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PHYSICAL FOUNDATIONS OF ULTRASONICS RESEARCH TRENDS AND ITS APPLICATION IN POLAND

1. Introduction

After the Second World War, the development of acoustics in Poland started from nearly the zero level. Thanks to the effort of a few specialists of the older generation, the enthusiasm of young students and support of organizers, much progress was made in a relatively short time in both audio-acoustics and ultra-acoustics. From the very beginning acoustics was the subject of interest of the authorities and this was testified by establishing the Scientific Committee of Acoustics of the Polish Academy of Sciences in 1965. Since 1973 research activities in acoustics have been largely conducted within the framework of the "key" project "Application of acoustics in technology and medicine", a high priority on the governmental level. The project is supervised by the Committee of Acoustics and financed by the Polish Academy of Sciences. Moreover, it includes the full-time work of 140 scientists employed in 22 centres. Acoustic problems also appear in the highest level governmental programmes, such as electronics, coal-copper mining construction and cancer diseases. This paper presents some selected problems in physical acoustics, in particular those connected with ultrasounds. It shows those problems which, in our opinion, are significant from the practical point of view. The main emphasis was put on research falling under the mentioned "key" project. As the scope of this paper is very large, problems have been grouped according to the following:

1. Acoustic of solids,
2. Acoustics of liquids and polymers,
3. Quanta acoustics,
4. Ultrasonics non-destructive testing,
5. Bioacoustics.

The problems of opto-acoustics are treated jointly with acoustics of liquids. Underwater acoustics as a separate branch of acoustics is not considered in our analysis.

1. Acoustic of Solids

Acoustic research in solids follows from the relationship between the parameters characterizing the physical properties of matter and its structure, and the acoustic field.

The characteristic feature of real media is their heterogeneity at the levels of the atom, microstructure and texture. This heterogeneities are decisive for electrical, mechanical , optical and thermal properties of materials. In real media the displacement vector and elastic operator should be treated as random variables which depend on the position vector. In investigations of heterogeneous materials it is convenient to use acoustic waves of wavelengths much longer than the mean linear dimensions of heterogeneities. Such an approach makes it possible to treat the material as a substitutional homogeneous medium. A particular case of solids is the so-called grained solid.

The idea of replacement of the grained medium by a substitutional homogeneous medium was presented in 1956 by I.Malecki in [1]. The autor determined ultrasound attenuation and velocity in the system composed of a homogeneous carrier medium containing inclusions in the form of spherical grains of another material. An example of a grained solid is a porous solid containing inclusions in the form of pores. Work [2] is one of the earliest Polish publications devoted to acoustics of porous solids.One of the first applications of the results of the theoretical treatment of grained media was the experimental determination of the porosity of ceramic materials. Porosity is a factor which affects its dielectric and mechanical resistivity. Figure 1 shows the theoretical and experimental curves of the velocity of longitudinal ultrasonic waves versus porosity.

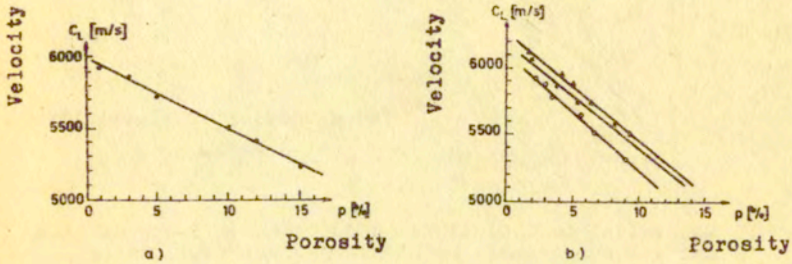

Fig.1. Velocity of ultrasonic longitudinal waves versus porosity for various types of technical porcelain

In the 1970s this problem was extended by taking into account the effect of the nonspherical shape of pores on the velocity of the elastic wave. Research work in this field was done jointly by the Institute of Fundamental Technological Research, the Polish Academy of Sciences and the Center of Physics of Ceramics in Dresden /GDR/ [3]. Further research on the acoustic properties of heterogeneous media /mainly ceramic/ was linked to the evaluation of mechanical resistivity.Ceramic is generally a brittle medium containing pores and microcracks [4,5]. The starting point of experimental works was the relationship between the mechanical resistivity and elastic constants measured by ultrasonic methods. The relationships are shown in Fig.2.

