DESIGN AND DEVELOPMENT
OF
ULTRASONIC INSTRUMENTATION SYSTEM

A DISSERTATION

submitted in partial fulfilment of the
requirements for the award of the degree
of
MASTER OF ENGINEERING
in
ELECTRICAL ENGINEERING
(With Specialization in Measurement and Instrumentation)

By

M. W. TRIKANDE

DEPARTMENT OF ELECTRICAL ENGINEERING
UNIVERSITY OF ROORKEE
ROORKEE-247667 (INDIA)

January, 1986

CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in the thesis entitled 'DESIGN AND DEVELOPMENT OF ULTRASONIC INSTRUMENTATION SYSTEM' in partial fulfilment of the requirement for the award of the Degree of MASTER OF ENGINEERING with specialization in MEASUREMENT AND INSTRUMENTATION, submitted in the Department of Electrical Engineering, University of Roorkee, Roorkee, is an authentic record of my own work carried out for a period from July, 1985 to January 1986 under the supervision of Dr. P.Mukhopadhyay, Prof. and Head, Department of Electrical Engineering, and Dr. D.S.Chitore, Reader, Department of Electrical Engineering, University of Roorkee, Roorkee.

The matter embodied in this dissertation has not been submitted by me for the award of any other degree or diploma.

Dated: JAN 23, 86

[redacted]

This is to certify that the above statement made by the candidate is correct to the best of my knowledge.

DSChitore 23/1/86
(Dr. D.S.Chitore)
Reader
Deptt. of Electrical Engg.
University of Roorkee,
Roorkee.

(Dr.P.Mukhopadhyay)
Prof. and Head
Department of Electrical Engg.
University of Roorkee
Roorkee

ACKNOWLEDGEMENTS

It is indeed a great pleasure to express my deep sense of gratitude to my beloved guides Dr. P.Mukhopadhyay, Prof. and Head, and Dr. D.S.Chitore, Reader, Department of Electrical Engineering, University of Roorkee, Roorkee, who have spared no efforts to show this thesis work, the light of the day. It is due to their valuable guidance and constant encouragement that I could complete the thesis work successfully and as scheduled. I will, in particular, long cherish fruitful and enjoyable discussions I had with them, on varied aspects of this work.

I also take an opportunity to express my sincere thanks to Dr. S.K.Jain, Scientist, National Physical Laboratory, New Delhi, and Mr. N.N.Bhise, Scientist, C.B.R.I., Roorkee, who extended me the Library facilities of NPL and CBRI, without which the work would have been impoverished.

It would not be out of place to express my heart-felt thanks to my friends who have rendered a lot of assistance to complete this work, especially to Mr. S.S.Umale, Mr. V.M. Bothale, Mr. S.S.Phaltankar and Mr. P.S.Pajgade.

Finally I wish to express my thanks to the technicians of Measurement Laboratory, Mr. C.P.Kansal and Mr. G.R.Varma.

(M.W.Trikande)

Roorkee :
Dated : JAN 23, 86

SYNOPSIS

Non-destructive testing is nowadays becoming a basic inspection tool of industry. It serves an important role in many areas of development and manufacturing of products. These areas include product development, process control, flow detection, quality evaluation , measurement of mechanical and physical properties and product improvement.

In this dissertation, essentials of piezoelectric transducer assembly required for ultrasonic non-destructive testing of materials have been described. Physical principles of such non-destructive testing techniques and noise problems encountered in ultrasonic instrumentation systems have also been discussed.

Two ultrasonic instrumentation systems viz. for flow detection and for wall thickness gauging have been designed, developed and tested.

Pulse-echo method which has been developed in the present work for flow detection system uses a single transducer assembly called probe, which acts first as emitter of ultrasonic pulses and then as a receiver to detect echoes from defects or other interfaces. Necessary signal processing is done at both, the transmitting and receiving ends of the probe. The signals are displayed on CRO,time sweep of which is externally driven from separately developed time base generator. Various echoes obtained at the interfaces and/or flaw locations are

displaced in time from transmitted signal indicating the presence or absense of flaw. In the case if flaw is present it is possible to estimate its location from either of the ends.

The pulsed transit-time method which is utilised in the present work for wall thickness gauging uses dual probe operation with one probe acting as a transmitter whereas another as a receiver. The duration between transmitted and received pulses which corresponds to the thickness of the object under test has been digitally measured and displayed on a seven segment LED display unit. Thickness of the object has been evaluated when number of counts displayed are multiplied by the acoustic velocity of the material.

The design details and test results of these schemes are also given. The test of the flaw detection system is carried out on a specially prepared specimen with artificial flaw developed in it. The wall thickness gauge is calibrated for steel rods' measurement. The developed instruments operated with reasonable accuracy during testing.

In the end suggestions for future work are given.

CONTENTS

CERTIFICATE

ACKNOWLEDGEMENT

SYNOPSIS

PAGE NO

CHAPTER-1 INTRODUCTION

CHAPTER-2 PHYSICAL PRINCIPLES OF ULTRASONIC TESTING

CHAPTER-3 DESIGN AND DEVELOPMENT OF INSTRUMENTATION SYSTEMS FOR ULTRASONIC TESTING OF MATERIALS.

CHAPTER - 1

INTRODUCTION

1.1 WHAT IS ULTRASONICS

Ultrasonics is a science of sound waves and a branch of acoustics. Vibrational waves of frequency above the hearing range of normal human being (20 KHz) can be referred to as ULTRASONICS. In ultrasonics there are many other frequency boundries e.g. infrasonics, supersonics, hypersonics, macrosonics, etc. The upper frequency limit is indefinite. However, it is about 10^{13} Hz, which gives a wavelength comparable to the atomic spacing.

1.2 A BRIEF HISTORY OF ULTRASONICS

Ultrasonics as a technology can probably be said to have had its birth during world war I in a laboratory in Toulon, France [2]. There Prof. P.Langevin was diligently searching for ways and means to combat the submarine menance which threatened France at the time. In the course of his investigations he designed and built a high- power ultrasonic generator which used quartz crystal as active elements. In 1927 more experiments in ultrasonics were performed by Wood and Loomis [2]. These investigators used quartz disks vibrating at resonance as a source of ultrasonic energy. The disks were submerged in oil and then excited by applying about 50 KV to them.

In the 10-year period following the work of Wood and Loomis many other workers [2] investigated various aspects of ultrasonics and looked for practical applications of this new technology.

their output in terms of published papers - amounted to more than 600 references. In spite of all this activity ultrasonics as a processing tool remained primarily in the realm of the laboratory until about 1946 when commercial equipment became available.

There has been a continuing steady increase since 1946 in the amount of research work that is being done in ultrasonics specially in industrial processing applications and non-destructive testing methods.

1.3 RANGE OF APPLICATIONS

The numerous technical applications of ultrasonics may be divided into two groups: as in medicine where X-rays are used for two completely different purposes, viz. therapeutically for their action on tissue (cancer irradiation) and diagnostically for studying certain conditions (radioscopy of lungs). Likewise ultrasonics can be used to act on a given material or/and reveal its physical condition. In the first case the energy of the waves is used, for instance, for ejecting particles of dirt from fabrics during washing, for detaching foreign bodies from a given surface during cleaning, for emulsification, for mixing, and for many other applications of mechanical energy. This concerns the explcitation of ultrasound energy.

In other cases the energy of the sound wave is utilised only to the extent required for transmitting a sufficiently clear signal, e.g. in public address system, for locating ships at sea, for sounding ocean depths, locating shoals of fish, and for nondestructive testing of materials. These are known as diagnostic applications. These methods use mechanical stress waves produced by tensile, compressive, shearing or flexural force but these stresses are of low intensity. Other indirect testing method for material testing is possibly a magnetic test which reveals the magnetic field lines produced near a mechanical defect in the specimen. However magnetic testing requires unambiguous correlations between the mechanical properties of the specimen concerned and physical means applied, such as magnetism, electricity, radiation, etc. Sound waves have been in use in past also for testing individual specimen, for instance in forgings or castings, gross internal defects were detected by the change in the ringing note when the specimen is struck with a hammer, a method still practised.

One can therefore with justice maintain that testing by sound is one of the oldest non-destructive methods for detecting hidden defects. By the application of modern electronics it has become one of the most recent and most versatile testing tools. In regard to diagnostic applications, testing of materials is of utmost concern here.

1.4 CLASSIFICATION OF ULTRASONIC INSTRUMENTS FOR NON-DISTRUCTIVE TESTING (NDT)

Ultrasonic nondestructive testing instruments for NDT can be distinctly classified under two major heads:

1) Flew detection instruments
2) Wall thickness gauging instruments.

There are different methods for flew detection as well as for wall thickness gauging. Following lines give a brief review of all such methods.

1.4.1 Flaw detection instruments

A) Intensity Method:

It is the oldest application of ultrasonic waves for non-destructive testing. It dates back to 1930 and was originated by R.Pohlman and O.Muhlhauser of Germany and Sokolov of Russia [17]. In Intensity method, the intensity of the ultrasound is measured after it has passed through the test piece. In literature it has been sometimes referred to as through transmission method [17]. The principle is shown in Fig. 1.1 in which the intensity method is portrayed schematically.

B) Pulse-echo method:

Pulse -echo method for nondestructive testing was developed by Fred Firestone of the University of Michigan [17],in the early 1940's. He utilized ultrasonic pulsed wave trains to determine the depth and relative extent of small flaws. Access to only one side was necessary because the system was monitoring reflected energy, not loss of transmitted energy.

Later on the work by Sokolov,Hiedemann,et. al [22] added much more improvement in the pulse- echo method. From that time on, pulse-echo ultrasonics has been developed into a reliable and efficient nondestructive testing tool with uses in widely varying systems [18].

1.4.2 Wall thickness gauging Instruments:

A) Resonance Method:

Erwin and Rassweiler [5], General Motors, U.S.A., have built the first resonance thickness gauge in 1947. This instrument, called Sonigage functions according to the basic diagram shown in Fig.1.2.

The rotary capacitor is driven by a motor at high speed, resulting in the high frequency generator changing its frequency at the ratio 1:2, e.g. between 0.75 to 1.5 MHz. The rise of the plate current at the resonance points was displayed via an amplifier on the screen of an oscilloscope.

Later on various systems were proposed based on resonance frequency by different authors [5].

The disadvantage of the resonance method results from the fact that the plate to be measured no longer oscillates undisturbed as soon as it is touched by the probe. With closer the coupling of the probe, the resonance frequency shifts more towards lower frequencies. This shortcomingshave limited use of resonance method. [2].

B) Frequency measuring method:

This method was first proposed and used in 1948 by Hiedemann [5]. In this method a **returning** echo of a pulse triggers the next pulse and so forth. Consequently, the echo repetition frequency equals the pulse repetition frequency which can be measured with a frequency meter. Fig. 1.3 shows the principle of this method. It is called a sing round method.

The transit- time is the reciprocal of the repetition frequency. This method has inherent drawbacks because as the thickness of the specimen decreases, the repetition frequency increases e.g. for a 10 cm steel bar the frequency is as much as 50 KHz. For smaller pieces frequency increases to a large extent which makes the operation of the instrument difficult. Also it has a systematic error arising out of the time elapsed between the reception of the given echo pulse, its amplification, the triggering of the electrical transmitting pulse and the actual start of the transit time of the ultrasonic pulse.

C) Transit- time method:

The transit-time method is based on the principle to measure the time required for the pulse to reach the far end of the object. It was proposed by KrautKramer J.in 1966 [5]. With the advent of electronics transit-time method can be a useful tool for measuring thickness in nondistructive tests [19].

1.5 ULTRASONIC TRANSDUCERS:

An ultrasonic transducer is used to convert electrical signal into ultrasonic signal. This ultrasonic signal is thus directed in the medium to be treated or examined. In case of a testing device ultrasonic transducer picks up the received signal and changes it back into electrical oscillations for amplification and presentation.

