24508

ULTRASONIC TECHNIQUES AND EQUIPMENT FOR MATERIAL TESTING

A MASTER'S THESIS
in
Engineering Physics
University of Gaziantep

By
Ramazan KOÇ
February, 1992

Approval of the Graduate School and Applied Sciences.

Prof. Dr. Mazhar ÜNSAL
Director

I certify that this thesis satisfies all the requirements as a thesis for the degree of Master of science in Engineering Physics Department.

Assoc. Prof. Dr. Ata SELÇUK
Chairman of the Department

We certify that we have read this thesis and that in our opinion. It is fully adequate, in scope and quality, as a thesis for the degree of Master of Science in Engineering Physics Department.

Assist. Prof. Dr. Refik KAYALI
Supervisor

Examining Committee in Charge:

Assoc. Prof. Dr. I. Hüseyin FİLİZ
Assoc. Prof. Dr. Ata SELÇUK
Assoc. Prof. Dr. Celal KORAŞLI
Assist. Prof. Dr. Refik KAYALI
Assist. Prof. Dr. Cengiz DOĞAN

ABSTRACT

ULTRASONIC TECHNIQUES AND EQUIPMENT FOR MATERIAL TESTING

KOÇ, Ramazan
M.S. in Eng. Physics
Supervisor: Asst. Prof. Dr. Refik KAYALI
February 1992, 82 pages

In this study, an ultrasonic transmitter-receiver probe is designed and developed. An ordinary microphone crystal is used in the construction of probes, and its frequency response is determined. Then various experimets are set up to investigate the propagation of sound waves in different mediums applying different methods. Some physical parameters of different materials are measured by using the developed probes.

Finally experimental results have been compared with the theoretical results and it has been found that they were in a good agreement with each other.

Keywords: transducers, piezoelectric, probe,
nondestructive methods, ultrasound

ÖZET

MALZEME TESTİ İÇİN ULTRASONİK TEST TEKNİKLERİ VE DÜZENEKLERİ

KOÇ Ramazan
Yüksek Lisans Tezi, Fizik Müh. Bölümü
Tez yöneticisi: Yrd. Doç. Dr. Refik KAYALI
Şubat 1992, 82 sayfa

Bu çalışmada, mikrofon kristali kullanılarak bir ultrases alıcı-verici tasarlandı, geliştirildi ve frekans bağımlılığı tesbit edildi. Daha sonra ses dalgalarının değişik maddler içindeki hareketi çeşitli deney setleri kurularak değişik metodlarla incelendi. Bu çalısmalardan yararlanarak geliştirilmiş olan prop değişik ortam ve materyallerin bazı fiziksel parametrelerinin deneysel olarak ölçülmesinde kullanıldı.

Sonuç olarak, deney sonuçları teorik sonuçlarla karşılaştırıldı ve birbirleriyle iyi bir uyum içinde oldukları görüldü.

Anahtar kelimeler: iletme sistemi, piezoelektrik, prop, ultrases, hasarsız metod

ACKNOWLEDGEMENTS

I would like to express my gratitude to Asst. Prof. Dr. Refik KAYALI for his inspiring and illuminating supervision and continual encouragement through the progress of this thesis.

I am thankful to Mr. Ziya GESOGLU for his helps in drawing.

I also wish to thank to Murat ARI and Turgay DAG for their helps in typing.

TABLE OF CONTENTS

3. GENERATION AND PROPAGATION OF ULTRASONIC WAVES

4. DEVELOPING ULTRASOUND PROBES AND EXPERIMENTAL STUDIES

5. DISCUSSION OF RESULTS AND CONCLUSION

LIST OF FIGURES

LIST OF SYMBOLS

A	Area of the transducer
α	Attenuation constant
B_T	Isothermal bulk modulus of the fluid
C_s	Capacitance of the tansducer
C_p	Specific heat at constant pressure
d	Thickness of the transducer
E	Electric field vector
ϵ	Permittivity constant
f	Frequency of the wave
F	Electric force vector
G	Shear modulus
γ	Gamma ray
	Specific heat ratio
k	Spring constant
	Wave vector
κ	Thermal conductivity
ℓ	Distance between two atoms
	Length of the specimen under test
δL	Strain
λ	Wavelength of the wave
η	Viscosity of the medium
P	Electric dipole moment
	Pressure on medium
q	Electric charge
R_s	Electrical resistance

R	Acoustic resistance
ρ	Density of the medium
S	Salt concentration(%)
σ	Poisson's ratio
t	Time
T	Absolute temperature
θ	Diffraction angle
t	Relaxation time
V_{π}	Electric potential
V,v	Sound velocity
Y	Young modulus
ω	Angular frequency
ξ	Wave function

CHAPTER 1

INTRODUCTION

Acoustical engineering is a domain of technology and science now being developed dynamically. The most important branch of acoustical engineering is the ultrasonic and their applications which cover metallurgy, molecular physics, biophysics, chemical industry, ship navigation...

There are various methods for testing materials and to determine the physical properties of matter, such as, x-ray method, γ-ray method, eddy current method, spectroscopic methods, ultrasonic method. Especially, for nondestructive testing(NDT) of materials, sensitivity of ultrasonic technique used was superior to all the other methods.

In the area of physics and physical chemistry measurements of attenuation and velocity of ultrasound have been utilized to clarify the molecular structure and to measure some physical properties of matter. Similarly, material scientists and metallurgists have used, the same results to study on the submicro-, micro-, and macro structure of materials and the mechanism of inelastic deformation. The rate of measurement of attenuation of vibration and the natural frequencies of vibrations have been the subject of many investigations. The damping and natural frequency test are both nondestructive, because the vibration amplitudes, usually so small that the stresses produced have no, or a negligible effect on the material.

There are many types of ultrasonic devices used in ultrasonic testing methods.The most important part of every device is the probe which contains a piezoelectric element used to produce and receive the ultrasonic wave. This element has effects on the cost of the device, since manufacturing such a piezoelectric crystal requires high technology. On the other hand, the accuracy and sensitivity of the probes designed for special purposes are the factors which increase the cost of these devices. Because of this, many of the theoretical and experimental studies have been based on developing more sensitive and cheaper devices which can be used for measuring physical properties of gases, liquids and solids instead of expensive apparatus.

Our study is one of them. In laboratory conditions, the velocity and the attenuation of longitudinal sound waves in a material can be accurately measured by adaptation of a piezoelectric microphone crystal. In this study we developed a probe whose cost incomparatively less then the cost of the probes sold with a high price in market, and give comparable good results with the results obtained using these expensive apparatus.

There are many different measurement techniques of ultrasonic used for various purposes. One of the famous methods is known as high frequency-pulse method especially serviceable for nondestructive testing(NDT). The other methods are resonance method, interference method, modulated wave method, radiation pressure method, acoustic streaming method, optical methods and modulated-pulse method. These methods are generally, used for structural analysis of material, by means of, measurement of velocity, attenuation, natural frequencies of materials, damping rate, reflection, refraction and transmission coefficients of wave in matter.

The developed probe can be employed for measuring the velocity and attenuation of wave with high accuracy. During our study, resonance method and optical interferometer method was experienced for velocity measurements. Modulated-pulse method was experienced for attenuation and velocity measurements. A comparison also was made between modulated-pulse method and the other methods. It was found that modulated-pulse method were as sensitive as the other methods for measurement of velocity and attenuation.

This study has been arranged as follows: Chapter 2 consists of historical development and literature survey on the subject under investigation. General design procedure and characteristic of probes considered in chapter 3. Chapter 3 also includes the theoretical consideration of propagation of waves in matter and their interactions with solids and liquids. The construction of apparatus and performed experiments are occupied in chapter 4. Finally the experimental results have been discussed in chapter 5.

CHAPTER 2

LITERATURE SURVEY

2.1. Introduction and Historical Development

As in many other branches of science, major advances in acoustic have been preceded by empirical observation. Most acoustical phenomena are transient in nature. In ancient Egypt, Syria and Babylon, knowledge of the nature of sounds was very limited. However, it was known how to propagate sound signals over large distances.

Nondestructive testing of material is older than usually thought. It involves striking a specimen with a hammer and listening to the sound produced; as was done by the ancients to check if their clay pots and glass bottler were sound. Nowadays when the frequencies of vibrations lie beyond the audible range suitable electronic instruments should be employed for their detection, so that the range of study has been considerably broadened.

Although in the fifteenth century the interest in the surrounding world and consequently in the diversity of sound phenomena increased markedly, before 1800, scientific apparatus in acoustic was of the simplest kind.[1]. The pendulum had been used as demonstration instrument by Galileo (1564-1642). Measurement of speed of sound was made and the value obtained was 349.9 m/sec. The speed of sound was again studied by a commission of the French Academy of sciences and in 1738 they announced their result to be 333.4 m/sec.

The problem of propagation of sound waves, and the acoustic of theatres and mosques were studied in Greek culture and Ottoman culture. At the end of the seventeenth century, the term acoustic (derived from the Greek words) was used in modern sense of the word.

At the beginning of the nineteenth century there appeared some books containing a systematic study of principal branches of acoustic. The first significant advance of the nineteenth century was the work of CHLADNI in 1802 in determining the wave patterns of vibrating bodies. He also made elaborate investigations of longitudinal and torsional vibrations of rods and strings and of the transverse vibrations of bars and plates.

Between the years 1810-1830 YOUNG, FRESNEL, FOURIER, POISSON, LAPLACE and others developed the theory of propagation of elastic and thermal waves. Between 1858 and 1862 RUDOLPH KOENIG devoted himself specially to the perfecting of Scott's phonoutograph. The climax of the period of integration of different branches of classical acoustic came between the years 1870-1880.

An optical method for the determination of the strength of a sound wave was first described by BIOT in 1820 and developed by KUNDT in 1864 and MACH in 1872. A second optical method was devised by TOEPLER and BOLTZMAN in 1870. Their method consisted in producing interference bonds by combining to rays of emitted light originating from the same source one of which passed through the air in its normal state, and the other through a nodal point of a vibrating air column, so that changing in path lengths was observed.[1]

The work by RAYLEIGH constitutes a complete, and still valid, study of the theory of vibrating systems, and propagation of sound waves in free space and around obstacles.

By the end of the nineteenth century, the acoustic-mechanical methods of measurements were greatly improved; for instance, the absolute measurements of intensity of the acoustic field and the measurement of absorbtion coefficient were accomplished. The end of the nineteenth century brought about new discoveries in the realm of room acoustics. The principal advances of the nineteenth century involved four aspects of acoustical science:

Measurement of the velocity of sound, determination of frequency, determination of particle velocity, and observations on timbre.

It was only the discovery of the principle of the electronic amplification of electric signals which opened new perspectives, not only for engineering applications in acoustics, but also for its development as a science. At the same time acoustic become a discipline exceeding the bounds of physical investigations and ventured into medicine, the building industry, telecommunication, metallurgy and chemistry. This expansion of researches collected under one common term of acoustics proceeded between the years 1914-1939.

Research on molecular acoustic was conducted by many physicists. Molecular acoustic constitutes a scientific bases for new passive applications of ultrasound in the investigation of organic liquids and for active applications, chiefly in the chemical and food industry. Between the years 1922-1925, that the first precise and convenient instruments were devised for measurements of velocity and attenuation of sound waves in liquids and gases. In the investigation of the molecular structure of liquids, there has been a growing interest since 1960 in the propagation of sound waves in liquids, was collected on the acoustic properties of many liquids and gases. The collected experimental material became a starting point for theoretical generalization.

The ultrasonic waves have found important practical applications between the years 1940-1960 the interest in the physical properties of ultrasound and their papers appeared and many experimental investigations were carried out.

The measurements of the sea depth and the detection of icebergs was made by LANGEVIN, in 1920. This is known as the first original application of ultrasonic waves. Ten years later SOKOLOV constructed the first ultrasonic flow detector.

After this rapid review of history of the acoustic we return the literature survey of some special subject which we interested during our studies.

2.2. Development of Ultrasonic Transducers

After the discovery of piezoelectricity, many investigations have been made on that subject. In 1970's it was recognized that piezoelectric materials could be exploited in other domains than structural applications, particulary in electronic systems. Ultrasonic transducers for medical and nondestructive testing applications are intended, like hydrophones, to transmit and receive high frequency signals in water, but they operate at much higher frequencies (0.5-20 MHz). This section contains review of some papers about transducers.

Auld, B. A. studied about to determine the input electrical impedance of piezoelectric composite materials which initially developed for sonar applications, are now being more and more widely used for ultrasonic transducers [2].

Shaulov, A., and his coworkers developed a spherically curved transducers using a composite piezoelectric material [3]. Relation between the frequency and insertion loss of transducer was studied. Matis, I.G.[4],examined the quality of the composite materials for nondestructive testing. Design consideration of matrix type transducers was investigated.

Anson, L. W., Chevers, R. C. studied on the sensitivity of ultrasonic transducer materials and calculation of the frequency response of different piezoelectric transducer materials. The result was compared with experimental results [5]. Acoustic impedance and attenuation in particle polymer composites for transducer backing application was examined by Greve and his coworkers. The acoustic impedance of composites was modelled [6]. A transducer from PZT polymer composite was designed for working at temperatures over 100 degrees C. The designed transducer uses an electrically conductive polyamide decomposition at 550 degrees C.[8].

J. Wenczel designed an ultrasonic pulse pulse generator from a square wave for driving transducers. He compared his experimental results to results obtained from several pulses. Some test books were tested at 5 MHz pulse frequency, and input output relation of pulses was discussed in this paper [10].

2.3. Development of Ultrasonic Test Methods

The acoustic emission technology starts with the doctoral investigation of Joseph Kaiser. He designed tensile machine having special features, then he observed if load applied to the material, then sound were emitted during external loading by most of materials. Many of his observations have proved to be correct [11].

Packman, P. F., and his coworkers studied about the ability of four nondestructive testing techniques to locate, identify, and measure fatigue cracks was determined experimentally. x-ray, magnetic-particle inspection, penetrant inspection, ultrasonic inspection compared to each other. They showed that no cracks smaller than 0.10 inc. can be detected. The sensitivity of the ultrasonic technique used was superior to all other methods examined [12].

Raju, N. K., made fatigue and crack tests under repeated loads, by measuring the change in velocity. Prismatic specimens was used for testing.

Typical changes have been observed in the velocity with number of cycles of load as indicated in figure 1. He observed that low strain stiffness, typically of the fatigue specimens [13].

