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Magnitude and phase spectral analysis of through-transmitted ultrasound pulses for the determination of the ultrasound velocity and the thickness of solid plates.

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Abstract

A method that combines transmission of air-coupled ultrasound pulses through solid plates and magnitude and phase spectral analysis is presented. The purpose is to determine, simultaneously, velocity and attenuation coefficient of the ultrasounds in the material, and the thickness and the density of the plate. This is especially useful when thickness can not be measured independently and it is necessary to obtain estimations for the velocity and the attenuation coefficient of ultrasounds in the plate.

Keywords: air-coupled ultrasound, magnitude and phase spectroscopy, plate resonances, materials characterization

1. Introduction.

Thickness resonances of solid plates have been largely used in the context of air-coupled ultrasound with the purpose to increase the amount of transmitted energy and improve the signal to noise ratio [1]. The first thickness resonance appears at frequency given by: v/2h, where v is the velocity of sound in the plate and h is the thickness. So if we have the proper combination of transducer frequency band, ultrasound velocity in the material and plate thickness, we can observe such resonances.

Later, these resonances have been used to study the properties of the solid material. The most basic approach is to get an independent measurement of the thickness, and then work out the velocity of the ultrasounds in the solid from the relation given above. A more complete characterization of the solid can be obtained from the analysis of the whole resonance curve and not only from the location of the frequencies of maximum transmission. Fitting theoretically calculated transmission coefficient to the experimental data permits us to obtain velocity and attenuation coefficient of ultrasounds in the plate as well as its density. This procedure is explained in detail in [2] and [3] and has been used successfully to study polymeric porous membranes, silica aerogels and paper.

An important limitation of this method is that the thickness of the plate must be independently measured. In some cases this is either not possible or not accurate enough. For example, in the case of very soft and thin membranes the

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relative error produced in the determination of the thickness using conventional techniques can be very large. In other cases, like in the study of water content and drying dynamic of some vegetables, the thickness depends on the water content and the sample can not be manipulated during the drying cycle to measure its thickness. Finally, in the context of ultrasonic NDT of plates having a large surface, possible thickness variations has to be considered when A-scans are going to be performed and analyzed, however, it is completely unpractical to measure the thickness of the plate along the A-scan. However, if both magnitude and phase spectra of the transmission coefficient are simultaneously measured, and not only the magnitude spectrum, it is possible to overcome this problem and to obtain, simultaneously, both ultrasound velocity and plate thickness without the need of any other measurement. In some cases, where the signal to noise ratio is good enough, the phase spectra can be sufficient for this objective, that is, velocity of ultrasounds in the plate and thickness can be obtained from the phase spectrum of the transmission coefficient without the information of the magnitude. The purpose of this work is to explain the procedure and to apply it to several cases of interest

2. Experimental set-up and procedure.

The experimental set-up consists of an ultrasonic transmitter and a receiver specially designed for efficient transmission/reception to/from the air, (air-coupled transducers) in the frequency range 0.1-5 MHz. The transducers are positioned in opposition. Transmitter is driven by a negative square semi cycle tuned to the centre frequency of the transducers and generated by a Pulser/Receiver (Panametrics 5077 P/R). So it launches an ultrasonic signal that travels across the air-gap between transmitter and receiver transducer and is eventually received by the receiver. This converts the ultrasonic signal into electrical, it is then amplified and filtered by the Receiver section. Afterwards, it is displayed and digitized in a digital oscilloscope (Tektronix DPO 5074).

The measuring procedure is as follows. First, the signal received without any sample is stored as reference, both in the time domain and in the frequency domain. Towards this end, we applied a real time FFT algorithm and obtained both magnitude and phase spectra of this signal. The signal is centered within this temporal window so that the phase spectrum is rather flat. Then the sample is put in between the transducers at normal incidence, and the procedure is repeated, hence we calculate the phase shift ($\Delta\phi$) and the insertion loss. When the sample is thick enough (or its velocity is sufficiently different from the velocity of the surrounding air) the temporal window is shifted so that the signal is again centred in the temporal window. This time shift is conveniently registered because it is necessary to obtain velocity and thickness of the plate (see section 4.3). Although this time shift is not necessary for the calculations, this provides a clearer graphical representation of the effect of the thickness resonance on the phase spectrum. This is the only reason to introduce such time shift in this work.

