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Acoustic scattering by a two-layer cylindrical tube immersed in a fluid medium: Existence of a pseudo wave

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ABSTRACT

The present paper studies the acoustic signal backscattered by an air-filled copper–solid polymer two-layer cylindrical tube immersed in water. The work is done from the calculation of the backscattered pressure, an inverse Fourier Transform, which allows us to obtain an impulse signal. Smoothed pseudo Wigner–Ville and Concentrated spectrogram representations have been chosen to analyze the scattering phenomenon. For reduced frequencies ranging from *0.1* to *200*, the resonance trajectories and time–frequency images have shown the presence of the guided waves. The bifurcation of the A_0 wave into the A_0^- and the A_0^+ waves has also been observed. The authors provide the phase and the group velocities of guided waves and investigate the differences between curves. The findings are then compared with those obtained for the copper and the solid polymer one-layer cylindrical tubes. Group velocity values have also been extracted from smoothed pseudo Wigner–Ville and Concentrated spectrogram time–frequency images. A good agreement with the theory has, therefore, been observed. The study of acoustic backscattering by a copper–solid polymer two-layer tube has revealed the interaction and the coupling of guided waves, specially the presence of a pseudo A_1 wave; which is a very interesting, remarkable phenomenon.

1. Introduction

The problem of acoustic scattering from elastic solids excited by a monochromatic plane wave has been theoretically formulated by Überall and his collaborators [1,2]. In this respect, the results of Resonant Scattering Theory (R.S.T.) show that the resonances of an air-filled shell immersed in water are related to the propagation of various circumferential waves around its periphery. The Method of Isolation and Identification of Resonances (M.I.I.R.) experimentally confirms the (R.S.T.) [3,4]. Using M.I.I.R., the backscattering spectrum, the resonance spectrum and the modes of vibration can be completely determined. Studies of submerged air-filled cylindrical and spherical shells have shown, in the low frequency range, the bifurcation of the dispersion curve for the circumferential antisymmetric Lamb A_0 wave [5–7]. The authors of these references suggested a repulsion phenomenon in the phase velocity dispersion curve of the circumferential A_0 wave when the cylindrical shell is in contact with the outer fluid. The two corresponding waves were denoted by A_0^- and A_0^+. Other studies are concerned with the acoustic scattering from cylindrical shells filled with water or a polymer coupled by a thin layer of water [8,9]. Guided waves and resonances were experimentally examined. While studies on acoustic wave scattering from one-layered shells are abundant in the literature, very few investigated acoustic scattering from multi-layer tubes. Previous works have examined the acoustic scattering from two-layered cylinders and multi-layered spherical curved plates [10–12]. Using smoothed pseudo Wigner–Ville (*SPWV*) and Concentrated spectrogram (*CSP*) representations [13–19], the authors propose the study of an acoustic signal backscattered by an air-filled copper–solid polymer two-layer tube immersed in water. For reduced frequencies ranging from *0.1* to *200*, the acoustic backscattering involves the propagation of different types of surface and interface waves. Evaluations made on resonance trajectories and velocity dispersion curves show the existence of a pseudo A_1 wave. The process of the interaction and the coupling of guided waves are manifested in the acoustic scattering. Results computed for a copper–solid polymer two-layer tube, are compared to those of copper and solid polymer one-layer tubes.

2. Calculated form function and time impulse response

2.1. Theoretical study

Fig. 1 shows an infinite plane acoustic wave of angular frequency ω normally incident on a submerged cylindrical

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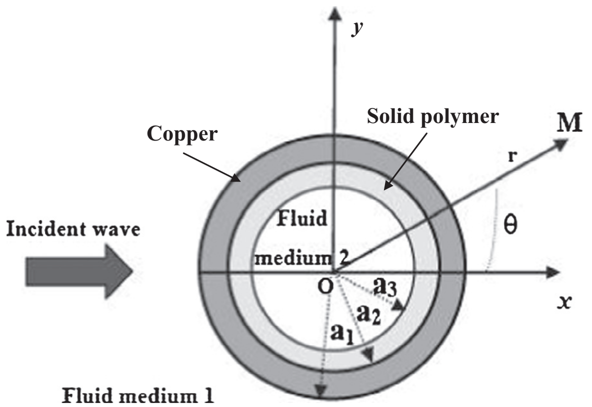

Fig. 1. Geometry of a plane wave normally incident on an air-filled two-layer tube immersed in water.