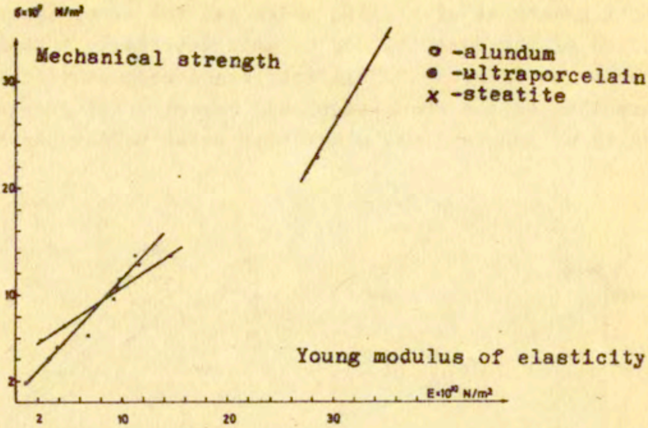

Fig.2. Mechanical resistivity as a function of Young modulus for various ceramic materials /experimental data/

It was possible to evaluate stresses in heterogeneous materials by means of ultrasonic methods taking into account the fact that the free energy of a composite crystalline system effects an increase of attenuation of ultrasonic waves. On the basis of this regularity it was possible to detect the stressed domains arising on the boundaries between domains of different structures in ceramic elements /Fig.3/. Figure 4 presents the wave attenuation as a function of the percentage of defects in the structure of a ceramic isolator [6].

The effect of internal friction can also be utilized to investigate the structure of solids. Internal friction characterizes the behaviour of materials under stresses caused by diffusion, thermal conduction or displacements of lattice defects. Various mechanisms occur in the strained sample and their contribution to the overall damping is not equal for different frequencies. If the particular mechanisms are independent of each other, then the resultant damping can be treated as the sum of their contributions. The curve of the Q - factor of the material as a function of frequency ranging

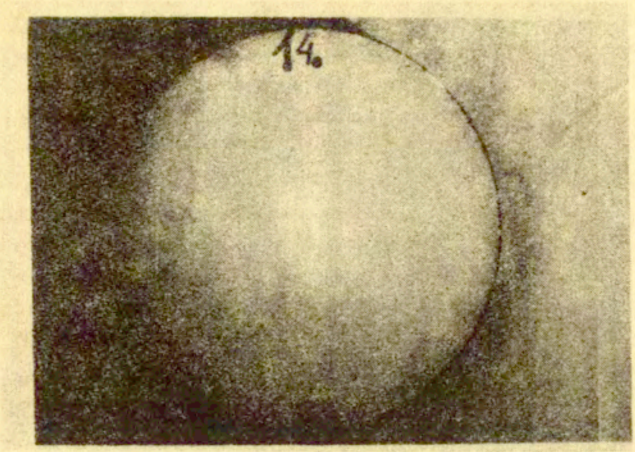

Fig.3. Ceramic isolator body cross-section
showing structural defects

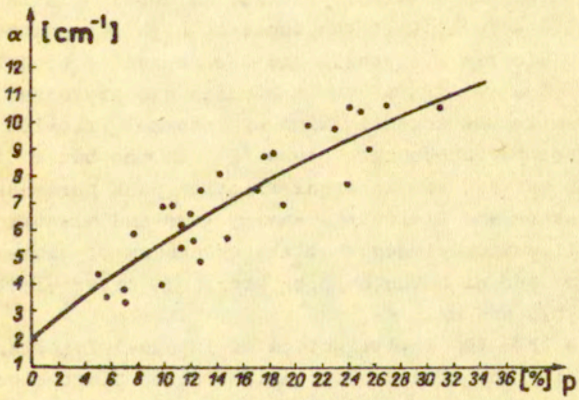

Fig.4. Acoustic wave attenuation as a function
of percentage of defective area of
cross-section from Fig.3

from infra to hypersounds $Q^{-1} = Q^{-1}(\omega)$ has numerous extrema. Likewise in optics, such a curve can be called the acoustic spectrum of absorption and utilized to obtain information on the structure of the solid under consideration. Internal friction is extremely sensitive to microstructural changes; this is why this method can be employed to investigate the properties of matter at the atomic level. It is especially workable for studies on the kinetics of phase transformations, formation of auxiliary phases, diffusion, determination of the concentration of impurities at lattice nodes, dynamics of dislocations and the movement of domains in ferromagnetic and ferroelectric materials. Studies on internal friction are now pursued in Poland in the following centres:

- Institute of Physics, Technical University of Gdańsk,
- Faculty of Metallurgy, Intitute of Metallurgy, Academy of Mining and Metallurgy, Cracow,
- Institute of Fundamental Technological Research, Polish Academy of Sciences, /IFTR/,
- Institute of Physics and Chemistry of Metals, Silesian University.

One of the most important results in the recent years is the research on the internal friction in cobalt-platinum alloy, in which it was found that the cause of high attenuation is the magneto-elastic hysteresis and the degree of ordering in this alloy. The results of these studies are presented in [7]. Another item is the investigation of internal friction in the semiconductor ferrophosphate glass [8]. On the basis of the correlation between the internal friction peak parameters at low-temperature and dielectric energy loss and electric conductivity it was concluded that the mechanism of these processes is connected with the hopping transport of an electric charge /Figs.5 and 6/.

