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Detection and classification of a cylindrical target partially or completely buried in thin sand/water mixture by time - frequency representation

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Numerous papers show that it is possible to characterize an air-filled cylindrical shell immersed in water from a backscattering spectrum. The scattered impulse time signal is constituted by echoes related to the reradiation of waves circumnavigating around the cylindrical target. For particular frequencies, these echoes make resonances which characterize this target. In first part, the scattered signal is calculated when the cylindrical shell is in water. In second part, the cylindrical shell is partially or completely buried in a thin sand-water mixture. It is insonified perpendicularly to the water/sand-water mixture interface. The impulse time scattered signal is recorded and is treated with a Fourier transform to obtain the resonance spectrum, and with a time-frequency algorithm of wavelet type. The comparison between the theoretical and experimental time–frequency representations shows us that it is possible to detect and classify the object buried in thin sand-water mixture.

1 Introduction

Since some years several authors have studied the possibility to detect and classify objects buried in silt at the bottom of sea [1-2]. In laboratory others researchers have developed methods to separate the acoustic signal in relation to the buried objects and the acoustic signal reverberated by the silt [3]. In this paper, two methods are described to detect and to classify buried objects in very thin sand: the Method of Isolation and Identification of Resonances (MIIR) [4] and the time–frequency representation by wavelet algorithm [5].

The Method of Isolation and Identification of Resonances (MIIR) that verifies experimentally the Resonance Scattering Theory (RST) developed in numerous papers [6] has shown that it is possible to characterize cylindrical and spherical shells from acoustic resonance spectra. The authors of the RST have shown that the backscattering acoustic spectrum of a cylindrical shell, insonified by a plane wave perpendicularly to its axis, is constituted by a background due to the reflection on the object and by resonances in relation to the propagation of circumferential waves which circumnavigate around the target in the shell or at the interface between the target and the water. The characteristics of the circumferential waves are strongly influenced by the material and the radius ratio ***b/a*** of the shell (***b***: inner radius; ***a***: outer radius). In the frequency domain studied in this paper, only the resonance modes of two types of circumferential waves are observed: the A_0^- or ***A*** wave [7] and the S_0 wave. These waves, during their propagation, are coupled with the fluid surrounding the cylindrical shell and reradiate progressively their energy in this fluid. For the S_0 wave, the coupling is weak and this wave can propagate during several circumferences before to it vanishes, even though the ***A*** wave be attenuated after few number of circumferences. In this work, the influence of the sand on the propagation of circumferential waves in and around the buried tube is specially analyzed and the resonance spectra and the time-frequency representation are plotted to determine if it is possible to characterize this buried tube by an acoustic method.

2 Experimental setup

The experimental arrangement is described on figure 1. The studied object is an aluminum cylindrical shell. Its geometrical characteristics are: length L=25 cm, outer radius a=1 cm and radius ratio b/a=0.95. The physical characteristics are: the velocity of longitudinal and shear waves respectively C_L=6380 m.s^{-1} and C_T=3100 m.s^{-1}; the aluminum density is ρ_A=2900 kg.m^{-3}. This target is immersed in water of density ρ_w=1000 kg.m^{-3} and the acoustic velocity is C_w=1470 m.s^{-1} or buried in water-sand mixture with density ρ_s=1250 kg.m^{-3} and the acoustic velocity C_S=1650 m.s^{-1}.

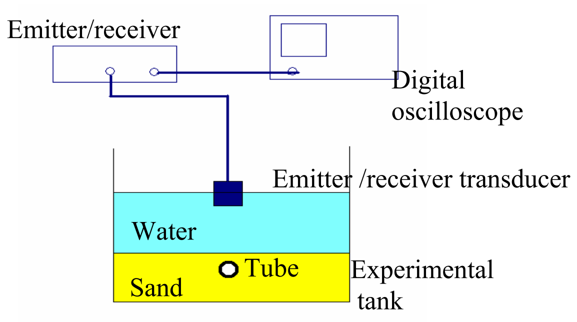

Fig. 1: Experimental arrangement.

