SCATTERING EXPERIMENTS IN ULTRASONIC SPECTROSCOPY

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INTRODUCTION

In the field of object characterization by ultrasounds, the aim of Spectroscopy is to get information on the object by Fourier analysis of scattered echoes when the sample is irradiated by short ultrasonic pulses. This technique has been proposed in 1960 by O.R. Gericke |1| in material evaluation. Since then, it has been used in all fields of investigation by ultrasounds mainly non destructive testing of materials and biological tissue characterization.

PRINCIPLE OF ULTRASONIC SPECTRAL ANALYSIS

In evaluating the shape of an object by ultrasounds, one is concerned with the diffraction problem. Indeed, ultrasonic sources are spatially coherent sources. For a given frequency, there is a unique phase relationship between the waves received by two points of the objects. The shape and the intensity of the signal given by a receiver will then depend on the time of coherence of the emitter. If the coherence time is great, echoes received from two scattering centres will not be separated; It is the diffraction regime ; And, for a given geometry, the amplitude of the sum of two echoes is changing according to the frequency of the emitter. For a correct evaluation of the scatterers, it will be necessary to vary frequency. The difficulty of great coherence time is that it exists a possibility to include spurious signals coming from scatterers located in the neighbourhood of those of interest.

On the contrary, a short coherence time will allow a better time separation of signals. In ultrasonic spectroscopy, the sample is insonified with short ultrasonic pulses with very broad band Fourier spectrum. One can Fourier analyse some selected parts of the signal, creating anew the situation of long coherence time without spurious echoes. Most of the existing scattering theories are concerned with monochromatic waves and their results are given as functions of that frequency. So, with ultrasonic spectroscopy using signals with wide frequency band, one can easily compare

experimental Fourier amplitude as a function of frequency with theories describing the scattering of monochromatic waves.
Besides, one can use short pulses technique to make signal processing operations such as deconvolution, improvement of signal over noise, etc...

EXPERIMENTAL EQUIPMENT

In order to be able to transmit very short pulses, the emitter and receiver of ultrasounds have to be non resonant. One uses now ferroelectric ceramics , Titanate Zirconate of lead PZT, Barium Titanate Ba Ti O_3; These ceramics are cut as discs whose thickness is half the wavelength in the ceramic of the sound of the highest frequency that has to be emitted. The back faces of discs are damped by contact with an absorbing material of the same acoustical impedance of the ceramic, and so the resonance of the ceramic is highly damped. When the plated faces of the disc are submitted to a short electric pulse, the ceramic sends out a short ultrasonic pulse with broad band frequency content. To improve the frequency bandwidth, it is useful to be able to adjust the rising time and the width of the electric pulse. Typically bandwidth at - 20 dB is one and a half the centre frequency (Fig.1).

For ultrasounds propagation, the transducers are in contact with the sample to analyse or immersed in water for coupling with the sample. Ultrasonic echoes may be detected by the emitter or by another transducer.

In the electronic part , an analogic gate selects the part to be analysed in the received signal. (Fig.2). The selected part can be Fourier analysed by an analogic spectrum analyser or digitized for further numerical treatment. The digitizing process mostly used for frequencies up to 30 MHz is a sweeping gate sampler.

CHARACTERIZATION EXPERIMENTS BY ULTRASONIC SPECTROSCOPY

We will restrict the examples given here to the propagation of one type of waves in a linear medium. The problem of the echo created by a given surface is then the resolution of the propagation equation $\Delta p - 1/c^2 \; (\partial^2 p/\partial t^2) = 0$ where p is the acoustic pressure, taken in account the boundary conditions on the surface.

The exact solution cannot generally be obtained and several approximations are made for peculiar cases; The mostly used | 2-8 | is the Kirchhoff approximation which assumes that the radiation scattered by a surface element is distributed evenly over a solid angle of 2 Π neglecting secondary diffraction of one surface element over another one. This approximation should be applied only when the radii of curvature of the surface are large compared with wavelength and if the surface slopes of the scattering surfaces are small, but it gives good results in less restrictive cases.

The formalisms which are usually used are, the Helmholtz integral, Green's functions, potential method. They lead, in Kirchhoff's approximation, to results very similar as Huygens' optical principle do.

