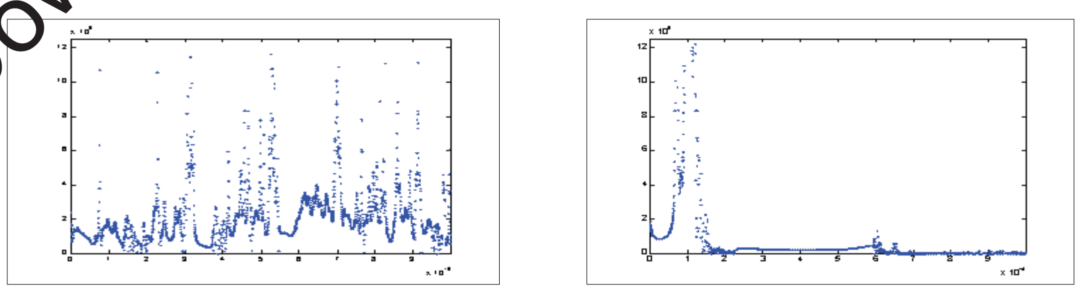

Figure 5. Hilbert Huang Transform (HHT) for signal 01 in the left and for signal 02 in the right (Phase in degrees)

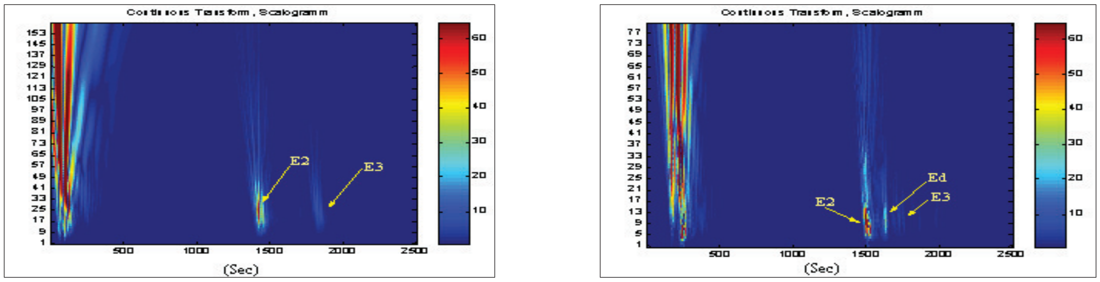

Figure 6. CWT of signal 01 and signal 02 (time-scale)