Thus ultrasonic transducer is a critical element in any treating,testing and measuring instrument and the development of ultrasonic application system is dependent on efficient transduction systems.

Signal Transducers can be classified as receivers and transmitters inspite of the fact that it is quite common to use one transducer for both transmission and reception. Signal conversion sensitivity of these transducers tends to be overriden by considerations such as loop gain, permissible damping, impedance, noise and surface wave generation. Conversion sensitivity may be **defined:** the amplitude of a sound wave generated for a given amplitude of electrical oscillation applied to a transducer or the electrical amplitude produced by a given mechanical deformation of the material. These two quantities are by no means the same. Some ultrasonic devices are used for conversion of electrical power to ultrasonic power and they are loosely termed as ultrasonic power transducers.

Piezoelectric, ferroelectric and magnetostrictive transducers span both signal and power classifications. Mechanical devices- whistles and sirens are used almost exclusively for power generation.

1.5.1 Piezoelectric Materials:

When a voltage is applied across a piezoelectric slab of material, the slab undergoes a mechanical deformation which is directly proportional to the voltage applied. Examples of such materials are the crystals of Rochelle salt, ammonium dihydrogen phosphate (ADP), potassium dihydrogen phosphate (KDP), dipotassium tartrate (DKT), ethylene diamine tartrate(EDT), lithium sulphate and quartz. One hundred volts applied to a quartz slab will deform it approximately $(2)(10^{-10})$meters.

If a voltage is applied to an electrostrictive substance, which includes most insulators and semiconductors (crystalline or amorphous), the material deforms mechanically by usually a small amount. Certain types of electrostrictive substances, called ferroelectrics (in analogy to ferromagnetic materials) exhibit a large electrostrictive effect. A typical ferro electric material is the polycrystalline compound barium titanate ($BaTiO_3$), which, when properly prepared and subjected to about 100 volts will contract or expand approximately $2x10^{-8}$m.

Ferroelectric mode of sound generation is little desired in sonic technology but is easily changed to the piezoelectric mode by the way described. If the material is heated above its curie point and a bias voltage of 1000 volts per mm of thickness is applied, and maintained while the slab cools, the material retains a permanent dipole moment, i.e., the domains are frozen in the oriented position which they assumed under bias. Consequently, the resulting polarized material may be treated in all respects as though it were piezoelectric.

1.5.1.1 Quartz:

For ultrasonic transducers the Y cut quartz crystal is used occassionally to generate surface waves, but the X-cut is by for the most common configuration. Different cuts of quartz crystals are shown in Fig. 1.4. The X crystal generates longitudinal waves, i.e. it vibrates like a piston. Quartz transducers have low transmitting sensitivity. But mechanically quartz is dense, hard, strong, resistant to chemical attack, impervious to moisture and easily worked to close tolerances and high polish.

X cut quartz exhibits low coupling coefficients for other than longitudinal vibrations. It has high acoustic-to-electric conversion sensitivity.

A few important physical characteristics of quartz are listed in Table- I.

1.5.1.2 Ceramics:

Ceramics, though are not the best choice for every instance, have largely replaced quartz in many applications ceramics have a large d constant. The g constant is lower than that of quartz, nevertheless, the loop gain (the total sensitivity of the transducer when used as both a transmitter and receiver) is superior so that these materials are useful for testing purposes. One of the major drawbacks of the ceramic transducers is that,as testing transducers they are noisy and generate objectionable surface waves. At present single crystals of barium titanate and the other ceramics are being grown which should reduce the surface wave problem and, of course, there is continuous development in the mounting and insulating of ceramic transducers to improve their characteristics [8].

The specifications of typical specimen of ceramic are listed in Table I.

TABLE - I

CONSTANTS FOR PIEZOELECTRIC TRANSDUCERS

Constants	For Quartz	For Ceramics
Curie Temp.	575°C	350°C
Sound velocity, $V_{1\infty}$	5570 m/sec	5000 m/sec.
Density, ρ	2650 kg/m^3	7200 kg/m^3
Acoustic impedance (Z)	$\rho V = 14.7 \times 10^6$ $kg/sec\text{-}m^2$	36×10^6 $kg/sec\text{-}m^2$
Transmission sensitivity (d)	2×10^{-12} m/V	200×10^{-12} m/v
Reception sensitivity(g)	0.05 Vm/N	30×10^{-3} Vm/N
Modulus of elasticity (Young's Modulus)	$C_{11} = 8.5 \times 10^{10} N/m^2$ (X cut)	9×10^{10} N/m^2

Barium titanate, $BaTiO_3$ has the typical characteristics as:

Curie temp; $T_c = 120\,^{\circ}C$

Transmission Sensitivity, $d_{33} = 190 \times 10^{-12}$ m/V

Reception sensitivity, $g_{33} = 12 \times 10^{-3}$ Vm/N

Dielectric dissipation factor D= 0.5 percent at 1 KHz.

1.6 PIEZOELECTRIC TRANSDUCER ASSEMBLIES:

The piezoelectric crystal is shown in Fig. 1.8. It is mounted in a holder and is backed up to the left rear by some material of acoustic impedance, Z_b, such as Textolite or in some cases air. It radiates useful energy to the right front into the load (which may be water, steel, oil etc). With an impedance Z_l, and it has, of course, its own characteristics impedance, Z_t.

The testing transducer should, in general, be matched as perfectly as possible both, in front and rear. In addition, the backing material should have a high absorption coefficient for ultrasound so that no energy is reflected back into the crystal.

1.6.1 Matching and Damping Layers:

The desirable features of the transmitting transducer is its maximum efficiency to generate and deliver energy into the material that is being treated, tested or measured. For testing transducers it is usually desired that energy incident at the rear boundary passes into the backing layers and be absorbed there. This condition gives a maximum damping fast rise and fall times of the mechanical crystal vibrations, and short pulse length of the wave packet- all conducive to accurate testing and measurement procedures.

Fig. 1.7 shows the testing transducer assembly. The piezoelement of ceramic (such as $BaTiO_3$) is faced with a layer of amorphous quartz or sapphire to absorb wear and is backed with multiple alternate λ layers(where λ is the wave length of natural vibrations of crystal)of fibre glass and tungsten-filled rubber to provide an approximate impedance match to the crystal and at the same time absorb energy directed backwards from the vibrating element. Thus a heavily damped, broad-band transducer is achieved with fast rise and fall time of the acoustic oscillations.

1.6.2 Transition Layers:

Transition layers are material layers interposed between the vibrating surface of piezoelectric crystal and its load in order to provide maximum power transfer in one or both directions or to provide maximum damping, which is usually synonymous with the first requirement. In practice they are employed in three forms as follows:

i. A thin plate or membrane whose thickness is small compared to a sonic wavelength.

2. A half wave-length plate.

3. A quarter wave-length plate (which acts as an impedance transformer).

The materials used for transition layer are such as phenol formaldehyde loaded with 30 percent of powered permalloy. The use of powdered metal is an excellent way to add transition layer. [21].

1.6.3 Backing layers:

Testing transducers, particularly those designed for accurate rate pulse work, are more interesting (as far as backing layers are concerned). Here, the transition layers may be employed to transmit and receive maximum power into and from the load to achieve maximum testing sensitivity. Further, maximum power transfer requires maximum damping of the crystal at the back for minimum ringing of the crystal after the electrical pulse packet is shut off. The ideal backing layer should be a perfectly absorbing rigid wall which clamps the back face of the piezoelectric slab. Only with the back face fixed could a pulse packet be generated in which the first acoustic oscillation is the maximum [12].

Dr. J.U.H.Krautkramer [5] has suggested the use of rubber with as much powered tungsten milled into it as possible, the acoustic impedance being controlled by the degree of vuleanization of the rubber. Kossoff [24] used tungsten powder in Araldite backing material by adding 100-200 g of tungsten powder to 40 ml of Araldite, and centrifuging the mixture.

Fig. 1.6 shows oscillograms of pulses, generated by the application of a fast electrical transient (of the order of microsecond rise time) to 2.5 MHz transducers with various backing materials. The degree of damping provided in the transducer used to obtain Fig. 1.6a was heavy, that in Fig. 1.6c light, and that in Fig. 1.6b an intermediate value.

The observed pulse continues to build up for about six half- cycles in the case of the lightly damped transducer.

1.6.4 Generators incorporating direct-radiating plane transducers:

Having considered all the theoretical aspects of ultrasonic generators and receptors, it is worthwhile to concentrate on the actual construction thereof.

Three typical arrangements are illustrated in Fig. 1.5. The assembly of these units depends upon epoxy resin adhesive (Araldite) which forms excellent bonds between metals and ceramics, and some plastics.

Ceramics are used as transducers. Air provides a low impedance backing so that almost all of the energy is available for transmission into the load.

Fig. 1.5a shows the simplest system, in which the front electrode lies between the transducer and the load. This has the advantage that there is very little to go wrong, but the assembly is rather fragile.

A more robust arrangement is shown in Fig. 1.5b: the transducer is protected from the load by a plate (usually of metal) of $\lambda/2$ thickness. The principal difficulty here is to ensure a continuous bond between the transducer and the plate, since contained air greatly reduces the transmission into the load. In practice, the characteristic impedance of the transducer is very different from that of the load, but this does not give rise to problems in continuous wave application. For moderately short-pulse work the arrangement shown in Fig. 1.5c has the advantage that the characteristic impedance of the transducer is matched to that of the load by means of a quarter-wave length layer. The limitations of this system are stringent requirement of perfect bonding and high absorption coefficient.

After having considered in detail the piezoelectric transducer and assemblies other types of transducers are described in brief as follows.

1.7 MAGNETOSTRICTIVE TRANSDUCERS :

Magnetostriction [6] is the name given to the effect of an externally applied magnetic field on the length of a piece of magnetic material. It gets longer or shorter when surrounded by the magnetic field. Polarised magnetostrictive materials have been catagorised as piezo-magnetic.

Nickel, iron and cobalt are the three ferromagnetic materials which exhibit important dimentional changes in a magnetic field. Of **these**, Nickel is the only one which is used in the pure form: iron and cobalt invariably appear compounded. In particular iron forms a new class of ferromagnetic ceramics called ferrites ($X.Fe_2O_4$ where X stands for any metal) which exhibits high efficiencies particularly at high frequencies (100 KHz to 1 MHz) and a low cost of manufacture.

In any particular application, the choice of magnetostrictive material depends upon several factors, such as the operating frequency, the ultrasonic intensity, the environment and economics.

1.8 ELECTROMAGNETIC TRANSDUCERS:

Electromagnetic transducers [5] make use of attractive and repulsive forces of electromagnets to generate vibrations. They are used to obtain high amplitude vibrations at frequencies usually below the ultrasonic range for example: load-speakers, marking tools, etc.

1.9 PNEUMATIC TRANSDUCERS

Pneumatic transducers [2] such as whistles and sirens, are useful at frequencies extending into the lower ultrasonic ranges for producing small particle sprays of liquids for the use in burners and in certain type of bulk cleaners. They have been used to dry materials and to break-up foams resulting from various chemical processes.

Whistles and sirens deserve notice for two reasons, firstly, they produce high power intensity outputs at potentially high efficiencies, and secondly they require apparatus (compressors, pumps, motors etc.) which are readily available.

1.10 MECHANICAL TRANSDUCERS:

These are the devices which are actuated mechanically [4] Their applications are more correctly classed as macrosonics. They are used to obtain high amplitude, often high intensity vibrations at low sonic frequencies.