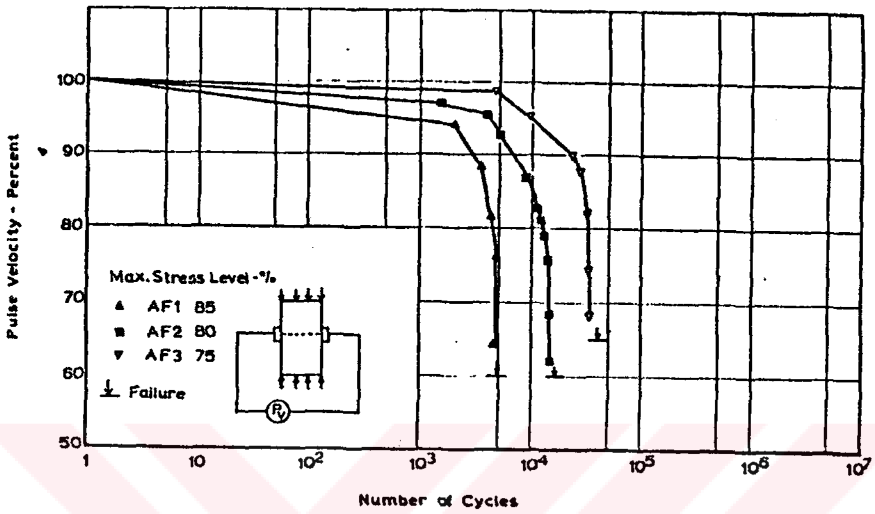


Fig.1. Variation of pulse velocity in the transverse direction with cycles of load-AF test group.

S. P., Shah and S., Chandra investigated the formation of cracks in the specimens under compressive load by measuring the velocity and attenuation. They derived an empirical relation between the crack length and velocity, from experimental results. They observed that pulse velocity decreases with increasing length of cracks. Their test equipment is indicated in figure 2. Note that the accuracy of the time measurement was 1 µsec, while that of the amplitude measurement was 10 mV/cm [14].

Ohozawa, M., Katomine, A. and Ishii, Y., detected the surface flows by ultrasonic method. They constructed a probe which for that purposes, dead zone was specially designed. Flow detection sensitivity of probe compared the other probes and the results were indicated [15].

The time-of-flight velocity of plane ultrasonic waves in thin sheets discussed by C.C. Habeger to determine the elastic stiffness of thin polymeric sheets. the velocity measurements were performed with a robot which all mechanical motions of robot was controlled by pc class personal computer. The transducer was triggered by a function generator which controlled a computer [16].

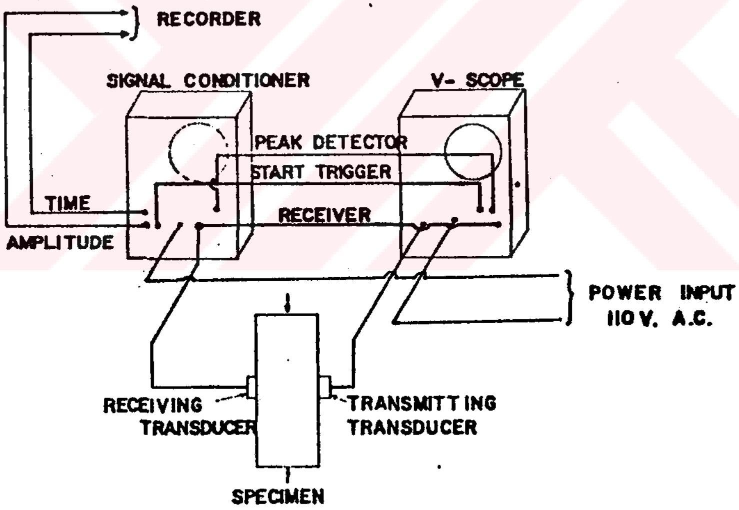


Fig. 2. Schematic diagram of ultrasonic apparatus.

Mase G. T. and his coworkers studied for determining the effect of applied stress in structure of materials. Their study based on the fact that as a material under stress goes deformation, the longitudinal and shear wave speeds change. Changes in speed were determined by using modulated pulse method. The aluminium plates were used as test material [17]. Similar tests were made by J.J. Dike and G.C. Johnson to determine the residual stress by measuring velocity changes [18].

The paper prepared by A.H. Nayfeh, T.W. Taylor contained a theoretical treatment, for calculation of displacements and stresses within multilayered media subjected to incident ultrasonic waves. They supposed that the waves incident from water with an arbitrary angle. The developed model has value in material characterization and in the nondestructive evaluation of advanced material applications [19]. The other similar paper was prepared by Joseph L. Rose Adnan Nayfeh, Aleksander Pilarski, for material characterization. They studied about the propagation of harmonic surface waves on a transversely isotropic layer rigidly bonded to a transversely isotropic substrate of different materials [20].

Many Author studied on characterization of material by ultrasonic methods. Allain Foure, Gerard Maze, and John Ripoche observed ultrasonic surface waves on plane and cylindrical solids. Effect of density and strain on velocity of ultrasound were investigated by A. L. Nalamwar and Epstein. Interaction of ultrasonic waves on to a liquid-solid interface was demonstrated by M. A. Breazeale and his coworkers using Schlieren photography. Velocity measurement of surface waves and on plane and cylindrical samples have been experienced. Many papers which contained similar studies as mentioned above can be found given addresses at the reference section.

2.4. Sound Waves in Liquids and Underwater Acoustic

Reflection transmission and attenuation of sound waves in liquids analogous to biophysical studies and measurements of parameters are used to characterize the liquids. Many authors studied on this subject, a little of them briefly will be given here.

D" Arrigo, G., and Paparelli, A. measured the ultrasonic absorbtion coefficients in the water-ethanal mixtures in the frequency range 10-250 MHz and for a temperature interval extending from +30 to -40 degrees C was presented. Compressibility of the mixture was determined by the measuring the velocity of sound waves. The relation between the absorbtion coefficient and frequency, temperature was analyzed [21].

Kashkooli, H. A. Dolan, P. J., Smith, W. studied on measurements of the acoustic nonlinearity parameters in water and some other liquids by two methods. One of them was light diffraction and the other was finite amplitude loss method [22].

Avanesav, A. M.; Avetisyan, I. A. studied on the propagation of sound in a mixture of viscoelastic relaxing liquid with gas bubbles. They obtained the dispersion relations for the velocity and acoustic attenuation. Analysis was made numerically [23].

Acoustic wave propagation through a dense suspension of solid elastic particles in water was studied by Ma, Y., Varadan, V. K., Varadan, V. V.. The particles in suspension have a size distribution and their relative positions were described. Numerical results presented were of interest in the study of marine sediment [24]. The theory of the scattering of compression waves in viscous fluids was examined by Harker, A. H. Temple, T. A. G.. The effects of fluid viscosity, of difference in density and in elastic modulus between the particles and the fluid, of heat transfer and concentration was considered. Ultrasonic phase velocity and attenuation were derived. The feasibility of using ultrasound to characterise suspensions was discussed [25].

Adler, L. and Nagy. P. B. investigated the surface roughness from the reflected and transmitted ultrasonic waves. Experimental results were presented to show good agrement with calculated predicatory of the suggested simple technique. Transmitted and reflected wave components were compared and showed that the attenuation of wave depends on the surface roughness [26].

The particle velocities of a system of a pair of square transducers and that of a pair of circular ones were computed and compared with each other by Imamura, T. The computation was based on Rayleigh's theory and numerical multiple integration was achieved [27].

CHAPTER 3

GENERATION AND PROPAGATION OF ULTRASONIC WAVES

3.1. Introduction

A transducer is a device which transforms energy from one form to another. Ultrasonic transducers transforms high-frequency electric energy into high frequency mechanical energy, or vice versa. There are only two types of transducers for generation and detection of ultrasound. One of them is designed by using magnetorestrictive elements which produce ultrasonic frequency range up to 100 kHz. Above that range, usually transducers are designed by using piezoelectric elements. However, piezoelectric transducers may be used widely for the 30-to-100 kHz range in future. There are another important type of transducers which are known as electroacoustics or electrostrictive transducers used for the production and reception of airborne sounds at audible frequencies. In this study, we are dealing with only piezoelectric transducers. Electrostrictive and magnetostrictive transducers are out of the scope of this thesis.

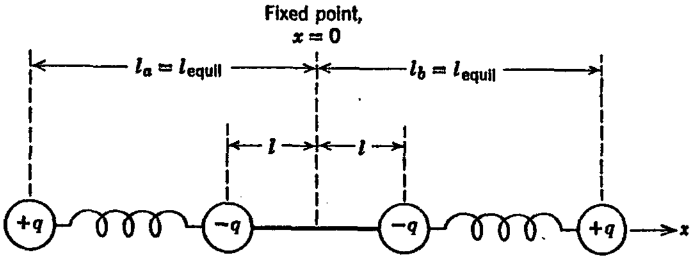
This chapter will also include the propagation of ultrasonic wave in matter. The basic equations needed to describe waves in fluids and solids will be derived. The relation between the velocity, attenuation and some physical properties of matter will be obtained in this chapter.

3.2. Piezoelectricity

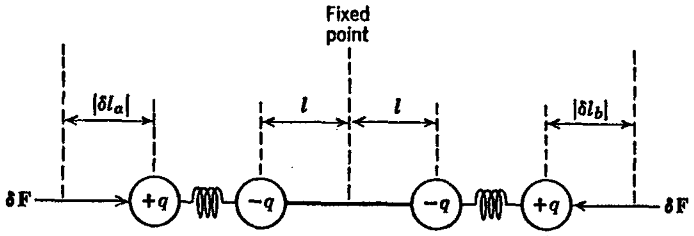
Certain materials become electrically polarized when they are strained. This effect, called the direct piezoelectric effect. It is linear phenomenon and the polarization changes sign when the sign of the strain is reversed. Piezoelectricity is related to the microscopic structure of solids and it can be explained qualitatively in terms of a rather simple atomic model.

3.2.1. One-Dimensional Model of Piezoelectric Effect

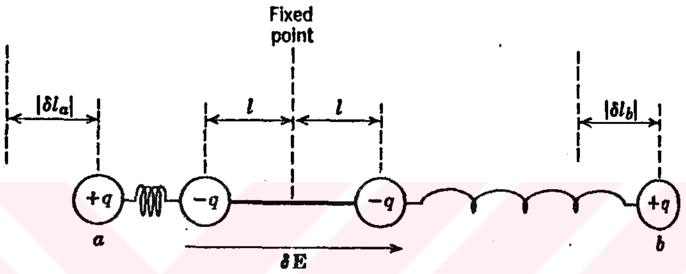
The model chosen is an electrically neutral system of charged particles connected together by rigid and elastic bonds as shown in figure 3.1 and 3.2.[30]. In this model our assumption corresponds that all charges in an actually solids are constrained to move along the x-axis. The centre point of the system is rigidly fixed at $x=0$. The mechanical forces applied to the system are equal and opposite direction. Electrical forces applied by means of an electric field. If the mechanical forces applied to the system the physical dimensions of the



(a) Equilibrium state ($l_a = l_b = l_{equil}$)



(b) Applied mechanical force



(c) Applied electric field

Fig. 3.1. Model of nonpiezoelectric solid.

system change. The total change in the length of the system is δL, and can be written

$$\delta L = \delta l_a + \delta l_b \qquad 3.1$$

where δL is known as the strain in a solid. The electrical response is defined as the change in the total electric dipole moment P_x of the system, then the definition of electric dipole moment gives

$$P_x = \sum_n q_n X_n \qquad 3.2$$

where q is the charge of each point mass and X corresponds the distance between them.

To analyze this model firstly we will find the equilibrium configuration and then we will calculate the configurational changes produced by the impressed forces. Equilibrium configuration is determined by evaluating the combined spring and electrostatic forces acting on the movable charges a and b. If there is no external applied force to the system then we can set equal to zero force acting on charges a and b. The springs are assumed to have identical force constant k and unstrained lengths l_0. Then the force equation for the left-hand spring of figure 3.1. is,

$$f_a = k(l_a - l - l_0) \quad . \; . \; . \; . \; . \; . \; . \; . \qquad 3.3$$

for the right-hand spring is

$$f_b = k(l_b - l - l_0) \quad . \; . \; . \; . \; . \; . \; . \qquad 3.4$$

The electrostatic forces on the charge a and b are determined from the Coulomb's force law, for charge a, F_a can be written as

$$F_a = q^2[(l_a - l)^{-2} + (l_a + l)^{-2} - (l_a + l_b)^{-2}] \quad . \; . \; . \qquad 3.5a$$

for the charge b, F_b is,

$$F_b=-q^2[(l_b-l)^{-2}+(l_b+l)^{-2}-(l_a+l_b)^{-2}] \quad . \; . \; . \qquad 3.5b$$

The combined spring and electrostatic forces acting on charges a and b in figure 3.1(c) for example, are therefore;

$$(F_a)_x=k(l_a-l-l_0)+q^2[(l_a-l)^{-2}+(l_a+l)^{-2}-(l_a+l_b)^{-2}] \qquad 3.6a$$

$$(F_b)_x=-k(l_b-l-l_0)-q^2[(l_b-l)^{-2}+(l_b+l)^{-2}-(l_a+l_b)^{-2}] \qquad 3.6b$$

The equation 3.6 implies that l_a must be equal to l_b because of the equilibrium conditions, then we will write

$$\underline{l}_a=\underline{l}_b=\underline{l}_{equal} \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \qquad 3.7$$

Since the equilibrium configuration in figure 3.1 is symmetric, then the equilibrium dipole moment is zero.

$$(P_x)_{equil}=-\underline{q}\,\underline{l}_{equil}+\underline{q}\,\underline{l}-\underline{q}\,\underline{l}+\underline{q}\,\underline{l}_{equil}=0 \; . \; . \; . \; . \qquad 3.8$$

This system, therefore does not have a spontaneous electrical polarization. The equation 3.8 is true if only if the charges a and b have equal magnitudes.

Consider the effect of mechanical forces. Because the applied forces are symmetric (figure 3.1b) we can write that without calculation, the movable charges a and b are displaced inward by equal amounts,

$$|\delta l_a|=|\delta l_b| \quad . . . . \quad 3.9$$

Under above condition the change in the length of the system, can be written,

$$\delta L=-2\delta l_a \quad . . . . \quad 3.10$$

The change in the polarization of the system,now also zero,

$$\delta P_x=q\delta l_a-q\delta lb=0 \quad . . . . \quad 3.11$$

When uniform antisymmetric electric field applied to the system as in figure 3.1c, charges a and b are again balanced. That is

$$(F_a)_x+q\delta E_x=0 \quad . . . . \quad 3.12a$$

$$(F_b)_x+q\delta E_x=0 \quad . . . . \quad 3.12b$$

If applied electric field is small, then we may use approximation and we obtain

$$(F_a)_x=(F_a)_{xequil}+(\partial(F_a)_x/\partial l_a)_{equil}\delta l_a+(\partial(F_a)_x/\partial l_b)_{equil}\delta l_b \quad 3.13a$$

$$(F_b)_x=(F_b)_{xequil}+(\partial(F_b)_x/\partial l_a)_{equil}\delta l_a+(\partial(F_b)_x/\partial l_b)_{equil}\delta l_b \quad 3.13b$$

where the equilibrium forces equal to zero. Since $l_a = l_b$ at equilibrium. So that, from equation 3.5 we can write

$$(\partial(F_a)_x/\partial l_a)_{equil} = -(\partial(F_a)_x/\partial l_b)_{equil} = A \;.\;. \qquad 3.14a$$

$$(\partial(F_a)_x/\partial l_b)_{equil} = -(\partial(F_b)_x/\partial l_a)_{equil} = B \;.\;. \qquad 3.14b$$

where A and B are constants. Substituting equations 3.13 and 3.14 into equation 3.12 then we obtain

$$\delta l_b = -\delta l_a = q\delta E_x/(A-B) \;.\;.\;.\;.\;.\;.\;. \qquad 3.15$$

Under the applied electric field change in polarization of the system is therefore,

$$\delta P_x = -q\delta l_a + q\delta l_b = 2q^2\delta E_x/(A-B) \;.\;.\;.\;. \qquad 3.16$$

and the change in the length of the system is,

$$\delta L = \delta l_a + \delta l_b = 0 \;.\;.\;.\;.\;.\;.\;. \qquad 3.17$$

Equations 3.10, 3.11, 3.16 and 3.17 implies that for nonpiezoelectric materials there is no mechanical response to applied electrical forces and no electrical response to applied mechanical forces.

