Ultrasonic Waves Propagation in Fluid-Saturated Materials

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Abstract- This work deals with the application of an ultrasonic nondestructive technique to characterize poroelastic materials: the results of ultrasonic experiments in the laboratory are used to investigate the wave propagation models in a poroelastic medium filled with fluid. The laboratory precision is required to extract, from measurements, powerful parametric models, describing the wave propagation, by mean of a frequency-domain inversion technique. The ultrasonic equipment consists of a constructed water immersion system using non-destructive testing-type transducers. In order to simulate the mechanical behavior of sediments, the device under investigation is a composite multilayer saturated with water. Immersion experiments are made at frequencies ranging from 0.3 to 3MHz. The physical parameters of the used material are estimated and attention is paid to the evolution of the phase-velocity dispersion and the absorption over the frequency band.

I. INTRODUCTION

In the last few years, high interest has been dedicated to model the acoustic wave propagation in a saturated porous medium. A saturated porous medium is a medium formed by the interpretation of two phases. One of them is the solid phase and constitutes the matrix of the material concerned, and the second is the liquid phase, constituting the saturated fluid. This interpretation can occur in two different ways, shown schematically in Fig. 1a and Fig. 1b, respectively. In the first case, a discontinuity exists in the liquid phase, consisting of a group of disconnected pores, with continuity of the solid phase. In the second case, both the liquid and solid phases are continuous. The combination of these two cases is also possible [1]. In dealing with the problem of acoustic wave propagation in saturated porous media, two approaches are possible: the first approach draws on homogenization processes [2-5], which helps to pass from microscopic laws to macroscopic laws. Note that two homogenization methods essentially exist. One of them is based on an averaging process. This procedure was used by Biot [2]. The second homogenization method relies on the assumption of periodic repetition of the microscopic heterogeneous structure. This method has been used successfully in recent years, [3],[4], for the problem of saturated porous media. The second approach consists in ignoring the microscopic level and assuming that the concepts and principles of continuum mechanics can be applied to measurable macroscopic values. This approach is discussed by Biot [6],[7]. In this work, the ultrasonic waves propagation in a multilayered media is parametrically modeled through the macroscopic approach. The parametric approach consists on estimating the model parameters that contains the elastic properties of the multilayer, directly from the measured data. A Maximum Likelihood Estimator (MLE) is proposed for this task. The multilayer used in this work is constructed with viscoelastic composite materials (*polyester and polyurethanes*): two layers with almost identical acoustical parameters (DF1013 100/20 and DF1013 100/40) and one layer B2900. The former layers resemble a liquid corresponding with soft sediments (mud), while the latter has high acoustic impedance simulating hard rock [8]. In order to study the broad band absorption and dispersion of the used layers, a very wide frequency band is investigated using three different piston immersion transducers. This work is organized as follows: in section II, the wave propagation model is represented both in normal and oblique incidences as well as in reflection and transmission. In section III, the inverse procedure using the Maximum Likelihood Estimator (MLE) is established. Experimental results and discussions are given in section IV. Finally, conclusions are drawn.

II. ULTRASONIC WAVES PROPAGATION

The measurement configuration is shown in Fig. 2. An immersion piston type transducer (Panametrics) generates ultrasonic waveforms that are transmitted or reflected from the investigated materials and received with a transducer of the same kind. The time domain signals are Fourier transformed and transferred to the computer for the estimation latter. These experiments are carried out through a multi-layer structure constructed from a L1 layer (DF1013 100/20) with a thickness of 1cm, followed by a second layer L2 (DF1013 100/40) with a thickness of 1.1cm, and finally a L3 layer which is a B2900 plate with a thickness of 5.7cm. The acoustic properties of the used materials are summarized in Table 1. Note that uncertainty of 10% should be taken into account on the reported values.