Three pairs of special air-coupled transducers with centre frequency of 0.25, 0.75 and 2.00 MHz were designed and constructed. These transducers present some modifications with respect to those described in Ref [3] and are similar to those of Ref. [4], though higher frequencies are considered here. Active element is a 1-3 piezocomposite disk made of piezoelectric fibres embedded in an epoxy matrix (65% vol. concentration of ceramic). Matching to the air is achieved by attaching a stack of three quarter-wavelength matching layers. The first one made of epoxy resin (acoustic impedance Z = 2.6 MRayl, and attenuation coefficient at the resonant frequency α = 20 Np/m at 0.25 MHz), the second made of cardboard (Z ≈ 0.5 MRayl, α ≈ 300 Np/m), the third one is a porous membrane (Z = 0.075-0.3 MRayl, α = 300-500 Np/m) as proposed in Ref. [3]. Use of electrostatic transducers can be an interesting option in this case, for they can provide a larger bandwidth than piezoelectric transducers [1], [5].

3. Theoretical relations.

When the transmission through the plate is composed only by the through transmitted signal (i.e. the contribution of the reverberations inside the wall are negligible or can be filtered out in the time domain) and given the experimental set-up described above, then the velocity of the wave in the plate is given by:

$$v(\omega) = \frac{h}{h/v_f - (t_0 - t)} \qquad (1)$$

where h is the thickness of the sample and v_f is the velocity in the fluid (in this case 340 m/s), t_o the time of arrival of the signal when there is no sample between transducers and t the time of arrival when the sample is put in between the transducers.

In this case, the phase shift ($\Delta\phi$) is directly related to the difference in the time of arrival (Δt) of the wave in the plate, so we can calculate the phase velocity from the phase shift ($\Delta\phi$):

$$v(\omega) = \frac{h}{h/v_f - \Delta\phi/\omega} \tag{2}$$

where ω is the angular frequency. This is the procedure employed in Ref. [5] and [6] which is similar to the well known method of Sachse and Pao [7]. In this case, and if the material of the plate is non-dispersive, phase spectra vs. frequency consist of a straight line whose slope is given by ωt. (this is the blue line that appears in Fig. 1)

Presence of reverberations inside the plate modifies this situation. Amplitude ratio of transmitted to incident wave potentials for normal incidence is given by [8]:

$$\xi = \frac{-2Z_1Z_2}{2Z_1Z_2\cos(kt) + i(Z_1^2 + Z_2^2)\sin(kt)} \tag{3}$$

where Z_1 and Z_2 are the acoustic impedances of the plate and the surrounding fluid and k the wave number. The appearance of a complex magnitude (ξ) implies that the transmitted and incident waves are not in phase. This change of phase is produced by the ultrasound reverberations within the plate. As an example, Fig. 1 shows the calculated ultrasonic transmission coefficient for a plate whose properties are: density: 500 Kg/m^3, phase velocity: 600 m/s, and thickness: 140 μm. Two different cases (corresponding to two different attenuation values) are presented. The phase spectrum for the case of negligible reverberations is also shown.

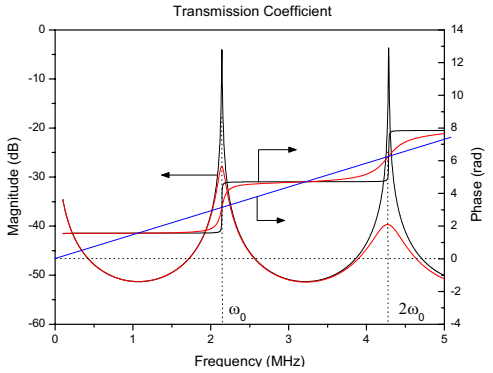

Fig.1 Calculated magnitude and phase spectra of the ultrasonic transmission coefficient of a plate (density: 500 Kg/m^3; phase velocity: 600 m/s; thickness: 140 μm) vs. frequency. Black line: material of the plate with constant attenuation coefficient (10 Np/m). Red line: attenuation coefficient with linear variation with frequency, attenuation at 1 MHz equals 100 Np/m. Blue line: phase spectra in absence or reverberations inside the plate.

