Detection and classification of an object buried in sand by an acoustic resonance spectrum method.

D Décultot Université Le Havre, LAUE UMR CNRS, Le Havre, 76110, France.
K Cacheleux Université Le Havre, LAUE UMR CNRS, Le Havre, 76110, France.
G Maze Université Le Havre, LAUE UMR CNRS, Le Havre, 76110, France.

1 INTRODUCTION

The Method of Isolation and Identification of Resonances (MIIR)[1,2] that verifies experimentally the Resonance Scattering Theory (RST) developed in numerous papers[3,4] has shown that it is possible to characterize cylindrical and spherical shells from acoustic 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 related to the propagation of circumferential waves which circumnavigate around the target in the shell or at the interface between the target and the water[5,6]. The characteristics of the circumferential waves are strongly influenced by the material and the radius ratio **b/a** (**b**: inner radius; **a**: outer radius) of the shell. In the frequency domain studied in this paper, only the resonance modes of two types of circumferential waves are observed: the $\mathbf{A_0^-}$ or **A** wave and the $\mathbf{S_0}$ wave, they are similar to the Lamb waves on the plane plate[7]. A circumferential wave is generated in the cylindrical shell at the critical angle which depends on the ratio: sound speed in water / phase velocity of this 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 $\mathbf{S_0}$ wave the coupling is weak and it can propagate during several circumferences before to vanish, even though the $\mathbf{A_0^-}$ wave the number of circumference is limited. Some authors have shown that acoustic methods could allow the identification of a spherical target buried in silt[8,9]. In first part of this paper, the theoretical spectra are calculated, the cylindrical shell is in water or in a medium with characteristics similar to the mixture sand/water used for the experimental measurements. In a second part, the experimental setup is described and the method to plot the resonance spectrum is explained when the cylindrical shell is in water. In third part, the cylindrical shell is partially buried in a thin sand/water mixture. The resonance spectrum is obtained after to have suppressed the reflected echo on the shell surface and the reverberation echoes related to the interface between the water and the sand/water mixture. The comparison between the last resonance spectrum and the one obtained in water shows us that it is possible to detect and classified the object.

2 THEORETICAL ACOUSTIC SPECTRA

The general form of the scattered pressure field in a plan perpendicular to the z-axis can be expressed as[10]:

$$P_{scat}(\omega)=P_0\frac{1-i}{\sqrt{\pi k_1 r}}\exp i\,(2\,k_1\,a)\exp i\,(2\,k_1\,u-\omega\,t)\sum_{n=0}^{\infty}\varepsilon_n\frac{D_n^1(\omega)}{D_n(\omega)}\cos(n\theta) \qquad (Eq.1)$$

where ω is the angular frequency, $\boldsymbol{k_1=\omega/C_1}$ is the wave number with respect to the wave velocity in the external fluid ($\boldsymbol{C_1}$), $\mathbf{P_0}$ is the amplitude of the incident plane wave, $\boldsymbol{D_n^1(\omega)}$ and $\boldsymbol{D_n(\omega)}$ are determinants obtained from the boundary conditions of the problem on the two interfaces, $\boldsymbol{\varepsilon_n}$ is the Neumann coefficient ($\boldsymbol{\varepsilon_n}$ =1 if $\boldsymbol{n}$=0 and $\boldsymbol{\varepsilon_n}$ =2 if $\boldsymbol{n}\neq$0), 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 relation (Eq. 1) is presented on figure 1.

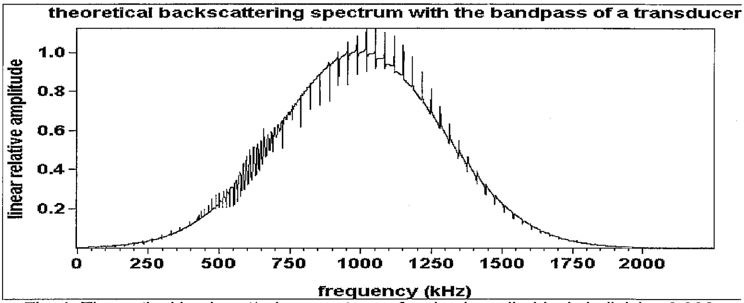

Fig. 1: Theoretical backscattering spectrum of a circular cylindrical shell, b/a= 0.982.

