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Simultaneous determination of the ultrasound velocity and the thickness of solid plates from the analysis of thickness resonances using air-coupled ultrasound

Tomás E. Gómez Álvarez-Arenas *

Ultrasonic Signals, Systems and Technologies Dept., Instituto de Acústica, CSIC, Serrano 144, 28006 Madrid, Spain

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ABSTRACT

A method that combines transmission of air-coupled ultrasound pulses through solid plates and amplitude and phase spectral analysis is presented. In particular, the method analyzes the first thickness resonance of the plates. The purpose is to determine, simultaneously, velocity and attenuation coefficient of the ultrasounds in the material and the thickness of the plate. This is especially useful when thickness can not be measured independently. The method is successfully applied to soft membranes, biological samples and FRP composites.

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 to improve the signal-to-noise ratio [1,2]. The first thickness resonance appears at a frequency given by the following relation:

$$v(\omega_o) = 2\omega_o h/2\pi \quad (1)$$

where v is the velocity of sound in the plate, ω the angular frequency and h is the thickness. So if the proper combination of transducer frequency band, ultrasound velocity in the material and plate thickness is given, thickness resonances are observed.

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 vs. frequency curve. This procedure is explained in detail and used in [3] and [4] and has been successfully used 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.

However, if both amplitude and phase spectra of the transmission coefficient are simultaneously measured, it is possible to overcome this problem and to obtain, simultaneously, both ultrasound velocity and plate thickness without the need of any other measurement.

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. The transducers are positioned in opposition. Transmitter is driven by a negative square semi cycle tuned to the centre frequency of the transducers. 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. Afterwards it is displayed and digitized in a digital oscilloscope.

* Tel.: +34 91 561 8806; fax: +34 91 411 7651.
E-mail address: tgomez@ia.cetef.csic.es

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The measuring procedure is as follows. First the signal received without any sample is acquired and FFT (amplitude: $A_0(\omega)$ and phase $\phi_0(\omega)$) is calculated and stored as reference. The signal is centred 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 amplitude and phase spectra are again measured ($A(\omega)$ and $\phi(\omega)$, respectively), hence we calculate the phase shift ($\Delta\phi = \phi(\omega) - \phi_0(\omega)$) and the insertion loss (IL) as $IL = 20\log(A(\omega)/A_0(\omega))$. 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 accounted for together with phase shift in order to calculate the velocity in the sample (see Section 3). Although this not strictly necessary, this provides a clearer graphical representation of the effect of the thickness resonance on the phase spectrum.

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. [4] and are similar to those of Ref. [5]. 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 $\alpha = 20$ Np/m at 0.25 MHz), the second made of cardboard ($Z \approx 0.5$ MRayl, $\alpha \approx 300$ Np/m), the third one is a porous membrane ($Z = 0.075$–0.3 MRayl, $\alpha = 300$–500 Np/m) as proposed in Ref. [4].

As an example, Fig. 1 shows the reference signal (centre frequency of the transducers: 2.0 MHz, 1.5 cm separation, 100 V excitation – semi cycle of a negative square wave – 0 dB amplification and 20 times averaged) and the measured signal for the polyethersulfone (PSU) membrane studied in Section 4.1, (same conditions, but 40 dB amplification).

3. Theoretical relations

When the transmission through the plate is only composed 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:

$$v(\omega) = \frac{h}{h/v_f - (t_0 - t - t')} = \frac{h}{h/v_f - \Delta\phi/\omega + t'} \tag{2}$$

where h is the thickness of the sample and v_f is the velocity in the fluid (in this case 340 m/s), t_0 the time of arrival of the signal when there is no sample between transducers, t the time of arrival when the sample is put in between the transducers, t' the time shift introduced in the received signal so that it is centred in the time window, $\Delta\phi$ is the phase shift and ω is the angular frequency. In this paper $t' \neq 0$ only in the case of the thick composite plate (Section 4.3). This is the procedure employed in Refs. [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 plot consists of a straight line whose slope is given by t (this is the dotted line that appears in Fig. 2).