This makes impossible to use the methods of [5] and [6] to determine the phase velocity from phase spectrum measurements. However, at resonance condition (kt=nπ, n=0, 1, 2, …, where we get maximum transmission) ξ is

real valued (if dissipation in the plate can be neglected). Then Eq 3 also holds at resonance. This can be seen in Fig. 1. At resonance, both phase spectra with and without reverberations coincide. That is, at resonance we have:

$$v(\omega_o) = \frac{h}{h/v_f - \Delta\phi_o/\omega_o} \tag{4}$$

$$v(\omega_o) = 2\omega_o h/2\pi \tag{5}$$

where ω_o is the first order resonant frequency and ϕ_o is the phase shift measured at ω_o. The value of ω_o is obtained either from the frequency location of the maximum of the magnitude of the transmission coefficient or from the point of inflection of the phase spectrum. The frequency of maximum transmission is, in general, more easily measured than point of inflection of the phase spectrum, however, when this later can be measured (especially in the case of low attenuating materials), then the information of the magnitude spectrum is redundant in what concerns the determination of the ultrasound velocity in the plate and the thickness. Finally, we get two Equations (4 and 5) that can be solved for two unknowns given: velocity and thickness.

4. Materials.

4.1. Thin and soft membranes

First, the possibility to use this technique to determine the properties of two different highly porous membranes is analyzed. The first is a polyetersulfone membrane that exhibit low acoustic impedance and low attenuation coefficient. The second is a thicker cellulose membrane that has larger acoustic impedance and much larger attenuation coefficient. This larger attenuation coefficient gives rise to a spectral response of the thickness resonance that is heavily damped. Even in this case the method can be successfully applied. In this case, the interest of determining the thickness using a non-contact ultrasonic technique is due to the soft character of these materials and the thickness of these membranes (about 150 μm). Thickness measured with a conventional micrometer may produce large inaccuracies due to the small but significant deformation of the material under the pressure of the micrometer and to the irregular surface. For some extremely soft materials, like silica aerogels or some very soft polymeric membranes, the use of a micrometer can even damage the surface of the material. The two materials selected in this case do not present any of these problems and have been selected with the purpose to check the accuracy of this method by comparing the thickness measured with this technique with the thickness measured with a micrometer.

Figures 2 and 3 show the magnitude and the phase spectrum of the ultrasonic transmission coefficient of the polyethersulfone membrane and the cellulose membrane, respectively. In both cases theoretical calculations and experimental data are shown.

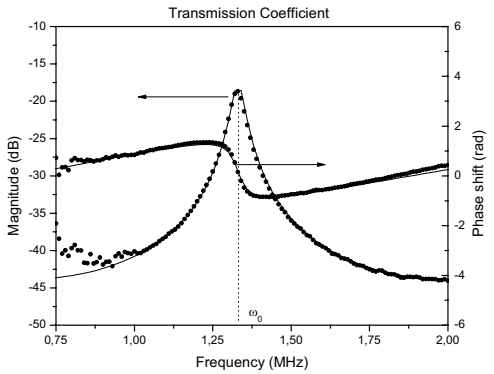

Fig.2 Magnitude and phase shift spectra of the ultrasonic transmission coefficient of a polyethersulfone membrane. Dots: experimental data. Solid line: theoretical data from Eq. 3

The influence of the larger attenuation of the cellulose membrane can be clearly appreciated in Fig. 3. In this case, the location of the resonance has to be determined from the theoretical curve. On the other hand, in Fig. 2, the resonance is so clear, that the location of the resonance can be directly determined from the location of the point of inflection in the phase spectrum curve.

Table1 shows the material parameters obtained from the fitting of the experimental data to the theoretical results given by Eq. 3. Velocity and thickness are calculated using the proposed procedure. In addition, the thickness measured with a micrometer is also shown. It can be seen that differences between the two thickness values are small and are within the experimental error range of the micrometer.