The tube can be immersed in water or buried in sand as shown on fig.1. The broadband transducer, with central frequency 500 kHz, perpendicularly insonifies the tube and the interface of water/sand-water mixture. The tube is excited by a short impulse with large band pass. The backscattered signal is recorded by the digital oscilloscope and transferred to a micro computer to be treated by a Fourier Transform algorithm and a wavelet algorithm.

3 Theoretical results

The general form of the scattered pressure field in a plan perpendicular to the z-axis can be expressed as [3]:

$$P_s(\omega)=P_0\frac{1-i}{\sqrt{\pi k_w r}}\exp i(2k_1 a)\exp i(2k_w u-\omega t)\sum_{n=0}^{\infty}\varepsilon_n\frac{D_n^1(\omega)}{D_n(\omega)}\cos(n\theta) \quad (1)$$

where ω is the angular frequency, $k_w = \omega/C_w$ is the wave number with respect to the wave velocity in the external fluid (C_w), P_0 is the amplitude of the incident plane wave, $D_n^1(\omega)$ and $D_n(\omega)$ are determinants obtained from the boundary conditions of the problem on the two interfaces, ε_n is the Neumann coefficient (ε_n =1 if n=0 and ε_n =2 if $n\neq0$), u is the distance between the transducer and the surface of the cylindrical shell and r is the distance between the z-axis of the tube and the position of the emitter – receiver transducer, point where the pressure is calculated. The acoustic backscattering spectrum of the studied tube obtained with the equation (1) is presented on figure 2. Figure 2(A) presents the backscattering spectrum from the target immersed in water; a band pass of the used transducer is applied in the computation. The resonances of ***A*** wave are observable in the reduced frequency window ($10<k_wa<35$). The first resonances, at left of the figure, are thin with a thickness increasing with the frequency. The resonances of $\boldsymbol{S_0}$ wave are wide in low frequency and their width decreases with the frequency. The figure 2(B) is the impulse time signal backscattered from the tube.

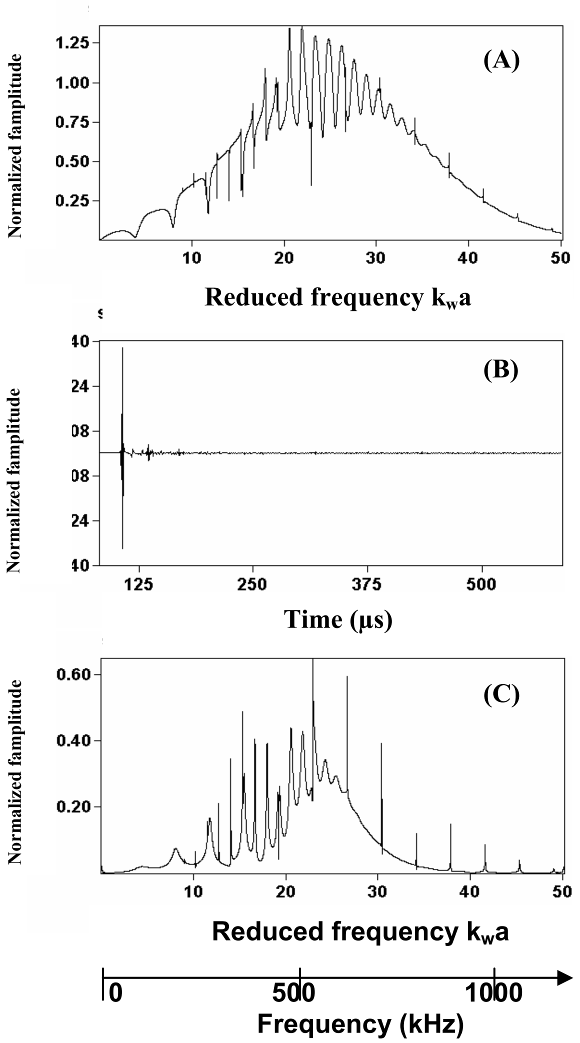

Fig.2**:** Theoretical results of the air-filled aluminum cylindrical shell immersed in water; (A): backscattering spectrum, (B) impulse time signal, (C): resonance spectrum.