We will now show three types of applications :

1/ Scattered pressure by an object wholly contained in the field created by the emitter

This concerns the important problem of characterizing a defect in non destructive testing of materials.

Using Kirchhoff approximations, A.Freedman has shown that the echo to a short incident pulse was made of separate pulses, each one being created at a discontinuity of the solid angle w(r) subtended by the surface as seen by the transducer at the distance r. E.Lloyd |3,4| developped the method in back scattering geometry to practical cases and showed that the electrical signal given by the transducer was proportionnal to the second time derivative of the solid angle where $t = \frac{r}{2c}$ (c is the sound velocity).

Figure 3 gives, after Lloyd the formation of the two pulses in opposite phase given by a sphere and the resultant amplitude spectrum.

L.Adler and H.L. Whaley |5| have shown that Ultrasonic Spectroscopy is a powerful method to get evaluation of defects size in materials. They use a method based on extracting the defect size from the minima in the backscattered spectrum. Their experiences are well explained by D.M.Johnson |6| who, following an argument based on Huygens' principle, showed that the backscattered pressure at the frequency f was given by

$$P_S\ (f) = - \frac{2i\pi fB}{2\pi r^2 c} \iint_A \cos\theta \exp - \left(\frac{i4\pi rf}{c}\right) dA$$

where dA is a scattering surface element at the distance r of the emitter inclined of θ on the direction of wave incidence. B is an amplitude factor.|Fig.4|.

We can see that this formulation is very practical for numerical calculus

Figure 5, after Johnson, shows the good agreement of this formulation with the experience of Adler and Whaley on the diffraction by a disc for different inclinations θ.

The method of using the minima in the backscattered spectrum to characterize the size of a defect may be also used for evaluating surface defects by surface waves |7| where one can say in first approximation that the two edges of the defect are two points scatterers out of phase. But it has to be pointed out that the inverse problem, i.e. the determination of the shape of an object is not solved by one spectroscopic experiment. In order to get more information, some other parameters, such as angles of incidence, have to be varied.

2/ Surface roughness characterization by Ultrasonic Spectroscopy

The scattered ultrasonic pressure by a rough surface can give parameters of the surface roughness |8-10|. Ultrasonic Spectroscopy has been applied for both periodic and random roughness.

a) <u>One dimensional periodic surface |11-12|</u>

In the Kirchhoff approximation, following Beckmann |9|, the backscattered pressure amplitude at angle θ of incidence in the far field is given by :

$$A(f,\theta) = B \int_{-L}^{+L} \exp - \frac{4i\pi f}{c} \ (x \sin\theta - \zeta\ (x) \cos\theta)\ dx$$

where B is a coefficient, 2 L is the insonified part of the grating, $\zeta(x)$ is the equation of the surface profile .

In the case of small roughness, when $\left|\frac{4\pi f\ \zeta(x)}{c} \cos\theta\right| << 1$ one can expand the exponential in series and get

$$A(f,\theta) = B \int_{-L}^{+L} \left(1 + \frac{4i\pi f}{c} \ \zeta\ (x) \cos\theta \right) \left(\exp - \left(\frac{4i\pi f}{c} \ x \sin\theta \right)\right) dx$$

which is the sum of two integrals, the first one is negligible for θ ≠ 0, the second one appears to be proportional to Fourier transform of the surface profile.

In function of frequency, the backscattered intensity will be made of peaks whose amplitudes are proportional to the Fourier coefficient of the decomposition of the surface profile in series. The two first coefficient of gratings have been shown to be well estimated by ultrasonic measurements |11|.

On Fig.6, are shown both ultrasonic and computed amplitude spectra after mechanical measurement of the profile and correction by the frequency response of the transducer for two samples. They appear in good agreement.

On Fig.7, are shown the spectra obtained for a sample having defects in periodicity. In both experimental and computed spectra and in the same order of magnitude, it appears ghosts peaks at half harmonics characteristic of defects in periodicity.

b) <u>Randomly rough surfaces</u>

As shown by C.S. Clay and H. Medwin |13|, the intensity scattered in the specular direction allows the evaluation of statistical parameters of the surface.