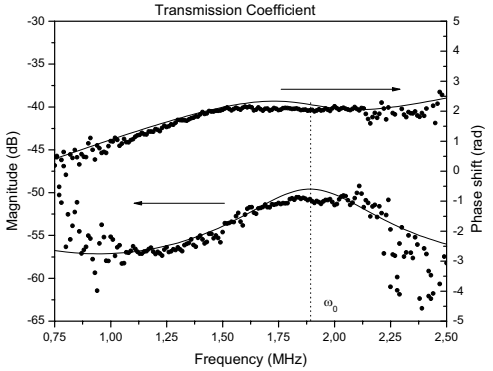

Fig.3 Magnitude and phase shift spectra of the ultrasonic transmission coefficient of a Cellulose membrane. Dots: experimental data. Solid line: theoretical data from Eq. 3

Table1. Ultrasonic properties of the membranes

Sample	Density (Kg/m^3)	Attenuation coefficient (Np/m)	Velocity (m/s)	h (μm)	h* (μm)
PES	354	435	357.5	134.4	140
Cel	950	3000	567	141.8	135

h: thickness measured with the proposed method

h*: thickness measured with a micrometer.

4.2. Wet vegetable sample.

Ultrasonic study of the drying of different vegetables, in particular, of the variation of the moisture content, was developed by [9] and [10]. The ultrasonic transmission coefficient of thin slices of different vegetables was measured along the drying process being possible to determine the properties of the vegetable at different stages from the analysis of the first thickness resonance. In this case, an important problem arises from the fact that the thickness of the vegetable slice is reduced during the drying process as a consequence of the loss of water. Then the use of the thickness resonances of the ultrasonic transmission coefficient to determine the material properties has to be accompanied by an independent measurement of the thickness of the plate. This is, in most of the practical situations, not possible. Hence, in the context of the determination of water content and other mechanical properties of some porous vegetables it is important the possibility to determine simultaneously both ultrasonic velocity and plate thickness from the same ultrasonic measurement.

To illustrate the applicability of the method it is employed to determine the properties of the leaf of a black poplar in the first stages of drying. Measured and calculated magnitude and phase of the ultrasonic transmission coefficient are shown in Figs. 4 and 5. In Fig 4 the response of the water-saturated leaf is shown, while Fig. 5 corresponds to the response of the same leaf after leaving it to dry for 3 min. at room conditions. In this case, see

Figs. 4 and 5, it is possible to determine the frequency value for the first thickness resonance from the point of inflection of the phase spectra curve.

Similarly to what happens with the evolution of the ultrasonic transmission coefficient of wet polymeric porous membranes during drying [9], as the vegetable looses water, the attenuation coefficient increases and the location of the resonance is shifted towards lower frequencies. This is due to the loss of elasticity produced by the loss of water content. Calculated parameters are shown in Table2. Thickness is reduced as a result of the loss of water, this is an expected behaviour, moreover, the density remains constant, that is, the loss of water is compensated by the volume decrease.

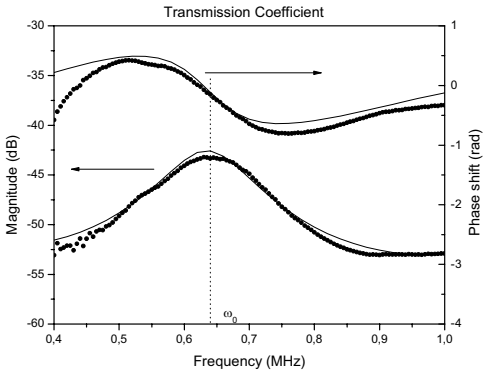

Fig.4 Magnitude and phase shift spectra of the ultrasonic transmission coefficient of a black poplar leaf at water saturation. Dots: experimental data. Solid line: theoretical data from Eq. 3

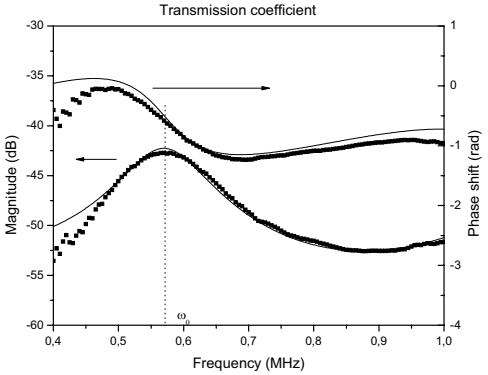

Fig.5 Magnitude and phase shift spectra of the ultrasonic transmission coefficient of a black poplar leaf after drying for 3 minutes. Dots: experimental data. Solid line: theoretical data from Eq. 3