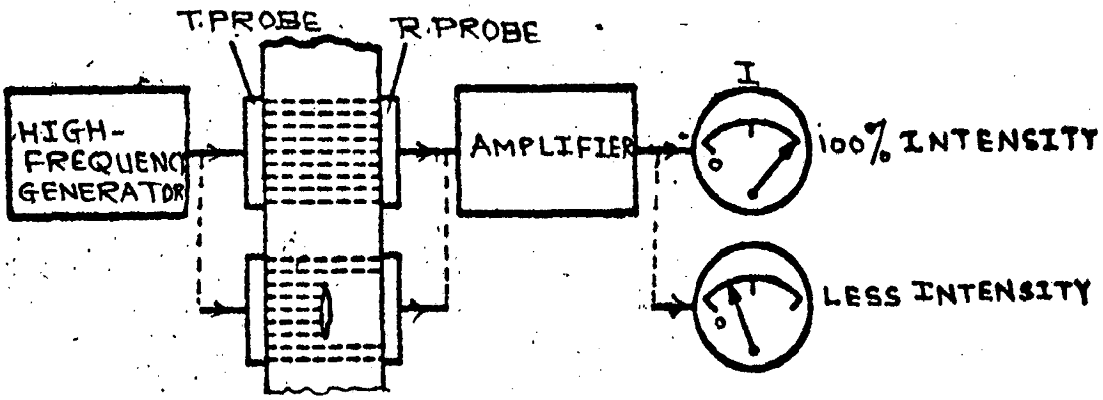
1.11 DEPLETION LAYER TRANSDUCERS:

They consist of a plate of piezoelectric semiconductor [2] (such as gallium arsenide or cadmium sulphide) on which a thin layer of metal is deposited. The film constitutes a rectifying contact with zero ohmic resistance which causes the formation of depletion layer (similar to p-n junction).

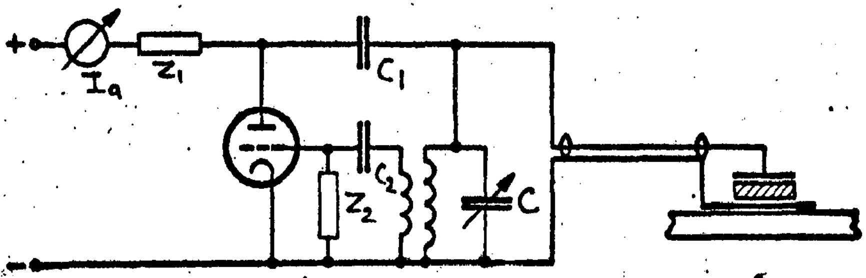
When ac voltage is applied to the electrodes most of the voltage drop occurs across the layer. This layer then behaves as a very thin piezoelectric crystal which is bonded to a solid. Since the layer is very thin, the electric field is large and stress is also very large. Ultrasonic wave thus produced radiates into solid to which depletion layer is attached. Resonant frequency can be varied by varying bias voltage, a feature not found in conventional piezoelectric crystal transducers.

1.12 SOLID HORNS:

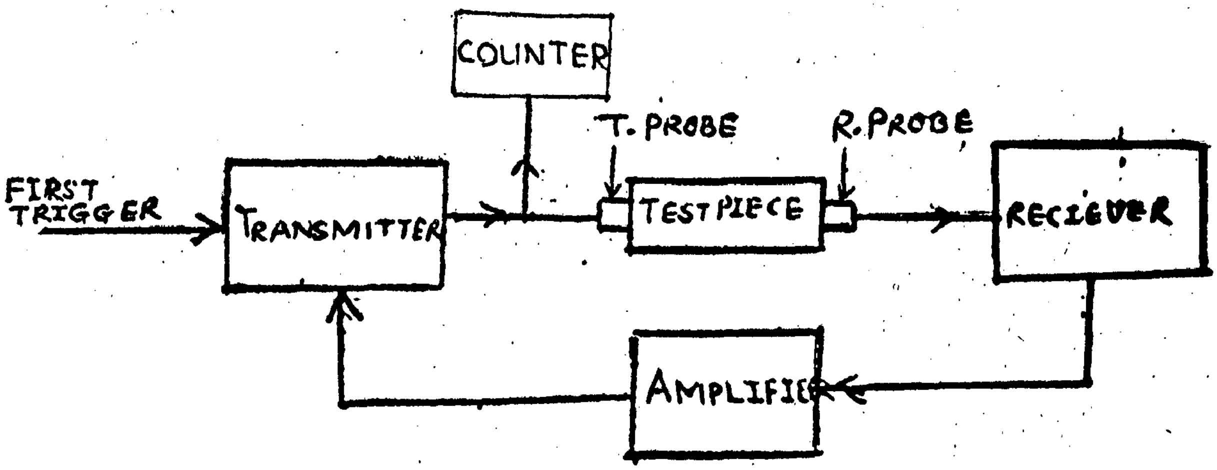
Solid horns [5] can be used on either piezoelectric or magnetostrictive transducers to amplify displacement or particle velocity of the transducer. They can also provide a more suitable impedance match between the transducer and the load to which it is to be coupled.



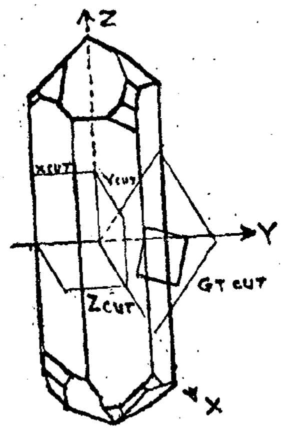
1.1 INTENSITY METHOD



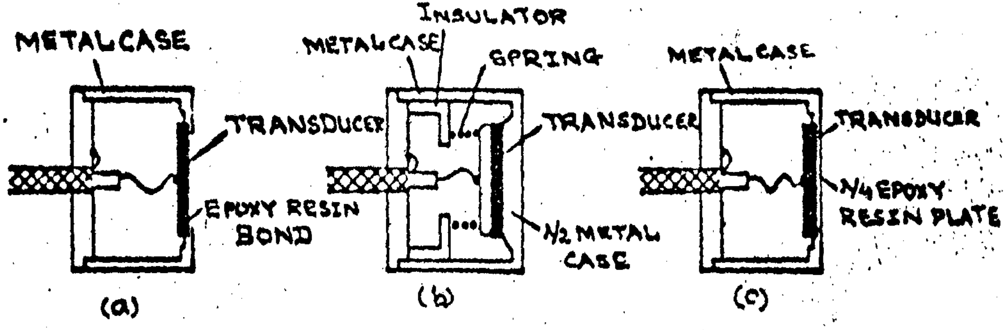
1.2 BASIC DIAGRAM OF 'SONIGAUGE'



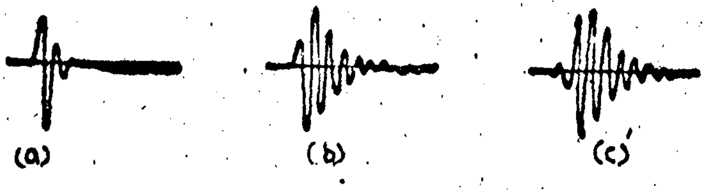
1.3 SING-ROUND METHOD.



1.4 DIFFERENT CUTS IN QUARTZ CRYSTAL



1.5 TYPICAL GENERATORS

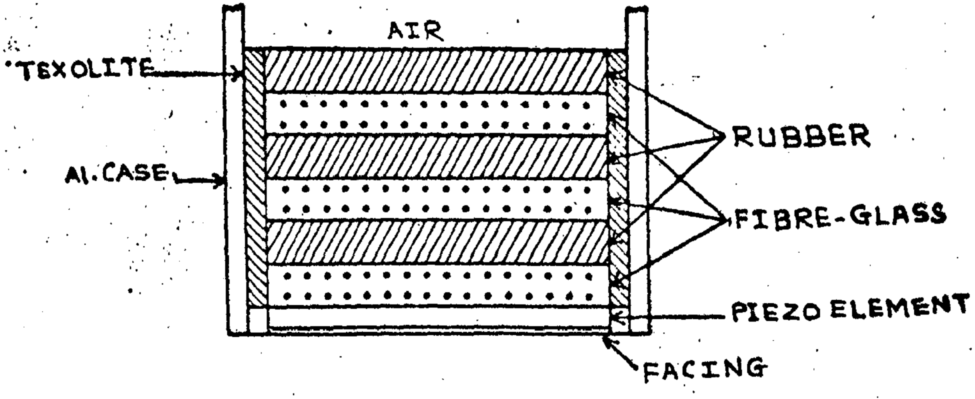


1.6 RECEIVED VOLTAGE PULSES FOR

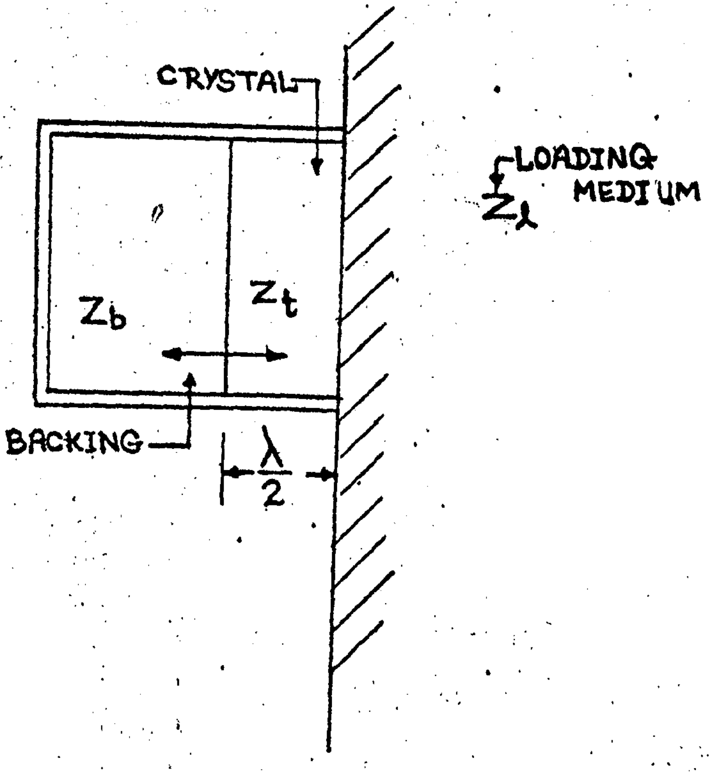
a]→ HEAVY DAMPING

b]→ INTERMEDIATE DAMPING

c]→ LIGHT DAMPING



1.7 TESTING TRANSDUCER ASSEMBLY



1.8 A SIMPLE ULTRASONIC GENERATOR

CHAPTER -2

PHYSICAL PRINCIPLES OF ULTRASONIC TESTING

2.1 INTRODUCTION:

Ultrasonic testing makes use of mechanical waves composed of oscillations of discrete particles of material. Sound waves act like light waves in many respects, in that they undergo intereference, diffraction, reflection, and refraction; it is even possible to have polarised waves of sound in solids. In addition to these properties, a sound wave has an attenuation coefficient and a velocity that are dependent on the type of wave and the medium in which it is travelling.

2.2 TYPES OF SOUND WAVES [17]

Longitudinal wave is encountered in all branches of ultra sonic engineering and can be produced in solids, liquids and gases. These are shown in Fig. 2.1a.

In solids, it is possible for sound waves to have all or part of their vibrational amplitude perpendicular to the direction in which they are travelling, these waves are called transverse or shear waves. A unique characteristic of these waves is that they have no regions of rarefaction or compression. In other words, there are no localized fluctuations in density. Shear wave motion is shown in Fig. 2.1b.

Surface waves produce an elliptical motion of the medium as shown in Fig. 2.1c. The amplitude of the motion decreases exponentially with depth. These surface waves are also called Rayleigh waves.

Another type of surface wave,i.e. Love wave; is possible in a thin layer of material lying on a substrate. The direction of vibration of the particles of the layer is parallel to the surface, but transverse to the direction of wave propagation, as shown in Fig. 3.1d.

Waves produced in a plate whose thickness is comparable to the wavelength are referred to as plate or Lamb waves. The waves that produce particle motion in a plate are called symmetrical and asymmetrical waves. Symmetrical wave is similar in some respect to a longitudinal or compressional wave as shown in Fig. 2.2a.The asymmetrical wave is a flexural type of wave much like that which is produced by shaking a rug. These are shown in Fig. 2.2b. The particle motion at the centre of the plate is transverse, at the surface it is elliptical, as is the case for symmetrical waves.

