ULTRASONIC PULSE SCATTERING TRANSITION ZONES.

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Abstract

The behavior of ultrasonic scattering is studied for different configurations by means of the variation of the radius of the scatters, the fraction of volume and half of propagation.
We analyze the variation of different associated parameters of scattering (l_S, l^*, v_G, v_F and energy ratio) in function of the configuration and specially of the depth of the sample.
The obtained results show that the transition from a single scattering regime to a multiple one and then from this to the diffusion regime take place in two respective transition regions with dimensions of several times the scattering mean free path.It evidences the coexistence of the regimes.
Furthermore, we observed in all of the analyzed configurations, that in the starting depth of the transition zone between multiple scattering and diffusion the ratio between this depth and l_S is approximately constant.

Introduction

The study of the scattering and their states in the propagation of an ultrasonic pulse troughout heterogeneous media of different nature has been target of several works in the recent years. The parameters which characterize this phenomenon in an medium have been studied and experimentally determined [1-5].
In addition to the fact that these works was precursory of the study of this matter, they established a good agreement between the theory of the scattering (used in other areas of the Physics) and the experimental results.
This work is intended to take a contribution to the understanding of the ultrasonic scattering phenomena.
We experimentally analyzed on which depth of the sample occur the scattering changes in the propagation regime, using different geometries and concentration of scatterers for different media.
We try to determine how the scattering parameters varies in function of the way path of the wave for a given configuration (geometry of the scatter, volume fraction and medium propagation constants).
We determined the group (v_G) and phase (v_F) velocity, the scattering mean free path l_S and transport l^*.
Ultrasonic pulses of 2.25 MHz central frequency insonorize the samples, formed by cylindrical scatterers of "infinite" length, whose radios vary from 0.3 to 1.2mm with volume fraction between 0.03 and 0.35.
Moreover, several coupling fluid was used (water, saline water, oils and glycerin).
From the obtained results one can observe that the transition from a regime of single scattering to multiple scattering and from it to the diffusion, take place in a transition region with dimension of several times the scattering mean free path due to the coexistence of the different regimes. We can also see that for all of the analyzed configurations the relationship between the starting depth of this zone and the scattering mean free path is approximately constant.

Experimental work

Measures have been made in a tank, using piezoelelectric inmersion transducers located in far field from the sample as sources of plane ultrasonic waves. A needle hydrophone of smaller diameter that the used wavelength is used as field detector. It locates in the central portion of the rear face of the sample. The slab type samples formed by identical cylindrical scatters. They are parallel disposed to their axial axis which vertical dimension is sufficiently bigger than that the used wavelength. This fact allows us to consider it as a two-dimensional case.

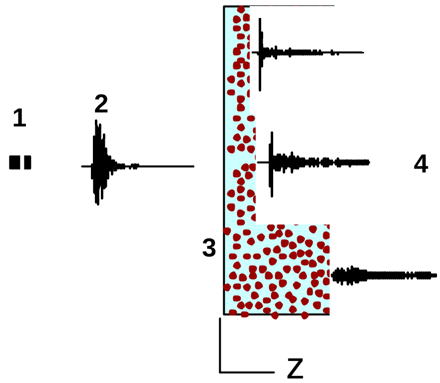

Figure 1 : Experimental diagram 1-Emission transducer 2-incident signal 3-Medium 4-Transmitted signal to different depths (Note: different temporal basis are used in 2 and 4)

The different used slabs are defined by the mean radius of the scatter (a), the fraction of volume (ϕ) and the medium of propagation. The configuration parameter values for the samples vary in the range of $0.3=a=1.2$mm and $0.03=\phi=0.35$. The different propagation medium are water, saline water, oil and glycerin. The slab depth z varies between 0=z=35mm, that is, several times the scattering mean free path. The spatial distribution of the scatters is random and keep unchanged the mean value and standard deviation from the group of cylinders for any depth.