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 and makes impossible to use the methods of [5] and [6] to determine the phase velocity from phase spectrum measurements. This is illustrated in Fig. 2. However, at resonance condition (Eq. (1)) ξ is real valued (if dissipation in the plate can be neglected). Then Eq. (2) also holds at resonance. This can be seen in Fig. 2: at resonance, both phase spectra with and without reverberations coincide. Hence, at resonance, Eq. (2) also holds. The magnitudes to be measured are then the frequency of maximum transmission (or alternatively the point of inflection of the phase spectrum) and the phase at this frequency. Finally, with these two measurements, Eqs. (1) and (2) can be solved for the

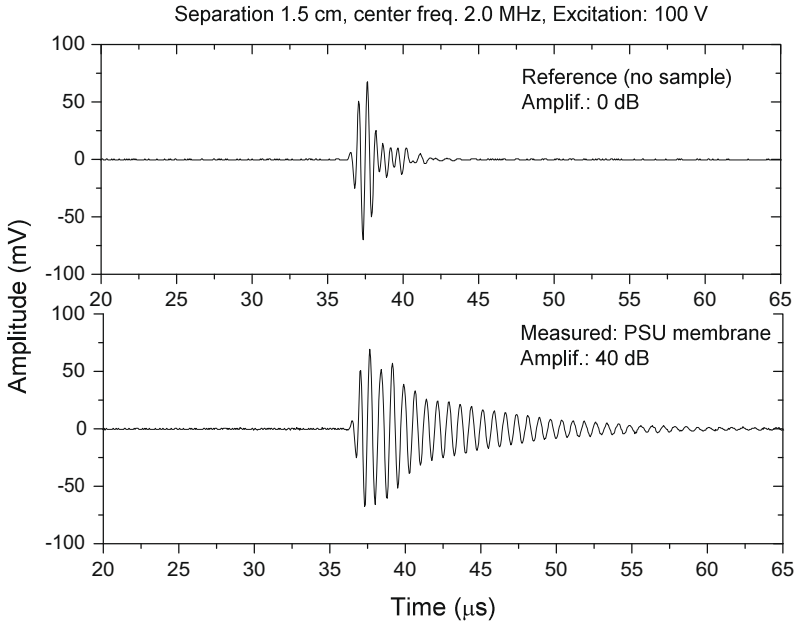

Fig. 1. Transmitted signal from transmitter transducer to receiver in the time domain. Up: reference signal (no sample), down: transmitted signal through the PSU membrane.

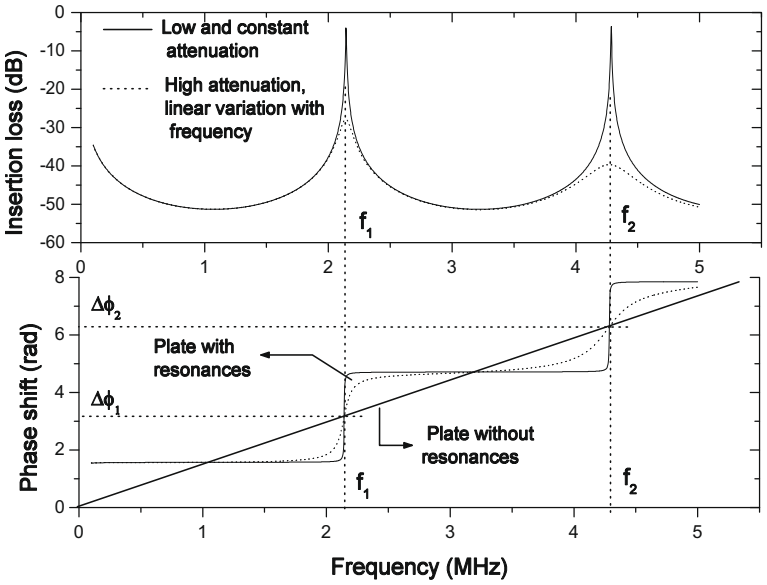

Fig. 2. Calculated amplitude (insertion loss) and phase spectra of the ultrasonic transmission coefficient of a plate (density: 500 kg/m^3; phase velocity: 600 m/s; thickness: 140 μm) vs. frequency. Solid line: material of the plate with constant attenuation coefficient (10 Np/m). Dashed line: attenuation coefficient with linear variation with frequency, attenuation at 1 MHz equals 100 Np/m.