On figure 2(A), the backscattered pressure is plotted in reduced frequency band: 0-50 that corresponds for the cylindrical shell used in this paper: 0 - 1.17 MHz. In the whole frequency band, transitions in relation to the $\boldsymbol{S_0}$ wave are observed. In low frequency these transitions are large valleys while in high frequency, they are thin. Figure 2(B) is obtained from the backscattering spectrum applying an inverse Fourier transform. The biggest echo is due to the specular reflection on the tube, the other echoes are in relation with the ***A*** and $\boldsymbol{S_0}$ waves, the time between two echoes of ***A*** wave is approximatively 25µs and the time between two echoes of $\boldsymbol{S_0}$ wave is approximatively 11µs. The ***A*** wave echoes have shorter frequency band than the $\boldsymbol{S_0}$ wave echoes in consistent with the remarks previously given. The resonance spectrum on figure 2(C) is obtained applying a Fourier transform to the impulse time signal of figure 2(B) after having replaced the specular echo by zeroes. The resonances appear as peaks with a good resolution. This spectrum can be used to classify an underwater target.

4 Experimental results

4.1 Target immersed in water

In this paragraph, an experimental study is developed to verify the theoretical results presented in previous paragraph. The air-filled aluminum cylindrical shell is immersed in a large tank. It is excited by a short impulse emitted by an ultrasonic broadband transducer with a central frequency 500 kHz. The backscattered time signal is detected by the same transducer and is recorded with a personal computer to be treated by FFT algorithm or wavelet algorithm. The results are shown on figure 3.

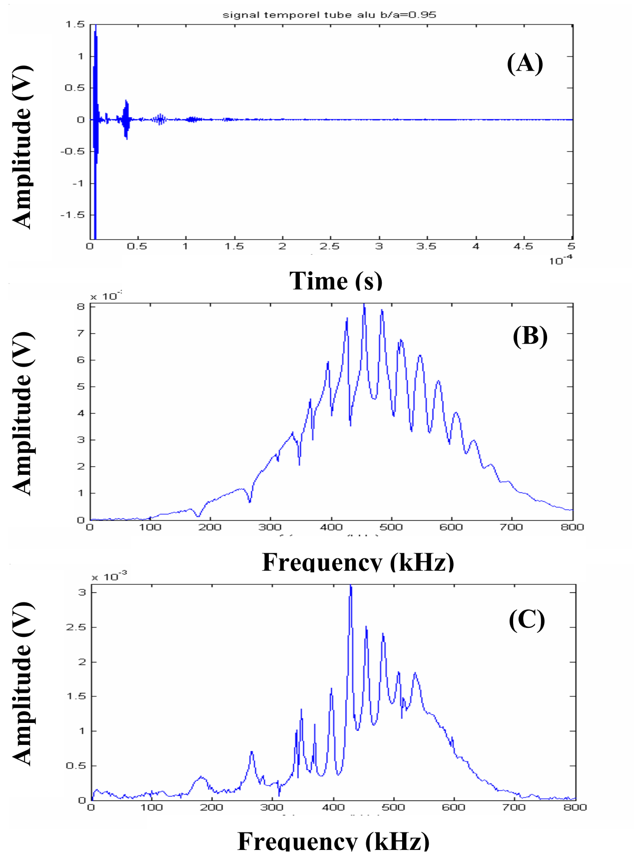

Fig.3: Experimental results of the air-filled aluminum cylindrical shell immersed in water; (A): impulse time signal, (B) backscattering spectrum, (C): resonance spectrum.