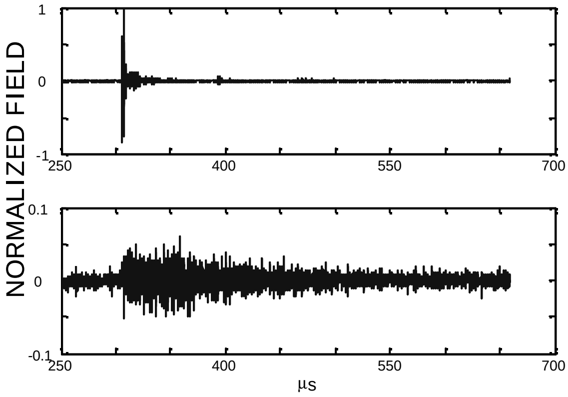

Figure 2:Ballistic pulse is obtained for z= ½ l^* (up) by averaging 100, but not for z=5 l^* (down)

The detected ultrasonic wave contains information about the amplitude and phase of the acoustic field, starting from which the evolution of the transmission coefficient, the phase and group velocity can be obtained. The signal, after traveling for a scattering medium consists of a coherent and an incoherent portion[6]. The coherent wave is formed by the ballistic pulse and the contributions of the scattering in the propagation forward direction. This contribution, as well as the incoherent part, grows with the increase of the depth of the sample; making the ballistic pulse disapears despite of using temporarily short pulses. The coherent wave is not evidenced in a single realization, it emerges when averaging more than 100 signals of the scatter field.

To experimentally determine the transition zone of scattering regime, we use pulses which allow to temporarily separate the coherent part of the contributions of the scattering to the coherent wave (the ballistic pulse prevails in a single realization). The existence of transition zones in the propagation regime is evidenced through the behaviour of the coherent transmission coefficient and the group velocity, in the change of slope of the phase velocity and in the weight the incoherent energy gains regarding the coherent one in the ballistic wave as a function of the slab depth. The depth where the change from single to multiple scattering take place is determined by the loss of directivity of the wave. It is the transport mean free path l^*, the depth where the wave "loss the memory of its initial direction") [5].

The single scattering is characterized by the exponential decrease of the coherent intensity $I_C \propto \exp(-z/l_S)$ [7,8]. The fit parameter is the scattering mean free path, l_S. It is determined by the measures of the coherent transmission coefficient, i.e the ratio between the coherent transmitted and the incident intensity. Starting from the exponential adjustment of the ballistic intensity the l_S is obtained.

First transition zone: Single to Multiple scattering

The analysis of the coherent transmission coefficient in depth shows a discrepancy with the theoretical model of the single scattering. The influence of the incoherent energy in the forward direction increases with the depth of the sample, affecting the adjustment of the T_{cohe} (i.e. in the ls value).

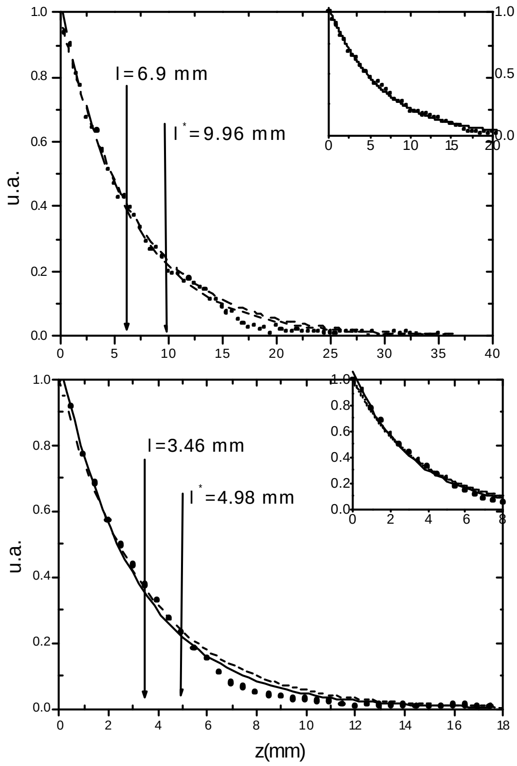

Figure 3 : T_{COHE} vs. z (slab depth) From z0 begins the directivity loss (the process leaves the single scattering model). Labs: a=0.75mm, water, λ=0.6mm. Up: ϕ=0.10, z_0=11.5mm (l^*=9.96mm) Down: ϕ=0.20, z_0=5.5mm (l^*=4,98mm)
---theoretical curve, ? experimental data fit.

The scattering mean free path (l_S) value is 3.38±0,21mm (it differs 2,1% from the theoretical value). We observed that the experimental data disagree from the theoretical curve of the single scattering model starting from 5 mm and 15 mm (fig 2 down and up respectively). The incoherent field of the signal begins to be relevant accordin to the directivity loss of the transmitted signal, characterized by the transport mean free path l^*. The anisotropy index ($\overline{\cos} = 0.3217$) allows to determine the mean free path of transport, $l^* = l_s / \left(1 - \overline{\cos}\right)$ giving a theoretical value of l^*=4,98 mm (and 9.96 mm) [5]. For a small z (z≈2 l_S) it is observed that the experimental data present a better fit that when the depth is duplicated (figures 3), but discontinuity some is not observed that denotes a regime change. This evidences that exists a large zone where the energy originated in the multiple scattering is superimposed with the coherent energy, hiding this way the depth to which the regime change occurs.