In the IFTR the investigation of internal friction was concerned with the effect of polarization of piezo-electric ceramics and diffusion on the boundary between ceramics and metal [9]. The attenuation processes related to the displacement of dislocations were also studied; these effects follow

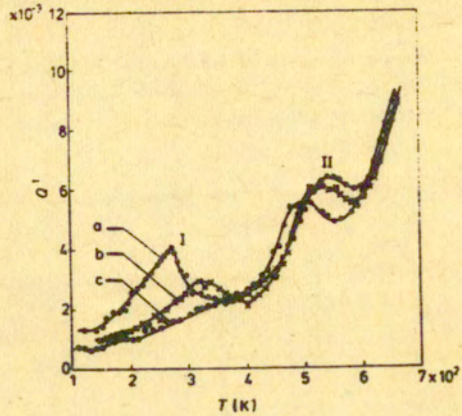

Fig.5. Dependence of internal friction on temperature for three kinds of glass of different composition:
a/ 50% FeO+50% P_2O_5 ; b/ 40% FeO+10% MgO+50% P_2O_5;
c/ 50% MgO+50% P_2O_5 /% - molar percentage/

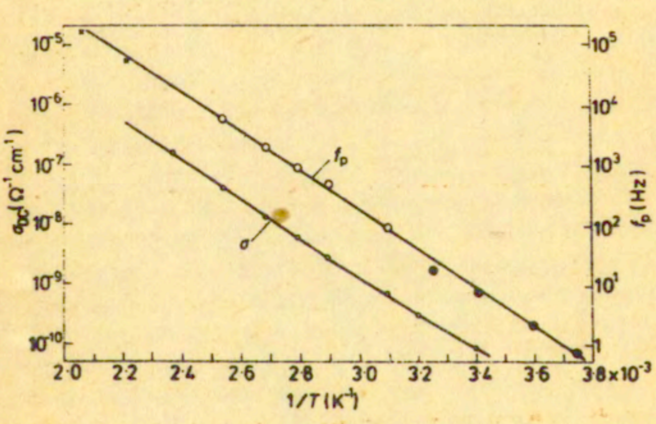

Fig.6. Temperature dependence of electrical conductivity and frequency corresponding to the maxima:
O - maximum of dielectric dissipation,
● - maximum of mechanical dissipation

mainly from the responce mechanism of attenuation /the Granato -Lücke theory/.

The model of frequency-dependent attenuation was made use of to evaluate the degree of impurity of metals of as high purity as 99.999 and more /Fig.7/.

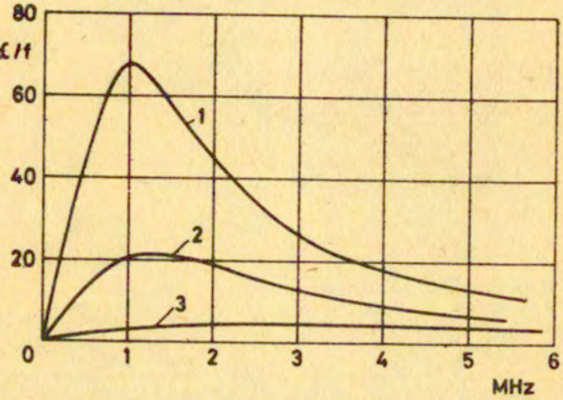

Fig.7. Attenuation versus frequency for three aluminium samples of different purities /the content of impurities increases from sample 1 to 3/

The determined resonance curve provides information on the degree of impurity. This method is applicable only for very pure materials as otherwise it is impossible to extract the dislocation attenuation from other processes [10].

Further research work was concerned with the effect of plastic deformation on the mobility of dislocations and the related absorption of ultrasonic waves. The effect of plastic deformation and gamma-irradiation on the propagation of ultrasonic waves was investigated on copper monocrystals along the direction <111> at frequencies ranging from 10 to 290 MHz.Two maxima of absorption were obtained from the measurements for deformations of 0.5% and 20%.

Figure 8 shows attenuation versus plastic deformation for various exposure times of gamma-radiation. It was found that the dose of 1000200 μAh gamma-radiation accounts for the fact that all dislocations become stabilized and thus the first maximum disappears. It was found that gamma radiation exerts no influence on the 2nd maximum, hence it may be concluded that it has nothing in common with dislocations.

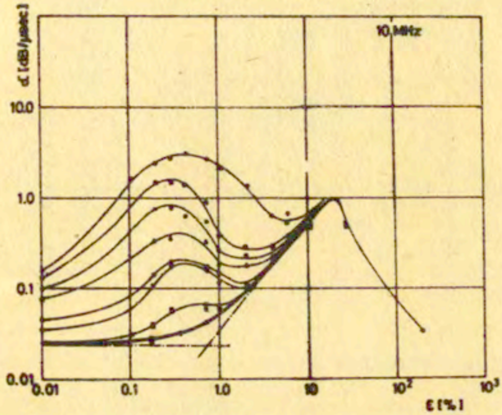

Fig.8. Attenuation of 10 MHz ultrasonic longitudinal waves versus plastic deformation for different times of exposure to gamma radiation