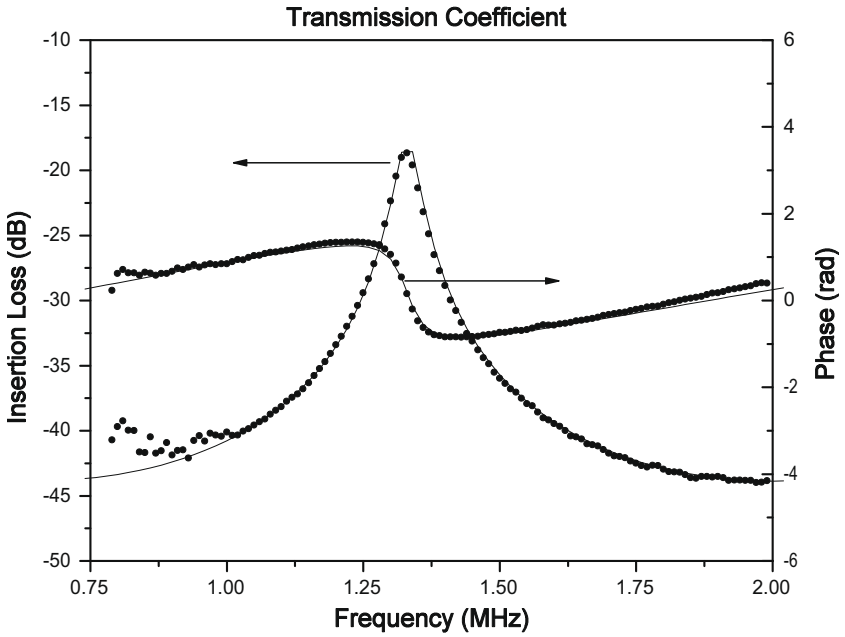

Fig. 3. Amplitude (insertion loss) and phase shift spectra of the ultrasonic transmission coefficient of a polyethersulfone membrane. Dots experimental data. Solid line: theoretical data from Eq. (3).

two unknowns given: velocity and thickness. When dissipation in the plate can not be neglected, frequency location of the resonance is displayed away from the theoretical value given by Eq. (1). To account for this fact, these values of velocity and thickness have to be introduced in Eq. (3), and then attenuation is introduced by fitting the theoretically calculated resonance (Eq. (3)) to the experimentally measured one.

4. Materials

4.1. Thin and soft membranes

A polyetersulfone (PSU), and a cellulose (CEL) membrane have been studied. In this case, the interest of determining the thickness using a non-contact ultrasonic technique is due to the soft character 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. The CEL-membrane has a larger impedance value and attenuation coefficient than the PSU-membranes. This gives rise to a more damped spectral response of the thickness resonance and a poorer signal-to-noise ratio. Even in this case the method can be successfully applied.

Figs. 3 and 4 show the amplitude and the phase spectra of the ultrasonic transmission coefficient for these membranes. In Fig. 3, PSU-membrane, the resonance is so clear, that the location of the resonance can be directly determined from the location of