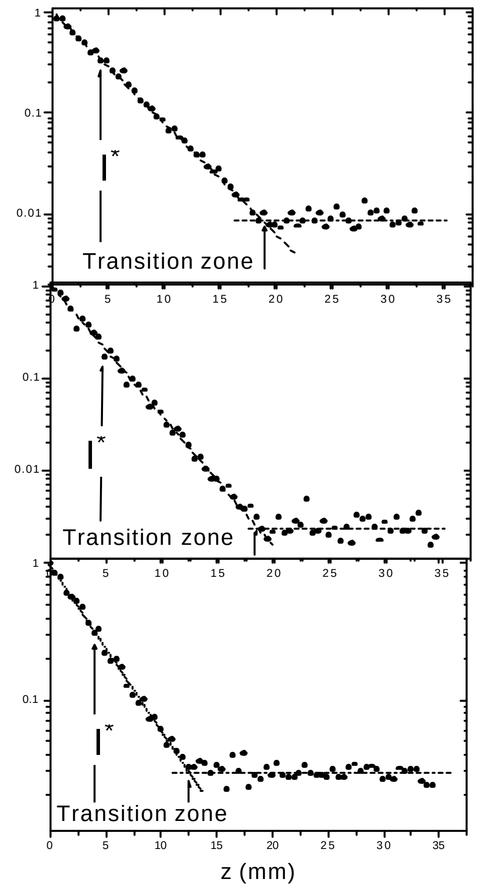

Figure 4 : Ratio of the incoherent and coherent energy of the ballistic wave vs depth. Slab *a*=0.75mm, ϕ=0.20, f=2.25MHz. Propagation media: glicerin (up), oil (midle) and water(down)

Second transition zone: Multiple scattering to diffusion

We study the second transition zone measuring three parameters in function of the depth: energy ratio, phase and group velocity. The second zone begins from l*. To show the existence of it in the scattering of an ultrasonic pulse we experimentally examine the relationship between the coherent and the incoherent energy of the acoustic field, y , in the band width Δw , with central frequency of emission w_0

$$\frac{\int F^{-1}\left[F\left(\left|\langle\psi\rangle\right|^2\right)\Pi\left((\omega-\omega_0)/\Delta\omega\right)\right]dt}{\int F^{-1}\left[F\left(\left|\psi\right|^2\right)\Pi\left((\omega-\omega_0)/\Delta\omega\right)\right]dt}$$

where Π is the function rectangle centred in ω_0 and $\mathcal{F}$ is the Fast Fourier Transform and it inverse $\mathcal{F}^{-1}$. We make it instead of continuous analysis of the coherent transmission coefficient for bigger z values (the zone where the analysis is required) because the coefficient $T_{cohe} \rightarrow 0$.

We observed (figure 4) that there is a change in the slope in the energy ratio curves. There is a constant slope from the start of the multiple scattering until the beginning of other zone that we associate to the diffusion (being z_T the depth where the diffusion prevails). The value of the slope as well as the reached depth varies according to the medium in which the given configuration is inmerse. This fact is probably is related to an important difference between water and the other analyzed medium. Possibly the last two media analyzed present a higher absorption and then the absorption free mean path l_a is not negligible

$$1/l = 1/l_S + 1/l_a$$

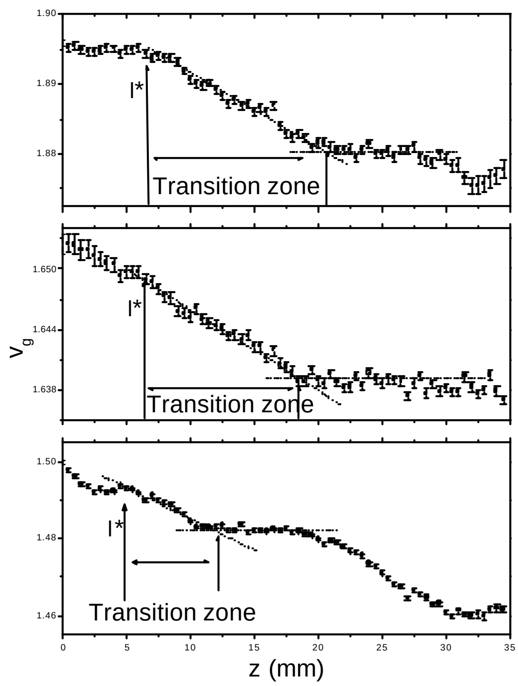

Figure 5: Group velocity vs depth. It shows the transition regime changing zone from l*. Slab: a=0.75mm, ϕ=0.20, f=2.25MHz. Propagation media: glicerin (up), oil (midle) and water (down)