The charge distributions of the piezoelectric materials are antisymmetric. Because of the antisymmetric charge distributions, the response of the crystal is quite different for piezoelectric materials.

The electrical and mechanical response of piezoelectric materials can be analyzed, in detail, as the nonpiezoelectric materials. At equilibrium again ($l_a=l_b=l_{equil.}$). According to figure 3.2[30] polarization of the systemcan be written as

$$P_{xequil}=-ql_{equil}+ql+ql-ql_{equil}=2q(l-l_{equil}) \quad . \ . \quad 3.18$$

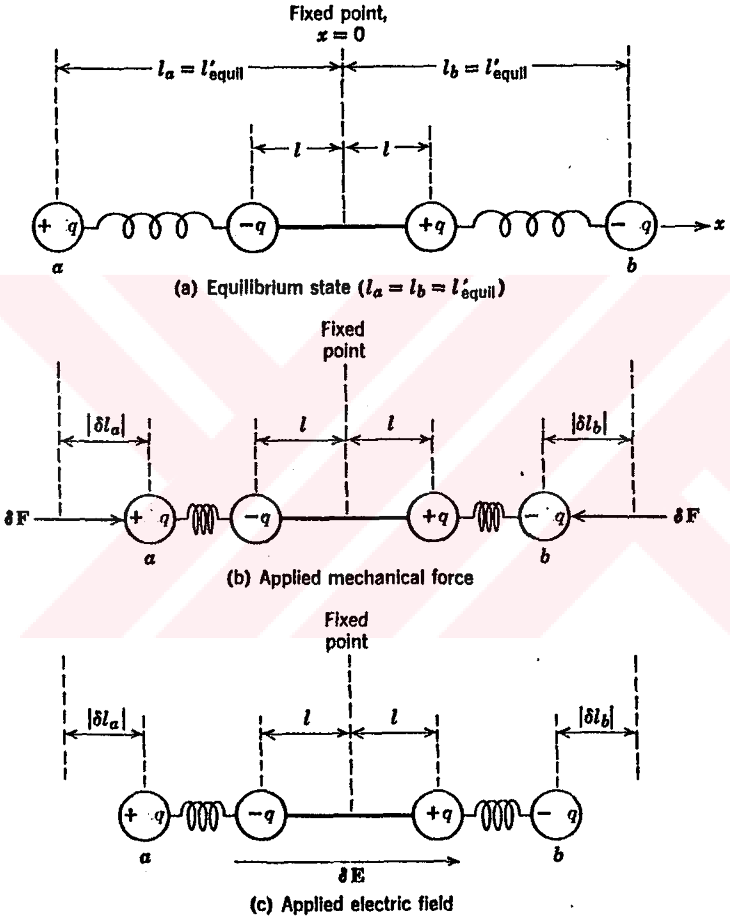


Fig. 3.2. Model of piezoelectric solid.

It can be shown that there may be spontaneous polarization in this case. If the the mechanical or electrical forces are applied to the system, as it is seen in figure 3.2b and 3.2c, the change in length of the system are both symmetric and we can write

$$|\delta l_a| = |\delta l_b| \quad \ldots\ldots\ldots \quad 3.19$$

For both situations (c) and (b) the mechanical and electrical response of the system can be written

$$\delta L = 2\delta l_a \quad \ldots\ldots\ldots \quad 3.20a$$

$$\delta P_x = -q\delta l_a - q\delta l_a = -2q\delta l_a \quad \ldots\ldots \quad 3.20b$$

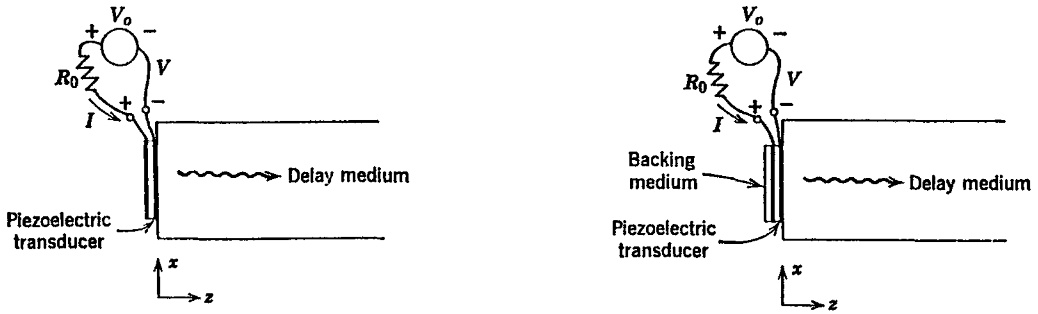
are now nonzero for both mechanical and electrical applied forces. In equation 3.20b $P_{equil.}$ is taken zero for simplicity.

The electrical polarization changes calculated from equation 3.2 are due to changes in position of the charged particles, which are supposed to represent ions in an actual solid. This type of polarization is called ionic polarization. There is another important effect where by the ions themselves become polarized in an applied electric field is known as electronic polarization. This could be included in the model, but this would not change the basic piezoelectric relation; 3.20.

3.2.2 Excitation of Thin Disc Transducer

The thin disc transducer in which the thickness of the transducer is orders of magnitude smaller than its transverse dimensions. The deposited film transducers can be used in ultrasonic applications.

Figure 3.3 shows the usual experimental arrangement, in which a thin disc transducer is attached to a solid cylinder of finite cross section. A voltage V is applied across the two electrodes on the transducer by means of a voltage generator with open circuit output V_0 and internal resistance R_0. In some cases a backing plate is attached to the transducer in order to modify the frequency response. The terminal voltage V is not equal to the open circuit voltage V_0 and must be calculated by analyzing the series circuit consisting of the generator, the resistance R_0, and the transducer. If the piezoelectric coupling is very weak, the excitation of acoustic waves does not produce significant changes in the electrical displacement vector **D** within the transducer plate. In this case the input electrical impedance at the transducer terminals can be calculated to a good approximation from the geometrical capacitance



(a) Unbacked transducer

(b) Backed transducer

Fig. 3.3. Typical piezoelectric disc transducer configuration.

$$C_0 = \epsilon_{szz} A/d \quad \ldots\ldots\ldots\ldots \quad 3.21$$

where

ε = Effective permittivity

A = Transducer area

d = Transducer thickness

The terminal voltage is then

$$V=[V_0]/[jwC_0R_0+1] \quad . \; . \; . \; . \; . \; . \; . \quad 3.22$$

and there is a uniform applied field, within the piezoelectric disc.

$$E_z=V/d=[1/(jwC_0R_0+1)][V_0/d] \quad . \; . \; . \; . \; . \quad 3.23$$

For many applications, weakly coupled piezoelectric transducers are unsatisfactory because of their low electromechanical conversion efficiency. It is therefore necessary to consider the more complicated behaviour of strong coupling materials. In this case the acoustic waves excited can produce significant changes in the electrical displacement, and this reaction causes the input electrical impedance of the transducer to vary with the strength of the acoustic excitation.

3.3. Probe Design Considerations

This section deals exclusively with piezoelectric converters, which are the most commonly used converters, especially in ultrasonic nondestructive testing, and the other branches of ultrasonic applications.

In design procedure each probe has its own characteristic. In this section, we will discuss the common characteristics of ultrasonic probes, which are basics to choice piezoelectric element, electrode type, electrical contacts on crystal electrode, backing materials and its characteristics, frontal member and transducer housing. Transducers are available in two basic forms and are known as single crsytal transducers and twin or combined double crystal transducers. The most commonly used metarial for ultrasonic transducers is PZT. (Lead Zicronate Titanate). Each properties of probe briefly explained in this section.

3.3.1. Selection of the Piezoelectric Element

For each application, the choice of crystal is critical (material shape, dimensions, etc.). Two kinds of crystal are commonly used: Monocrystals such as quartz, zinc sulphate, and polycrystal such as ceramics. These two types of material differ fundamentally in their acoustic properties.

The monocrystal is homogeneous which produces homogenous acoustic beam (coherence). The ceramics are inhomogeneous. In high-frequency crystals parallelism of the main faces is of the primary importance for coherence of the sound beam. Another important factor effecting the efficiency of crystal is acoustic adaptation. Optimum adaptation of the crystal to the transmission medium is obtained by matching the acoustic impedances as closed as possible.

3.3.2. Electrodes and electrical contacts

Metallization of the crystal faces is very critical factor in probe design. The crimping, cracking and flaking of the metal layer cause incoherent or inhomogeneous sound beam from the crystal. The best method is to applied deposit of nickel under vacuum. Nickel, as compared with gold is not subject to diffusion within the crystal.

The contacts or wires that carry the electrical signals to the crystals are generally a major source of error within probes. To optimize the source of contact error, the best method is to connect a number of very fine aluminium wires to different points of the transducer rare surface, by using ultrasonic welding method.

3.3.3. Backing Member

The function of the backing is to load the crystal mechanically for rapid damping of the acoustic bust. Acoustic oscillation occurs in the crystal as the sound waves are reflected back and fourth within it. To obtain a short pulse all the acoustic energy must be absorbed in the load. This load may be of two kinds: A quarter wavelength reflector/damper, or a scattering diffusing backing. The first method is new and excellent with high Q crystals. The scattering method is classical, and is generally based on the use of tungsten powder in epoxy resin or sintered metals.

3.3.4. Transducer Housing

The best type of crystal holder seems to be an insulating ceramic housing, one end of which holds the crystal. The external and internal surfaces of both housing and crystal are vacuum metallized. The interior space of the housing is then filled with backing or damping material and the housing itself is inserted into another metallic housing. This type of construction is well suited to produce very short high-power pulses.

3.3.5. Transducer Excitation Sources

The selection of the ultrasonic apparatus depends primarily on the spectroscopic technique. In the following schematic block diagram will be given that show the basic features of electronic instrumentation used with each technique. Each block on these diagrams will represent a commercially available device.

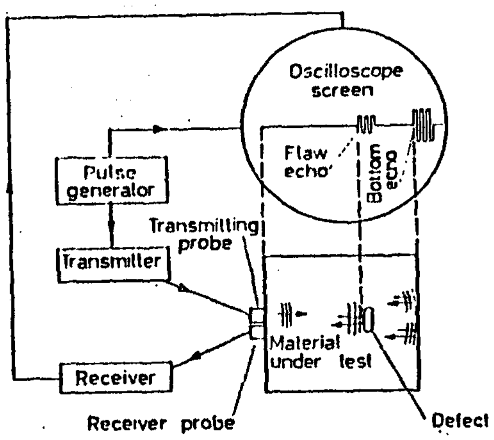


Fig.3.4. Block diagram of pulse spectroscope.

3.3.5.1. Pulse Procedure

The electronic instrumentation used for pulse spectroscopy are illustrated in fig (3.4) as a block diagram. The circuit shown in figure (3.4) consists of a pulse generator for transducer excitation, a transmitting probe for generation of ultrasound wave and a receiving probe to detect the echoes, and an oscilloscope which displays the detected echoes.

The transducer excitation is periodic to produce a stationary time domain pattern on the oscilloscope screen.

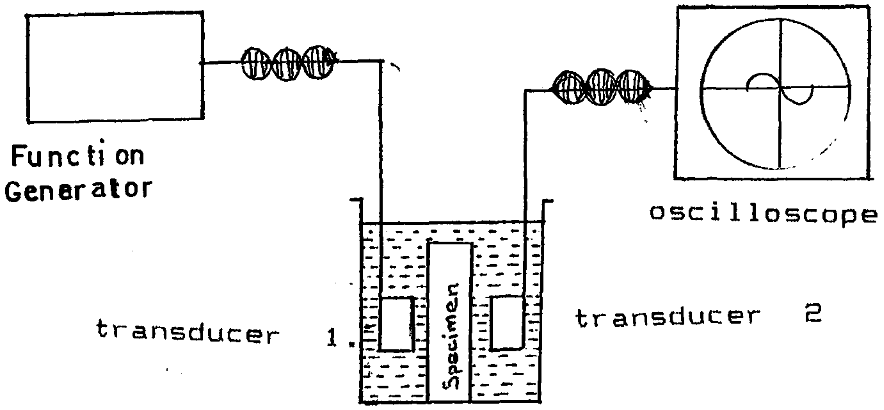


Fig.3.5. Block diagram of frequency modulation spectroscope.

3.3.5.2. Frequency-Modulation Procedure

The frequency-modulation technique which involves a practically continuous transmission of test signals, in general requires the use of individual transducers for transmission and reception. The frequency modulated system of ultrasonic testing offers a potential high resolving power. Fig 3.5 illustrates equipment operating with two electrically isolated transducers. The heart of the instrument is a function generator which derives transducer 1. During testing of material, the ultrasonic signal traverses the specimen and is picked up by transducer 2, which reconverts it to an electrical signal. The electrical signal detected by transducer 2 is only a small fraction of the generator output and may be amplified by a wide-band amplifier to obtain a voltage sufficient for the vertical deflection of the beam of the oscilloscope.

Another arrangement for the frequency modulation procedure to employ a single transducer. The arragement is same as the double transducer procedure except that receiving transducer. The back echoes from the material detected by the same transducer. An ohmic resistor is inserted between the function generator and transducer. Its purpose is to convert changes in transducer current into voltage fluctuations.

As a result, the decrease in transducer current encountered at a specimen resonance will increase the radio frequency potential across the transducer terminals and thereby produce an amplitude peak in the spectrum displayed by the oscilloscope. If the one specimen resonance occurs more than within the range of the swept-frequency generator and the transducer response, the spectral trace will exhibit several such peaks.