Figure 3(A) shows us the impulse time signal which can be compared with the time signal of figure 2(B). Four echoes of ***A*** wave are observed as well as several echoes of $\boldsymbol{S_0}$ wave. These last echoes have small amplitude but their amplitude decreases slowly between two consecutive echoes. This small decreasing is due to the weak coupling between this wave and water. The $\boldsymbol{S_0}$ wave makes numerous rounds in the tube shell before it vanishes. Figure 3(B) is the backscattering spectrum obtained with a FFT algorithm; it is comparable with the theoretical backscattering spectrum of figure 2(A). The influence of the ***A*** wave is important in frequency window (300<F (kHz)<700) and hides most of the resonant effects of the S_0 wave. The resonance spectrum on figure 3(C), comparable with the resonance spectrum of figure 2(C), shows us the resonance peaks of the two waves. The last remark is still valid. To complete this study, the time/frequency image with wavelet algorithm has been plotted. Figure 4 presents the result obtained when the cylindrical aluminum shell is immersed in water.

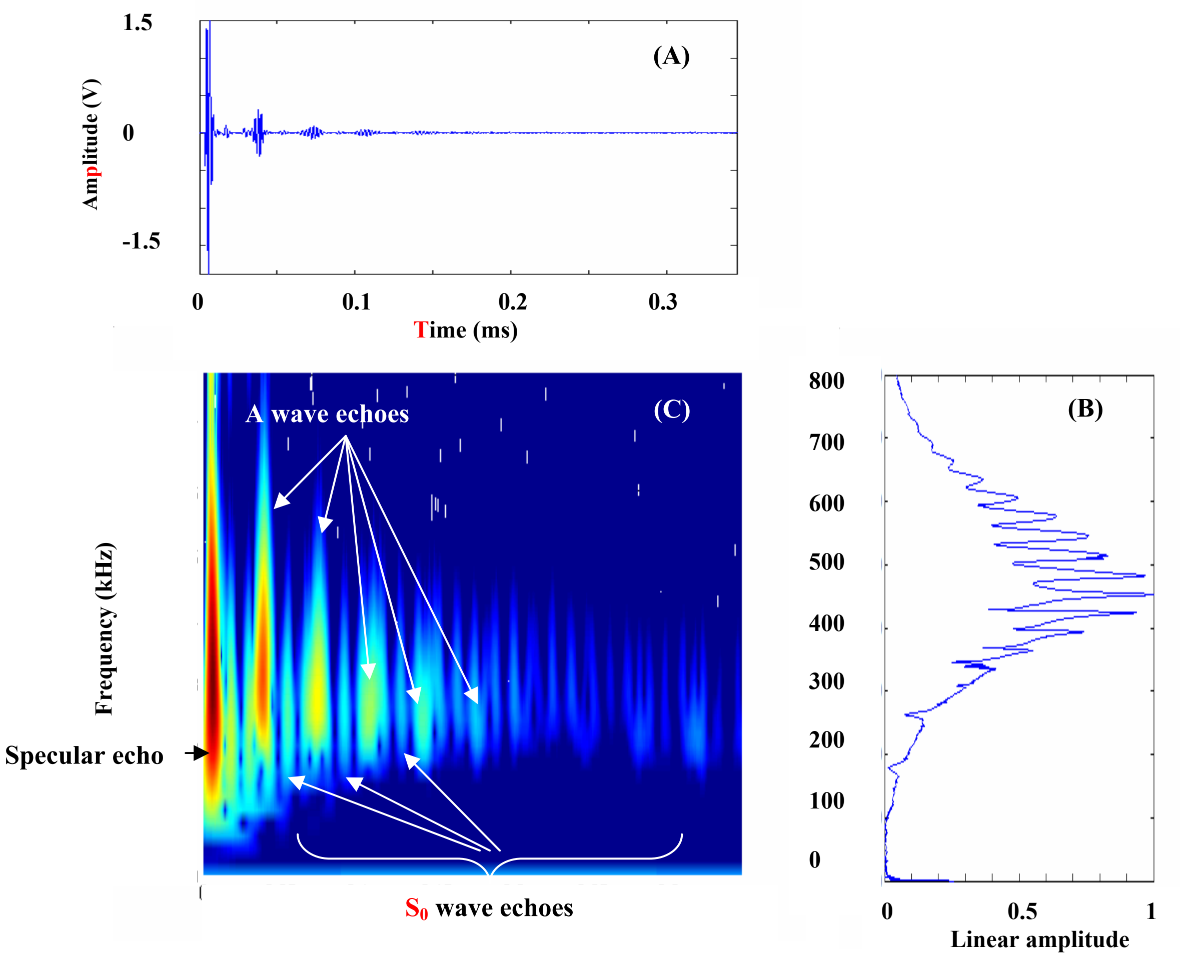

Fig.4 : Wavelet image for the backscattering signal of an air-filled aluminum tube in water ; (A) impulse time signal ; (B) backscattering spectrum ; (C) wavelet image.

On this figure, the wavelet image (Fig.4(C)) is associated to the time signal (Fig.4(A)) and to the backscattering spectrum (Fig.4(B)). On the wavelet image are observed: (i) the specular echo on the left of this figure, the frequency range of this echo takes place on the whole frequency band of the transducer; (ii) five echoes in relation of the ***A*** wave; the frequency range of these echoes is smaller than the frequency range of the transducer and it decreases with the time; this remark