Table2. Ultrasonic properties of the leaf

Sample	Density (Kg/m^3)	Attenuation coefficient (Np/m)	Velocity (m/s)	h (μm)
1	1050	1300	324	253
2	1050	1400	277	240

4.3. Thick FRP-plates

Finally, the proposed method is applied to a plate sample of fibre reinforced polymer (FRP), in particular, epoxy resin reinforced with glass fibres. This material is used in civil engineering for the construction of structural components (Ref. [11]). Unlike composite materials used in the aeronautical industry, in this case the structure is coarser and the plates may have significant variations of the thickness. Therefore, an A-scan of such a plate must include information of the actual plate thickness in each point, in order to correctly interpret the measurements, so a conventional method may become unpractical. The advantage of the method proposed here is that the thickness in each point can also be obtained from the ultrasonic measurements.

Figure 6 shows the transmitted ultrasonic signal from the transmitter to the receiver with and without the FRP-plate in between them. It can be clearly appreciated that when the sample is in between the transducers the signal arrives before. This is because velocity in the FRP panel is considerably larger than the velocity in the air. This time shift produces a drift in the phase spectra that can be compensated by displacing, in the time domain, the temporal window used to perform the FFT of the signal. This is the procedure followed in this section.

The ultrasonic transmission coefficient (magnitude and phase) of the FRP-composite plate is measured in nine different sample points. Obtained properties following the procedure here described are collected in Table3.

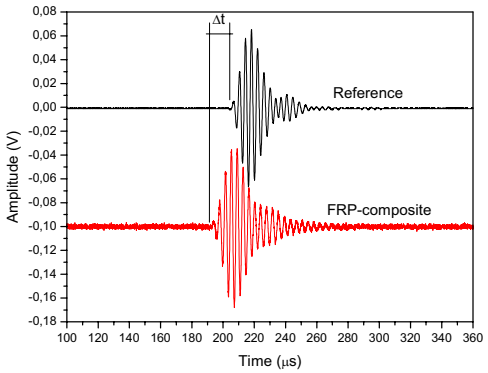

Fig.6 Signal transmitted from the transmitter to the receiver transducer. Black line: no sample between them. Red line: FRP-composite plate between them (gain of 78 dB).

Table3. Ultrasonic properties of the FRP plate

Point	Density (Kg/m^3)	Attenuation coefficient (Np/m)	Velocity (m/s)	h (mm)
#1	2200	40	2599	4.80
#2	2200	25	2616	4.85
#3	2200	45	2499	4.97
#4	2200	30	2675	4.78
#5	2200	25	2788	4.87
#6	2200	30	2759	4.88
#7	2200	30	2643	4.95
#8	2200	30	2643	4.95
#9	2200	30	2703	5.05

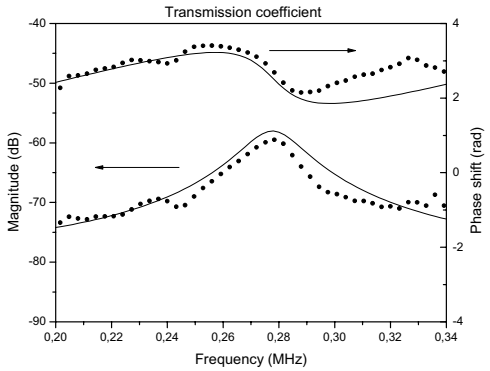

Fig.7 Magnitude and phase shift spectra of the ultrasonic transmission coefficient of a FRC panel. Composite #2. Dots: experimental data. Solid line: theoretical data from Eq. 3.

Figures 7-11 show the ultrasonic transmission coefficient of the FRP-composite plate in different points. It can be appreciated the significant variations of the properties of the plate, in some cases, the lack of parallelism of the faces of the plate produces a significant distortion of the resonance peak (especially in Figs. 7 and 8).