3.3.5.3. Pulsed Frequency-Modulation Procedure

By combining the frequency-modulation with the pulse technique as illustrated in figure 3.5 the transducers can be excited. The time gate contained in the circuit opens and closes periodically at a rate that is considerably higher than the frequency sweep rate. During transmission pauses the transducer is able to function as a receiver for echoes returning from the specimen. It is possible to use double transducer, during measurement or testing of materials, as in frequency-modulated procedure. The spectrum attributable to a particular echo signal is presented on the oscilloscope screen by decreasing its normal trace intensity and using the suitably delay time gating pulse to brighter the trace momentarily during the arrival of the selected echo at the transducer.

Compared with the pulse procedure, pulsed frequency-modulation requires longer pulse durations. The technique is therefore not suited for applications requiring optimum resolution in the time domain. But using this procedure excitation of transducer is easier than pulse method and its possible to measure velocity, attenuation of the signals accurately.

3.4. Fundamentals of Wave Propagation

3.4.1. Introduction

In a broad sense, acoustic may be defined as the generation, transmission, and reception of energy in the form of vibrational waves in matter. As the atoms or molecules of a fluid or solid are displaced from their normal configuration an internal elastic restoring force of stiffness arises. Typical examples of such a force include the tensile force produced when a spring is stretched, the increase in pressure produced when a fluid is compressed into a lasser volume, and transducer restoring force produce when a point on a stretched wire is displaced in a normal to its length.

Many different types of vibration occur in the generation and propagation of acoustic waves. In a narrow sense their frequency limited to the range from about 20 Hz to 20 kHz, which produce auditory sensation of sound. However, in a broader sense they also include both the ultrasonic frequencies above 20 kHz, which although audible have important practical applications in numerous fields, and the inaudible infrasonic frequencies below 20 Hz. The knowladge of sound wave propagation in liquids had its impact not only on experimental work but also several studies on the theory of sound waves. This section will include the basic equations needed to describe waves in fluids and solids.

3.4.2. Wave Propagation in Fluid Media

The propagation of the wave depends on the physical properties of medium, namely its inertia by virtue of the mass of the molecules, and elasticity arising as a result of the action of the intermolecular forces. The mechanism of propagation of perturbation in such a medium can be illustrated by a simple model (fig 3.6) consisting of a chain of rigid balls connected by a spring. If ball A is struck, the motion will be transmitted via a spring to ball B which will deviate from its equilibrium position

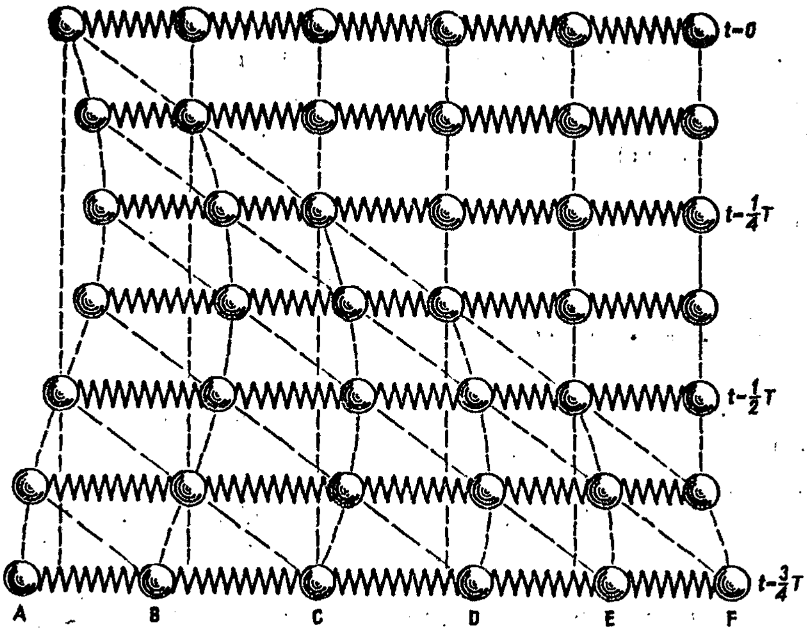


Fig 3.6. Mechanical model of wave propagation in medium.[1]

with a certain time delay as a result of its inertia, and in turn will transfer the motion to the next spring and ball C, and so on. The perturbation will, therefore, propagate with a finite velocity.

Perturbation of equilibrium causes the medium to move. Let us assume that a plane wave propagates along the axis x with the velocity V, without distortion and negligible attenuation. After the time t the perturbation will have been transferred by a distance Vt: the magnitude of the perturbation being thus a function of f(Vt-x) or f(Vt+x) depending on whether the wave propagates in the positive or negative direction of the x-axis. So that the components of displacement can be written as,

$$\xi=f(Vt-x),\partial\xi/\partial t=\partial f(Vt+x)/\partial t \quad . \; . \; . \; . \qquad 3.24$$

twice differentiation of equation 3.22, gives,

$$\partial^2\xi/\partial t^2=V^2(\partial^2\xi)/(\partial x^2) \quad . \; . \; . \; . \; . \; . \qquad 3.25$$

This equation describes the simplest type of time and space changes for plane waves with an arbitrary waveform is valid, for both electromagnetic and acoustical waves. The solution of equation 3.23 in a complex form, that is

$$\xi=Aeexpj(wt-kx)+Beexpj(wt+kx) \quad . \; . \; . \; . \qquad 3.26$$

where A is the displacement amplitude of a plane wave of frequency w and wavelength constant k travelling in the positive x direction with a velocity V, and B is the same amplitude of a similar wave travelling in the negative x direction.

3.4.3. Velocity of Sound Waves in Fluids

The velocity of sound wave propagated trough a fluid medium is constant and defined as

$$V=\sqrt{dp}/\sqrt{d\rho} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad 3.27$$

where p is the pressure produce on the medium by sound waves and ρ is the density of the medium. Note that the characteristic property of the medium is dependent on the elastic nature of the matter and as well on such thermodynamic variables as temperature, pressure and density.

When a sound wave propagated through a gas, the adiabatic gas law relating pressure and density, may be utilized to drive an important special form of equation 3.25. Let us express the adiabatic gas law in the form

$$P=Kg^{\gamma} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad 3.28$$

where is the ratio of specific heat of the gas at constant pressure to that at constant volume and K is a constant differentiation of equation 3.28 leads to

$$dp/d\rho=\gamma p/\rho_0 \big|_{p=p_0,\,\rho=\rho_0} \quad . \; . \; . \; . \; . \; . \quad 3.29$$

if this expression is substituted into equation 3.27 we can obtain velocity of sound in gases,

$$V=\sqrt{\gamma p_0}/\sqrt{\rho_0} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad 3.30$$

In actual practice the changes in the velocity that result from changes in temperature are of much greater significance. One form of the general gas law states that

$$P=rT\rho \quad . . . . 3.31$$

where r is a constant whose value depends on the particular gas involved and, T is the absolute temperature of the gas in K (kelvin). An alternate expression for the velocity of sound in a gas is obtained

$$V=\sqrt{(\gamma rT)} \quad . . . . 3.32$$

A theoretical prediction of the velocity of sound in liquids is considerably more difficult than it is for gases. By analogous equation 3.30 velocity of sound in liquids can be written as

$$V=\sqrt{(\gamma B_T/\rho_0)} \quad . . . . 3.33$$

where B_T is the isothermal bulk modulus, an elastic modulus measuring the difficulty of compressing a liquid.

The velocity of wave propagation in water increases with the temperature and at 74 C it attains a maximum A general analytical relation for water-salt content at atmospheric pressure is given by

$$V=1448.6+4.618t-0.0523t^2+0.00023t^3+1.25(S-35)$$

$$-0.011(S-35)t+2.7\times10^{-8}(S-35)t^4$$

$$-2\times10^{-7}(S-35)^4(1+0.577t-0.0072t^2) \quad . . . 3.34$$

where

V = wave velocity in m/sec

t = temperature in C

S = salt content in %

3.4.4. Absorbtion of Sound Waves in Fluids

Losses in the medium may be divided into three basic types, viscous losses, heat conduction losses and losses associated with molecular exchanges of energy. The viscous losses result from relative motion occurring between various portions of the medium during the compressions and expansions that accompany transmission of a sound wave. There is a tendency for heat to be conducted from regions of condensation where temperature is raised to neighbouring regions of rarefaction where the temperature is lowered. The dissipation of acoustic energy that is associated with changes in the molecular structure of the medium results from the finite time that is required for these changes to take place.

3.4.4.1. Viscous Absorbtion

As a relatively simple introduction to the more complicated mechanism of sound absorbtion, let us first solve in same detail the case of viscous attenuation of a plane wave. The equation 3.25 satisfies for nonattenuating mediums. If the attenuation is taken into consideration then,

$$\partial^2\xi/\partial t^2=V^2(\partial^2\xi/\partial x^2)+R/\rho_0(\partial^3\xi/\partial x^2\partial t) \quad . . . \quad 3.35$$

where R is the acoustic impedance of medium and ρ is the density of the medium. Since solution of equation in the form of

$$\xi=A\exp(-\alpha x)\exp(j(wt-kx)) \quad . . . . . . \quad 3.36$$

substituting equation 3.36 into equation 3.35 yields that

$$\alpha=\omega/\sqrt{2}V\sqrt{[1/\sqrt{(1+\omega^2\tau^2)}-1/(1+\omega^2\tau^2)]} \quad . . . \quad 3.37$$

where α is attenuation constant, k is propagation constant and τ is the relaxation time, and defined by

$$\tau=R/(2\rho_0 V^2) \quad . . . . \quad 3.38$$

In the majority of fluids, the relaxation time is so short that even frequencies in the megacycle range the product $w\tau \ll 1$. Then equation 3.37 can be expressed that

$$\alpha=\omega^2\tau/2V \quad . . . . \quad 3.39$$

it can be shown that attenuation directly proportional to the square of frequency.

Since acoustic impedance R is result of viscosity, then R and viscosity of fluid derived from fundamental hydrodynamic equations, such that

$$R=4\eta/3 \quad \cdots\cdots\cdots \quad 3.40$$

where is the viscosity of fluid. Combination of equations 3.38, 3.39 and 3.40 gives an important relation

$$\alpha=(2\omega^2\eta)/(3\rho_0 v^3) \quad \cdots\cdots\cdots \quad 3.41$$

It can be shown that α is directly proportional to the viscosity of the fluid.

3.4.4.2. Heat Conduction as a Source of Attenuation

In the compression of the fluid in the passage of a sound wave, the temperature is raised and a temperature gradient is locally established. This leads to a flow of heat by conduction. Theory indicates that the relaxation time for this process is given by

$$\tau=\kappa/\rho_0 v^2 C_p \quad \cdots\cdots\cdots \quad 3.42$$

where k is the thermal conductivity of the fluid and C_p is its specific heat at constant pressure. For most liquids this quantity is so small for all practical frequencies, that the simplified theoretically equation for attenuation associated with heat conduction is given by

$$\alpha=\omega^2\tau(\gamma-1)/2v \quad \ldots\ldots\ldots \quad 3.43$$

substituting the equation 3.42 into equation 3.43. Then

$$\alpha=\omega^2(\gamma-1)/2\rho_0 v^3 C_p \quad \ldots\ldots\ldots \quad 3.44$$

When the absorbtion is small, it is possible to assume that viscosity and heat conduction act independently in producing an attenuation of sound waves. Under this assumption, we may add equations 3.41 and 3.44, to give

$$\alpha=\omega^2/2\rho_0 v^3[4\eta/3+\kappa(\gamma-1)/C_p] \quad \ldots\ldots \quad 3.45$$

as the theoretical coefficient of attenuation for acoustic waves.

3.5. The Velocity of Propagation of Ultrasonic Waves and the Elastic Properties of Materials

They allow one to determine the elastic properties of materials from the measurements of the velocities of ultrasonic waves. The development of ultrasonic elastometry during recent years can be attributed to number of factors. One of the most important of these is the constantly growing demand for accurate determination of elasticity of materials in the forms of manufactured components. The various shapes and sizes of components are rapidly increasing in number and they defy the application of classical methods used hitherto (statistical measurements of elongation as a function of stress). The versatility of ultrasonic methods is particularly valuable for the examination of brittle materials such as glass and ceramics, of finished products of different shapes, and of variations of elasticity with either temperature or pressure. Rapid strides have been made towards improving both the methods and types of equipment used.

Without considering the specific elastic constants or types of waves in great detail. We shall briefly summarize those relationships which form the basis of elastrometry. The velocities of elastic waves in nonattenuating media are connected by simple relationships to the elastic constants for those media. These relationships also apply in practice to attenuating media, provided that the damping not too great; this may have a value, as high as 20 dB per wavelength.

The velocity v of dilatational waves in thin rods is given by

$$v=\sqrt{Y}/\sqrt{\rho} \quad \ldots\ldots\ldots\ldots \quad 3.46$$

The velocity V_L of longitudinal waves infinite media is given by

$$v_L=\sqrt{[Y(1-\sigma)/\rho(1+\sigma)(1-2\sigma)]} \quad \cdot\cdot\cdot\cdot\cdot\cdot \quad 3.47$$

The velocity V_T of shear waves infinite media and torsional waves in rods is given by

$$v_T=\sqrt{G}/\sqrt{\rho} \quad \cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot \quad 3.48$$

where Y is the Young's modulus, G is the shear modulus & the density of the medium and σ the Poission's ratio.

The terms `thin rods' and `infinite media' may be defined as follows. The formulae for thin rods are correct when the diameter d is less than 0.1 of the wavelength λ. For rods of greater diameter, the wave velocity becomes a complicated function of the ratio d/λ and the elastic constants. Measurements on such rods are those not recommended. A medium is regarded as `infinite' when the dimensions in the direction perpendicular to that of propagation exceed five wave lengths. A decrease in the area of cross-section leads to a complicated relationship between velocities, dimensions and elastic constants.

From a practical viewpoint one can consider two separate cases, one where the wavelength is much greater than and the other where the wavelength is much less than the diameter of typical specimen. For convenience we shall call the first **acoustic elastometry** and the second **ultrasonic elastometry.** With acoustic elastometry the elastic constants are determined by measuring the velocities of dilatational and torsional waves having wavelengths a few times greater than the diameter of the specimen. Measurements are usually made in rods at frequencies of the order of 20 kc/s, although one can use this technique for frequencies ranging from 200 c/s to 200 kc/s. With ultrasonic elastometry the velocities of longitudinal and shear waves having wavelengths a few times less than the diameter of specimen are measured. This can be done for rods, plates, thin layers or any complex shape of materials provided that waves can be passed through them and the path lengths measured. Typical frequencies for this technique lie within the range 2 to 4 Mc/s although quite often frequencies both higher and lower than this range are used. Ultrasonic elastometry can be carried out with any ultrasonic flaw detector, modified if necessary.