The general case of wave propogation in a plate can be considered to consist of a pair of longitudinal waves and a pair of transverse waves bouncing back and forth in the plate from one side to the other, as shown by the directions of the long arrows in Fig. 2.3. These waves combine in their effect on the motion of the particles in the plate to produce the symmetrical ar asymmetrical forms of Lamb waves.

2.3 APPLICATIONS OF VARIOUS WAVES

The alternate compressions and rarefactions of the longitudinal wave are normally the only wave motion which can exist in liquids and gases. This type of wave is generally utilised for power generation, cleaning in tanks of solvent, dispersal of aerosols and agglomeration of fogs and precipitates, emulsification, grain refinement in steel melts, ultrasonic machining and in testing and measurement problems. Location of hidden flaws in metallic objects measurement of the depth of liquid in tanks and determination,of the thickness of boiler tubing or heavy castings where only one side is available can all be done by means of longitudinal waves.

Shear waves are useful for many testing purposes, particularly where the beam must be introduced at an angle, as in the testing of welds [25].

At present, the examination of thin sheet and plate stock is carried out to a limited extent with lamb waves, although little effort has been expended on their development or on the understanding of their characteristics.

Surface waves find a limited, but important application in the location of surface defects in beams, spars, axle forgings and other items in which cracks close to the surface are dangerous. Surface waves have an unusual ability [16] to flow around corners and over bumps, edges and other irragularities, consequently they are sometimes of considerable aid in the surface examination of such items as airplane wing fittings where access is difficult or impossible.

2.4 INTEREFERENCE OF SOUND WAVES

Intereference refers to the manner in which two sound waves will combine at some point in a medium where they happen to meet. The effect on the medium is the same as if each wave acted separately on the material at that point. If they are of the same frequency and amplitude, there can be reinforcement of one wave by the other or else complete annihilation. The phases of the two waves determine which of these two events happens.

2.5 VELOCITY OF SOUND WAVES

The velocity of a sound wave depends on the type of wave that is being considered and the density and elastic constants of the material in which it is travelling. There are two kinds of velocity that can be specified: group velocity and phase velocity. Ordinarily the phase velocity and group velocities are equal. Table II lists some formulae for calculating the velocities of various types of waves in isotropic materials. The formulae for longitudinal and transverse waves assume an infinite medium. The velocity may be different if some dimension of the medium is comparable to the wavelength of the sound. Group velocities are given in formulae [20] in Table II.

2.6 THE ATTENUATION OF ULTRASONIC WAVES :

The intensity of an ultrasonic wave decreases as the distance from the source increases. The causes of this decrease may be divided into two general categories: (1) geometrical factors, and (2) energy absorption or scattering mechanisms.

TABLE - II

VELOCITIES OF VARIOUS TYPES OF SOUND WAVES.

Type of material	Type of wave	Velocity, C
Gas	Longitudinal	$\sqrt{\gamma p_0/\rho}$
Liquid	Longitudinal	$\sqrt{1/\rho B}$
Solid	Longitudinal	$\sqrt{\frac{E(1-\nu)}{(1+\nu)(1-2\nu)}}$
Solid	Transverse	$\sqrt{G/\rho}$
Solid	Surface or Rayleigh	$\sim 0.02\sqrt{G/\rho}$
Solid	Lamb	Depends on type and mode
Solid (Long thin rod. Diameter of rod $< 0.1\lambda$	Longitudinal	$\sqrt{E/\rho}$

where γ = ratio of specific heats

p_0 = static pressure

ρ = density

B = bulk compressibility

E = Young's modulus

ν = Poissons ratio

G = modulus of rigidity.

The first category takes into account the size of the sound source, the wavelength of sound, and the presence or absense of nearby reflecting surfaces. The maximum rate of decrease in intensity due to these factors is 6 decibels for each doubling of the distance. This corresponds to the decrease in the intensity that is encountered around a point source of sound located far from any reflecting surfaces.

There may be a loss of energy due to scattering and absorption of ultrasonic waves in air, liquids, and solids.

2.7 ACOUSTIC IMPEDANCE, ACOUSTIC INTENSITY:

Acoustic impedance of the medium in which a sound wave is travelling is defined [2] as the ratio of the sound pressure acting on the medium to a quantity called the volume velocity, that is:

$$Z_{ac} = \frac{\text{sound pressure}}{\text{volume velocity}}$$

The volume velocity is the velocity given to the particles of the medium by the sound wave multiplied by the area over which the pressure is considered to be acting.

The acoustic impedance Z_{ac} is complex quantity in the mathematical sense, namely,

$$Z_{ac} = R + j\,X.$$

The resistive term R is equal to the characteristic impedance, or the acoustic resistance. It is the component that is associated with the dissipation of energy. The reactive term jX is due to the inertia and stiffness of the medium. Hence it is a characteristic of the medium and depends on the frequency and the type of wave being propogated.

The acoustic intensity is defined [2] as the average rate of flow of energy through a unit area normal to the direction of wave propogation as a result of sound pressure acting on that area. Customary units are watts per square centimeter or decibels. The energy at any instant may be part Kinetic and part potential.

The average energy density is the quantity that is actually needed in calculating the intensity of a sound wave. To obtain the intensity, average energy density (over a wavelength or for one cycle of sound wave) is multiplied by the velocity with which the energy travels through the medium. Energy density can be expressed in terms of the amplitude of the particle vibration, the sound pressure, or the maximum velocity attained by a particle in a medium during its oscillation under the infleuence of the sound waves.

Some calculated values of acoustic intensity in various media corresponding to a fixed amplitude of vibration are given in Table III. [2].

TABLE - III

Values of Acoustic in various media
corresponding to an amplitude of 10^{-6}cm

Frequency	Medium	Intensity watts/cm^2
1 MHz.	Water	0.293
20 KHz	Water	0.000117
1 MHz	Steel	7.70
20 KHz	Steel	0.00308
1 MHz	Air	8.45×10^{-5}
20 KHz.	Air	3.36×10^{-8}

2.8 NOISE IN ULTRASONIC INSTRUMENTATION SYSTEMS

In addition to the noise introduced due to various circuit components as well as electrostatic and electromagnetic intereferences [11], there are a lot of noise sources in ultrasonic instrumentation systems. These arise from the various physical phenomenon associated with ultrasonic waves [3]. Hence from testing point of view understanding of these noise sources is of vital importance for correct interepretation of test results. In the description to follow, all such noise sources are enlisted and wherever possible, their elimination techniques are also given briefly.

2.8.1 Effect on Sound Field by Boundaries Parallel to the beam axis.

Disturbances of normal propogation occur if the peripheral rays strike a lateral boundary as in Fig. 2.4. This affects both the sensitivity and the direction of the original beam and additional echoes are produced by split-off transverse waves.

The reflected longitudinal wave intereferes with the direct wave and disturbs the original pattern of both the acoustic pressure and the sensitivity. In the case of the pulse-echo method the minimum distance between the beam axis and a side wall required to avoid this disturbing influences can be estimated as follows [5].

For (a) → $d > 3.5\sqrt{\frac{a}{f}}$ [mm]

For (b) → $d > 5\sqrt{\frac{a}{f}}$, f in MHz.

(d and a are shown in Fig. 2.5).

Hence the temptation to move the probe as close as possible to the edge in order to overcome the difficulty in detecting small flows due to strong decrease of the sensitivity close to wall, should be avoided.

2.8.2 Secondary Echoes produced by Split-off Transverse waves

Transverse waves split off as shown in Fig. 2.4 leave the side wall at an angle of approx. 33^0 to the vertical in the case of steel, furthermore those are independent of the angle of incidence of the longitudinal wave. For given values of probe diameter, frequency and distance from the edge, the transverse wave reaches a maximum at a certain distance as shown in Fig. 2.6. This maximum moves closer and becomes stronger if the probe is moved closer to the edge.

If this transverse wave is reflected directly back of the probe as shown in Fig. 2.7a, this hardly intereferes because the the probe is insensitive to it.

If the wave is reflected at an edge back into its own path, it is partially transformed into a longitudinal wave, producing an interfering echo as shown in Fig. 2.7 b.

On the screen calibrated for longitudinal waves, this echo has the apparent flow distance

$$a_s = a + 1.53d \text{ in steel.}$$

Echoes in the form of gross mound are frequently obtained with rough internal surfaces of holes or threads.

If the side walls are parallel, the transverse wave can also travel between the walls along a zigzag path and produce multiple interefering echoes. According to Fig. 2.8 the transverse wave, when it strikes the wall, is partially retransformed into a longitudinal wave reflected at a certain angle, and is partially reflected as a transverse wave at an angle of approx. 33°. If the test piece concerned is narrow enough, the longitudinal wave, after reflection on the backwall, can again return directly to the probe. The echo obtained will have only half the delay and will therefore appear only 0.76 d behind the backwall echo. At the next reflection the reflected transverse waves is again split, resulting in a further secondary shifted 1.53d. In this way a sequence of secondary echoes is obtained in slender test pieces behind every backwall echo and flaw echo, as shown schematically in Fig. 2.9.

If such test pieces give no indication of flaws, the secondary echoes cannot be mistaken for flaws because they appear only behind the end echo. However, if flaw echoes are present, the secondary echoes cause confusion and they may give the impression that there are more flaws than actually present.

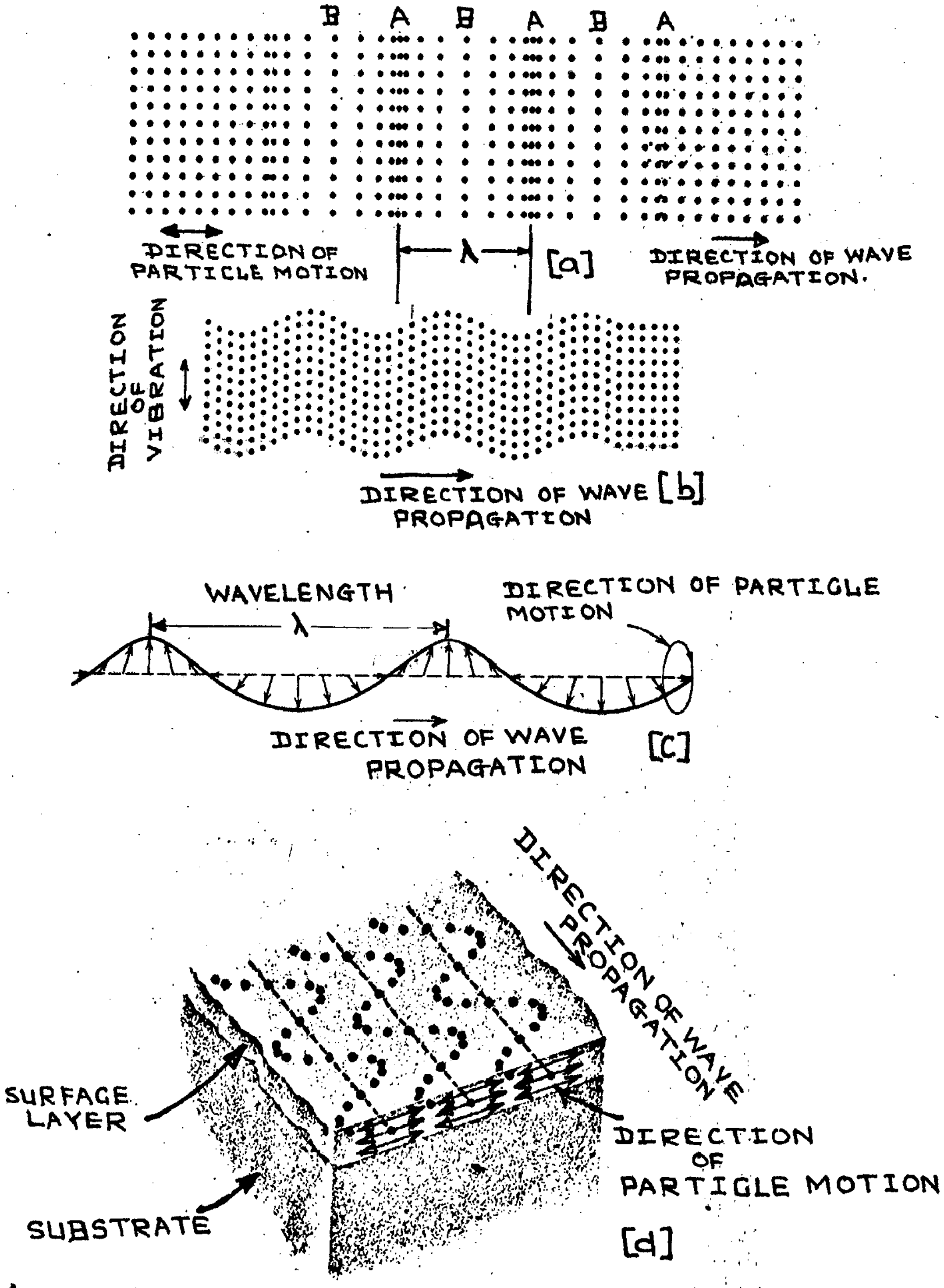
Secondary echoes appear as a long sequence of considerable height only if the conditions for reflection are good at all points owing to a smooth surface. If, however, in the case of a given specimen these echoes are comparatively badly distorted in spite of a good surface, this points to elongated flaws in the specimens which, while still passing the direct longitudinal wave, supress the oblique transverse waves.