Following Beckmann | 9|, one can write the mean scattered intensity at a point B as a sum of two terms. The first one called coherent intensity is dominant at low frequency, the second one called incoherent intensity is dominant at high frequency. $\langle I \rangle = \langle P_S^* \rangle \langle P_S \rangle$ + Variance $|P_S|$, $\langle P_S \rangle$ being the mean value of the acoustical pressure.

We will restrict here to the case of normal incidence.

In low frequency regime

$$\langle P_S \rangle = - \frac{ik}{2\pi} \iint_A D_o \frac{e^{2ikR_o}}{R_o^2} \langle e^{-2ik\zeta} \rangle\ dx\ dy$$

k is the wave number, D_0 the directivity function of the emitter, R_0 the distance from the emitter to the plane $\zeta = 0$, ζ (x,y) is the height of the surface.
When $\zeta = 0$, P_S is the scattered pressure, P_R, by a plane surface so that one can write

$$<P_S> = P_R < e^{-2ik\zeta} >$$

This expression is valid even in the Fresnel approximation.
If we note W (ζ) the probality density function of the height one has

$$< e^{-2ik\zeta} > = \int_{-\infty}^{+\infty} W(\zeta)\, e^{-2ik\zeta}\, d\zeta$$

which is the characteristic function of the surface.

In the general case $<P_S> / P_R$ is a complex quantity and one can see that it is theoretically possible to measure the parameters of the heights distribution function. When W (ζ) is gaussian with h root mean square deviation from zero height, one has in low frequency $<I> = I_R\ e^{-4k^2h^2}$
So, the departure of the intensity from the plane surface case gives a measurement of h.
At high frequency, for a gaussian autocorrelation function, with $\sqrt{2}\,h/L$ being the mean slope, one has $I = I_R \frac{\pi}{4Ak^2} \frac{L^2}{h^2}$

with I_R intensity scattered by a plane surface, A being the insonified Area.

Ultrasonic spectroscopic experiments have been done | 14 | and it has been shown that one can evaluate the roughness h from the low frequency part of one backscattered spectrum and get the value of the autocorrelation length L from the intensity at high frequency.

Comparisons are made with mechanical measurements of the surface for samples with $8\ \mu m < h < 60\ \mu m$; $80\ \mu m < L < 200\ \mu m$
The agreement for h is good 10% for L the method is less accurate (error in range of 30%).
On Figure 8 (a et b) are plotted the intensities for two different samples.
We see the quickest decrease of the roughest sample at low frequency and the smaller high frequency value of the sample with the greatest h/L ratio, i.e. the greatest slopes.
The method can be applied to characterize roughness even for inside surfaces after crossing a wall.

3/ Characterization of scatterers distributed in volume

N.F. Haines et al |15| have studied layered media by spectroscopy, both in amplitude and in phase. They obtain very good agreements between the experimental and theoretical values.

F.Lizzi and M.A. Laviola |16| used the concepts of layered media in ophtamology to study the detachment of the retina and the detection of tumors behind the retina; From typical minima in the amplitude spectrum, they get the size of the different layers. Several authors use spectroscopy for tissue characterization in biology. D.Nicholas and C.R.Hill |17| use the concept of Bragg diffraction to get correlation of the back-scattered intensity versus the angle of incidence with several tissues structures. E.Holasek et al |18| and P.P. Lele |19| using transmission or backscattering experiments obtained attenuation measurements characterizing many biological tissues.

To conclude, Ultrasonic Spectroscopy is a technique which can give quickly some parameters of the scattering objects specially in non destructive testing of materials and biological tissue characterization.

One can think that the possibility of signal processing will enlarge the results already obtained in the inverse problem.

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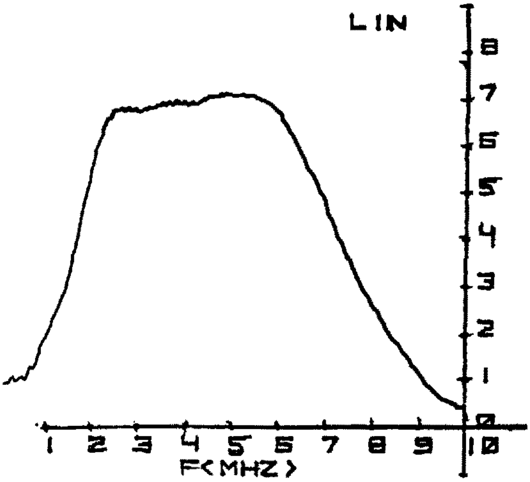