The cylindrical shell is in stainless steel. The velocities of the longitudinal wave and the shear wave are respectively C_L = 5790 m/s and C_T = 3100 m/s. The density is ρ = 7900 kg/m^3. The radius ratio is ***b/a*** = 0.982 and the outer radius is ***a*** = 0.0255 m. The domain of the dimensionless frequency is: $0 < k_1a < 245$ and the domain of frequency is: $0 < F = \omega/2\pi < 2247.83$ kHz. The band pass of the transducer has taken into account. To obtain the time signal (figure 2), an Inverse Fourier Transform is applied on the complex values of figure 1.

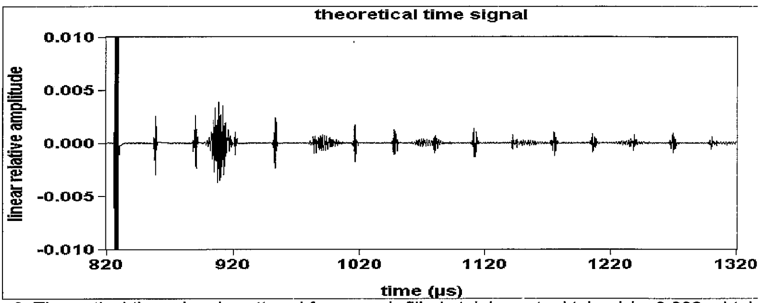

Fig. 2: Theoretical time signal scattered from an air-filled stainless steel tube, b/a=0.982, obtained from the backscattering spectrum of the figure 1

On figure 2, three types of echoes are observed: (i) at left of the figure, the specular echo, (ii) the large echoes with a weak frequency band pass related to the **A_0^-** or **A** wave, this wave is due to the interaction between the flexural Lamb wave A_0 propagating on a tube in vacuum and the Franz wave propagating on a rigid cylinder[11] and (iii) the other thin echoes with a broadband related to the compressional Lamb wave **S_0**. Figure 3 presents the resonance spectrum obtained after suppressing the specular echo, only the echoes related to the **A_0^-** wave and **S_0** wave are taken into account.

On the whole of the frequency band, the resonances of the **S_0** wave are observed and the resonances of the **A_0^-** wave are observed in the frequency window between 400 kHz and 700 kHz.

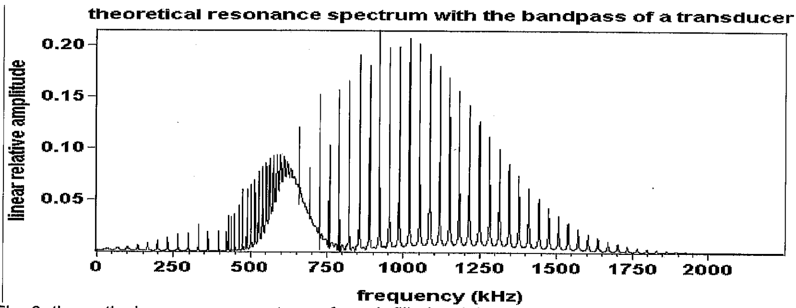

Fig. 3: theoretical resonance spectrum of an air-filled stainless steel tube, b/a=0.982, immersed in water. The amplitude is modulated by the band pass of the transducer.

On the whole of the frequency band, the resonances of the $\mathbf{S_0}$ wave are observed and the resonances of the $\mathbf{A_0^-}$ wave are observed in the frequency window between 400 kHz and 700 kHz. The previous results are obtained when the cylindrical shell is in water. To interpret the experimental results, the cylindrical shell buried in water/sand mixture, it is necessary to know the parameters of this mixture. It is supposed homogeneous and isotropic: the sand is made of very thin grains with middle radius smaller than 10 µm. The density and velocity parameters are measured in the sand saturated with water after 24 hours, the density is ρ_s = 1290 kg/m^3 and the velocity of acoustic wave is C_s = 1650 m/s.