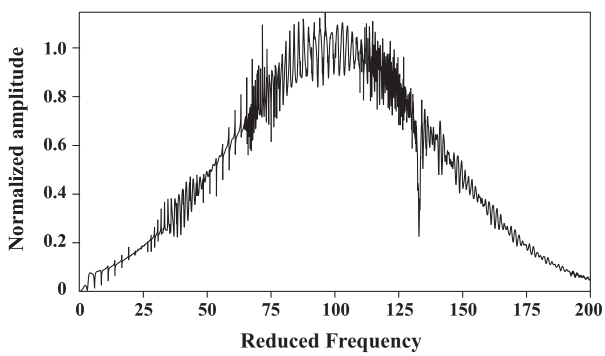

Fig. 2. Calculated form function of the copper–solid polymer two-layer tube.

two-layered tube of infinite length, outer radius a_1, intermediary radius a_2, and inner radius a_3. (x, y, z) is the Cartesian coordinate system with origin at O, the z direction is coincident with the axis of the cylindrical tube. The corresponding cylindrical polar coordinate system (r, θ) is chosen.

The incident acoustic pressure of the incident plane wave $p_{inc}(r,\theta)$ can be written as follows [3,33],

$$p_{inc}(r,\theta) = P_0 \sum_{n=0}^{\infty} \left[\varepsilon_n i^n J_n(k_{water} r)\right] \cos(n\theta) \tag{1}$$

where $k_{water} = \omega/C_{water}$ is the wave number in the fluid medium outside the tube (medium 1 = water), C_{water} is the sound velocity in water, ε_n the Neumann factor ($\varepsilon_n = 2 - \delta_{n0}$), $i^2 = -1$, P_0 the incident plane wave amplitude, and J_n are the cylindrical Bessel functions of the first kind of order n [34].

The scattered wave pressure p_{scatt} at point M must be symmetrical about $\theta = 0$ and, therefore, of the form [3],

$$p_{scatt}(\omega, r, \theta) = P_0 \sum_{n=0}^{\infty} \left[\varepsilon_n \frac{D_n^{(1)}(\omega)}{D_n(\omega)} i^n H_n^{(1)}(k_{water} r)\right] \cos(n\theta) \tag{2}$$

where $H_n^{(1)}$ are the Hankel functions of the first kind of order n, $D_n^{(1)}(\omega)$ and $D_n(\omega)$ the determinants [34]. By applying the boundary conditions of the problem (continuity of stress and displacement at the interfaces), the terms of these determinants are determined at any given value of reduced frequency $x = k_{water} a_1$.

The backscattered pressure in the far-field (form function F_∞) is obtained from the following equation [3,35],

$$F_\infty(x,\pi) \approx \frac{2}{\sqrt{\pi x}} \left| \sum_{n=0}^{\infty} (-1)^n \varepsilon_n \frac{D_n^{(1)}(\omega)}{D_n(\omega)} \right| \tag{3}$$

2.2. Form function and impulse response

Backscattering spectrum of a copper–solid polymer two-layer tube is calculated for reduced frequencies ranging from 0.1 to 200; see Fig. 2. This tube comprises an outer layer of copper in contact with water (fluid medium 1) and a layer of a solid polymer on the inner part in contact with air (fluid medium 2) in the cavity. Physical properties of the two-layer cylindrical tube and fluids are given in Table 1. The outer radius of the shell is $a_1 = 1$ m, the intermediary radius is $a_2 = 0.96$ m, and its inner radius is $a_3 = 0.94$ m. Thicknesses of the inner and outer layers are respectively a_2–$a_3 = 2$ cm and a_1–$a_2 = 4$ cm. The bandwidth of the transducer centered on the reduced frequency $x = 100$ is included so that the frequency response is reduced at both ends of the displayed spectrum.

Many amplitude variations due to the presence of resonances are observed on the form function (Fig. 2).

The total time signal is obtained from the form function by applying an inverse Fourier transform as the following equation [7,24,25]:

$$s(t) = \frac{1}{2\pi} \int_{-\infty}^{+\infty} h(\omega).p_{scatt}(\omega, r, \theta) \exp(-i\omega t) d\omega \tag{4}$$

The function $h(\omega)$ is the band pass of the transducer.

The total time signal is presented in Fig. 3(a). This signal comprises a specular echo (specular reflection) which one takes as origin of time. The specular echo is localized at time (very short duration), and characterized by large amplitude.

To obtain the resonance spectrum, the specular echo is suppressed and replaced by zeros. Fig. 3(b) presents the filtered signal for the studied two-layer tube.

3. Smoothed pseudo Wigner–Ville (*SPWV*) and Concentrated spectrogram (*CSP*)

Time–frequency representations (*TFR*) are important to analyze non-stationary signals [13–14]. *SPWV* and *CSP* representations are chosen for the study of an acoustic signal backscattered by an air-filled two-layer cylindrical tube immersed in water. *CSP* is motivated by many advantages [15–18], specially that it is linear; which simplifies the interpretation of the transform and has an inverse representation that ensures the possibility of the analyzed signal reconstruction. Moreover, it does not cause cross-terms that are a serious problem in a Wigner–Ville representation [19].

Table 1
Physical parameters.

	Density (kg m^{-3})	Longitudinal velocity (m s^{-1})	Transversal velocity (m s^{-1})
Water	1000	1470	...
Air	1.29	334	...
Copper	8630	4760	2325
Solid polymer	1500	2500	1200