Especially interesting can be the comparison of measurements obtained in points 3, 6 and 9 (see Table3) and Figs. 8-10. In points 6 and 9 material seems to have the same properties, but a different thickness, however, in point 3, attenuation is significantly larger and velocity smaller, this indicates the presence of a defect. To distinguish between the differences in these three points and the possibility to discern that there is a defect in point 3 is only possible thanks to dispose of the simultaneous determination of the thickness.

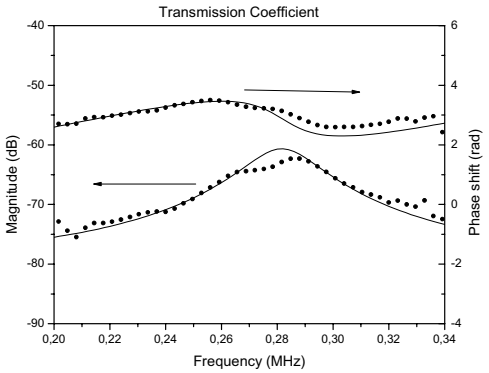

Fig.8 Magnitude and phase spectra of the ultrasonic transmission coefficient of a FRC panel. Composite #3. Dots: experimental data. Solid line: theoretical data from Eq. 3

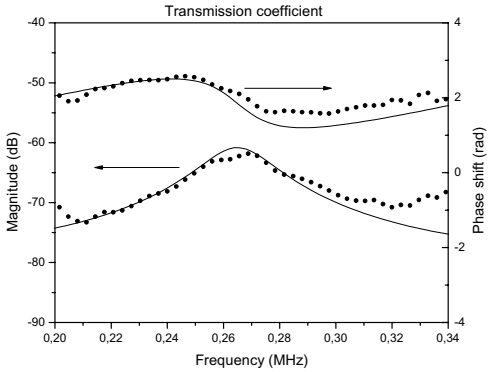

Fig.9 Magnitude and phase shift spectra of the ultrasonic transmission coefficient of a FRC panel (#6). Dots: experimental data. Solid line: theoretical data from Eq. 3

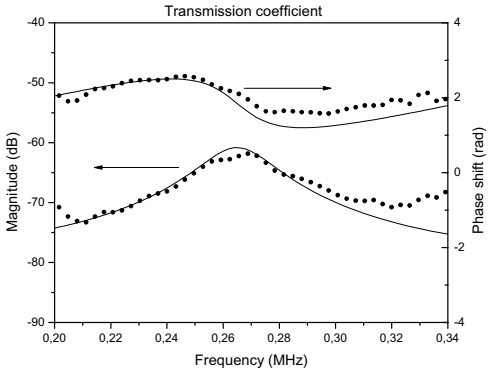

Fig.10 Magnitude and phase shift spectra of the ultrasonic transmission coefficient of a FRC panel composite #9. Dots: experimental data. Solid line: theoretical data from Eq. 3

5. Conclusions

A method to determine both velocity of sound and thickness of solid plates from the analysis of the ultrasonic transmission coefficient (both phase and magnitude spectra) is presented. In particular, air-coupled ultrasound is used to determine the ultrasonic transmission coefficient, though it can also be applied to water immersion measurements.

When the attenuation in the plate is low enough, it is sufficient with the analysis of the phase spectrum to determine both ultrasound velocity and plate thickness. The information of the magnitude spectrum can then be used to determine other properties: attenuation coefficient and plate density. However, when the attenuation is large, both phase and magnitude spectra have to be used to determine ultrasound velocity and plate thickness.

The method is applied to three different kind of materials: A. soft membranes, B. Wet vegetable during the drying process, C. FRP-composites used in civil engineering applications. In the first case, thickness measurement employing a micrometer may result inaccurate because the membrane can be deformed by the micrometer, or the surface roughness can affect the measurements, in some extreme cases, the membrane can even be broken. In the second case, measurement of the thickness of a vegetable during drying is not possible because the sample can not

be manipulated during this process without altering it. This non-contact ultrasonic technique is especially interesting in this case. Finally in the third case, it results unpractical to perform thickness measurements in all points of the plate in order to properly interpret the results of an ultrasonic A-scan. This technique permits, from the ultrasonic measurement, to get directly the thickness.

In all studied cases, it was possible to determine the thickness of the plate. In the first case studied, this value is compared with independent thickness measurements and the agreement is good.

Acknowledgements

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