The elastic constants as obtained from wave velocity measurements are called **dynamic constants,** as opposed to the **static constants** determined from static stress-strain measurements. Where the damping of the waves is small, the dynamic measurements should produce results which are very close to those obtained from static measurements. the small difference of about one to two percent arises from the fact that static measurements produce isothermal values of the elastic constants whereas dynamic measurements produce adiabatic values. In the literature on the subject it is often found that is difference between the static and dynamic values may be much greater than one to two percent.This is due to the application of stresses, in static measurements, which are cause variations of strain to deviate from the linear relationship of Hooke's law. For example, in the determination of Young's modulus the ratio T/ϵ, where T represents the applied tension and ϵ the resultant extension, measured statically can be either greater or less than the ratio $dT/d\epsilon$ as measured by an ultrasonic method. Also, with ultrasonic, one can measured the rate of change of the slope $dT/d\epsilon$ at various points along a static stress-strain curve by changing the static load.

CHAPTER 4

DEVELOPING ULTRASOUND PROBES AND EXPERIMENTAL STUDIES

4.1. Introduction

The main purpose of this study is based on developing an ultrasound transmitter and receiver probes and its usage to determine the physical properties of different liquids and to examine the structure of solid bodies such as steel or iron rods. Usually, the prices of these devices used in industry and research laboratories are very high, since the special piezoelectric crystals have been used in the construction of these devices. But in this study, an ordinary microphone quartz crystal has been used. It is very cheap and it can be found easily every time. Now we are going to represent studies that are done for developing such a device in the following order; design of the probes, construction of the device, setting up the experiment to measure the velocity and attenuation of sound waves in metarial, determination of characteristics of the probes and cost of the device for the probes mentioned above.

4.2. Construction of Probe

The transmitting and receiving probes are generally made of piezoelectric materials. Although the common materials are known as quartz, barium titanate and PZT (lead titanate zicronate) crystals, thin film zinc oxide and zinc sulphate crystals often give good result for same applications. we know that, if a piezoelectric crystal can be excited at high frequency, than, this crystal may be used for examining the acoustoelastic response of material. During examination of frequency response of some piezoelectric microphone crystals, it is observed that excitation of the zinc sulphate microphone crystals is possible at high frequencies, as illustrated in figure 4.2, so that we thought adaptation of the ZnS crystal is possible for ultrasonic measurements.

4.2.1. Geometrical Shape of Transducer

As mentioned in previous chapter, especially parallelism of the crystals is primary importance for the coherence of sound beam. This parallelism has been obtained in the microphone transducer that we used. Because of this, the transmitted sound beam propagates uniformly through the medium. The transducer used in this study consists of two metallic layer as electrode and piezoelectric crystal deposited between them.

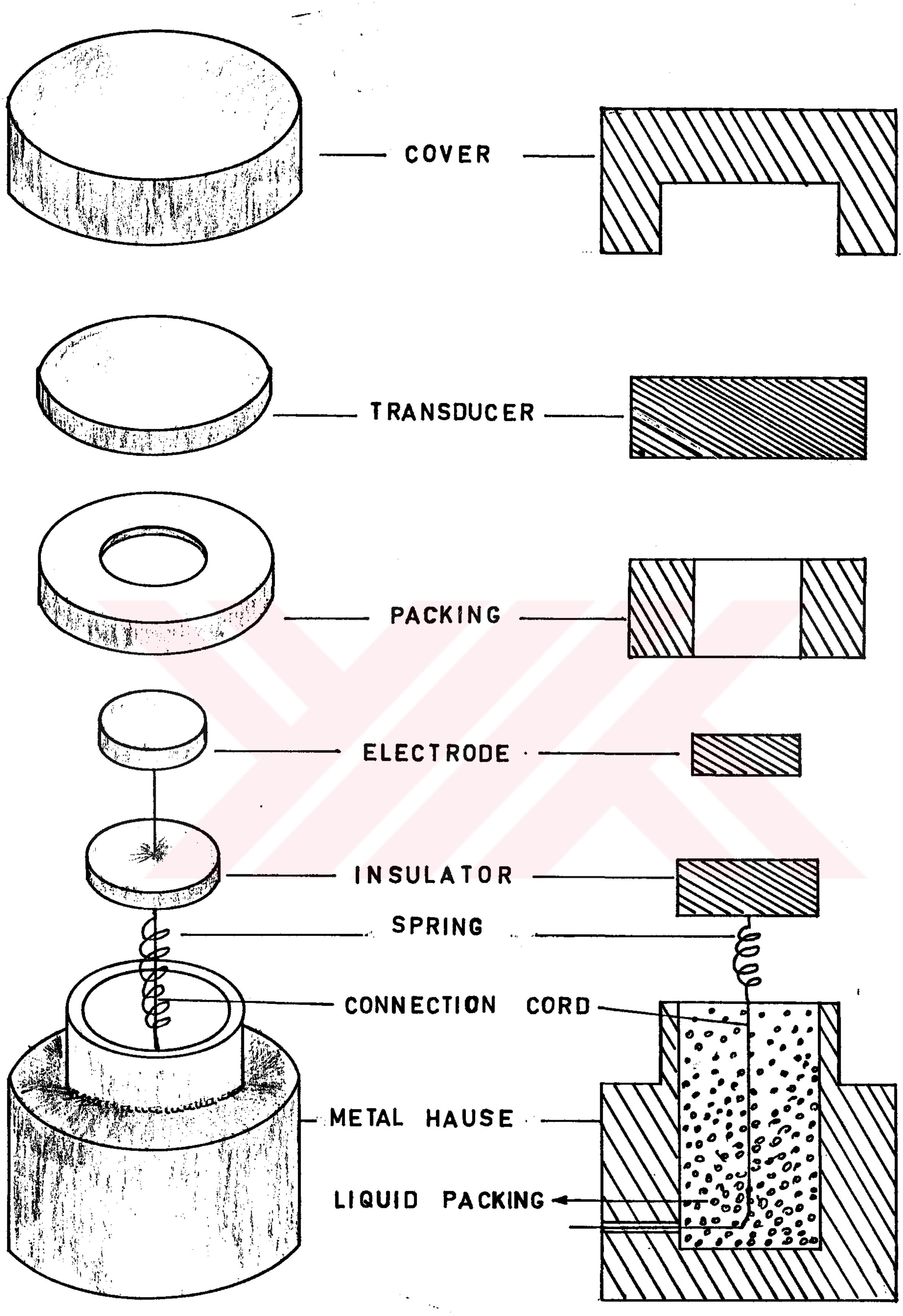


Fig. 4.1. Schematic illustration of ultrasonic probe

The shape and dimensions of any transducer must be given since the physical characteristics of it depends on tightly these parameter. For example resonance frequency of the transducer depends on the thickness of the piezoelectric material.

The dimension of the crystal and the parts which accomplish it are given as

Thickness of the transducer : 0.62 mm

Thickness of the metallic disc : 0.22 mm

Thickness of the piezoelectric crystal : 0.40 mm

Diameter of the transducer : 20.00 mm

Diameter of the 20 mm transducers are especially useful for measurement of velocity and attenuation and for examining the microcracks in materials.

4.2.2. Transducer Mounting

A probe is accomplished not only with transducer but also with many other parts which play important role on the operation of it. There are various methods for fixing a transducer into a probe, as mentioned in chapter 3. Figure 4.1 shows the diagram of the probe that we have developed in this study.As seen in the figure it consists of a cylindrical housing, a cover packing transducer, connection cables and liquid packing.

The cylindrical housing which contains a spring and is filled up with liquid packing as backing member, made of steel. The liquid packing protects the transducer from water. The spring which compresses the metallic thin disk on to rare surface of transducer, also acts as backing member at low frequencies.

The transducer is placed into cover which can be screwed to the cylindrical house, made of the same material as the housing. The compartment between the cover and the transducer is filled with oil for coupling. The thickness from front surface to inner surface of the cover which both smooth, is 2 mm and this region is always considered as dead region. The packing placed between the cylindrical house and cover is used to prevent the water to leak into system.

The inner leads of the coaxial cable is soldered to the metallic disk. The metallic disc contact with the rare surface of the transducer. If the inner leads of coaxial cables are directly soldered to the rare surface of the transducer, the ununiformity of the transmitted wave increases. To optimize these nonuniformities a small metallic disk is used.

The cylindrical house and front surface of transducer has been grounded, to prevent the transducer from the effect of the unwanted electromagnetic waves produced by electronic equipments.

The probes that we developed are water proof and can be operated at 95 °C with safety.

4.3. Frequency Response of the Transducer

To be able to use efficiently this transducer in our applications we must know that at which frequencies it can give good response. We set up an experiment to decide frequency response of transducer as seen in figure 4.2.

The function generator which produces a continuous wave in the sinusoidal form, feeding the transmitting probe. The wave frequency can be varied between the limits 1 kHz-13 MHz. The transmitting probe which excited by function generator converts electrical energy into mechanical energy in the form of longitudinal wave. The wave transmitted from the transmitting probe detected by

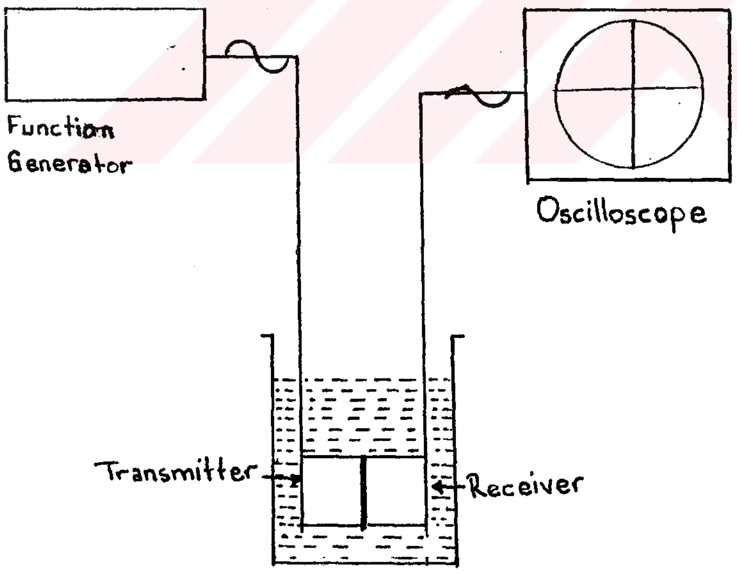


Fig. 4.2. The block diagram of the experimental set up to decide the frequency characteristic of transducer.

a receiving probe which converts again into electrical form, is directly coupled to the transmitting probe. electrical signals form the receiving probe is applied to x-plate of the oscilloscope. To keep the waves on, the oscilloscope screen stationary during experiment, y-plate of the oscilloscope is excited with a rectangular synchronized pulse having the same frequency, as applied wave to x-plate of it.

Since the receiving and transmitting probe has the same property, then the resonance and excitation frequencies of them must be same. So that, frequency changed from 1 kHz to 13 MHz and the frequency response of the probes can be determined, by reading the applied voltage to the oscilloscope screen, in milivolts scale.

Then we draw the curves which show the output changes of output voltage w.r.t. the frequency, give the frequency spectrum of transducer.

First of all, as seen in figure 4.3a we changed the frequency from 1 to 150 kHz and found that the resonance frequency of the crystal corresponded to 134 kHz. At this frequency the output voltage reached to the maximum value. Then the frequency of the input voltage changed from 150 kHz. to 1.5 MHz.and the response of the receiving transducer is illustrated in figure 4.3b. Finally we scanned the frequency interval which varied from 1 MHz to 13 MHz as seen in figure 4.3c

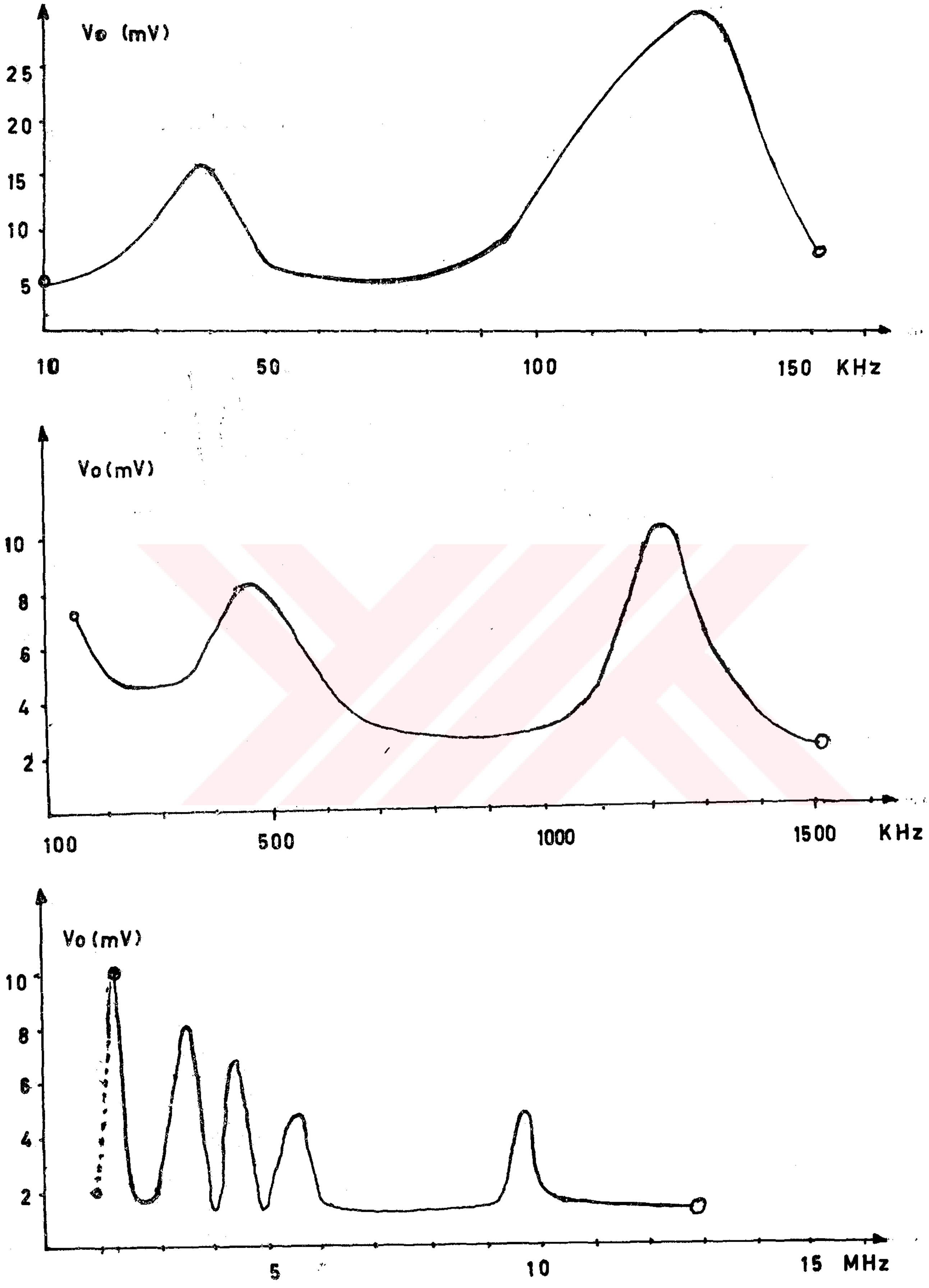


Fig. 4.3. Frequency response of transducer.