One of the more recent applications of physical acoustics is the acoustic method used to determine surface states in semiconductors. It makes use of the effect of interaction between the Rayleigh wave and charge carriers in semiconductors [11,12]. In the layered system consisting of a piezoelectric wavequide and semiconductor with a longitudinal drift field, the interaction of the wave with charge carriers depends on the surface conditions in semiconductors. The relative changes in the value of the critical drift field are of a relaxation character. The positions of maxima $\left(\Delta E_{d_{cr}}/E^{o}_{d_{cr}}\right)_{max}$ Fig.9, are utilized to determine the lifetime on surface traps $\tau = 1/\omega_m$

where $E_{d_{cr}}$ - the so-called drift field /the strength of the electric field in the semiconductor at which no interaction exists between the wave and carriers/

$E^{o}_{d_{cr}} = V_f/\mu_o$ - the critical drift field without surface states in the semiconductor /μ_o - carrier mobility/

τ - effective lifetime of carriers on surface traps.

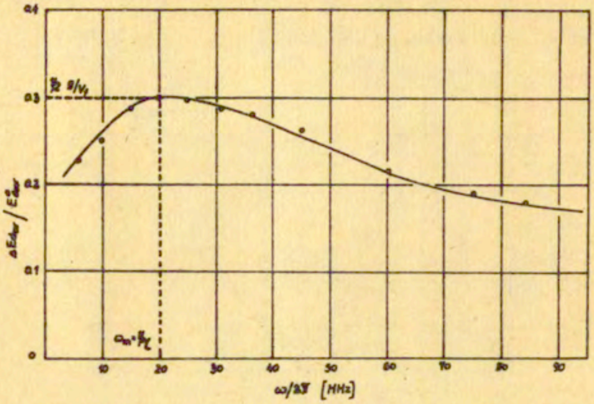

Fig.9. Frequency characteristic of the relative variations in the critical drift field of electrical charge carriers for Si - n monocrystal

The trapping rate of carriers g is found from the maximum value $(\Delta E_{dcr}/E^{0}_{dcr})$max. This method also allows to estimate the concentration N(t) of fast trapping states. The accuracy of this acoustic method is approximately 10%. Figure 9 presents the relative variation of the critical drift field versus the frequency obtained for a monocrystal Si-n /the measurements were performed in the argon atmosphere/.

2. Acoustics of Liquids and Polymers

Acoustics of liquids is useful to obtain information on its molecular and atomic structure on the basis of measurements of the propagation velocity and attenuation of acoustic waves. Using acoustic wavelengths that are much longer compared to molecular sizes, information about internal friction and heat conductivity is obtained. To get information on the internal structure of molecules it is necessary to use acoustic wavelengths that are comparable to their size. In the viscous liquid the wave propagation and attenuation depend on the frequency and relaxation constant of processes that result from the internal degrees of freedom of vibrating or rotational movements of molecules or their aglomerates.

In Poland research is pursued in the following domains of the acoustics of liquids:

- ultra and hypersonic spectroscopy,
- investigation of rheological phenomena,
- interaction of the acoustic wave with the coherent electromagnetic wave.

The starting point of spectroscopy research at the Institute of Fundamental Technological Research was the development of equipment designed for precision measurements of the attenuation and velocity of ultra and hypersonic waves within the range from a few MHz to approximately 1.5 GHz. Figure 10 shows the device used for evaluation of structural relaxation in a liquid at GHz frequency range.

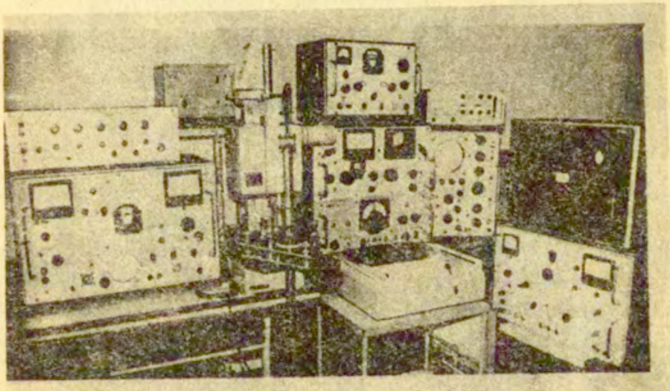

Fig.10. Measuring equipment for ultrasonic testing of liquids within frequency range up to 1.5 GHz

Figure 11 illustrates the way the resonators and measuring vessels are fastened. Measurements at GHz's frequencies range require extremely high precision in evaluating changes in the distance of resonator parts. In the system shown in Fig.10, variations in distance are measured by means of a laser technique.