Fig.1 Amplitude spectrum of a typical echo in the range 1.5-10 MHz

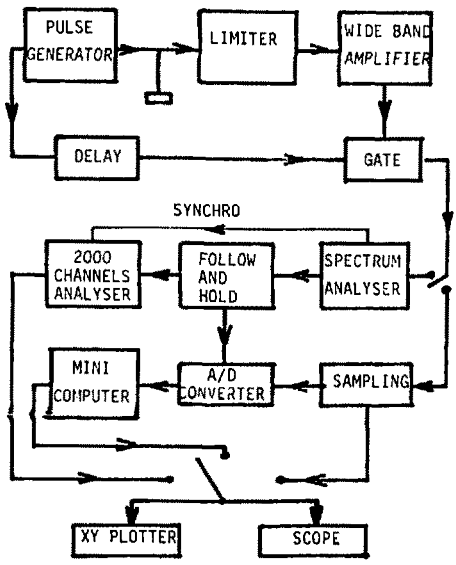


Fig.2 Experimental equipment used in an experience of ultrasonic spectroscopy.

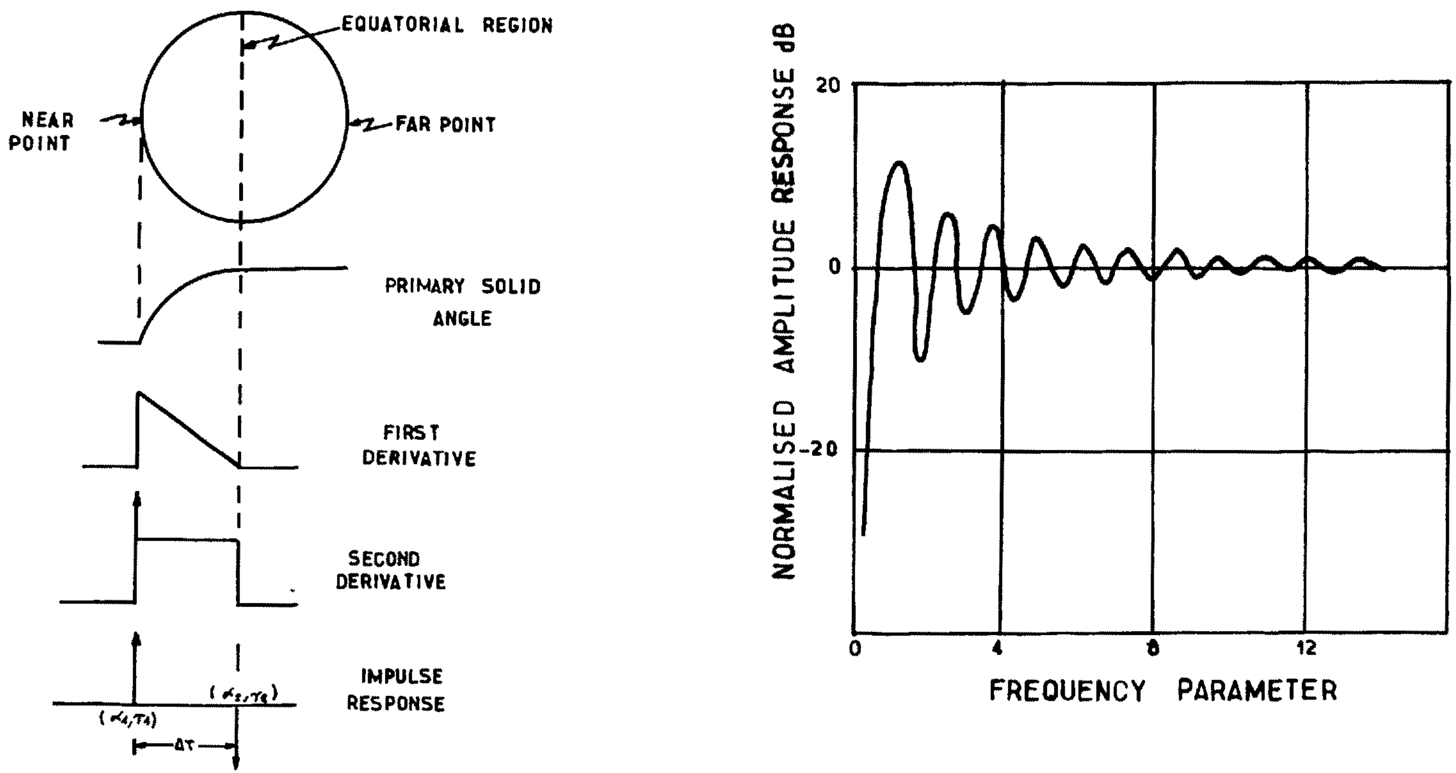


Fig.3 Formation of impulse response and