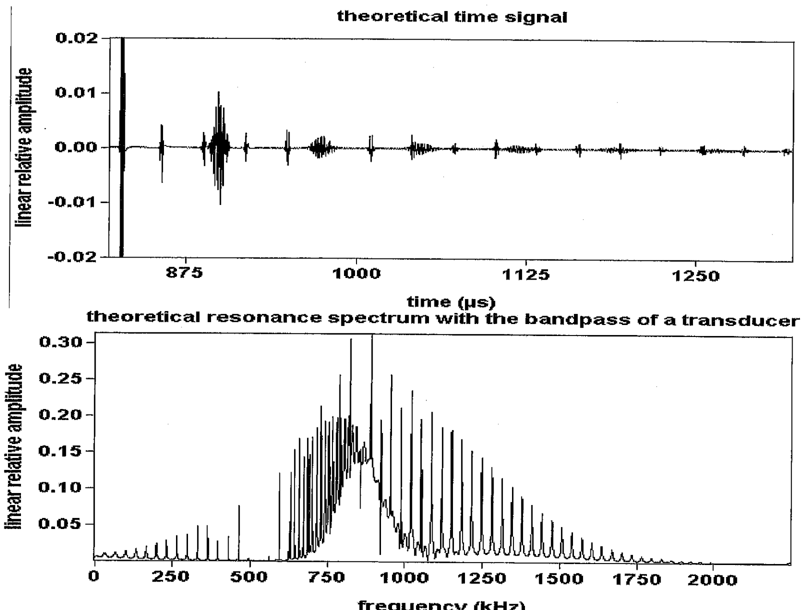

Fig. 4: (a): theoretical time signal and (b): resonance spectrum of the cylindrical shell in water/sand mixture.

Figure 4 presents the time signal and the resonance spectrum calculated in the conditions described previously when the cylindrical shell is in the mixture. The absorption of the mixture is not taken into account. The frequency window in which the $\mathbf{A_0^-}$ resonances are observed is shifted to high frequencies (600 kHz < F <1000 kHz). On Figures 3 and 4b, the peaks in relation to the S_0 wave are numerous and very thin, this result is due to the weak coupling between the wave and the fluid surrounded the cylinder. In vicinity of frequency 500 kHz, they are not observable, the coupling is quasi-null.

3 EXPERIMENTAL RESULTS

The experimental arrangement is described on figure 5. The broadband transducer with middle frequency 1 MHZ insonifies perpendicularly the surface plane of sand/water mixture.

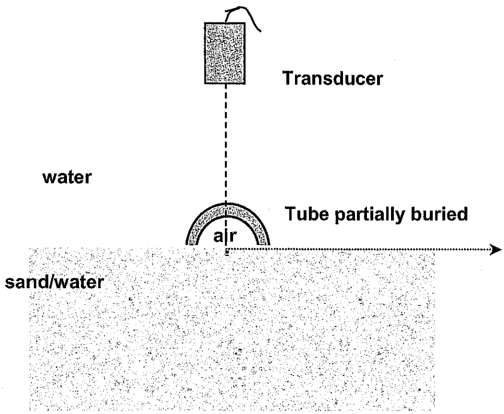

Fig. 5: Experimental arrangement. The acoustic excitation is perpendicular to the surface of sand/water mixture.

The characteristics of the stainless steel cylindrical shell are given previously. The cylindrical shell is half buried in sand/water mixture.

3.1 Acoustic scattering in water

To appreciate the results obtained when the tube is partially buried, the experimental time signal (figure 6a) and resonance spectrum (figure 6b) are plotted when the tube is in water and insonified with the broadband transducer. Figure 6a shows us the specular echo at the left of figure, several echoes related to the $\mathbf{S_0}$ wave, two echoes related to the $\mathbf{A_0^-}$ wave with a narrow band frequency and a large echo related to the $\mathbf{A_0^+}$ wave after the first echo of the $\mathbf{S_0}$ wave.
To obtain the resonance spectrum with the numerical time signal, the specular echo is suppressed with a computer and a FFT is applied on the time signal rest. Two types of peaks are observed, in low frequency the peaks of the $\mathbf{A_0^-}$ wave and in high frequency the peaks of the $\mathbf{S_0}$ wave. The $\mathbf{S_0}$ wave is especially interesting because of its weak coupling with the water. Between each echo of this wave, it has travelled in one circumference and these echoes are observed after many circumferences, in this case about fifteen rounds. This phenomenon induces the thin peaks on the resonance spectrum. The attenuation of this $\mathbf{S_0}$ wave has been measured, the result is given in the table 1.