2.8.3 Interefering echoes through surface waves [5]

Surface waves are frequently produced unintentionally. Whenever a probe is coupled to a solid surface waves are radiated unavoidably, but usually they are very weak compared with the longitudinal or transverse waves. This, however, is no longer the case if the sound beam is sharply defined, i.e. for a small d/λ ratio, as in the case of probes of exceptionally small diameter, incomplete contact, and probes for lower frequencies.

Using the probes of moderate frequencies (normal probe) on the polished face of a large forging or casting it is possible to obtain large and pronounced interefering echoes which are produced by surface waves at the edges of the specimen or the periphery of the ground face. Higher frequencies can still be damped by merely touching the surface with an oily finger, and this can be used for distinguishing such interefering echoes from true echoes. If one does not want to use considerably longer probes, which naturally require correspondingly larger coupling faces, specially designed probes can overcome this difficulty. Square transducer plates or transducers sub-divided into squares, do not radiate the surface waves in the contact plane uniformly in all directions but in the shape of a four-lobed directional pattern. By rotating this probe around the contact point, interefering echoes can be distinguished from true echoes. For reason of interefering surface waves, low frequencies should only be used on non-polished surfaces. Mill-rough surfaces damp the interefering wave quickly and merely produce a little grass.

Moreover, incomplete contact is frequently unavoidable, e.g. on a round stock. On small diameters strong surface waves are radiated even if higher frequencies are used.



2.1

a]→ A COMPRESSIONAL WAVE OF SOUND

b]→ TRANSVERSE OR SHEAR WAVE MOTION

c]→ SURFACE WAVES [RAYLEIGH WAVES]

d]→ LOVE WAVE PROPAGATION

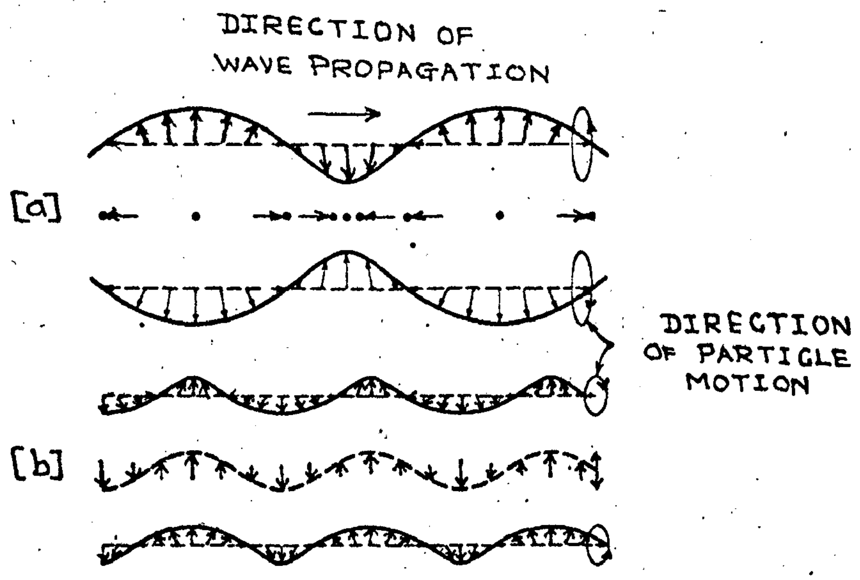
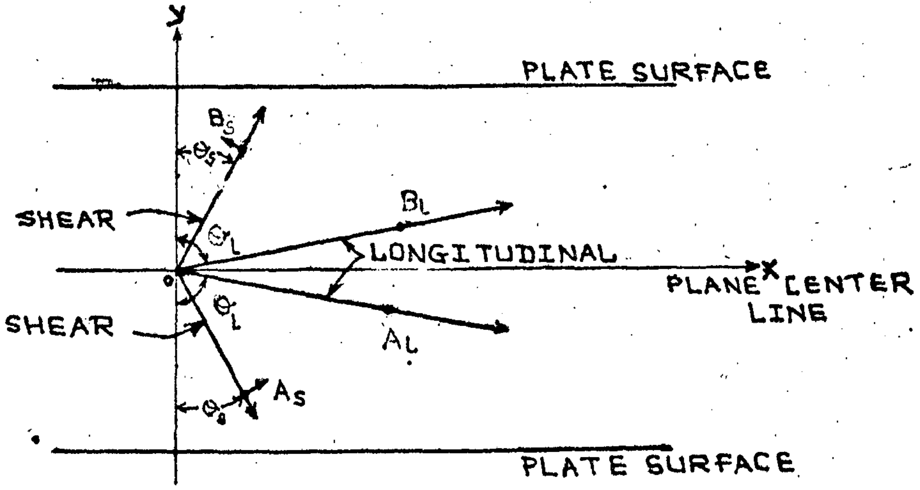


PLATE OR LAMB WAVES

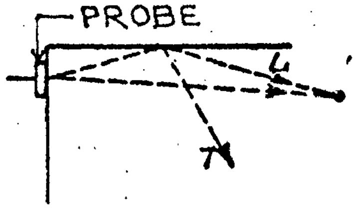
2.2 a] SYMMETRICAL WAVES b] ASYMMETRICAL WAVES



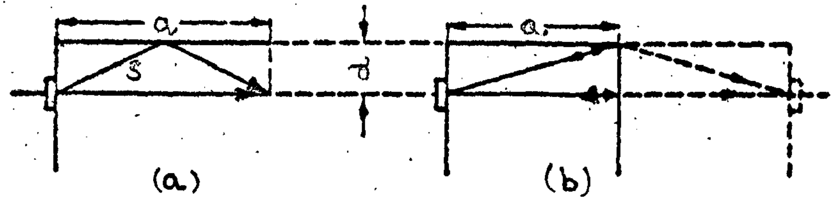
DIRECTIONS OF PROPAGATION OF

2.3 LONGITUDINAL AND SHEAR WAVES MODES

IN A PLATE



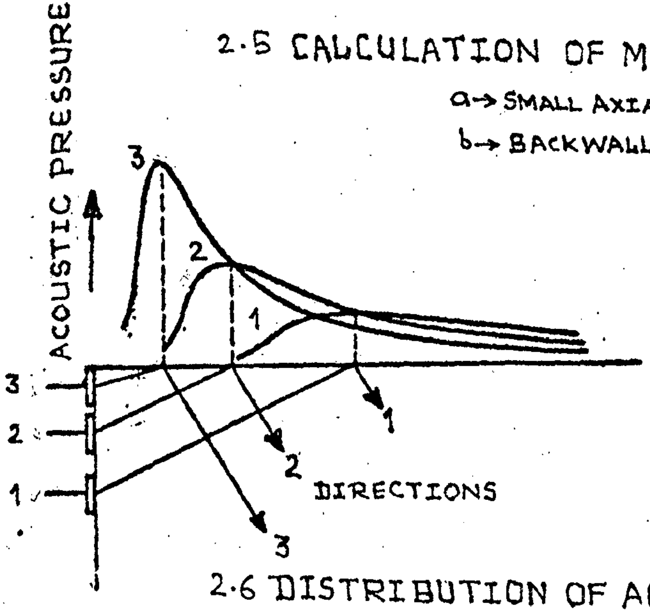
2.4 INTERFERENCE FROM LATERAL BOUNDARIES



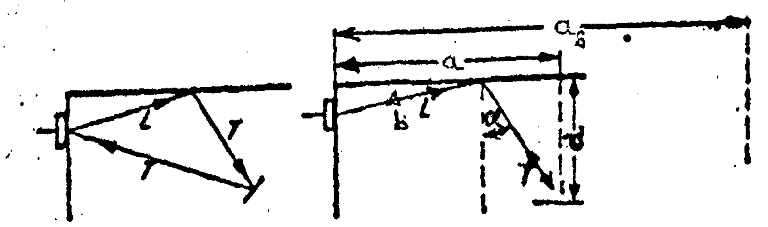
(a) (b)

2.5 CALCULATION OF MINIMUM 'd'

a→ SMALL AXIAL FLAWS
b→ BACKWALL ECHO



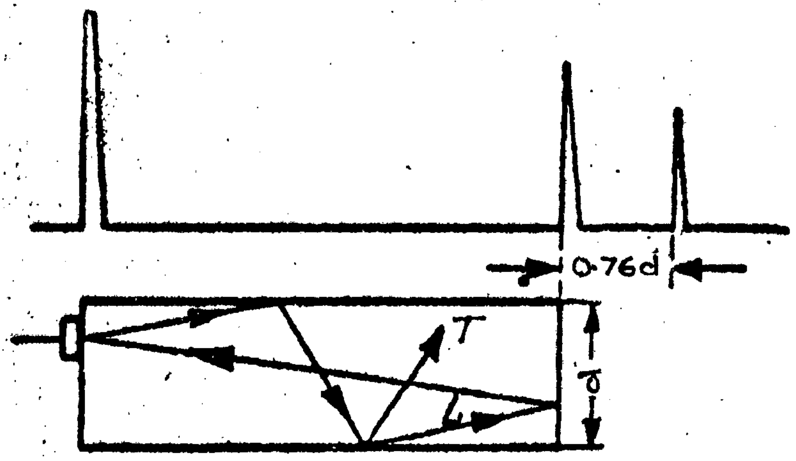
2.6 DISTRIBUTION OF ACOUSTIC PRESSURE OF SPLIT-OFF TRANSVERSE WAVE



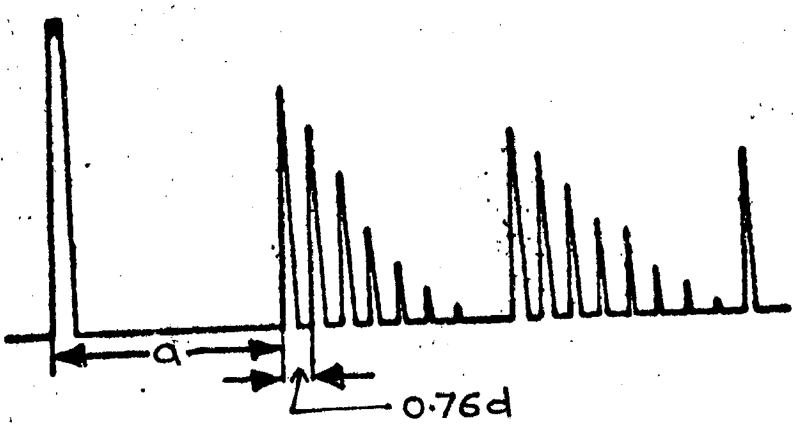
(a) (b)

2.7 SPLITTING OFF OF TRANSVERSE WAVE

a→ DIRECT REFLECTION WITHOUT INTEREFERING ECHOES
b→ MODE RECONVERSION INTO LONGITUDINAL WAVE



2·8 SECONDARY ECOES IN A SLENDER
CYLINDER [STEEL]



2·9 MULTIPLE BACKWALL ECHOES AND
SEQUENCES OF SECONDARY ECHOES
IN STEEL

CHAPTER - 3

DESIGN AND DEVELOPMENT OF INSTRUMENTATION SYSTEMS FOR ULTRASONIC TESTING OF MATERIALS

3.1 PULSE-ECHO METHOD

INTRODUCTION

Fig. 3.1 shows the principle of the pulse-echo method. The sound pulse coming from the transmitter is beamed into the material which encounters a flaw in its path. If the flaw is smaller than the cross-section of the sound beam, part of the beam bypasses the flaw and strikes the backwall. The flaw in turn transmits an echo wave which, depending on its form and size, is more or less specifically directed, of which a portion reaches the receiver. Receiver and transmitter need not necessarily be probes placed at different points on the test piece but can be combined in a single probe. The echo wave coming from the flaw is indicated according to its transit time from the transmitter to the flaw and to the receiver. Wave reflected from the back called backwall echo arrives after a correspondingly longer delay. Both echoes are indicated according to their intensity, or rather amplitude, which is referred to as echo height because of their usual prepentation as peaks above (or below) base line.