Figures 5 and 6 show the evolution of group and phase velocity of the ultrasonic wave in function of the depth. The value of v_G is obtained by correlation of the emergent wave of the sample with the incident pulse. v_F is calculated by the relationship $v_F = \omega(\partial\varphi/\partial z)^{-1}$, where φ is the phase and ω is the central frequency of the incident wave. Figure 6 shows the existence of a slope change. The values of z_T of the second transition zone are very similar to those obtained by means of the energy ratio.

In the following table is shown where the second transition zone ends. We observe that the depths reached are similar. It makes us conclude that this second zone really exists and that the incoherent energy of the multiple scattering is superimposed with the energy involved in the diffusion regime.

	z_T (mm)			z_T/l_S		
	A	B	C	A	B	C
1	12,5	18,9	18,23	3,7	4,7	4,5
2	10,4	17,6	18,7	3,1	4,4	4,6
3	10,5	18,0	19,6	3,1	4,5	4,9

Table 1. Experimental results for the second transition zone (1:energy ratio, 2:v_F, 3:v_G for ϕ=0,20, a 0,75mm, f=2.25 MHz and A:water, B:oil and C:glicerin)

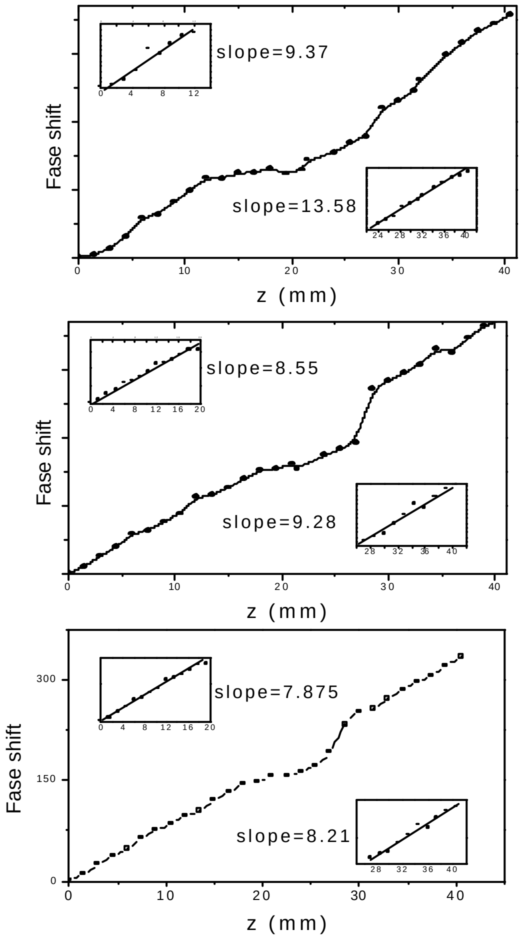

Figure 6: Phase velocity vs depth. It shows the transition regime changing zone from l*. Slab *a*=0.75mm, ϕ=0.20, f=2.25MHz. . Propagation media: glicerin (down), oil (midle) and water (up)

On the other hand it is observed that for a given configuration of the scatters immersed in different media the ratio between the ending depth of the zone and the l_S remains constant[9,10].

This leads to think that the wave in their propagation through a given medium and after passing all the scattering regimes conserves a memory of the signature of the medium, the scattering mean free path l_S.

Conclusion

As a contribution of this work to this topic we can point out some ending remark. The behavior of the ultrasonic scattering was studied for different configurations varying the radius of the scatters, the fraction of volume and the medium of propagation. A good agreement with the theoretical model was found.. In particular, the theoretical expression for calculation of the scattering mean free path starting from the wave transmitted in the medium diffuser was verified.

Starting from the behavior of the different parameters (ratio of the energy, group and phase velocity) for each configuration we found evidence that the regime transitions from single to multiple scattering, and from this to the diffusion happens in two regions that present a length of several times the scattering mean free path. That is, the change of one regime to another does not happen abruptly, and neither does it in a short distance, but rather there is an extensive coexistence of regimes.

Last, the constant value of the ratio between the starting depth of the diffusion regime and the scattering mean free path allows us to affirm that in spite of changes in the propagation regime the ulrasonic wave keep the memory of the signature of the scattering mean free path.

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