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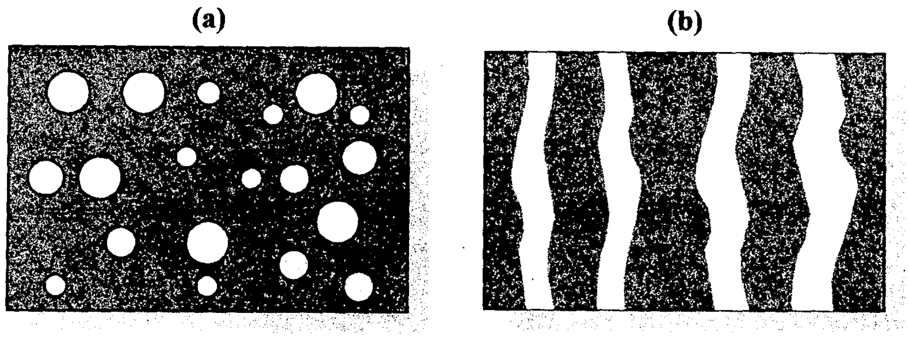

Fig. 1 Schematic diagrams of porous media
(a); The fluid phase (small ronds), is discontinuous, the solid phase (blue area) is continuous
(b): The fluid and solid phases are continuous

1) REFLECTION AND TRANSMISSION IN NORMAL INCIDENCE

The relationship between the spectra of the input and the output signals X(t) and Y(x,z,t), can be formulated for the reflection or the transmission experiments by the following formulae:

$$Y(x,z,\omega) = H^{t,r}_{prop}(P,x,z,\omega)H_T(\omega)\times H_R(\omega)X(\omega) \tag{1}$$

with $H^{t,r}_{prop}(P,x,z,\omega)$ the global transfer function describing the propagation between the emitter and the receiver in the presence of the multilayer structure (see appendix 1 for more details). The component P is the set of model parameters that includes the elastic properties of the used materials. $H_T(\omega)$ and $H_R(\omega)$ are the frequency responses of the emitter and the receiver respectively. These frequency responses should be eliminated in order to get an absolute estimation of the parameters set P. To do this, a calibration procedure is required. This calibration is just a reference measurement that should be introduced in the studied system in such manner to eliminate the frequency responses of the transducers. In that case, a simple configuration, called pitch-catch measurement that consists to measure the generated waves by removing the multilayer from the water paths, is used. The new system that should be used in the estimation process is presented in Fig. 3. The input is now the calibration measurements and the outputs are the transmission or the reflection measurements. With H^{np}_{cal} and $H^{np}_{t,r}$ are the nonparametric estimates for the calibration and the transmission or the reflection experiments, respectively. While $H^{t,r}_{p}(P,x,z,\omega)$ is the global parametric function describing the calibrated transmission or reflection through the multilayer.

III. INVERSE PROBLEM

In this section, the estimation of model parameters is elaborated using a Maximum Likelihood (ML) estimator [9]. This estimator requires the measured input and output spectra of the system under investigation as well as knowledge of the perturbing noise variances. The noise sources are assumed to be zero mean, complex normal distributed. The nonparametric estimates for calibration, H^{np}_{cal}, and for refraction, $H^{np}_{t,r}$, can be regarded, respectively, as the input

Table 1: The acoustic properties of the used materials

Material	Dilatational Velocity (m/s)	Shear Velocity (m/s)	Density (kg/m^3)
DF 1013 100/20	1500	0	1200
DF 1013 100/40	1500	0	1250
B2900	2900	1540	1900

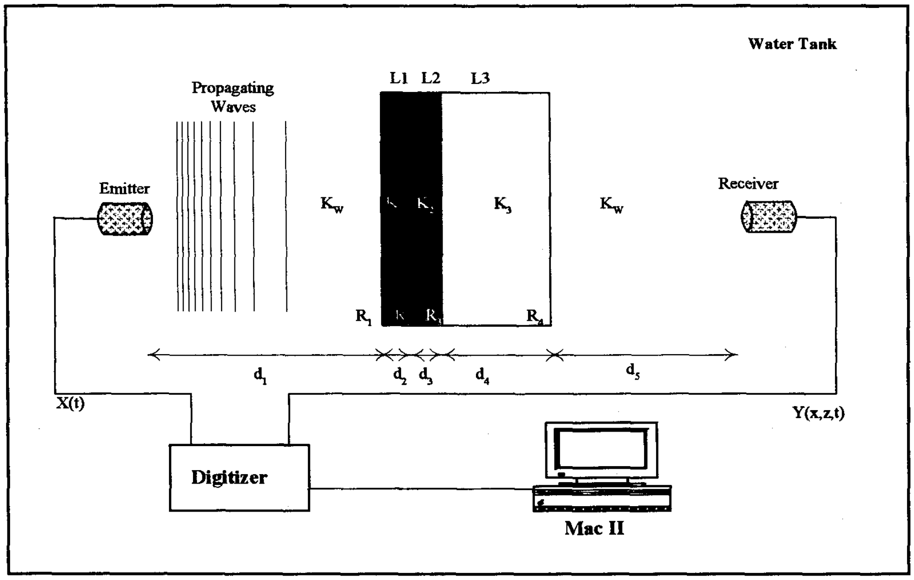

Fig. 2 Experimental Configuration

and the output of a single-input-single-output (SISO) linear system consistent with:

$$H_{t,r}^{np}(\omega) = H_P^{t,r}(P,x,z,\omega)H_{cal}^{np}(\omega) \quad (2)$$

The cost function to be minimized in ML sense for the SISO system is given by:

$$CF(\omega) = \sum_{i=1}^{F} |e(\omega_i)|^2 \quad (3)$$

with F the number of spectral lines. The error function between the measurement and the modeled transfer functions is written as:

$$e(\omega_i) = \frac{H_{cal}^{np}(\omega_i)H_P^{t,r}(\omega_i) - H_{t,r}^{np}(\omega_i)}{\sqrt{\sigma_{H_{cal}^{np}}^2(\omega_i)|H_P^{t,r}(\omega_i)|^2 + \sigma_{H_{t,r}^{np}}^2(\omega_i)}} \quad (4)$$

Equations (2) and (3) give rise to nonlinear minimization problems. In the minimization algorithm, the Levenberg-Marquardt method is incorporated to enlarge the convergence region.

IV. EXPERIMENTAL RESULTS AND DISCUSSIONS

The experimental results presented in this section are obtained for the structure shown in Fig. 2 and which is composed of two layers with almost identical parameters (DF1013 100/20) and (DF1013 100/40) and one layer (B2900). The density and the phase velocity of the composite DF1013 (polyrethane) can be changed by adapting the amount of tungsten powder. This explains the notation 100/20 and 100/40, which correspond with the amount of polyrethane and loaded tungsten powder, respectively.
Reflection and also transmission experiments are analyzed to allow a complete study of the acoustic behavior of the considered multilayer. The experimental set-up is shown in Fig. 2. A piston planar transducer (panametrics) generates ultrasonic broadband pulses that propagate in the water paths, reflect or transmit through the multilayer and so received either by the same transducer (monostatic mode) or by a

$$H_{cal}^{np} = mean(\frac{Y_{cal}(x,z,\omega)}{X_{cal}(\omega)})$$

$$H_{t,r}^{np} = mean(\frac{Y_{t,r}(x,z,\omega)}{X_{t,r}(\omega)})$$

Fig. 3 Model schematic

coaxial transducer of the same type as the emitter (bistatic mode). To cover a large frequency band, three different transducers are used to investigate the multilayer and having as central frequencies 500Khz, 1Mhz and 2.25Mhz, respectively. The digitized reflected signal through the multilayer, received from a 500Khz transducer in the time domain, is shown in Fig. 4, while the transmitted one is represented in Fig. 5.

Due to the strong absorption of the two first layers DF1013, only one multiple is present in the transmission experiment. This absorption is increasing enormously at high frequencies as it is shown in Fig. 6. With the reflected signal, the information is more present concerning the structure of the multilayer: a small reflection is created at the water/L1 interface, followed by a very weak reflection from L1/L2 interface. Next a strong reflection from the interface L2/L3 is observed. Finally, the reflection from the interface L4/water becomes very small due to the high attenuation of the ultrasonic field during propagation.