amplitude spectrum for a sphere (After Lloyd)

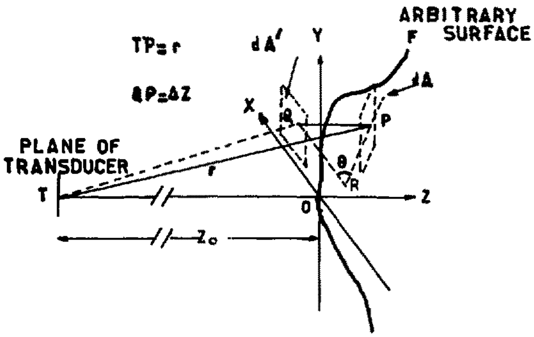


Fig.4 Geometry in the backscattering experiment (After Johnson)

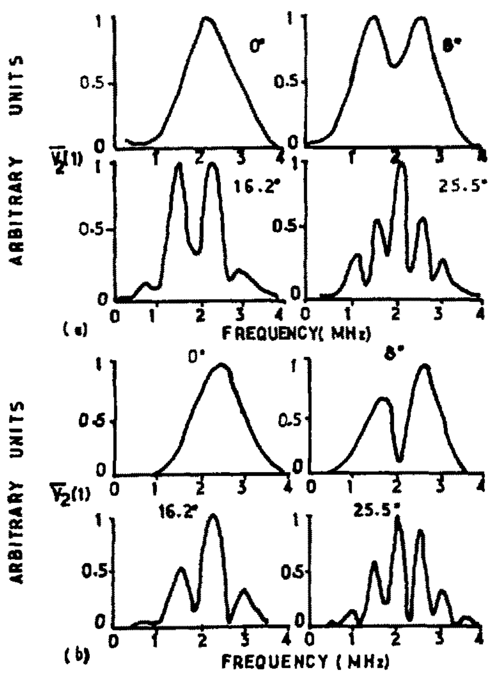
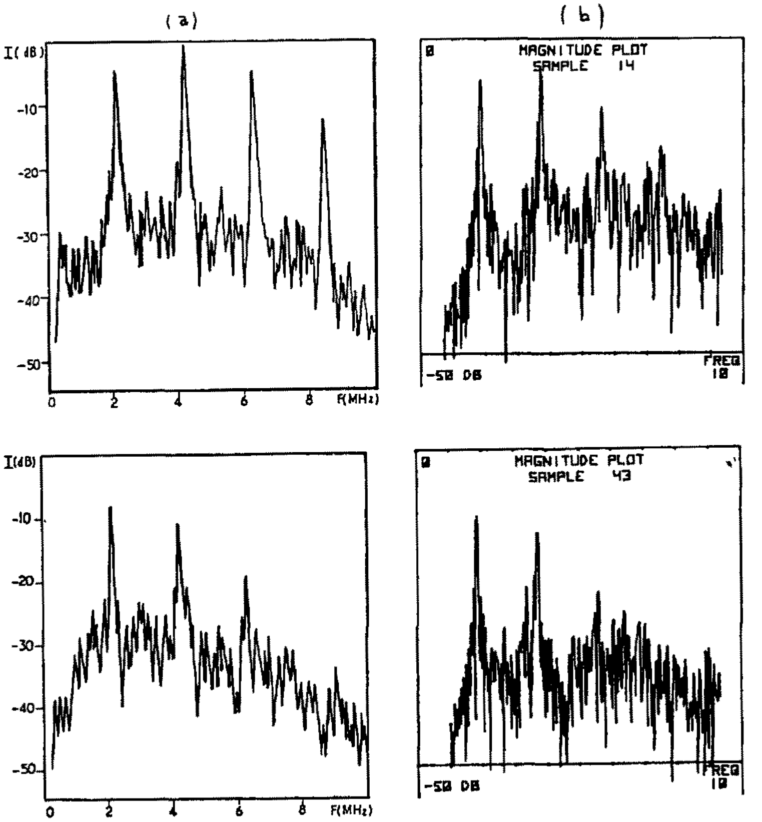
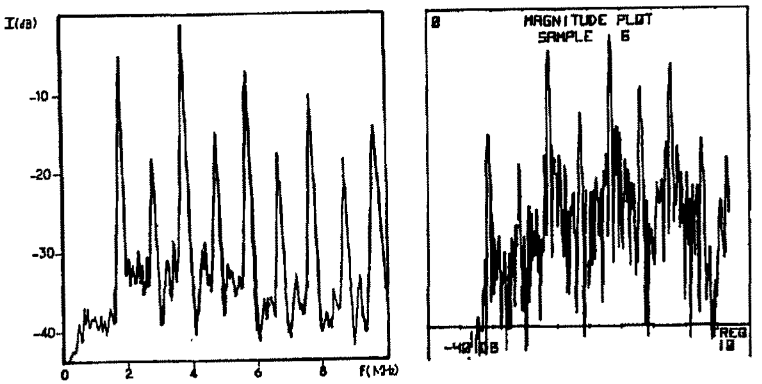