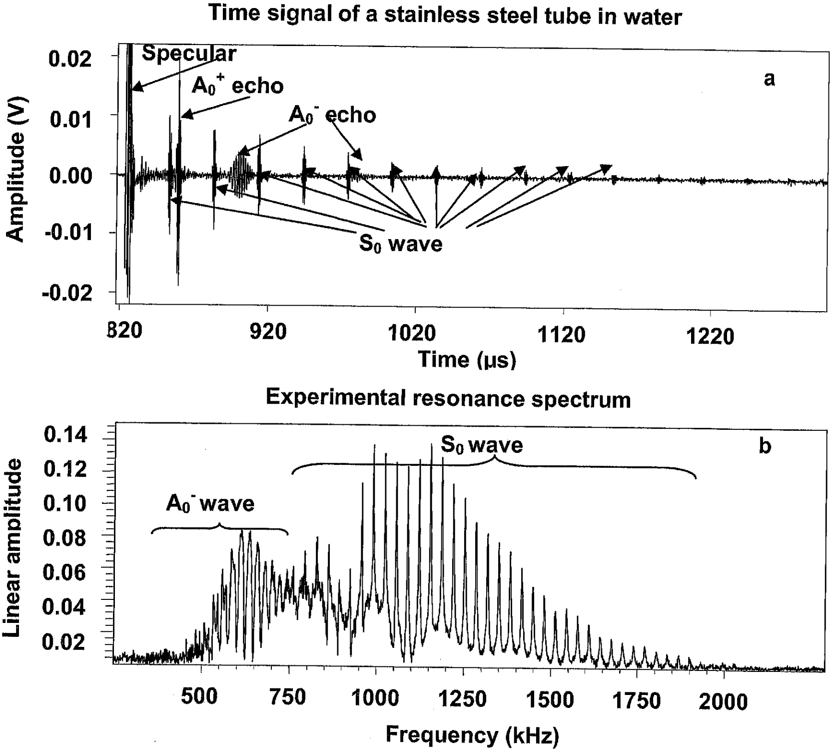

Fig.6: a) Time signal and b) Resonance signal of the tube immersed in water

3.2 Acoustic Scattering from a Tube Partially Buried in Sand/Water Mixture: Insonification is Perpendicular to the Surface Sand/Water Mixture

Figure 7 gives the time signal (a) and the resonance spectrum (b) obtained when the tube is partially buried. The insonification is perpendicular to the surface of the sand/water mixture. The time signal is constituted by a specular echo at the left, some echoes in relation with the reflection on the sand surface, a series of broadband echoes decreasing in the time in relation with the reradiating of the $\mathbf{S_0}$ wave and one echo situated at time corresponding to the first echo of the $\mathbf{A_0^-}$ wave between two $\mathbf{S_0}$ echoes. The decreasing of the $\mathbf{S_0}$ echo is not significantly affected by the presence of the water-saturated sand mixture (Table 1) on a half part of the target.