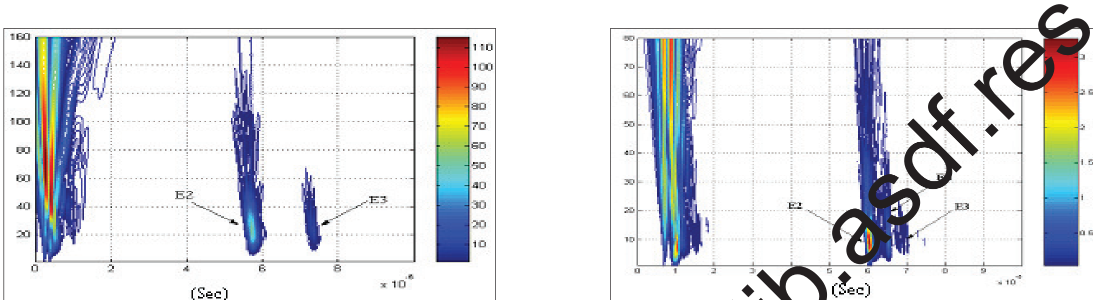

Figure 7. CW scalogram (time-scale edges) of signal 01 and signal 02

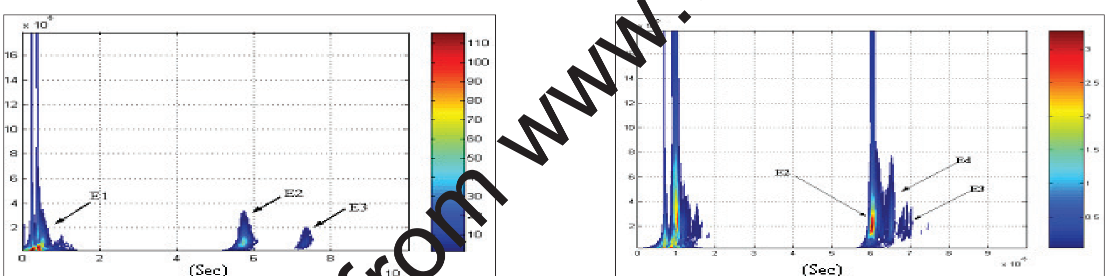

Figure 8. Time-frequency representation using CWT (db4) of signal 01 and signal 02

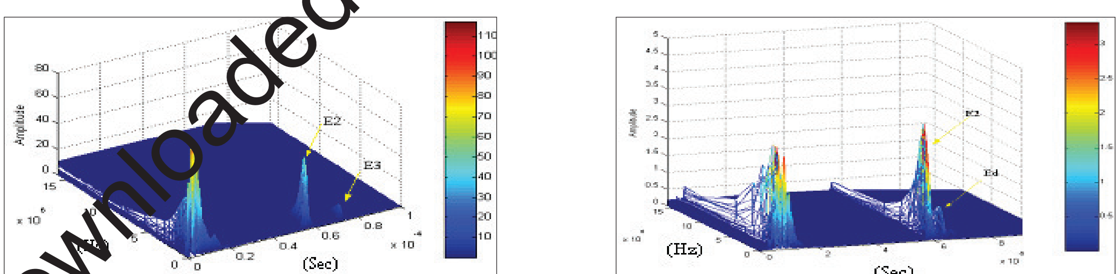

Figure 9. Spectrogram 3D using CWT (db4) of signal 01 and signal 02

TABLE III. CALCULATION OF THE PASTE CEMENT VELOCITY USING CONTINUOUS WAVELET TRANSFORM

Echo	Wavelet coefficient	Time (μs)	Frequency (MHz)	TOF (μs)	Velocity (m/s)
E.Face	C21 = 49.0241	57.68	0.63776	**15.28**	**3272.3**
E.Depth	C26 = 10.0707	72.96	0.68681		

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TABLE IV. CALCULATION OF THE THICKNESS OF DEFECTS IN THE MORTAR USING CONTINUOUS WAVELET TRANSFORM

Echo	Wavelet coefficient	Time (μs)	Frequency (MHz)	TOF (μs)	Thickness (cm)
E.Face	C9 =3.1372	60.48	1.9841	**4.92**	**1.55**
E.Defect	C10 =0.8346	65.40	1.7857		

I. CONCLUSION

The detection and identification of defects in materials by ultrasonic methods are often limited by the presence of noise in the internal structure of. In this paper, we studied two signal processing techniques namely Hilbert Huang and wavelet transforms and their improving in the NDT material characterization and defects detection and localization.

In a first part, we studied the Hilbert Huang Transform and its using in the NDT material characterization and defects detection and localization. For the signal of paste cement sample, we have measured the longitudinal velocities of waves based on the calculation of flight time in order to characterize materials and for the signal of the mortar sample we have detected and located its defect.

In the second part, we applied the wavelet transform on the same samples and we noticed that the wavelet transform offers a basic change and levels for the analysis of the accuracy of interfaces. For the first signal (signal of paste cement sample), we have measured the longitudinal velocities of waves based on the calculation of flight time in the sample in order to characterize materials and for the second (signal of the mortar sample), we have detected and located has the advantage of working with bands that leads to the separation of noise. Among available time-frequency analysis methods, wavelet transform may be the best one and so, has been widely used for ultrasonic signal analysis. Although wavelet transform still has some inevitable deficiencies. Generally the frequency of ultrasonic signals is often rather high, and according to the Shannon sampling theory, large size samples are needed for detecting the defect and/or for characterizing the material in question.

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