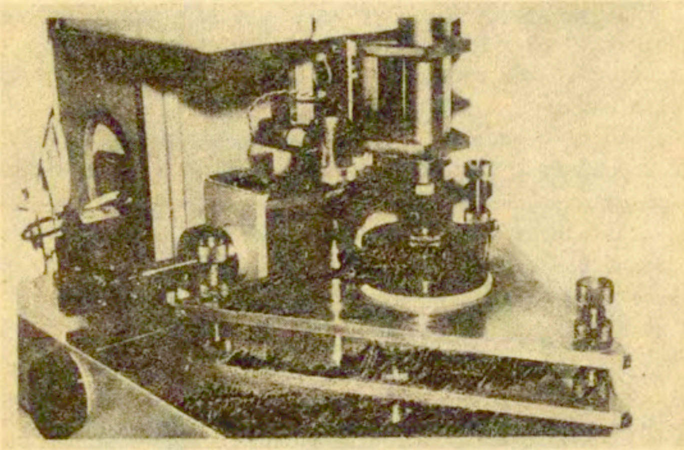

Fig.11. Fixing of resonators and measuring tank of the equipment shown in Fig.10

At the Cracow University the Institute of Chemistry also employed the equipment constructed by the IFTR to perform the structural investigation of a liquid. Two attenuation maxima were detected in the organic esters of the alkyl group for frequency ranges of 10 to 15 MHz and approximately 30-40 MHz. These maxima are related with the relaxation processes following from the rotation of molecules about the bonds $C_{ac} - O$ and $O - C_{atc}$ [13] /Fig.12/.

Rheological effects are related virtually with the laminar flow of liquid or its forced shear strain. The latter can be induced in the liquid by means of an acoustic field.

The ultrasonic shear stresses are applied, first of all, to determine the rheological properties of lubricant liquids, their relaxation spectra, dynamic viscosity, dynamic modulus and dissipation modulus as a function of frequency [15] /Fig. 13/.

Other measurements were performed jointly by staff members of the IFTR and the Institute of Chemistry, Wrocław University; these measurements concerned the effect of an electrolyte on the relaxation spectra of higher order alcohol [16]

Ultrasonic methods were also used to investigate the elastic moduli of polymers so as their relation with the degree of griding could be found [17].

The interaction between light and ultrasonic waves has been studied in Poland for nearly 50 years. Recently, these studies have become the subject of growing interest. They are related with the physics of liquids and solids, and can be applied in optical modulators, holography and other devices . In research of liquids at very high frequencies of acoustic waves, the method of light dispersion based on the Mandelstam -Brilouin /M-B/ effect is very important. After the introduction of coherent light sources /lasers/ these methods became commonly used. The M-B methods are presently developed at the Chair of Acoustics, Poznań University, and at the Institute of Physics, Silesian Technical University [19]. These methods were used to analyze, among others, the relaxation time spectra of the concentration fluctuation of the critical mixture of liquids. The velocity and attenuation of hypersounds was measured in organic highly viscous liquids.

Very high power laser beams are capable of generating higher elastic harmonics in the liquid and they interact with the ultra and hypersonic wave in a very specific manner. Such studies were conducted the Institute of Physics, Gdańsk University. Theoretical [20] as well as experimental [21] studies on the generation of the 3rd harmonic showed that the distributions of intensity in diffracted beams and of light modulation are different in nature as compared to those occuring when using low intensity light. Also these experiments allowed to defect effects [22] that had not been predicted theoretically.

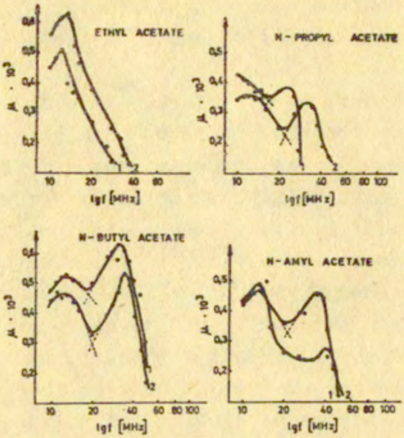

Fig.12. Attenuation per wave length $\mu=\alpha\cdot\lambda$ versus frequency for acetates with molecular chains of different lengths. One maximum corresponds to rotation about bond C - O, the other - to rotation about O - C

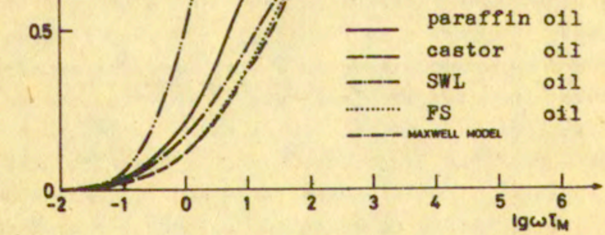

Fig.13. Characteristic of normalized dynamic modulus of elasticity G'/G_∞ as a function of normalized frequency $\omega\tau_M$ /where G_∞ - limit modulus value at very high frequency, τ_M - relaxating time for Maxwell model/

In particular cases of acousto-optical accommodation in media with anomalous dispersion, anomalous components in the diffractive spectrum were obtained in which black /absorption/ lines appeared at the positions corresponding to the bright lines of the ±1 order. Attempts were made to explain this effect as the result of the forced M-B dispersion interacting with diffraction on the ultrasonic wave.

In the field of acousto-optical interaction, it is worthwhile to mention a number of studies that utilize holographic optical interferometry of visualization of the ultrasonic field and vibration distribution in ultrasonic transducers. These theoretical and experimental studies are conducted at the Gdańsk University [23].