In this frequency interval, we found three maximum output voltages which corresponded to 1.6 MHz, 2.5 MHz and 3.5 MHz respectively. But, the frequencies which fall in the mid-frequency region which varies from 150 kHz to 1 MHz are more suitable in the nonviscous liquid for the application of the resonant method.

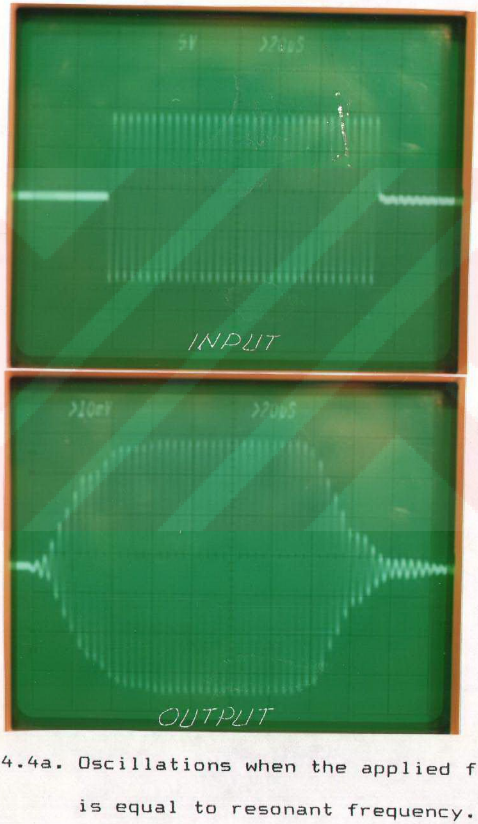


Fig. 4.4a. Oscillations when the applied frequency is equal to resonant frequency.

Modulated-pulse wave response of the transducer is the same as the continuous wave response. However we said that those are the same, we have observed a few different situations during our experimental studies as follows: When the frequency of the applied electrical signal is equal to the resonance frequency of the transducer, it oscillates with a maximum amplitude and with the same frequency as shown in figure 4.4a. If the frequency of the applied signal is less than the resonant frequency of the transducer, at that time it will be forced to oscillate not only with the frequency of the applied

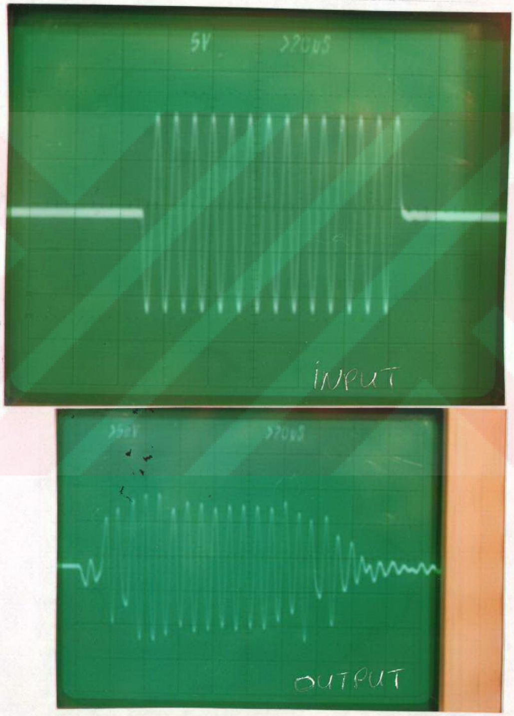


Fig.4.4b. Oscillations when the applied frequency is less than the resonant frequency.

electrical signal and also with the resonant frequency of the transducer, with a decreasing amplitude as seen in figure 4.4b. Figure 4.4c shows the situation of the output voltage when the frequency of the applied electrical signal is greater then the resonant frequency of the transducer.

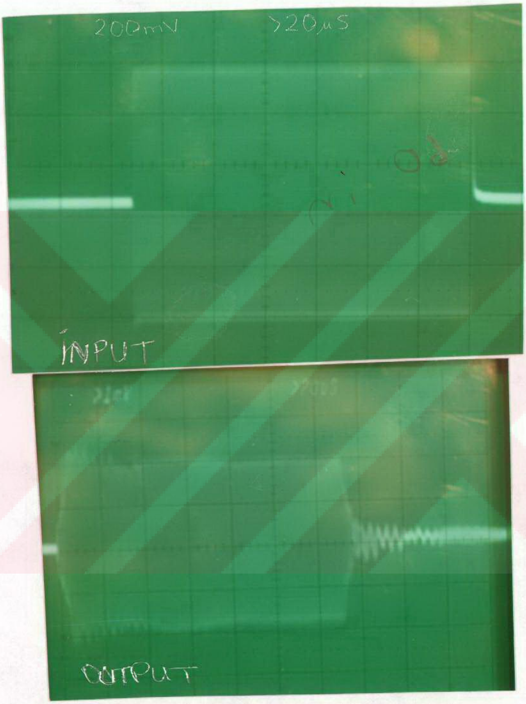


Fig. 4.4c. Oscillations when the applied frequency is greater than the resonant frequency.

Even the feeding electrical signal is removed, transducer doesn't cease immediately, it goes on oscillating till its amplitude decrease exponentially and goes to zero for a certain time.

In velocity measurements, frequency of the modulated-pulse wave generally plays an important role in reading the elapsed time accurately for the waves to travel in a material. This time can be read more sensitively at higher frequencies than at low frequencies.

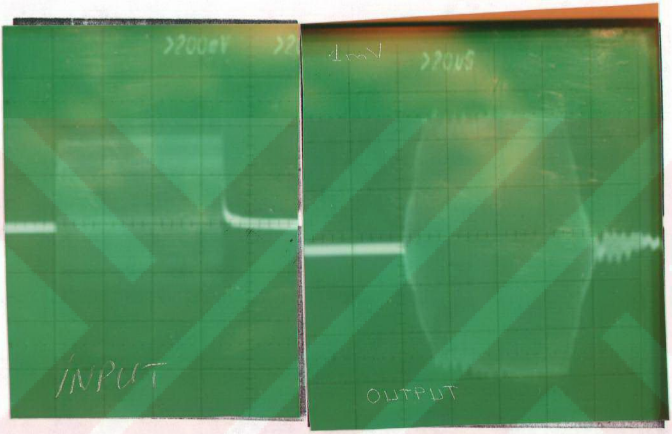


Fig. 4.5. Oscillations of ZnS transducer:(a) electrical pulse causing oscillations; (b) oscillations of the transducer.

Figure 4.5 shows in what form that the signals produced by a rectangular modulates pulse having a frequency at 1200 kHz can be detected by ZnS crystal.

4.4. Experimental Studies and the Methods Used in These Studies

Some physical properties of any material can be determined by using the relationships between the material and sound wave. As it known, the velocity of a sound wave and the attenuation in its amplitude vary from material to material. Therefore, measurements of these quantities are very important in any medium. In this section, we will tell the experiments we have done applying various ultrasonic methods, to measure them in different mediums, and explain the relationships between them and physical properties of the medium, such as water and carbon steels.

4.4.1. Optical Method

The alternate compressions and rarefactions accompanying a sound wave in a liquid produce a diffraction grating for light. So we set up an experiment to measure the velocity of the sound wave as seen in figure 4.6.

The sound wave produced by a quards probe was sent through the water downward an absorber has been placed at the bottom of the container to absorb the sound wave reaching it. Hence incoming waves are prevented from the destruction effects of the reflected waves. a monochromatic light been obtained from a He-Ne laser is

Fig.4.6. Experimental set up for optical method

sent horizontally through the water. Then, the traversed light beam is focused on a screen along various diffracted orders. The diffraction angle Θ can be measured experimentally and used to calculate the wavelength of the sound wave in the water from the relation

$$\sin\theta = n\lambda/\lambda_s \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; . \quad 4.1$$

in which λ is the wavelength of the incident light, λ_s is the wavelength of the sound wave and n is a positive integer. We calculated the velocity of the sound wave in the water using the value of the λ_s.

4.4.2. Resonance Method

The resonance method depends on the phenomenon of the phase differences which occurs between the transmitted and received ultrasonic waves. The stresses applied at a given point in the medium by ultrasonic wave travelling in to opposite directions are added. When the phase difference between the incident and reflected waves is such that zero or integer multiple of π, then the resonance occurs. The oscilloscope trace will be ellipse at resonance.

We set up an experiment to apply this method to measure the velocity of the sound wave in different liquids as shown in fig 4.7.

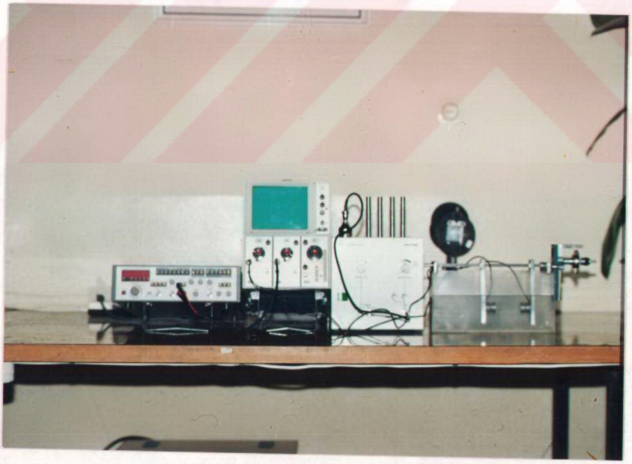


Fig. 4.7. Experimental set-up for measuring velocity of sound. Resonance method.

In this experiment, as the receiving probe is moved steadily relative to the transmitter, hence the phase of the received wave will vary with respect to the applied signal. On the other hand, the phase difference could be measured accurately at the low frequencies. Because of this we used low frequency signals in our studies.

To measure the velocity of sound in solids also in liquids, and the thickness of sheets or pipes having a known ultrasonic velocity can be determined by resonance method. The material which is going to be tested should be in form of a parallel-sided layer or cylindrical rod with suitably smooth surfaces to which the probes are coupled by a thin film of a liquid such as oil.

After we prepared the sample we sent the ultrasonic waves of the varying frequency into the test material. When the thickness or length of the specimen is equal to an exact number of half-wavelengths,at that time resonance occurs.We applied both of the output signals at the transmitter and receiver into an oscilloscope and we observed the combination of these signals on the oscilloscope oscilloscope screen. The resultant signal was ellipse, line or circle depending on the phase difference between applied and received signals. We counted the number of the ellipses by changing the frequency of the applied signal. Then we measured frequency difference between two resonance frequencies. We used this frequency difference to calculate the velocity of sound in rods, sheets or liquids from the relation

$$v=l\Delta f/n \quad \cdots\cdots\cdots\cdots \quad 4.2$$

where, n is the number of ellipses whose shapes are the same, Δf is the frequency difference between two resonance frequencies we mentioned above and l is the thickness of the sheet, or length of the rod between two probes.

4.4.3. Modulated-Pulse Method

In this method , ultrasonic modulated pulses are sent through the material and picked up by a receiver. Then the time delay between the transmitted and received pulses are measured. This delay of time shows the time required by a transmitted wave to travel from the transmiter to the receiver probe. If the distance between the probes is l, the velocity of the sound can be obtained from the equation,

$$v=l/t \quad \cdots\cdots\cdots\cdots \quad 4.3$$

Experimental set-up is the same as in the resonance method as illustrated in figure 4.7. There is only one difference which results from the types of the applied signal. The delay in probe heads and a possible triggering delay between the start of the time base and that of the modulated pulse can be eliminated by means of differential measurement.To do it, we placed two probes as they are in contact to each other and we read the time delay t_1 on the screen of the oscilloscope. Then, we replaced the sample wanted to be tested between the probes and read the second time delay t_2.We found the velocity of the sound wave in the material using the time delay values that we measured in the following equation

$$v=l/(t_1-t_2) \quad \ldots\ldots\ldots\ldots \quad 4.4$$

where l is path length travelled in the sound wave in the sample.

There is another way to measure the time delays. To do it, we placed the probes at a fixed distance which is equal to l_b and we measured the first time delay t_1 in liquid. Then we inserted the specimen between the probes and measured the second delay time t_2. The velocity of the sound wave inserted in liquid can be calculated, if the velocity of the sound is known from the equation.

$$v_s=1/[(1/v_0)+(t_2-t_1)/l] \quad \ldots\ldots\ldots \quad 4.5$$

where v_0 is the velocity of the sound wave in liquid.The schematic diagram of the experimental studies that we have done to measure the velocity of the sound wave in different mediums is shown in figure 4.8.

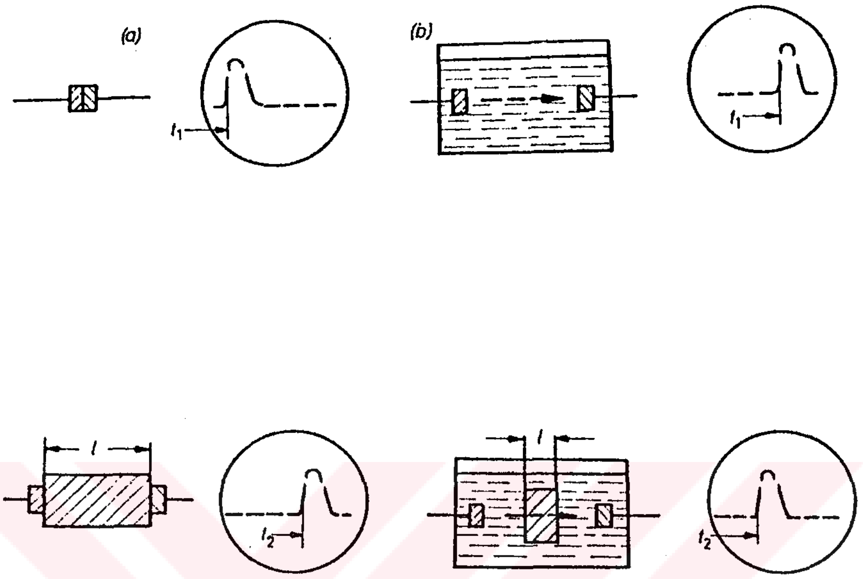


Fig. 4.8. Schematic diagram of modulated pulse method for measuring velocity using pulse delay (a) with probes in contact with the specimen (b) immersion method

For measuring the attenuation in liquids, the modulated pulse method is also suitable and simple. As its known, the amplitude of sound waves decreases with distances, as a result of attenuation. In this method, for measuring the decrement of amplitude of sound wave, the transmitting and receiving probes are immersed in a liquid and arranged at a constant distance. The transmitting probe transmits a modulated pulse for a short time. The transmitted sound waves which reaches the partially reflected from surface of the probe, and some of the transmitted wave converted into electrical signal. The reflected waves moves back and forth until all of the wave attenuate. The received signals applied to the oscilloscope screen decay in amplitude then converted voltage gives us the attenuation constant.