leads to that the first observable resonance modes of this wave are thin and that this thickness growths with the frequency; (iii) several echoes of S_0 wave with small amplitude but with a small decreasing in time. In low frequency few echoes contribute to the resonances, they are broad, in middle frequency much echoes contribute to the resonances, they are thin and observable and in high frequency the coupling between this wave and water is weak and it is not possible to observe resonances. In the frequency band where the effects of ***A*** wave are strong, the resonances of S_0 wave are not detectable, they are hidden.

4.2 Target buried in sand-water mixture

After having studied the acoustic scattering from a cylindrical shell in water, this target is buried under 1.5 cm of thin sand satured with water (Fig.1).

Figure 5 shows us the experimental results obtained in these conditions.

On figure 5(A), the impulse time signal is plotted. On the left before the specular echo, reverberation echoes are observable. The amplitude of specular echo is identical to that obtained when the target is in water; the detection of target is possible. The comparison with figure 3(A) shows us that the echoes of the ***A*** wave are not present. Only the S_0 wave echoes are observed. Figure 5(B) is obtained after having treated the whole time signal with Fourier transform algorithm. This spectrum is very different from the backscattering spectrum of figure 3(B), the oscillations of the curve are due to the interference between the specular echo and the reverberation echoes. Figure 5(C) is obtained after having replaced the reverberation echoes, at left of the specular echo, by zeroes, it is a backscattering spectrum on which the resonances of S_0 wave are detected by sharp minima. No effect of the ***A*** wave is seen.