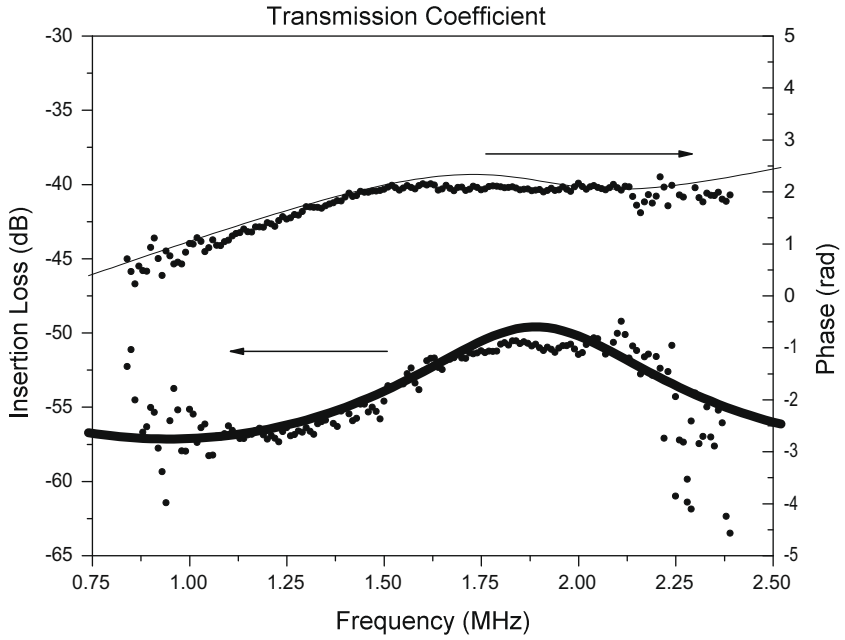

Fig. 4. Amplitude (insertion loss) and phase shift spectra of the ultrasonic transmission coefficient of a cellulose membrane. Dots experimental data. Solid line: theoretical data from Eq. (3).

Table 1
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.

the point of inflection in the phase spectrum curve. Table 1 shows the material parameters obtained from the fitting of the experimental data to the theoretical results given by Eq. (3). 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.

4.2. Wet vegetable sample

Ultrasounds have also been used for the study of the drying of different vegetables (see, for example, Ref. [9]). The ultrasonic

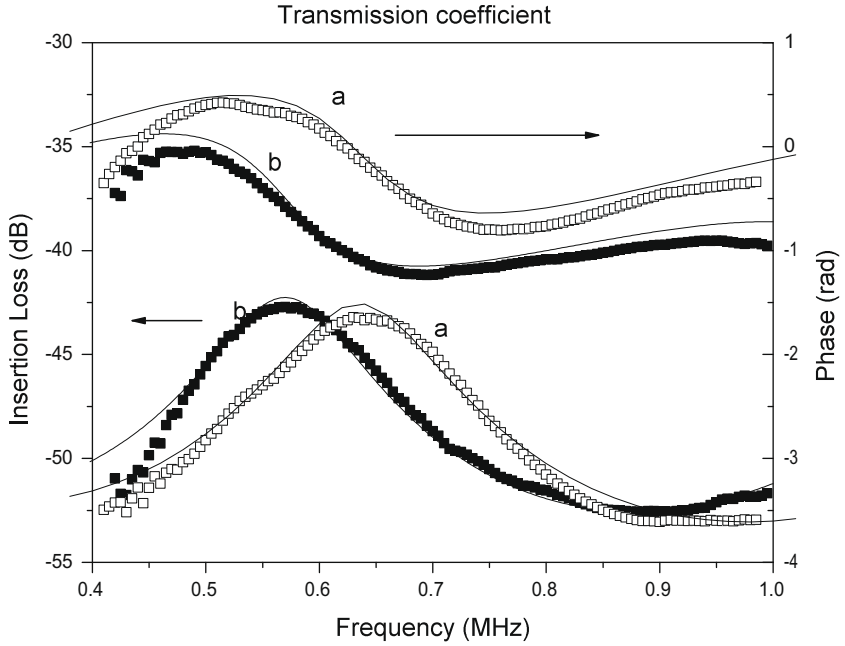

Fig. 5. Amplitude (insertion loss) and phase shift spectra of the ultrasonic transmission coefficient of a black poplar leaf. (a): water saturation, (b): after drying for 10 min at room conditions. Dots experimental data. Solid line: theoretical (Eq. (3)).