CHAPTER 5

DISCUSSION OF RESULTS AND CONCLUSION

5.1 Results and Discussion

In this section, we will present the results that we obtained from our experimental studies. While doing this, sametimes we will use only experimental results and discuss them, sometimes compare ours with the other results obtained from theoretical or experimental studies done by the other scientists or researchers and discuss these compared results.

In figure 5.1 curve (a) and curve (b) which have been obtained from theoretical and experimental studies respectively, show the variations in the wave velocity the as a function of temperature in the water. Curve (a) represents the velocity variations of the sound wave with varying temperature in pure water and curve (b) shows the same variations for sound wave in fresh water. As seen in figure, there is a difference between these two curves. This difference is the result of that fresh water contains some extra impurities, such as salt (NaCl), calsium (Ca) and the other particles then the pure water.

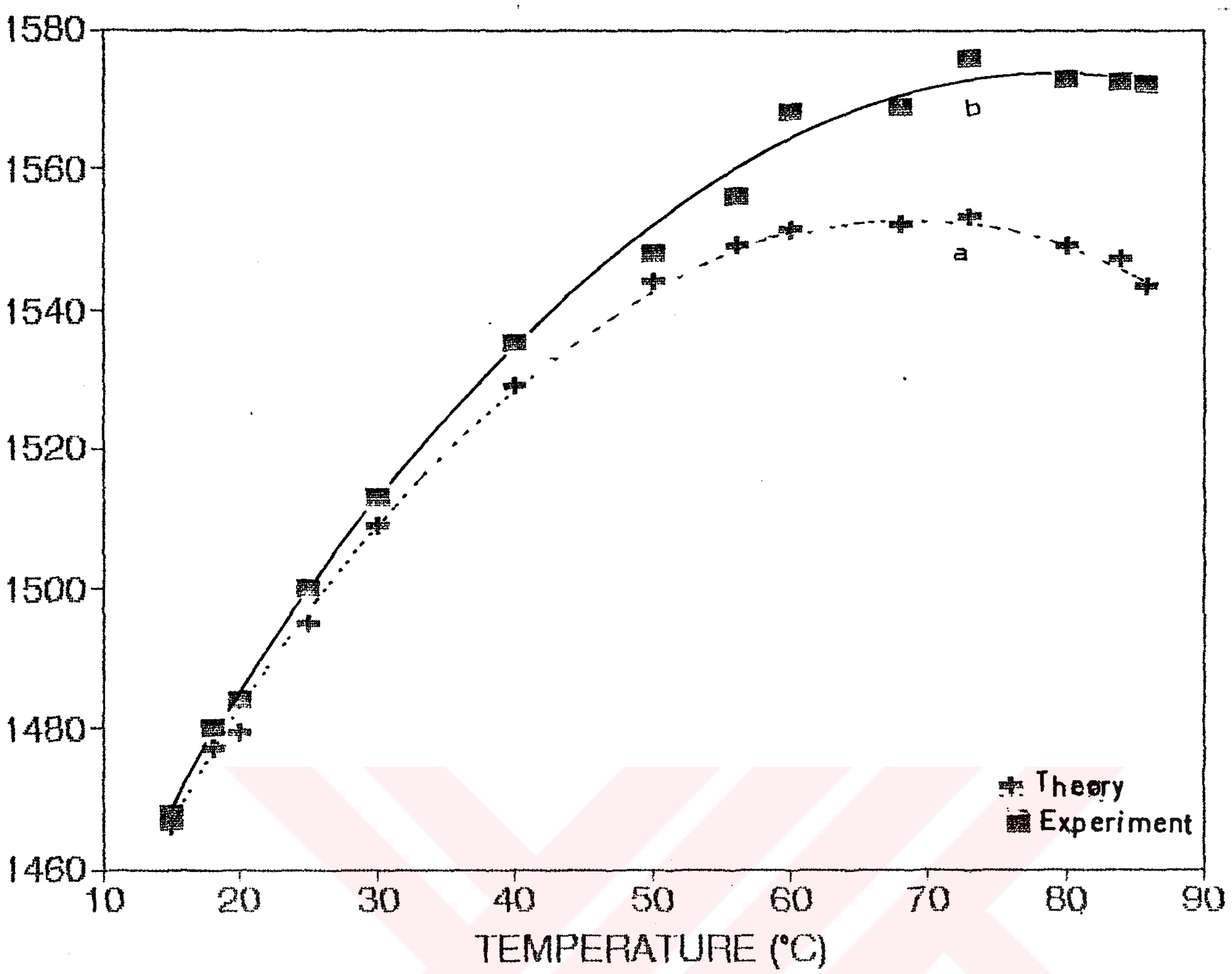


Figure 5.1 Wave velocity in water as a function of temperature at atmospheric pressure (a) theoritcal, (b) experimental.

On the other hand, the velocity of the sound wave increases with increasing temperature and reach a maximum at about 75 °C. The reason for this increase results from the dependence of the velocity of the sound wave to same parameters. As we mentioned before, the velocity of the sound wave is proportional to squareroot of the bulk modulus which is a function of compressibility at the medium and inversely propotional to the squereroot of the density of the medium. On the other hand the compressibility of the medium increases and the density of the medium decreases with inreasing temperature. Because of this, an increase of the sound wave was the expected result in these conditions. A decrease is also seen in the velocity of the sound wave after the temperature which is greater than 75 °C. This decrease is the result of noncotrollable random motions of the molecules and particles at high temperature.

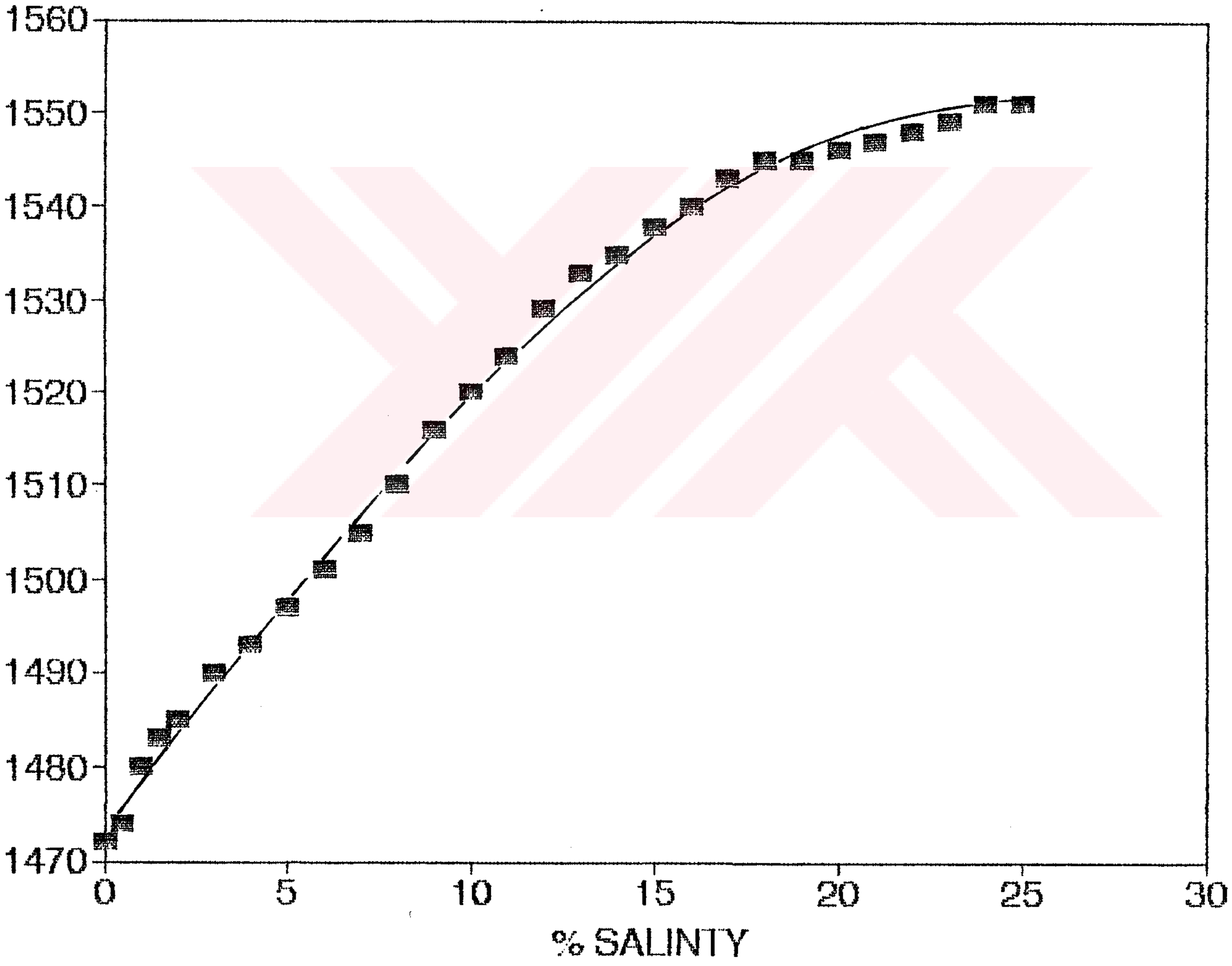


Fig. 5.2. Wave velocity in water as a function of salinity.

Figure 5.2 shows the charge in the velocity of the sound wave depending on the salt concentration in water. As seen from this figure sound wave reaches a constant velocity when the concentration is equal to 24%.

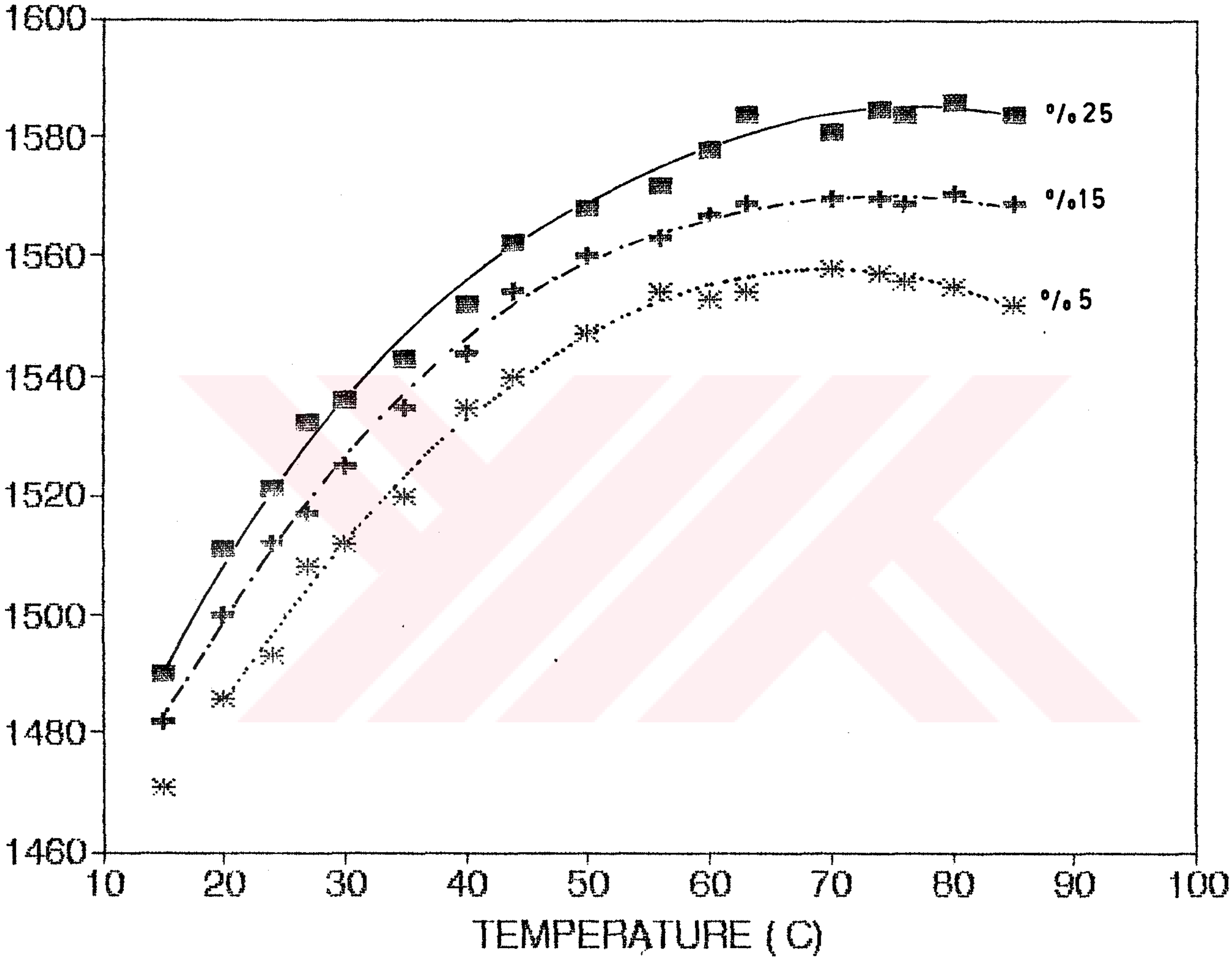


Fig.5.3. Wave velocity in water as a function of tempereture with salt contents, 5%, 15%, 25%.

We repeated the same experiment that we have used to obtain data of figure 5.2 to see the effect of the temperature changes on the velocity of sound wave in different mediums whose salinities are differnt each other. The concentrations of the water that are 5%, 10% and 25%. In figure 5.3, we prepared three curves which show the variation of the velocity of the sound wave according to the temperature variations. Curve (a), curve (b), and curve (c) correspond to 5%, 15% and 25% concentrations respectively.

The increase of the velocity of sound wave with increasing salinity and temperature of the medium is expected result as discussed above. As seen in figure, the temperatures that the sound waves reach their maximum values are different from each other. For example, in curve (a), curve (b) and curve (c) the turnig points correspound to 70°C, 80°C and 85°C. The reason for these changes comes from theory. According to theory, velocity of sound in salty medium is propotional to product of salinity and a term which includes a nonlinear temperature equation. Because of this nonlinearty, turning points of the curves will be different from each other.

Attenuation of sound waves in water is measured as a function of frequency as illustrated in figure 5.4. The measured attenuation of sound waves is about three times greater than the theoretically calculated classical attenuation contant [28].This great difference comes from scattering and diffraction of sound waves. The diffraction of sound waves is not eliminated completely, but at high frequencies, since the waveletgh of the wave is small, then the beam is not diffracted suddenly, so that it can be minimized.