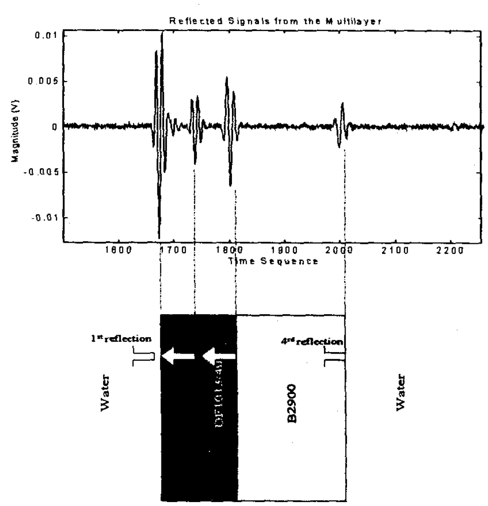

Fig. 4 Reflected signals from the multilayer in the time domain

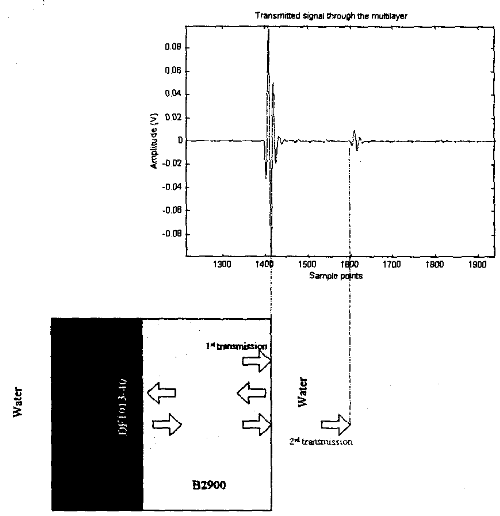

Fig. 5 Transmitted signals through the multilayer in the time domain

This reflection experiment is the only measurement containing visual information from all the interfaces, and since it corresponds to a scaled version of the real-life echosounding experiment, an estimation is carried out for this case.

The measured and estimated reflected transfer functions are depicted in Fig. 7 for a large frequency band ranging from 300Khz to 3Mhz. Even if the estimated transfer function unfit slightly the measured one at the high frequencies, good agreement can be seen at the lowest ones. This unfit in the high frequencies can be explained by the very high absorption of the first two layers that decrease considerably the value of the reflection coefficient. The estimated absorption and dispersion for the three layers are given in Fig. 8 for a frequency ranging from 300Khz to 3Mhz. It is clearly seen that the absorption on DF1013/40 is higher than that in DF1013/20 due to the different amount of tungsten injected inside. Continuation of the absorption curves in the three different bands of frequency shows that the estimated values are in the range of the real ones.

1) Oblique Experiment

To be closer to the real life measurements taking place at the sea, it is more convenient to investigate the material at the oblique incidence. A rotation scan around the multilayer structure is carried out from 20° to 90° with a step of 1° in reflection mode. The reflected signals are represented in Fig. 9 versus the time sequence (sample points) and the incident angles, respectively for the case of 500Khz transducer. It is shown from the figure that the multiple reflections present at smaller incident angles disappear at the higher ones due to the increase of the propagation paths in the spatial domain. A direct wave coming directly from the emitter can be seen by the receiver in the higher angles due to the large aperture of the transducers. Using the previous estimated parameters of the multilayer structure, the reflection coefficient is calculated.

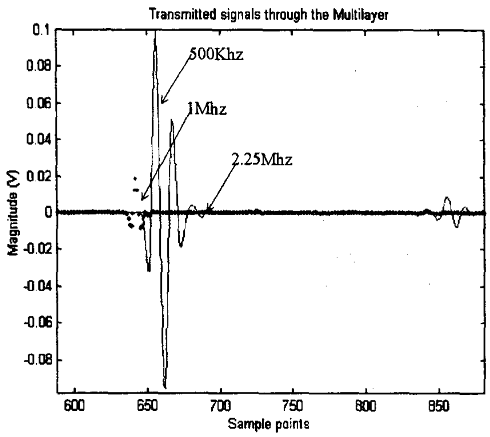

Fig. 6 Transmitted signals through the multilayer for three different emitters

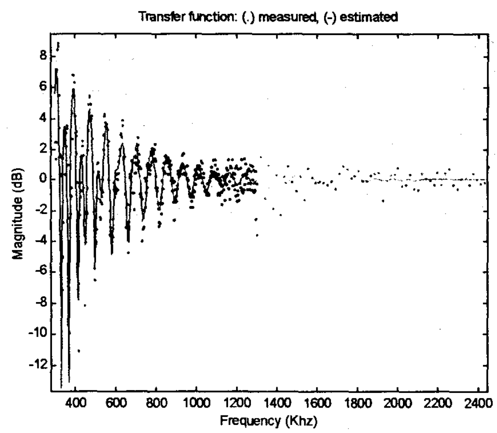

Fig. 7 Broad frequency estimated and measured reflected signals from the multilayer

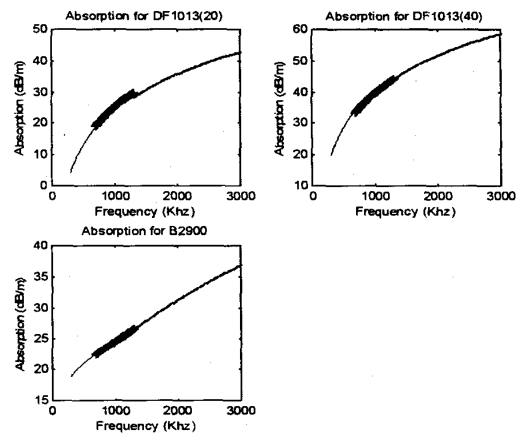

Fig. 8 Estimated absorption for the three layers of the material over a large frequency band

Comparison is made with the measured one. The two profiles are shown in Fig. 10. It is seen from the figure that good accordance between the two profiles is carried out with an increase of divergence at high frequencies. That is due to the loss of information caused by the high absorption at these frequencies that causes an inaccuracy on the estimation of material properties.