The transit time gives the distance to the flaw.In steel with velocity of sound c, approximately 6 km/sec, if the echo reaches after 1 usec,the flaw distance, a, is half of the total path travelled, i.e. a =3 mm. The delay scale can be calibrated in flaw distances instead of us. This would apply only to a definite velocity of sound, i.e. for a definite material and definite wave mode.

It is noteworthy that the height of the echo is determined not only by the size of the flaw but also by the position and form of the flaw and the instrument characteristics.

Figure 3.2 shows schematically the traces on the viewing screen for various cases of flaw detection. The exact location of flaw represents the decisive advance for most applications. If the flaw is not too large and the beam is incident at right angles on the backwall, a backwall echo appears in addition to the echo from the flaw on the viewing screen. The transit time of backwall echo corresponds to twice the thickness of the specimen. The flaw echo divides the distance between the beginning of the time scale and the backwall echo in the same ratio as the position of the flaw divides the distance between the front and the back of the specimen. If the time scale is linear, these three indications, therefore, provide an enlarged or reduced diagram of the location of the flaw. Even without measuring the transit time accurately, it is thus possible to locate flaw if present.

Several flaws in the sound beam through the test piece can be indicated simultaneously if none of them are masked completely by another flaw. If a large flaw is encountered first, smaller flaw followed by it will be completely masked alongwith the backwall echo because all the energy has been reflected back by the larger flaw. Sometimes, however, it is possible to detect a small flaw behind a larger flaw, owing to sound diffraction around the edge of the masking flaw. A rough geometrical presentation indicates that this echo dissappears if the flaw equals or exceeds the cross-section of the beam. This provides additional information concerning the minimum size of the flaw if the flaw is obliquely oriented. The backwall echo is also absent if the backwall is smooth and oblique relative to the axis of the beam, or if the attenuation of the sound in the specimen is too high because of scattering or absorption. Scattering is indicated by many irregular closely spaced echoes (grass).

3.2 BLOCK DIAGRAM AND WORKING:

Figure 3.3 is the block diagram showing the relationships between the various components of an ultrasonic pulse-echo system. This particular kind of display is called an A-Scan.

The clock provides a trigger pulse for the transmitter, the swept gain generator and the timebase. It is also referred to as synchroniser. It is literally the heart of this system. It sends out electrical pulses which cause all other operations to occur in proper time sequence. The transmitter, triggered by the clock, generates an electrical pulse, which excites the transducer to emit a stress wave of amplitude determined by the attenuator , whose inclusion is however optional.

The echo signal output from the transducer is fed to the radio-frequency amplifier. The gain of this amplifier may be increased with time, to compensate to some extent for the increasing attenuation of the echoes from deeper structures. Sometimes an arrangement in the form of bright up generator is incorporated to suppress flyback trace of the timebase. The timebase generates a voltage ramp which deflects the trace at constant velocity appropriate to the penetration. The output from r.f. amplifier is demodulated, and the dynamic range may be restricted by suppression of the smaller echo signals, before being fed to the next stage amplifier. The output from this amplifier is connected to the Y-deflection plates of cathode-ray tube to produce an A-scan. The main pulse is shown at the left edge of the screen, the echo from the opposite side of the test block at the right, and a flow echo in between. The vertical scale represents amplitude and the horizontal, time.

3.3 DESIGN OF FUNCTIONAL BLOCKS

Functional blocks are designed as follows.

3.3.1 The Pulse Generator [CLOCK]

This is regarded as the prime-mover of the system. Its function is to generate short initiating pulses at regular predetermined intervals. The clock pulses are characterised by operating time, t_a and its interval, t_p . The duration of the operating time, t_a has been decided by proposed testing range. It may be noted that if t_p is very small spurious echoes (called phantom echoes) may appear on the viewing screen due to multiple echoes returned from the specimen. Hence the interval has been selected to be adequately long. Table IV gives the experimentally verified basis for the pulse repetition frequency.

TABLE -IV

PULSE REPETITION FREQUENCIES

Testing range in steel/Brass	Operating time, t_a (Time interval for outgoing and return path for longitudinal waves)	Minimum pulse spacing	Max pulse repetition frequency
100 mm	0.034 ms	2 ms	500 Hz.
1000mm	0.34 ms	20 ms	50 Hz.

However, satisfactory brightness of the picture requires a high repetition frequency. The above values are therefore increased taking into account the fixed form of the specimen and that it does not produce multiple echoes.

Though the pulse generator may be a conventional oscillator, or it has been constructed by using timer IC 555 in astable configuration as shown in Fig. 3.5 [23].

$T_2 = 0.69\ R_BC$

$T_1 = 0.69\ (R_A+R_B)C$

where R_A should be 1 K ohms minimum

and R_A+R_B range = 1 K ohms - 20 M ohms.

Externally available oscillator is normally preferred to cover a wider range of frequencies for different specimen. In the photograph P3 the output from such an oscillator is shown with t_a and t_p to be almost equal. A factor of safety has been incorporated in deciding these intervals to avoid spurious flaw echoes by keeping t_p slightly more than required. Here t_p has been kept equal to 1800 us, which is sufficiently large for the chosen testing range of 2 meters of steel.

3.3.2 Transmitter Unit :

The small pulse output from the pulse generator circuit does not contain sufficient power to energise the crystal transducer. Therefore a further stage is required to generate the initial transmitter pulse. The transmitter circuit as suggested by Okyere,et.al [13], consists of a capacitor which is previously charged to a high voltage. This is then suddenly discharged across the transducer by means of an electronic switch. The switching action is achieved by using either a thyratron, a thyristor, or a transistor. A circuit which has been used in the developed scheme is as shown in Fig. 3.9.

The active element used is a medium power transistor SL100 which acts virtually as a short circuit when the base is made positive by the application of pulse to the base. This discharges the capacitor c its stored energy through the crystal transducer. By virtue of its piezo-electric action the crystal is shock excited into vibrations by the pulse of electrical energy and it will execute a short damped train of mechanical vibrations at its natural frequency. The mechanical energy generated by the crystal depends upon the electrical energy supplied to it, which is related to the capacitor value C and the charging potential of the supply. Here 40V supply is used which gives reasonably sufficient mechanical energy for the chosen testing range. In order to keep the duration of the transmitter pulse as short as possible, the capacitor value is kept fairly low. But this requires the supply potential to be large. Hence a compromise is made between these two facts. To obtain pulse fronts of rise time of monoseconds avalanche transistors can be used. For the quartz crystals often tuning circuit is employed across the crystal. Tuning provides [5] better conversion efficiency and greater output from the crystal can be achieved. This is of importance when the crystal pulse is required to penetrate large thickness of material. Damping to shorten the transmitted ultrasonic pulse in case of ceramic transducers can be achieved by either mechanical or electrical means. Mechanical damping has been introduced in the design of probe itself [13]. Also the electrical damping has been achieved by providing resistive load R_2 across the crystal. This is in addition to the mechanical damping to the probe. By varying the damping resistor, the operator has facility to vary the degree of damping to suit particular inspection conditions.

3.3.3 Time- Base Circuit [14]

The timebase circuit is required to provide a linear transverse from left to right across the cathode ray tube. The transmitter pulse and the various return echoes in succession are required to be displayed in vertical plane on this horizontal sweep. It is necessary that the circuit provides linear sweep so that equal distances along the trace representequal units of time. Further the time base must be capable of generating sweep time to cover the depth of material to be examined completely. In the system a time base of 1.5 ms has been encorporated as shown in photograph. The commencement of each stroke of the time- base should not follow immediately on the completion of the previous one and the CRT spot must rest at one end or other of the trace for a part of each cycle. Keeping in mind this, the spare time kept is of 1.8 ms The time-base signal is given to EXT terminal of CRO with the trigger position kept at EXT TRIG. The circuit used is shown in Figure 3.4.

The circuit is basically an integrator with a constant negative input. It has a transistor which acts as a reset switch. When the transistor is turned on it shorts the capacitor and thus force the output to virtual ground. A current limiting resistor is inserted in series with base. The effective value of integrator time constant is RC and it can be changed by changing the capacitors in the feedback path. The horizontal input amplifier of the CRO amplifies this sigaal and gives to its X plates.

The waiting time during sweep strokes is of no value and this merely causes a disturbing bright spot on the screen. The bright-up pulse generator (already incorporated in the CRO circuit) takes care of this. It switches on the display only during the time that echo information is being received, thus making the flyback of the time base invisible.

3.3.4 RF amplifier

One of the basic criterion for amplifier design in pulse echo system is the frequency response of the amplifier. The high-frequency amplifier can be of very large bandwidth i.e. covering all occuring ultrasonic frequencies e.g. from 1 to 10 MHz. The IC available in the market for such a wideband amplifier is LM 733I. This chip has a bandwidth of 120 MHz. Hence change in probe will not affect the amplifier design and practically it is able to cover almost all the ultrasonic operating range. It has also an advantage that short pulses with their wide frequency band pass through with little distortion or change. But the serious disadvantage is that of the amplifier noise. Noise limits the possible amplification. For IC 733 the viewing screen clearly indicates noise and therefore further amplification is futile because the noise masks the small echoes. The amplitude of the noise is proportional to the square root of the amplifier bandwidth [11]. Therefore narrow band amplifier permits higher amplification with lower noise. In addition to this hormonics of the frequency of the probe frequently predominate in the frequency band of echoes as compared with the hormonics of the transmitted sound wave, and pose the problem on the screen, producing undesirable background noise with which the flaw echoes to be detected no longer contrast sufficiently. However, if the frequency band in the amplifier is clipped, e.g. already excluding the third hormonic, the picture becomes clearer. An excessively narrow band width has the disadvantage that the pulses are broadened, resulting in reduced resolving power. ICLF356 is one which can meet the requirements for the pulse echo method. This is a compromise between opposing requirements based on practical considerations.

Other important points in the design of amplifier are quick recovery from overload and ability to withstand transmitter output. Also the provision of swept gain control is an essential feature. An overloading signal can change the bias conditions of the amplifying stages. The amplifier may become insensitive to small signals until the biasing conditions have returned to normal. This tendency of the receiver amplifier to paralyse is an undesirable feature and this results in a long transmission pulse. The problem of paralysis can be reduced to some extent by the limiting circuit included at the input to the amplifier. The protection circuit is shown in Fig. 3.6.