By reproducing the hologramme, it is possible to obtain a spatial image of the ultrasonic field or of vibration distribution on the transducer surface. These images are produced by the scanning technique /Figs.14 and 15/. Also at the Gdańsk University it was confirmed that light diffracts on two adjacent ultrasonic beams [24, 25]. In further experiments it was found that two beams with opposite directions of propagations and a frequency ratio 1:2 are capable of modulating the diffracted beams of frequencies 4 f.

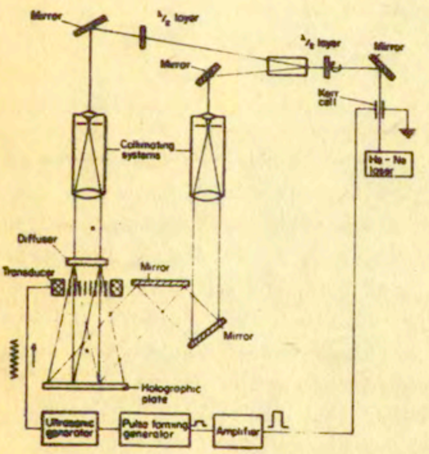

Fig.14. Scheme of holographic device for investigation of ultrasonic field

Fig.15. Interference pattern of ultrasonic transducers obtained by holographic method

3. Quantum Acoustics

It was J.Frenkel who introduced phonons as the quanta of the elementary excitation of the elastic field; this was the starting point for developing a new scientific discipline, namely, quanta acoustics. Rapid advances in this area are strictly connected with the urgent need of using GHz's frequencies range in the modern technology. At the IFTR I.Malecki and his co-worker developed a phonon model of the acoustic wave taking into account the effects of energy and space quantization [28, 28a]. It was shown, among others, that the degree of broadening of the phonon depends only on the relation of frequency and interatomic distances and is negligibly small for frequency below THz's range [27, 29]. A significant step forward in research conducted at the IFTR in the field of quanta acoustics was the description of the interaction of the hypersonic wave with quantum subsystems by means of a strain operator.This theory provided a new description of the generation of the second sound and the low-temperature effect in semi-metals [30].

Experimental studies were concerned with the application of quantum methods for the generation and detection of acoustic vibrations with frequency of order hundred GHz. Tunnel junctions were used as sources of such vibrations. The junction operates in such a way that disequilibrium state is produced in the thin semiconductor layers by the injection of electrons or phonons. Technological process was developed to obtain layered tunnel junctions /Sn - SnO - Sn/. The device generates phonons at 285 GHz. It was found that phonon frequency can be tuned by means of an external magnetic field.

4. Ultrasonic Non-destructive Testing

At the IFTR extensive research has been pursued on ultrasonic non-destructive testing for damage processes arising in machine elements under the influence of mechanical and thermal stresses and corrosion. Acoustic testing methods for use in geoacoustics have been widely developed in Poland. The results obtained indicate that transverse waves can be successfully applied for the ultrasonic control of the homogeneity of the freezing ground coat around mining shafts. The transverse wave provides additional information on the freezing conditions of geological layers. The elastic properties of the freezing ground coat can be determined on the basis of the measured velocities of the transverse and longitudinal acoustic waves. This is of vital importance for reasons of security and speed in constructing mining shafts in difficult hydrotechnical conditions. Figure 16 shows the propagation velocities of transverse waves in porous sandstone, sand and loam as a function of temperature below freezing point. Special apparatus "SONISCOPE" /see Fig.17/ is designed for acoustic testing of ground probes by drilling.

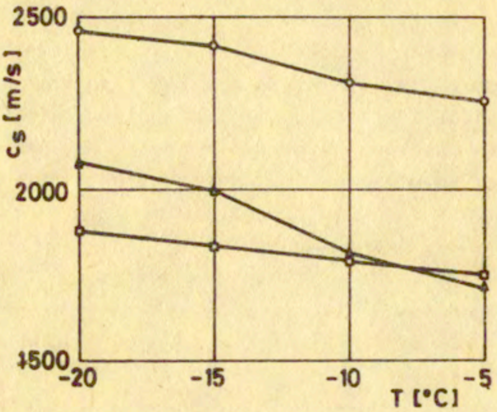

Fig.16. Velocity of ultrasonic waves in rocks as a function of temperature; o - sand, Δ - loam, ◻ - sandstone

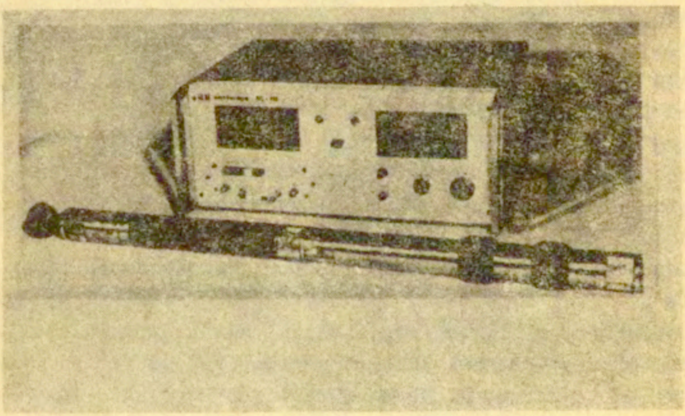

Fig.17. "SONISCOPE" equipment for testing the ground around drilling holes

The main advantage of this device is the small diameter /42 mm/ of the tube. It can be used for measuring the velocity and attenuation of acoustic waves in rocks around medium-size drilling holes applied more and more frequently for economic reasons.