The measurements are done at frequency range about 1-3.5 MHz, we observed that sound waves decay

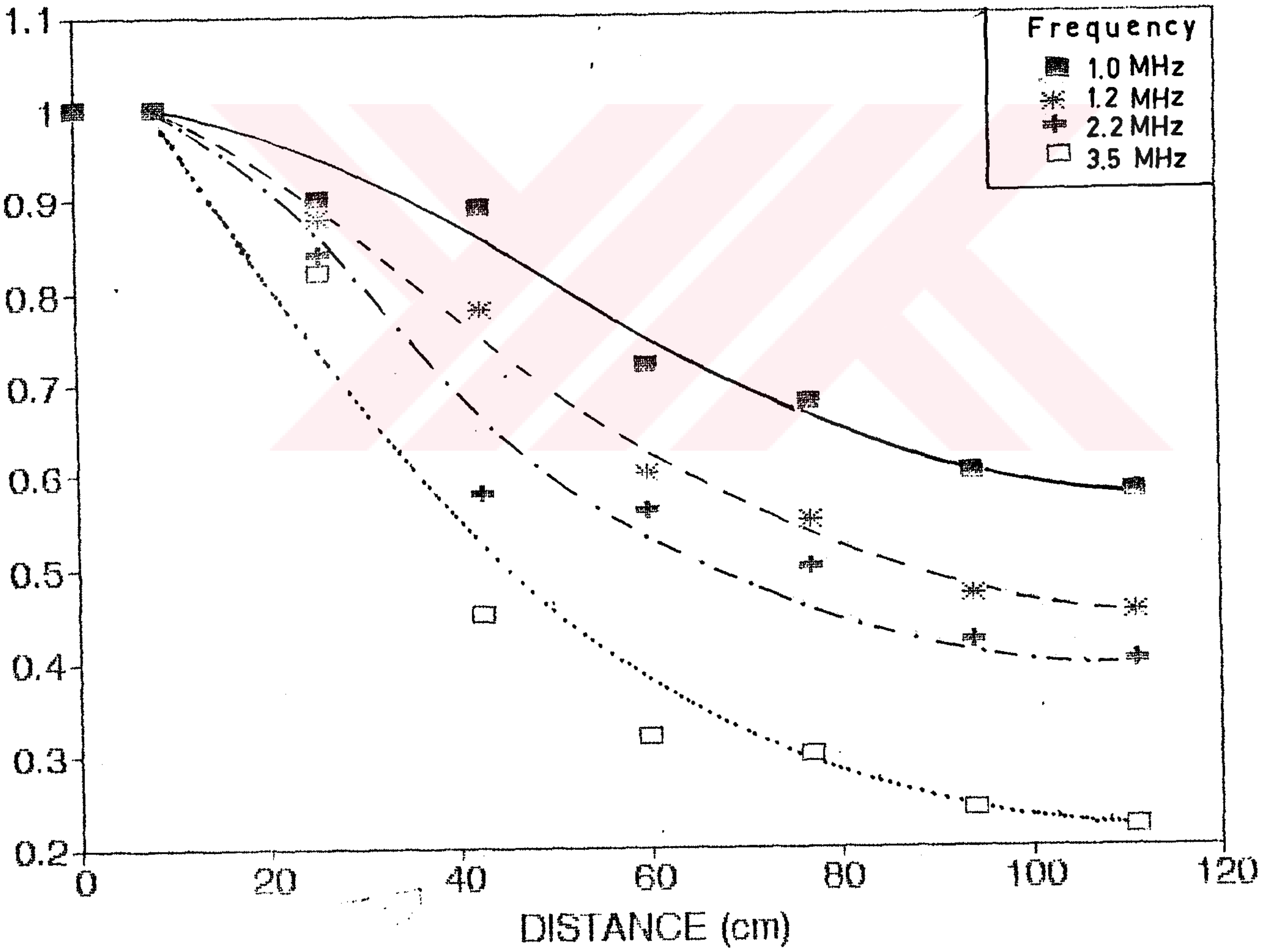


Fig.5.4. Attenuation of sound waves in water at different frequencies

exponentially with increasing distance. In some measurements, resonance of the modulated pulses which travelling back and forth between two probes, causes some unwanted peaks. If we measure carefully the attenuated voltage peaks from oscilloscope screen, we can easily observed that attenuation is proportional to the square of the frequency as illustrated in figure 5.5.

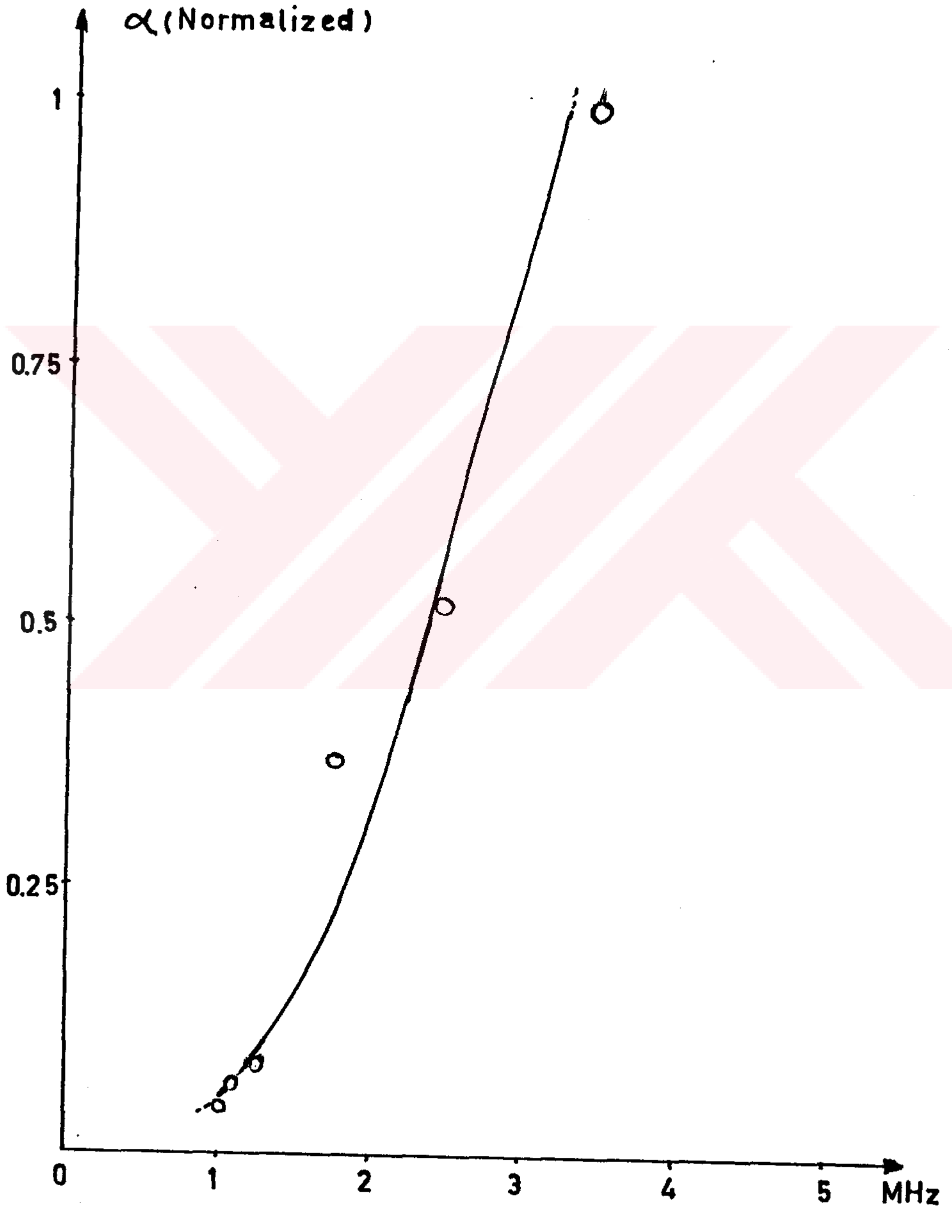


Fig. 5.5. Attenuation of sound waves as a function of frequency

The other experiment is set up for measuring the velocity of sound waves in metals. For this purpose, we prepared thin rods and parallel piped metal samples which are made of 1020 carbon steel. We applied the same method that we used in the previous studies for measuring the velocity of sound waves in liquids. To do this measurement, we replaced thin rod between the transmitter and receiver probes and measured the time delay. Then we found the velocity of sound waves in the rod 5100 m/s using the measured value of the time delay in the Eqn.[12] To measure the velocity of sound wave in the in parallel piped metals, we applied immersion technique. The same results have been obtained applying these two methods.

5.2 Conclusion

In this study, it has been demosrated that, by using an ordinary piezoelectric cyrstal, an efficient ultrasonic probe has been developed. This probe can be used for determination of some physical properties of material, and by making some modifications on our probe, it can be also used for nondestructive testing of the materials.

As it is known, these devices which are used either in labarotories or industry in TURKIYE, are imported from foreign countries by paying foreign currency. On the other hand, it is seen that this device can be used for some special purposes instead of some of the expensive devices.

We can not say that this device has been developed completely. It is possible to increase the efficiency of devices and to develope new types which can be used widely in many nondestructive testing areas.

LIST OF REFERENCES

1. Malecki, I., 1969. "Physical Foundation of Technical Acoustic". Pergamon Press.

2. Auld, B.A., 1989."Waves and Vibrations in Periodic Piezoelectric Composite Materials". Material Science and Engineering A., Vol.A112, pp.65-70.
3. Shaulov, A.; Smith,W.A.; Zola, J.; Dorman, D., 1989. "Curved annular array transducers made from composite materials ". IEEE Ultrasonic Symposium. Vol.2, pp.951-4, Newyork.

4. Matis, I.G. 1989. "Trends in the development of methods of nondestructive testing of composite materials". Mechanics of Composite Materials, Vol.25,pp.368-75, USA.
5. Anson, L.W.; Chivers, R.C., 1989. "Sensitivity of different ultrasonic transducer materials and effects of backing". Acoustica, Vol.68, pp.221-5, W.Germany.
6. Grewe, M.A.; Gururaja, T.R.; Shrout, T.R.; Newham, R.E., 1990. "Acoustic properties of particle/polymer composites for transducer backing applications". IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control, Vol.37, pp.506-14, USA.

7. Shana, Z.A.; Radtke, D.E.; Kelkar, U.R.; Haworth, D.T.; Josse, F., 1989."Theory and applications of quartz resonators as sensor for viscous conductive liquids". IEEE Ultrasonic Symposium, Vol.1, pp.567-71, Newyork.

8. Carcia-Olias, M.A.; Montero de Epinosa, I.R., 1990. "Nondestructive testing transducer for high temperature applications". Ultrasonics, Vol.28, pp.50-51, USA.

9. Lal, R.; Das-Gupta, D.K., 1989. "Time and frequency domain performance of ultrasonic transducers". 6th International Symposium on Electreds, pp.447-51, Newyork.

10. Venczel, J., 1988. "High-Efficiency suquare wave pulser for ultrasonic testing". Material Evaluation, Vol.46, pp.1072-77, USA.

11. Nichols, R.W., 1976. "Acoustic Emission". Applied Science Puplishers LTD., London.

12. Packman, P.F.; Pearson, H.S.; Owens, J.S.; Young, G., 1969. "Definition of fatique cracks through nondestructive testing". Journal of Materials, Vol.4, pp.666-700.

13. Raju, N.K., 1970. "Small concrete specimens under repeatet compressive loadsmby pulse velocity technique". Journal of Materials, Vol.5, pp.262-67.

14. Shah, S.P. and Chandra, S., 1970. "Mechanical behavior of concrete examined by ultrasonic

measurements"Journal of Materials, Vol.5, pp.550-63.

15. Onozawa, M.; Katamine, A.; Ishii, Y., 1987. "Ultrasonic testing of near surface flaws of castings". Fifth Pan Pasific Conference on Nondestructive Testing, pp.209-18, Canada

16. Habeger, C.C., 1990. "An ultrasonic technique for testing the orthotropic symmetry of polymeric sheets by measuring their elastic shear coupling coefficients". Journal of Engineering Materials and Technology, Vol.112, pp.366-71.

17. Mase, G.T.; Wong, T.E.; Johnson, G.C., 1990. "Acoustoelasticity in layered composites". Journal of engineering Materials and Technology, Vol.112, pp.226- 70.

18. Dike, J.J. and Johnson, G.C., 1990. "Residual stress determination using acoustoelasticity". Journal of Applied Mechanics, Vol.57, pp.12-17

19. Nayfeh, A.H. and Taylor, T.W.,1990. "Dynamic distribution of displacement and stress considerations on the ultrasonic immersion nondestructive evaluation of multilayered plates". Journal of Engineering Materials and Technology, Vol.57, pp.7-11.

20. Joseph L. rose; Adnan Nayfeh; Aleksander Plarski, 1990."Surface waves for material characterization". Journal of Applied Mechanics, Vol.57, pp.7-11.

21. D"Arrigo, G., and Paparelli, A., 1988. "Sound propagation in water-ethanol mixture at low temperatures".Journal of Chemical Physics, Vol.88, pp.7687-97.

22. Kashkooli, H.A.; Dolan, P.J.; Smith, W.,1987."Measurements of the acoustic nonlinearity parameter in water, methanol liquid nitrogen,and liquid helium". Journal of the Acoustical Society of America, Vol.82,pp.2086-89.

23.Avaneson, A.M.; Avetisyan, I.A., 1976."Effect of polymer additives on sound propagation in water containing bubles". Soviet Physics, Acoustics, pp.359-60.

24. Ma, Y. Varadan, V.K. and Varadan, V.V., 1984. "Application of Twersky's multiple scattering formalism to a dense suspension of elastic particles in water".Journal of The Acoustical Society of America, Vol.75, pp.335-39.

25. Harker, A.H.; Temple, J.A.G., 1988. "Velocity and Attenuation of Ultrasound in suspension of particles in fluids". Journal of Physics D, Vol.21, pp.1576-88.

26. Nagy, P.B. and Adler, L., 1987. "Surface roughness induced attenuation of reflected and transmitted ultrasonic waves". Journal of the Acoustical Society of America, Vol.82, pp.193-97.

27. Imamura, T., 1986. "Precise computation for response of ultrasonic transmission systems by numerical multiple integration". Journal of the Acoustical Society of Japan, Vol.7, pp.261-67.

28. Lawrence E. Kinsler, Austion R. Frey, 1960. Fundamentals of Acoustics, John Wiley & Sons,INC. London.

29. Warren P. Mason, 1964. Physical Acoustic,Vol.1-4, Academic Press, London.

30. Auld, B.A., 1973. Acoustic Fields and Waves in Solids, John Wiley & Sons, Vol.1,2. Newyork.

31. Sharpe, R.S., 1970. Research Techniques in Nondastructive Testing,Vol.1-4, Academic Press, London.

32. Robert C. Mc Master, 1959. Nondestructive Testing Handbook, Vol.2, Ronald Press INC.