V. CONCLUSIONS

Performing reflection experiments on the multilayer corresponds with a scaled test for the marine echosounding experiments: the first two layers simulate the behavior of fluid-like-sediments while the third layer model a semi-infinite elastic medium. Using the ML estimator in the inverse problem, one can retrieve with acceptable uncertainties, due to the complexity of the system, the acoustic parameters of the multilayer. As a validation for the quality of the estimation, the continuity of the estimated absorption in the three layers over the large frequency band, that use three different transducers, is shown (Fig. 8). Another validation for this quality is the comparison made between the measured reflected profile from the multilayer, at different incident angles, and the calculated one using the previous estimated parameters (Fig. 10).

The simulation, on reduced models, of the acoustic propagation problems in the real seafloor present a lot of advantages. A part its economical benefit, since it does not require heavy means necessary in the sea, it gives an experimental mean to validate theoretical models and the possibility to analyze some parameters that one can change at will, which is not possible when measuring in the sea.

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APPENDIX 1

At the normal incidence, the calibrated transfer function $H_p^{t,r}(P,x,z,\omega)$ cited in (2) can have two expressions according to the transmission or reflection experiment (see Fig. 2):

$H_p^t = \frac{N_t}{D}$ or $H_p^r = \frac{N_r}{D}$ with numerators:

$$N_t = T_1T_2T_3T_4 e^{-jK_w(d_1+d_5)} e^{-jK_1d_2} e^{-jK_2d_3} e^{-jK_3d_4} \quad (A1)$$

for the transmission, or:

$$N_r = e^{-2jK_w d_1}(R_1 + T_1R_2e^{-2jK_1d_2} + T_1T_2R_3e^{-2jK_1d_2} \times e^{-2jK_2d_3} + T_1T_2T_3R_4e^{-2jK_1d_2}e^{-2jK_2d_3}e^{-2jK_3d_4}) \quad (A2)$$

for the reflection.

The common denominator is given by:

$$D = e^{-jK_w(d_1+d_2+d_3+d_4+d_5)} \quad (A3)$$

that corresponds to the measurement in the water columns by removing the multilayer.

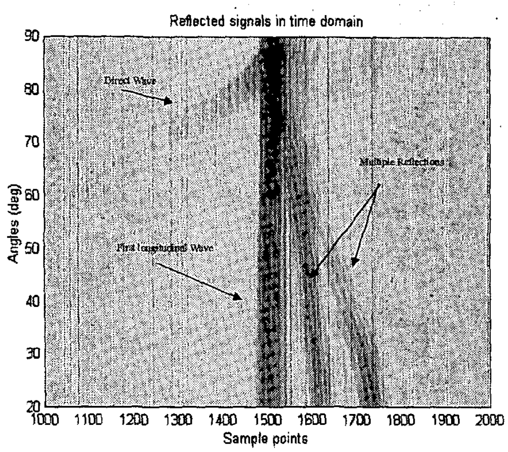

Fig. 9 Reflected signals from the multilayer for incident angles ranging from 20° to 90°

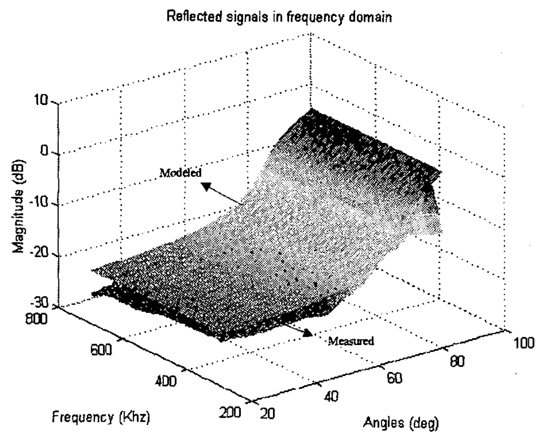

Fig. 10 Estimated and measured reflected signals from the multilayer

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