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 leaves of a black poplar in the first stages of drying. Measured and calculated amplitude and phase of the ultrasonic transmission coefficient are shown in Fig. 5. The responses of a leaf in the state of water saturation and after leaving it to dry for 10 min at room conditions are shown.

Calculated parameters are shown in Table 2. 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. In addition, 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 rigidity produced by the loss of water content.

Table 2
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

Table 3
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

4.3. Thick plates

Finally, the proposed method is applied to a plate sample of fibre reinforced polymer (FRP), in particular, epoxy resin reinforced with glass fibres. Fibres are oriented in the plane of the plate at two different directions at 90°. This material is used in civil engineering for the construction of structural components (Ref. [10]). 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, otherwise the 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.

The ultrasonic transmission coefficient (amplitude and phase) of the FRP-composite plate is measured in nine different points. Measured density, attenuation coefficient, v and h are collected in Table 3. Fig. 6 shows the ultrasonic transmission coefficient of the FRP-composite plate in two different points (6 and 9). 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 interesting can be the comparison of measurements obtained in points 3, 6 and 9 (see Table 3). 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,

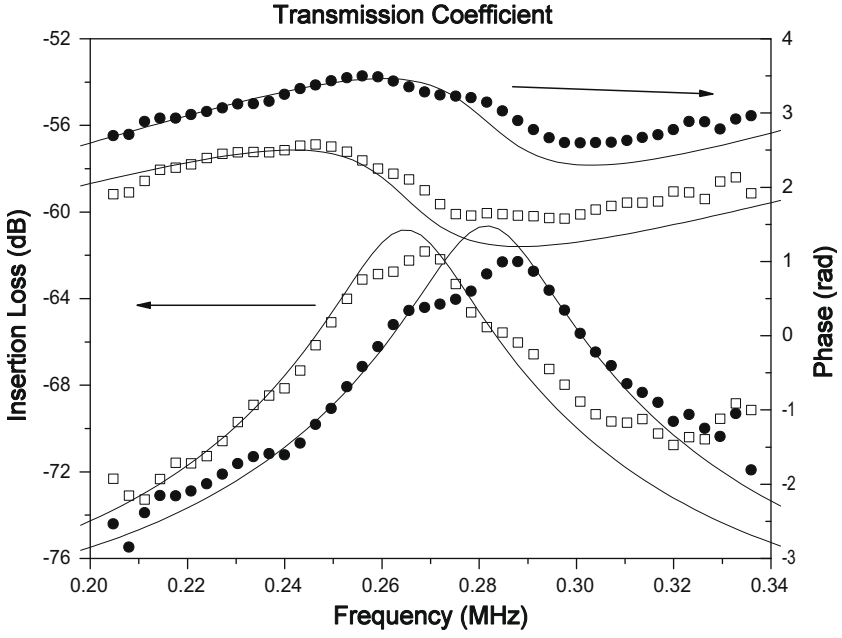

Fig. 6. Amplitude (insertion loss) and phase shift spectra of the ultrasonic transmission coefficient of a FRC panel. Composite #6 and #9. Dots experimental data. Solid line: theoretical data from Eq. (3).

this indicates the presence of a defect. To distinguish between the differences in these three points and to discern that there is a defect in point 3 is only possible thanks to the simultaneous determination of the thickness.

5. Conclusions

A method to determine simultaneously velocity of sound and thickness of solid plates from the analysis of the amplitude and phase of the ultrasonic transmission coefficient in the vicinity of the first thickness resonance is presented. In particular, air-coupled ultrasound is used, 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. However, when the attenuation is large, both phase and amplitude spectra have to be used to determine ultrasound velocity and plate thickness.

The method is applied to three different kind of materials: soft membranes, wet vegetable during the drying process, and FRP-composites. In the first case, thickness measurement employing a micrometer may result inaccurate because the membrane can be deformed by the micrometer. In this case, the obtained thickness value is compared with independent thickness measurements and the agreement is good. 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. 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.

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