Fig.5 Experimental (a) and theoretical(b) frequency spectra for reflection of an inclined disc (After Johnson)



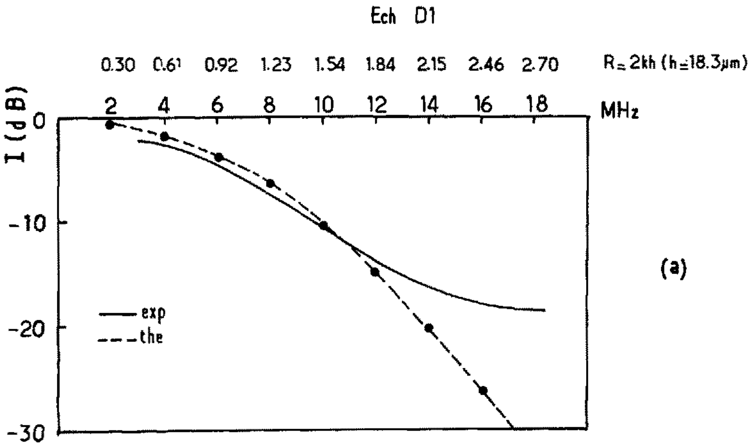
(a) (b)

Fig.6 Experimental (a) and computed (b) spectra obtained for two different gratings |11|



(a) (b)

Fig.7 Experimental (a) and computed (b) for a grating having defects in periodicity |11|



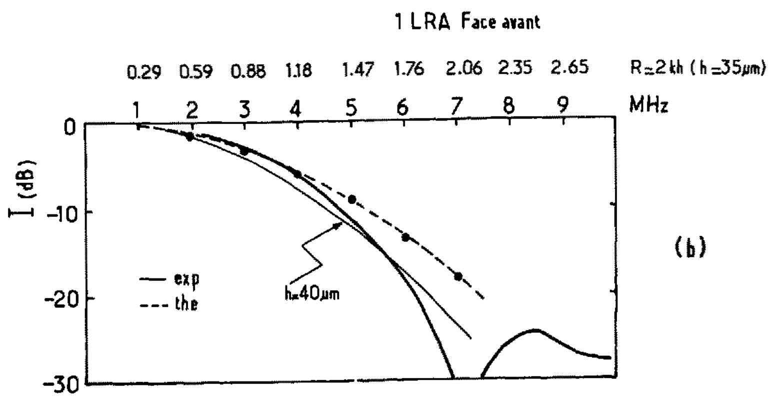


Fig.8 Backscattered intensity at normal incidence for two samples
a) h = 18,3 µm , L = 180 µm
b) h = 35 µm , L = 110 µm
Full curve: Experimental ; Pecked curve: exp $(-\ 4k^2h^2)$