The peak input to the receiver is limited to about 1V, being the forward voltage of the reverse connected diodes.

3.3.5 Swept-gain control

Swept gain control is employed to increase the amplifier gain with time. This feature of swept gain can, to a certain extent, overcome the difficulty arising due to drop in sensitivity with increasing distance of the flaw because of attenuation in the material and the beam spread. The swept gain is obtained by the alteration of feedback. In the system swept gain control is achieved by using FET. The circuit is as shown in Fig.3.8.

The FET is driven by the sawtooth signal with negative dc level. The FET is closed at the start of the sweep and thus the output voltage is very small but as the Vgs increases with time the resistance begins to add between D and S points, this resistance increases with time thus making the output voltage time dependent. At the end of sweep, the drain to source resistance is very large and the gain is maximum.

The circuit for obtaining sawtooth signal for applying to BFW11 is similar to that for time- base generator excepting the constant input polarity at terminal 2 is changed to +ve, as shown in Fig. 3.7.

3.3.6 Demodulation and Suppression

The output from the rf amplifier is the faithful amplification complete with both positive and negative-going excursions (as short clamped wave trains at 2.5 MHz). The presence of both positive and negative half-cycles make interpretation difficult and wastes valuable space on the CRT screen. Hence it is necessary to demodulate these signals.

Demodulation in the system is carried out by means of simple diode network, as shown in Fig. 3.10.

The circuit shown provides a half-wave rectified output signal. The amplitude of the output signal is proportional to the instanteneous forward value of the rf input signal.

3.3.7 Video Amplifier

The video amplifier amplifies the demodulated output from the rf amplifier to a level suitable for giving to CRO input. The simplest video amplifier is constructed out of LF356 with a gain of 1000.

The video amplifier is followed by a passive differentiating circuit. The output from this is given to the Y-deflection plate of CRO through Y-input terminal.

The complete circuit diagram of pulse-echo system is depicted in Fig. 3.11.

3.4 PRE-TESTING PROCEDURES

To obtain good test results following procedures are adopted. These are common for pulse-echo system as well as for pulse transit time thickness gauge.

3.4.1 Conditioning and Preparation of Surface

In any ultrasonic test the shape and roughness of the surface is of decisive importance. On the one hand these factors often limit the sensitivity of the method applied, making it necessary to first prepare the surface. On the other they have a decisive infleuence on the wear of the probe used for continuous and routine tests if in direct contact with the specimen. The surface condition, therefore, greatly influence the economics of testing.

In the case of direct contact which is employed here, the probe is pressed against the specimen covered by a thin film of coupling liquid. Foreign particles or layers are very disturbing because they considerably vary the thickness of the liquid film . It is therefore absolutely necessary to remove any dirt, loose scale and sand. Grinder with a rotating emery disc is used for surface finishing. Uniformly and strongly adhering films such as thin oxide layers or even paint, may not necessarily interfere and are often preferable to an unevenly cleaned surface.

The surface is polished lightly but it is not highly polished, because the probes stick due to suction and, therefore, cannot slide easily. In the case of contact tests on test blocks it is observed that a plained surface is therefore preferable in view of the better reproducibility of the echoes.

3.4.2 Coupling Media:

The effect of a curved or rough surface is compensated by means of a coupling medium. Here mobile oil is used as a coupling medium. But on rough surfaces oil of higher viscocity is needed. Glycerine also can be employed as a coupling medium. It is observed that the thickness of spacing layers plays an important role on the screen traces and thus in turn on the sensitivity of the testing method.

3.5 TEST RESULTS FOR PULSE ECHO SYSTEM

The pulse echo system thus developed has been tested on the flawless as well as flawed test specimen. A bar of brass measuring 108 cms is tested by single probe. The pulse repetition frequency (shown by Photograph P3) is 285.7 Hz which is sufficient for the test specimen. The X axis sweep is provided by the signal shown in photograph P4. The duration of operating time is 1.5 ms and the slope is 0.71. The pulses transmitted to the probe are of duration 10 us, having an amplitude of 36 volts (shown in photograph P6). Photograph P5 shows how the degree of damping of the probe affects the duration of transmitted pulse. The same pulse as shown in photograph P6 (probe not connected) gets lengthened several times due to moderate damping of the probe. This affects to a large extent the resolution of the images obtained on the screen. Thus it becomes clear that for good resolution to be obtained, the probe should be as heavily damped as possible. The swept gain control signal employed is shown in photograph P10, which indicates the slope of 16. The duration of the swept gain control function is 1.5 ms. The end surface of the brass rod is made smooth by turning on lathe. The probe is fitted on the end surface by properly preparing the surface before it. The transmitted signal and the backwall echo are obtained as shown in photographs P1, and P2. The distance between the transmitted signal and the backwall echo corresponds to the length of the brass rod. Thus 1 small division of the horizontal line of CRT corresponds to 9.810 cms of brass. The scale thus calibrated can be used for testing the flaws in the brass rods. Any flaw present will indicate the flaw echo in between the transmitted signal and the backwall echo. The distance of flaw echo from either backwall echo or transmitted signal will give the location of the flaw from rear or front end (to which probe is connected) respectively.

Nevertheless, the same scale can be used for testing the rods or slabs of other material such as steel by multiplying it with a factor equal to the ratio of the acoustic velocities of the two materials.

The acousstic velocity in brass is 4.40 km/s (longitudinal) and that in steel is 5.90 km/s (longitudinal). Hence the same scale is useful for testing of steel taking 0.745 as a multiplying factor for scale reading.

The test block made of steel with an artificial flaw created in it by making hole, is tested with this system. The presence of lfaw is indicated by the flaw echo as shown in photographs P8 and P 9. The flaw echo is distinct from the backwall echo as is seen from the photographs. The calibration of the scale is also verified from this test specimen.

The same system can be used for testing materials like Aluminium, copper, lead, etc conveniently. The scale factor will change for each case. Table V shows the acoustic data for these materials (including acoustic velocity).

TABLE V

ACOUSTIC VELOCITIES OF MATERIALS

Material	Acoustic Velocities	
	Long. C_l	Transv. C_t
	(Km/s)	(Km/s)
Aluminium	6.32	3.13
Bismuth	2.18	1.10
Brass	4.40	2.20
Cadmium	2.78	1.50
Cast Iron	3.5-5.8	2.2-3.2
Constantan	5.24	2.64
Copper	4.70	2.26
German Silver	4.76	2.16
Gold	3.24	1.20
Iron	5.90	3.23
Lead	2.16	0.70
Magnesium	5.77	3.05
Zinc	4.17	2.41
Tin	3.32	1.67

3.6 TRANSIT-TIME METHOD

Introduction

Basically ultrasonic transit time method is used for wall thickness measurements. The transit time method can be employed in continuous mode as well as in pulsed mode. The fundamental assumption on which ultrasonic transit time method is based is that there is uniform velocity of sound through the entire test piece, i.e. it is an isotropic material. In addition to this, the path of sound should be at right angles to the surfaces of the test piece.

Principally measurement of a given wall thickness is based on the transit-time, t. The velocity being known, this then furnishes the thickness.

$d = ct$

where c → known quantity

therefore if t is known then

d can be easily calculated.

In transit time method using pulse technique, pulse is passed through the test piece through transmitting probe. At the other end of the test piece the pulse is received by another probe called receiving probe. The time interval between these two events will give t. When the two ends of test piece are not accessible the same function can be done by one probe. But in this case the time interval between the transmitted and received signal will be equal to 2t. Since it is exclusively the transit time which is of interest, the presentation of the echoes on the image screen and their further informative content is omitted. Thus the main emphasis in the transit-time measurement using pulse technique is on the start of the transmitting pulse and the start of the receiving pulse. The former is used as a start and later as stop signal for measurement of time. It involves the transformation of the time into an electric quantity which can be processed readily.

The transit time measurement can be done by two ways:

1) Analog Measurement
2) Digital Measurement.

1) Analog Measurement: Analog measurement generates a ramp voltage corresponding to the start and stop signals and feeds it to the meter to be displayed. This is also called integration method.

2) Digital Measurement: Digital measurement is entirely different from analog measurement, and the same has been designed and developed.

Fig. 3.12 illustrates the principle of digital transit time measurement technique.

The initial pulse, i.e. a start pulse opens an electronic gate and the received signal, i.e. stop signal closes the gate. Hence the output of the gate is a pulse having a duration corresponding to the duration between the start and stop pulses. A precision oscillator feeds through another gate to a counter which counts the number of oscillation cycles reaching it through the open gate. Suppose the time interval is 100 us. This corresponds to

$$x = vt = [5.9 \times 10^5 \text{ cm/sec}] \; (100)(10^{-6})\text{sec}]$$
$$= 59 \text{ cms.}$$

where Sonic velocity for steel is used.

In the case of single probe operation the distance will be equal to 29.5 cms. The reading of the counter can be expressed in digital form if it is necessary to feed a computer or digital servo. The accuracy of digital method increases as the clock frequency increases.

3.7 BLOCK DIAGRAM AND WORKING

Figure 3.13 is the block diagram showing the Electronic transit time measurement system. It can also be called as the ultrasonic thickness gauge.

The clock provides trigger pulses to the transmitter which excites the transmitting transducer to generate ultrasonic vibrations. These vibrations pass through the test piece and the receiving probe collects them. These small signals are amplified by amplifier no.1 and given to demodulator circuit. The demodulator is employed to obtain steep front edge which is of interest. All the high frequency nodes are suppressed and clear envelope is obtained by using demodulator. The demodulated output is onee again amplified and given to the schmitt trigger. The schmitt trigger gives the square pulses with their front edges corresponding to the start of the received pulse. The schmitt trigger output and the output of clock is given to Gate No. 1 to obtain the square pulses corresponding to the time interval between transmitted and received pulses. A precision clock provides the known time base for period measurement. The output of precision clock and that of Gate No.1 is given to Gate No. 2 which allows the clock pulses to pass through it for a specific time, which ultimetly drives the decade counter, latch and display assembly. The reset pulse to the counter is provided from clock and the latch enable pulse from the schmitt trigger. The display is obtained in number of pulses, corresponding to the thickness of the test piece.

3.8 DESIGN OF FUNCTIONAL BLOCKS

Function blocks are designed as follows:

3.8.1 Clock:

It is a pulse generator used in pulse echo system. In transit time method the pulse repetition frequency is not the criterion for the design of the clock. The pulse repetition frequency, however is not kept comparable with the frequency of the probe because in this case the successive pulses will interefere with each other. Also the reactance of the dischange capacitor will be significant at such a high frequency. Hence the supply voltage required will be very large. In the developed system the clock is designed by using IC 555 in astable mode.

3.8.2 Transmitter Unit

The design of Transmitter unit for this method is similar to that for pulse-echo system.

3.8.3 RF Amplifier:

RF amplifier used in the transit- time method is IC LF356. The swept gain control is not needed in this method. The gain of RF amplifier can be varied by using a potentiometer in the feedback path of an amplifier. Here fixed gain is employed.

3.8.4 Demodulator and Suppression ckt:

Diode demodulator circuit used in pulse-echo system gives very good response in this method also.

3.8.5 Schmitt Trigger

The schmitt trigger is used to obtain square pulses corresponding to the pulses received by the receiving probe. The schmitt trigger circuit used is as shown in Fig. 3.14.

The schmitt trigger gives square pulse which starts at the instant when the input arrives.

3.8.6 Gate no.1:

The Gate no.1 is an exclusive OR Gate which gives the pulses corresponding to the time delay between the transmitted and received pulses. The waveforms shown in Fig. 3.15 illustrates the logic operation of EX-OR gate. Here quad two input EX-OR gate 7486 is used.

3.8.7 Precision Clock

A 7404 hex-inverter is used to construct a precision. TTL compatible quartz crystal clock, as shown in Fig. 3.16.