The "SONISCOPE" probe is equipped with one acoustic wave transmitter and two receivers that can be located at a distance adjustable from 1 to 5 feet. The measuring results are recorded by means of analogue and digital devices.

We have found that the method of acoustic emission is especially useful for testing the properties of brittle materials. This method consists in loading the sample by means of a relatively weak extensile force and recording simultaneously the frequency and energy of the acoustic emission /AE/ signals.The first AE signals appear on the average when the applied extensile force equals half of the force that destroys the sample . Measurement of the force at which the first AE signals appear is the basis for the non-destructive determination of the mechanical resistivity. Figure 18 shows an example of an extensile test of a sample.

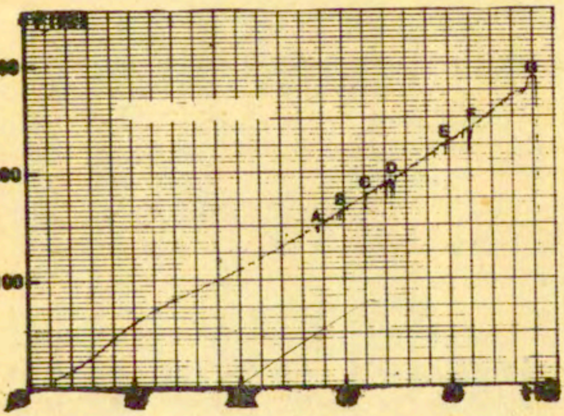

Fig.18. Extensile force acting on metal-ceramics bond sample. Appearence of acoustic emission signals are marked with letters A to F, point G marks the destruction of the sample. Force at point A is equal to half of the destructive force G

The apparatus designed and constructed at the IFTR and presented in Fig.19 is adapted for digital measuring of AE energy and recording it in an analogous method. The latest research dwells on non-destructive testing methods based on changes in propagation of surface waves.

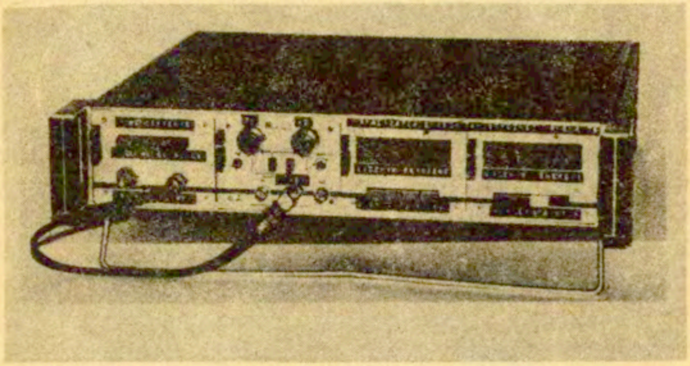

Fig.19. Apparatus for digital and analogue measurements of acoustic emission

Special apparatus ultrasonic refractometer is constructed for testing material using Rayleigh and Lamb waves [32,33]. By precise locating the angle of incidence L onto the liquid--solid interface at with the reflectivity minimum occures using Snell's law one can find out the fase velocity of Rayleigh or Lamb wave and evaluate all physical properties related to the velocity. The shape of reflectivity minimum is influenced by attenuation. Therefore both elastic /position of the minimum/ and anelastic /the shape/ properties can be tested.

Fig.20 shows the influence of tensile strength R_m of gray cast-iron on the angular position and shape of Rayleigh critical angle reflectivity minimum. Separate curves present amplitude variations of ultrasonic wave reflected from the water-cast-iron interface as a function of the angle of incidence α. At each plot a corresponding tensile strength value is noted. Smaller velocities /higher values of critical angle/ and larger attenuation /reflectivity minimum is broader/ are associated with weaker material. The surface wave velocity dates bring informations of texture of rolled prodacts, quality of heat treatment, thickness and profiles of surface layer a.t.c.The changes of surface waves attenuation can be related to the service time of metal parts.

