Classification of an object buried in sand by a

acoustic resonance spectrum method.

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ABSTRACT
Numerous papers show that it is possible to characterize an air-filled cylindrical shell immersed in water from its resonance spectrum. This spectrum is characterized by resonances due to the circumferential waves which circumnavigate around the shell. A resonance establishes when there is an integer of wavelengths in the circumference. The resonance frequencies depend on the constitution of the detected object. The knowledge of the resonance spectrum allows us to determine the object. 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 completely buried in a thin sand/water mixture. The resonance spectrum is obtained after to have suppressed the reverberation echoes related to the interface between water and sand/water mixture, and the specular echo (reflection on the shell). The comparison between the last resonance spectrum and the one obtained in water shows us that it is possible to classify a buried object.

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 \( \frac{b}{a} \) (\( b \): 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 \( A_0 \) or \( A \) wave and the \( S_0 \) wave, they are similar to the Lamb wave 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. For the \( S_0 \) wave the coupling is weak and it can propagate during several circumferences before to vanish, even though the \( A_0 \) 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 this paper after to have described the theoretical and experimental impulse MIIR applied on the cylindrical shell insonified perpendicularly to its axis in water, the target is buried in water/sand mixture and the resonance spectra are drawn showing a possible classification.

THEORETICAL ACOUSTIC SPECTRA
The general form of the scattered pressure field in a plan perpendicular to the z-axis can be expressed as [10]:
where $\omega$ is the angular frequency, $k_1 = \omega C_1$ is the wave number with respect to the wave velocity in the external fluid ($C_1$), $P_0$ is the amplitude of the incident plane wave, $D_n(\omega)$ and $D_n'(\omega)$ are determinants obtained from the boundary conditions of the problem on the two interfaces, $\varepsilon_n$ is the Neumann coefficient ($\varepsilon_n = 1$ if $n = 0$ and $\varepsilon_n = 2$ if $n \neq 0$), $u$ 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.

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 $\rho = 7900$ 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: $0 < F = \frac{\omega}{2\pi} < 2247.83$ kHz. The band pass of the transducer has taken into account. To obtain the time signal (Fig. 2), an Inverse Fourier Transform is applied on the complex values of Fig. 1.

On Fig. 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 $S_0$. Fig. 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.

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

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

**Fig. 3:** Theoretical backscattering spectrum with the bandpass of a transducer.
On the whole of the frequency band the resonances of the $S_0$ wave are observed and in the frequency window between 400 kHz and 700 kHz the resonances of the $A_0$ wave.

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 radii smaller than 10 µm. The density and velocity parameters are measured in the sand saturated with water after 24 hours, the density is $\rho_s = 1290$ kg/m$^3$ and the velocity of acoustic wave is $C_s = 1650$ m/s.

Fig. 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 new medium is not taken into account.
The frequency window in which the $A_0^-$ resonances are observed is shifted to high frequencies ($600 \text{ kHz} < F < 1\text{kHz}$). On Fig. 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.

**CYLINDRICAL SHELL IMMERSED IN WATER: EXPERIMENTAL RESULTS**

To appreciate the results obtained when the tube is in water/sand mixture, the experimental time signal (Fig. 5a) and resonance spectrum (Fig. 5b) are plotted when the tube is in water. Fig. 5a shows us the specular echo at the left of figure, several echoes related to the $S_0$ wave with a broadband frequency, two echoes related to the $A_0^-$ wave with a narrow band frequency and a large echo related to the $A_0^+\text{-} wave after the first echo of the $S_0$ wave.

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Fig.5: a) Time signal and b) resonance signal, the tube immersed in water

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 new time signal. Two types of peaks are observed, in low frequency the peaks of the $A_0^-$ wave and in high frequency the peaks of the $S_0$ wave. The $S_0$ wave is especially interesting because of its weak coupling with the water. Between each echo of this wave, it circumnavigates in a 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.

**CYLINDRICAL SHELL BURIED IN WATER/SAND MIXTURE: EXPERIMENTAL RESULTS**

In this paper, the cylindrical shell is completely buried in sand saturated with water. Fig. 6 describes the experimental conditions used during the measurements. The stainless steel 5 cm - diameter cylindrical shell is buried under 5 mm of water/sand mixture.
Fig. 6: Experimental arrangement. The acoustic excitation is perpendicular to the surface of sand/water mixture.

Fig. 7 gives the time signal (a) and the resonance spectrum (b) obtained when the tube is buried in the water/sand mixture.

**Time signal scattered from a tube buried in sand**

![Time signal scattered from a tube buried in sand]

**Resonance spectrum of a tube buried in sand**

![Resonance spectrum of a tube buried in sand]

Fig. 7: experimental results when the object is buried in water/sand, a) time signal, b) resonance spectrum.
The time signal is constituted by some echoes in relation with the reflection on the sand surface at the left, a specular echo, a series of broadband echoes with amplitude decreasing in the time in relation to the reradiating of the $S_0$ wave. The echoes related to the $A_0$ wave are not observed. This wave which is an interface wave with the outer fluid as support is attenuated by the water/sand mixture. The decreasing of the $S_0$ wave echoes is not significantly affected by the presence of the water/sand mixture. The attenuation of this wave $S_0$ has been measured, the result is given in the table 1.

<table>
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Table 1: attenuation of $S_0$ wave around the tube circumference.

**CONCLUSION**

In this paper, the resonance spectrum is used to classify an object buried in a water/sand mixture. This result is possible because the ultrasonic reverberation on the interface water / mixture is suppressed, only the echoes related to the circumferential waves are treated.

**References:**