	Tube in water	Tube partially buried
Attenuation of S_0 Wave	13 dB/m	14 dB/m

Table 1: attenuation of the S_0 wave for the two configurations

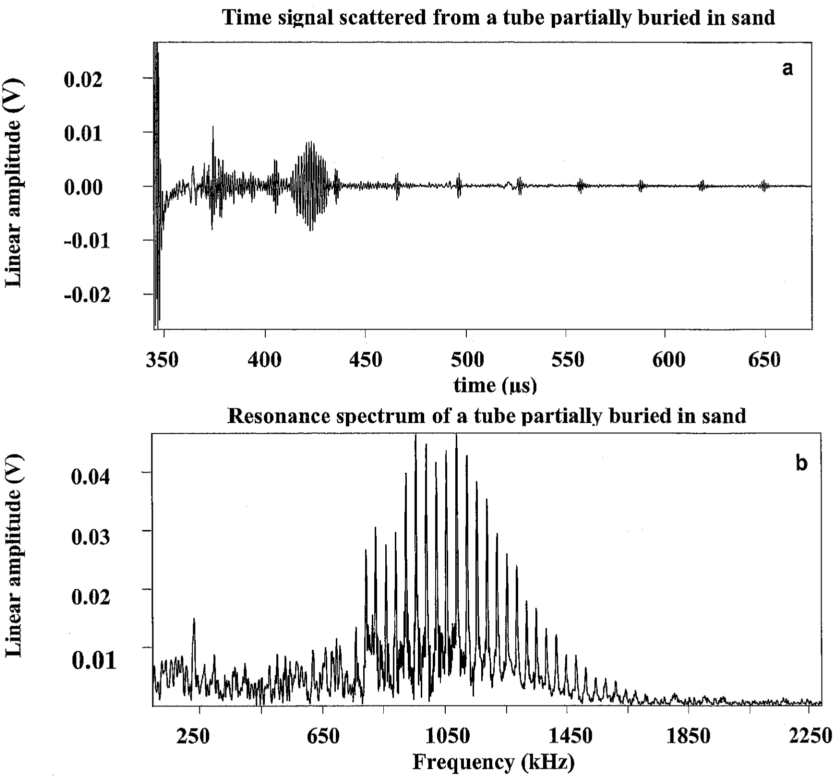

Fig. 7: (a) Time signal and (b) resonance spectrum for a tube partially buried in sand/water mixture

3.3 Acoustic Scattering from a Tube Partially Buried in Sand/Water Mixture: Insonification is Oblique to the Surface Sand/Mixture

In this last part, the cylindrical shell is partially buried as in previous part but the insonification is oblique on the surface of water sand mixture.

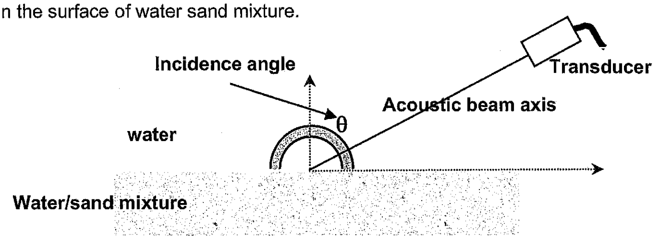

Fig. 8: Experimental arrangement. The acoustic excitation is oblique to the surface of sand/water mixture.

The incidence angle θ is equal to 78° larger than the critical angle defined by the relation:

$$\theta_c = \mathrm{Arc}\sin(\frac{1470}{1650}) = 63°.$$

This angle involves that the cylindrical shell is directly excited by the acoustic beam above the beam axis but for the symmetrical excitation, under the beam axis, the $\mathbf{S_0}$ wave is generated by surface wave at the interface water/sand. The time signal of figure 9 shows us, at the left, reflected and reverberation echoes, and after 750 µs pairs of echoes for which the time gap is equal to the time observed on figure 7a between two $\mathbf{S_0}$ echoes. The first is generated directly under the critical angle on the surface of shell and the second is generated after a propagation of surface wave on water/sand mixture on a short distance. The delay between the two successive echoes is due to the propagation of the surface wave.

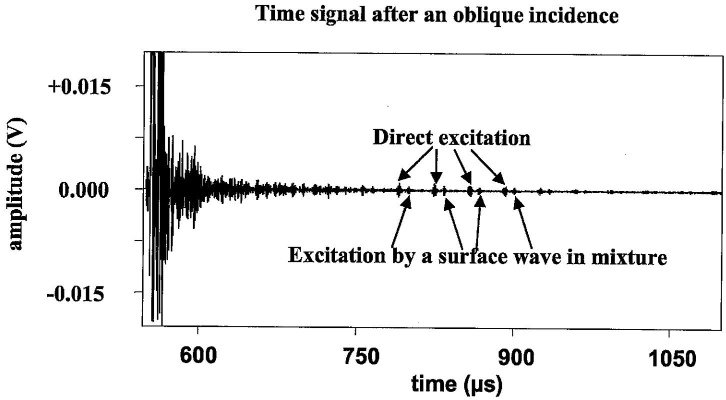

Fig. 9: time signal recorded with an oblique incidence excitation

4 CONCLUSION

In this paper, we show that it is possible to detect and to classify a target partially buried in water/sand mixture with the resonance spectrum obtained after a perpendicular excitation. Using the time signals, this possibility can be widened to a oblique excitation.

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