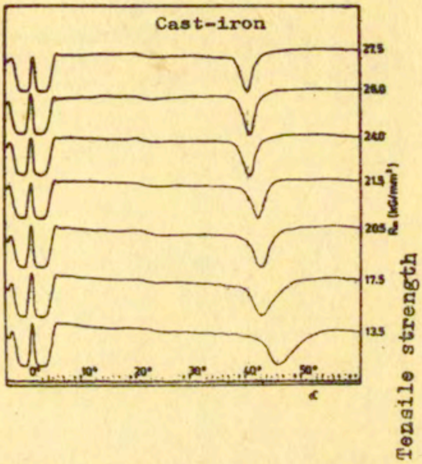

Fig.20. Amplitude variations of reflected ultrasonic wave as a function of the angle of incidence α for cast-iron samples of different strength R_m

Fig.21 presents plots of surface wave attenuation W /in dB/ versus normalized life time of aluminium samples subjected to low cycle fatique. The normalized life time is the ratio of current number N of loading cycles to the number N_f of cycles at which the sample is broken. The period of monotonous increase up to about 50% of normalized life time is the time of crack incubation. Arrow 1 indicates the moment at which the crack was first visually defected. Arrow 2 shows the beginning of fast attenuation increase which is related to the sudden propagation of the crack. Digits denote the numbers of loading cycles N_f in the entire lifetime of a given sample.

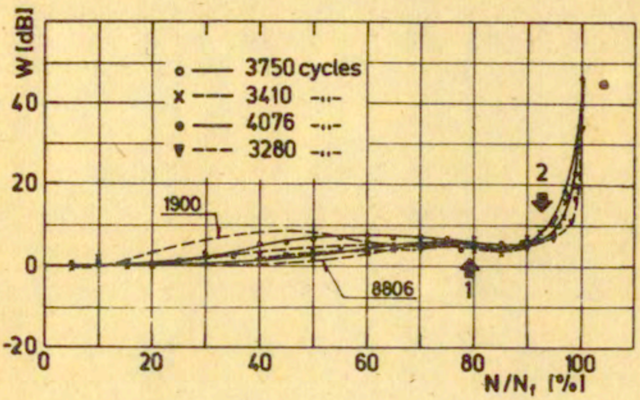

Fig.21. Attenuation of surface waves in aluminium samples in course of cyclic loading

5. Bioacoustics

The main subject of interest of Polish bioacoustics have been ultrasonographic diagnostic methods. These methods make internal organs visible without any harmful effects such as , for example, those accompaing X-ray diagnostics.

Doppler ultrasonic methods utilize the effect of scattering of ultrasonic waves by the moving blood cells which thus provide information on the velocity and flow rate of the blood in the vessels and in the heart.

The action of blood flow on the ultrasonic field and flow testing methods have been studied for many years.

A significant advance in this area is the development of a method for eliminating steady echoes by using delay lines as in the case of radar devices.

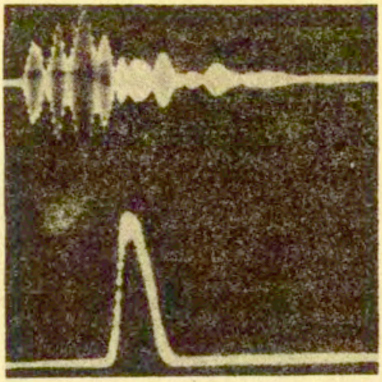

Fig.22. Doppler echoes obtained from the carotid artery:
a/ before elimination of steady echoes
b/ after their elimination the image shows only the signals scattered on the blood cells

Figure 22 shows the ultrasonograms of the carotid artery taken from the patient's neck surface by means of the Doppler ultrasonic pulse method. The echoes reflected from the boundaries of the tissues located between the patient's neck surface and the carotid artery are presented on the upper ultrasonogram. The signals scattered on the blood cells are visible here. After the system which suppresses the steady echoes, is applied, the image is changed substantially /the lower ultrasonogram/. Namely, only the signals scattered on the blood cells are visible while all steady echoes of the tissues disappear. From the ultrasonogram obtained in this way it is possible to read the velocity of the blood /signal amplitude/, its distribution across the vessel and the diameter of the vessel itself, as well as the depth at which it is located in the patient's body. The horizontal axis corresponds to the time or the depth of the vessel as counted from the patient's neck surface [34, 35, 36]. Figure 23 shows a Polish-made Doppler flow meter UDP-30/TES that uses 5 MHz ultrasonic pulse waves.

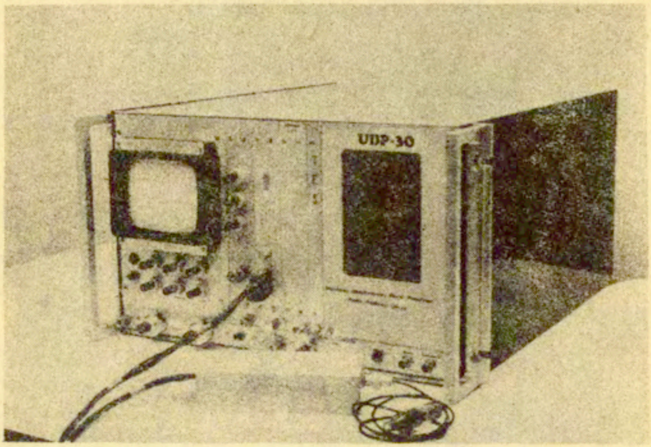

Fig.23. Doppler blood flowmeter for the tests presented in Fig.22

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