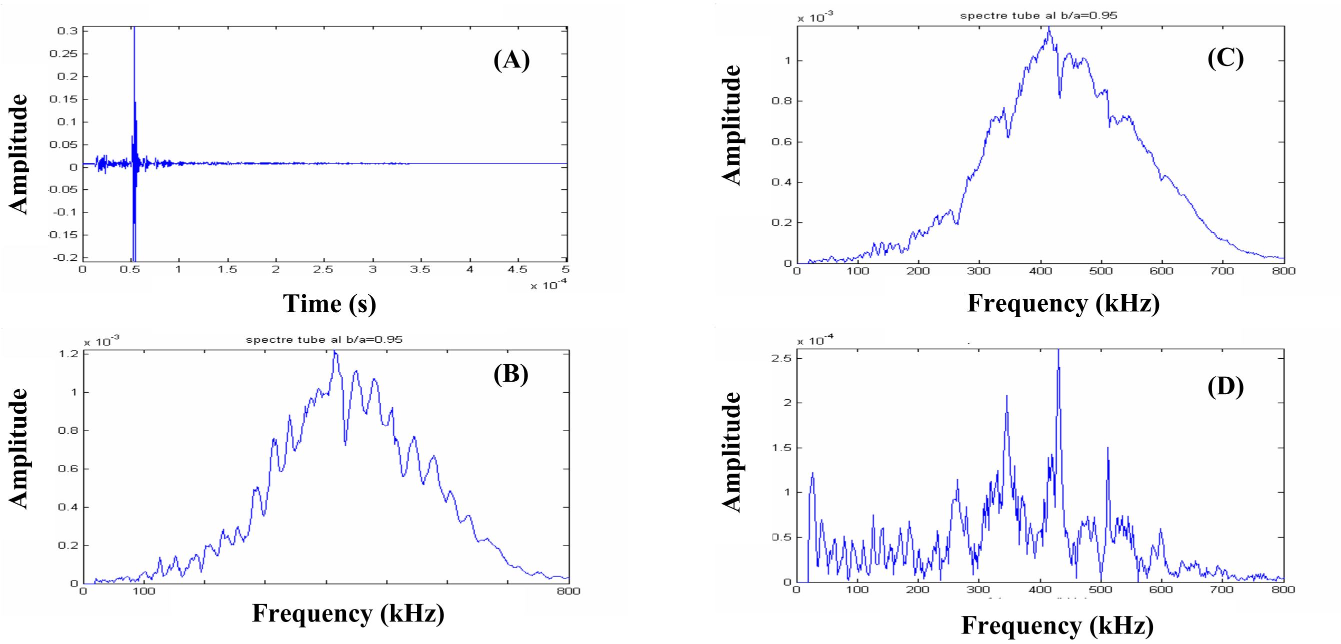

Fig.5: Experimental results of the air-filled aluminum cylindrical shell buried in sand-water mixture; (A): impulse time signal, (B) backscattering spectrum with reverberation signal, (C): backscattering spectrum without reverberation signal; (D): resonance spectrum.

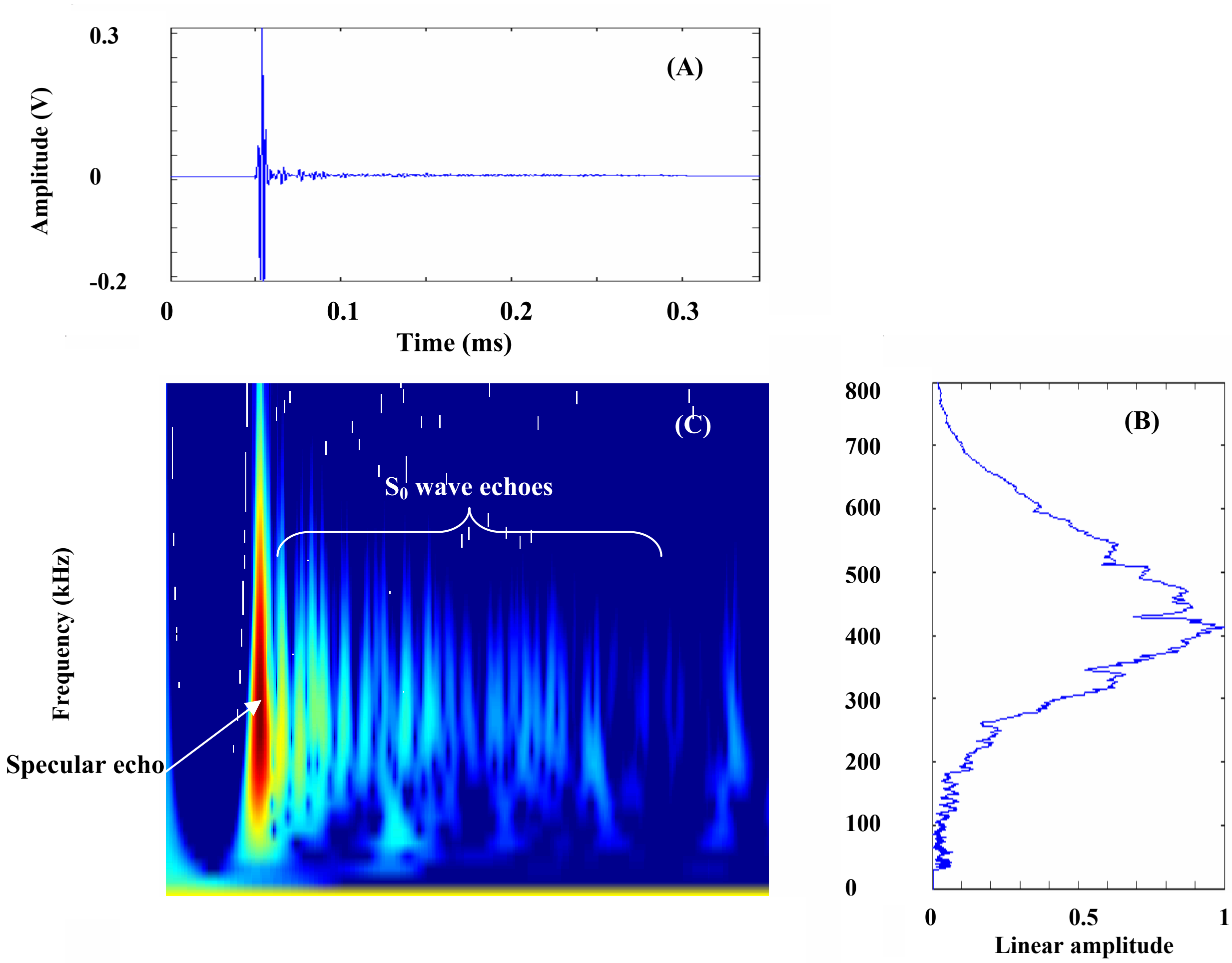

Fig.6 : Wavelet image for the backscattering signal of an air-filled aluminum tube in sand-water mixture ; (A) impulse time signal, ; (B) backscattering spectrum ; (C) wavelet image.

Figure 5(D) shows us the resonance spectrum obtained after having replaced the reverberation echoes and the specular echo by zeroes. The S_0 wave resonances are observed; their amplitude is weakly influenced by the sand-water mixture around the shell.

This spectrum is easy to analyze and allows us the classification of the target only with the S_0 wave resonances. It is not possible to determine the thickness of the tube wall with the frequency window in which the ***A*** wave resonances are observed. To confirm these results, the wavelet image is plotted on figure 6. On this figure are associated the wavelet image (Fig.6(C)), the impulse time signal (Fig.6(A)) and the backscattering spectrum (Fig.6(B)) obtained after having replaced by zeroes the reverberation echoes observed before the specular echo (Fig.5(A)). The echoes in relation to the ***A*** wave have disappeared but the S_0 wave echoes have practically the same amplitude. As seen previously the S_0 wave is little sensitive to the fluid in which the target is immersed. The sand-water mixture can be considered as a fluid.

5 Conclusion

The experimental results presented in this paper show us that it is possible to detect and classify a man made target using the resonance spectrum or the wavelet image in low frequency inferior to the reduced frequency $k_w a$=50. The resonances of S_0 shell wave, little sensitive to the fluid in which the target is immersed, water or sand-water mixture, can allow us a first possibility to classify a target. The resonances of ***A*** wave which allow the knowledge of the radius ratio ***b/a*** of the cylindrical shell cannot be used if the target is buried. They are not observed. To obtain a better classification and to know the type of target it is necessary to use a larger frequency band to detect the resonances of other circumferential waves with a weak coupling with the fluid.

Acknowledgments

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