Two inverters are used to construct two-stage amplifier with an overall phase shift of 360° between pin 1 and pin 6. Then a portion of the signal at pin 6 is fed back by means of a crystal to pin 1, and the circuit oscillates at a frequency determined by the crystal. Frequency oscillations is very stable. Here the clock frequency used is 10 MHz.

3.8.8. Gate no.2

It is an AND gate. Here 7408 quad two input AND gate is used. It controls the flow of pulses into the counter.

3.8.9 Decade Counting Assembly [9]

It is a combination of five decade counters. Each of the decade counter has four binary outputs corresponding to 2^0, 2^1,2^2 and 2^3. The output pulse corresponding to every ten input pulses is fed to the input of next decade counter. 7490 is TTL BCD counter which has a maximum input frequency of 18 MHz. These counters are used here. The decade counting assembly outputs are fed to the latches. The reset pulse to the counter is obtained by inverting the clock pulses using 7404 hex inverter.

3.8.10 Latches [9]

A latch isolates the display device from the counting circuit while counting is in progress. At the end of counting time, a latch enable pulse causes the display to change to the decimal equivalent of the final condition of the counting circuit. Here the count is held by enabling the latches at the instant when the receiving probe receives the transmitted pulse. At this instant, the counters are turned off. TTL 7475 is a 4-bit latch used here for each counter.

3.8.11 Decoders/Drivers [9]

The output from latches are given to decoders/drivers. TTL 7447 BCD to 7-segment decoder/driver is used for each counter here. It accepts 4-bit binary-coded-decimal and depending on the state of the auxillary inputs, decodes this data to drive a 7-segment display indicator. 7447 is used with LED displays and hence current limiting resistors in each of lines are incorporated (270 ohms for each line). The decoder sinks the display unit currents.

3.8.12 Display unit

The display unit consists of five common anode type MAN72 LED display. Each of the seven segment is connected to the corresponding point in the LED decoder/driver unit through 270 ohms resistance, which limits the current. The display is obtained in decimal digits. Complete circuit diagram of the system is shown in Fig. 3.17 and Fig. 3.18.

3.9 TEST RESULTS FOR TRANSIT-TIME SYSTEM

Designed and developed transit-time thickness measurement system has been tested on test specimen. Firstly a brass bar measuring 108 cms is tested for its length. The clock pulses are of frequency 555 Hz, as shown in photograph P11.

The transmitter circuit excites the transmitting probe by short duration pulses of 100 us as shown in photograph P12. The received signal is shown in photograph P13. Its amplified picture is as shown in photograph P14. The demodulated output is shown in photograph P15. A clear envelope is obtained when it is amplified. It can be seen from photograph P 16. The demodulated output is having a peak of 10 volts. This is a sufficient amplification. Photograph P 17 shows how the schemitt Trigger generates pulses at the arrival of received signal. It further shows that there is no delay between the received pulse and the pulse of Schmitt Trigger. The duration of the pulse is 1.2 ms. The output from the precision clock is shown in photograph P 18. For 10 MHz clock, each pulse will be of 0.1 us. For the brass rod of 108 cms,

$$c = \frac{d}{t}$$

$$4.40\times10^{3} = \frac{108 \times 10^{-2}}{t}$$

$$\therefore t = \frac{108\times10^{-2}}{4.40\times10^{3}}$$

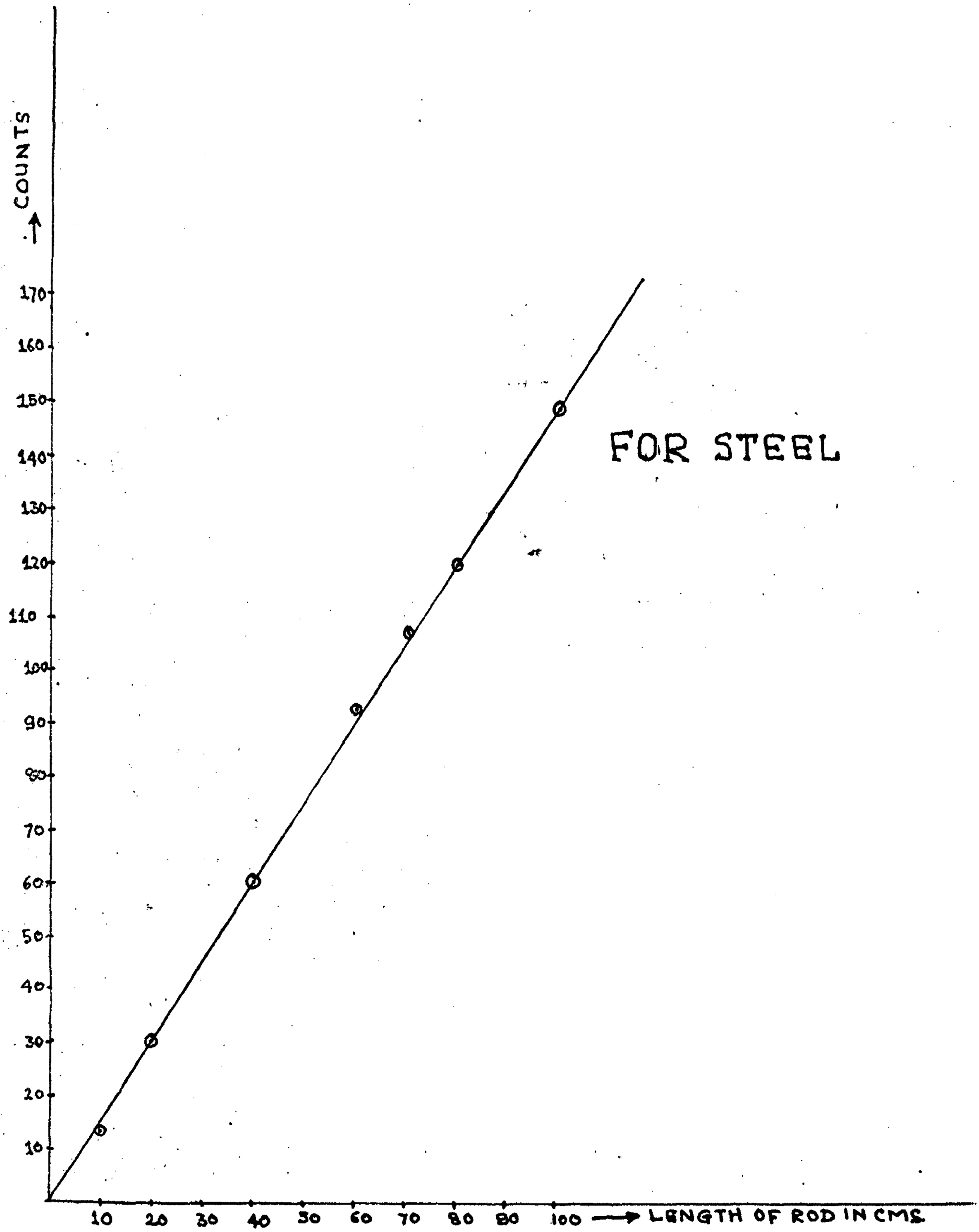
$$= 245.4 \text{ us.}$$

Thus the delay between the transmitted and the received pulses is of 245.5 us. Photograph P 19 shows the delay for the brass rod. It is 290 us. The error between the experimental and theoretical value is due to the fact that the acoustic velocity for the brass material which has been taken for calculation is a typical one for 70:30 composition. But the ultrasonic velocity for almost any material varies considerably depending upon the treatment the material has undergone and also on the composition of the material [10, 7]. Slight change in these factors lead to change in acoustic velocity.

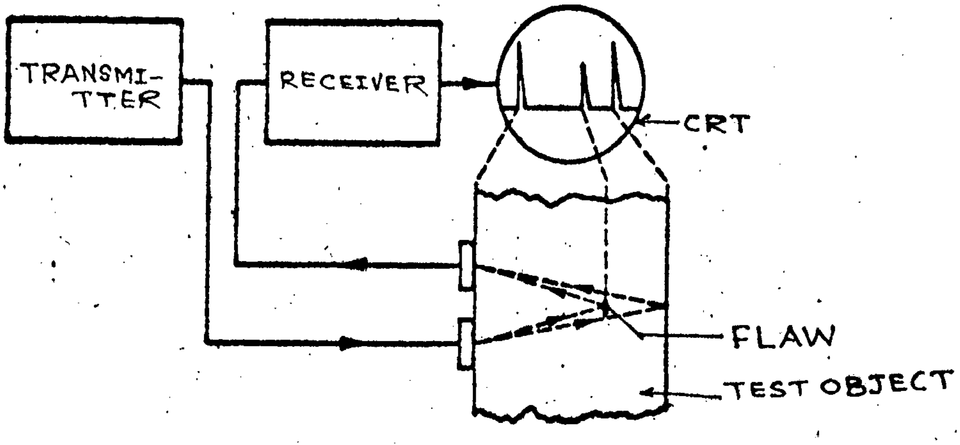
The display indicates the number of pulses passed through a period of 290 us. Thus the unknown distance can be easily obtained if the ultrasonic velocity for a particular material chosen is known.

The system has been further tested by using two rods of steel of different thicknesses. The waveforms obtained for these are shown in Photographs P20, P21, P22, P23,P24, P25, P26, P27. Photograph P 25 shows the display obtained for one such case of 26.8 us delay. The display gives value 268.

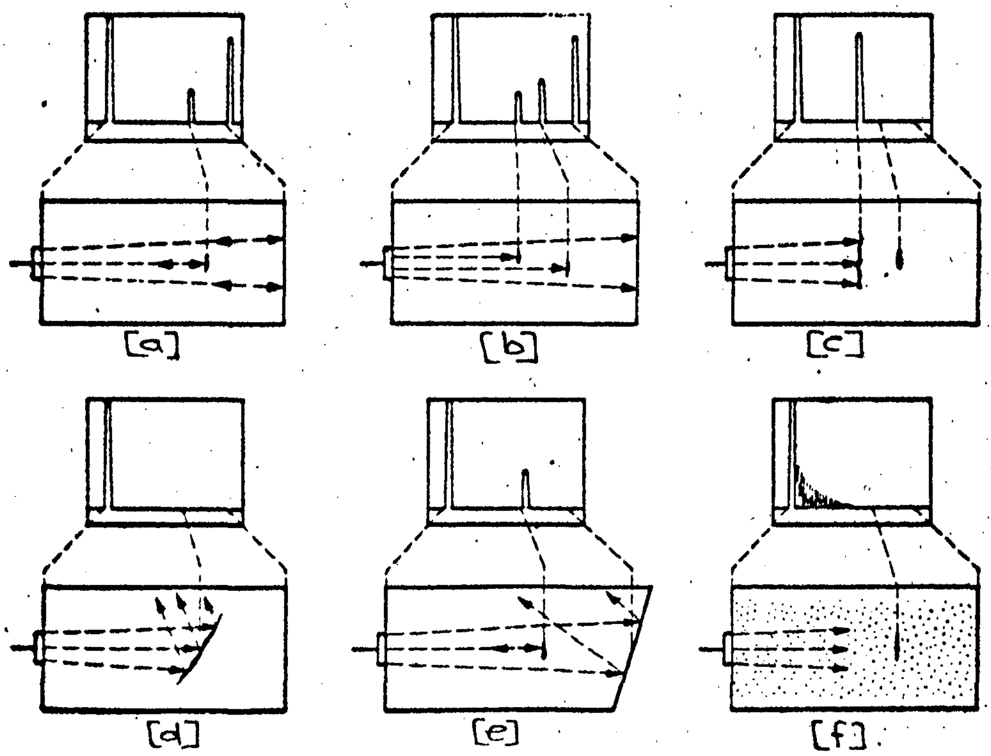
Steel rods of different lengths are tested on this system and the curve is plotted between the length and the number of counts corresponding to the delay. The curve shows the linear relationship between these two quantities. The calibration curve thus obtained can be used for directly getting the length of unknown rod of steel when number of counts shown by display are known, such curves can also be calibrated for rods of different materials.



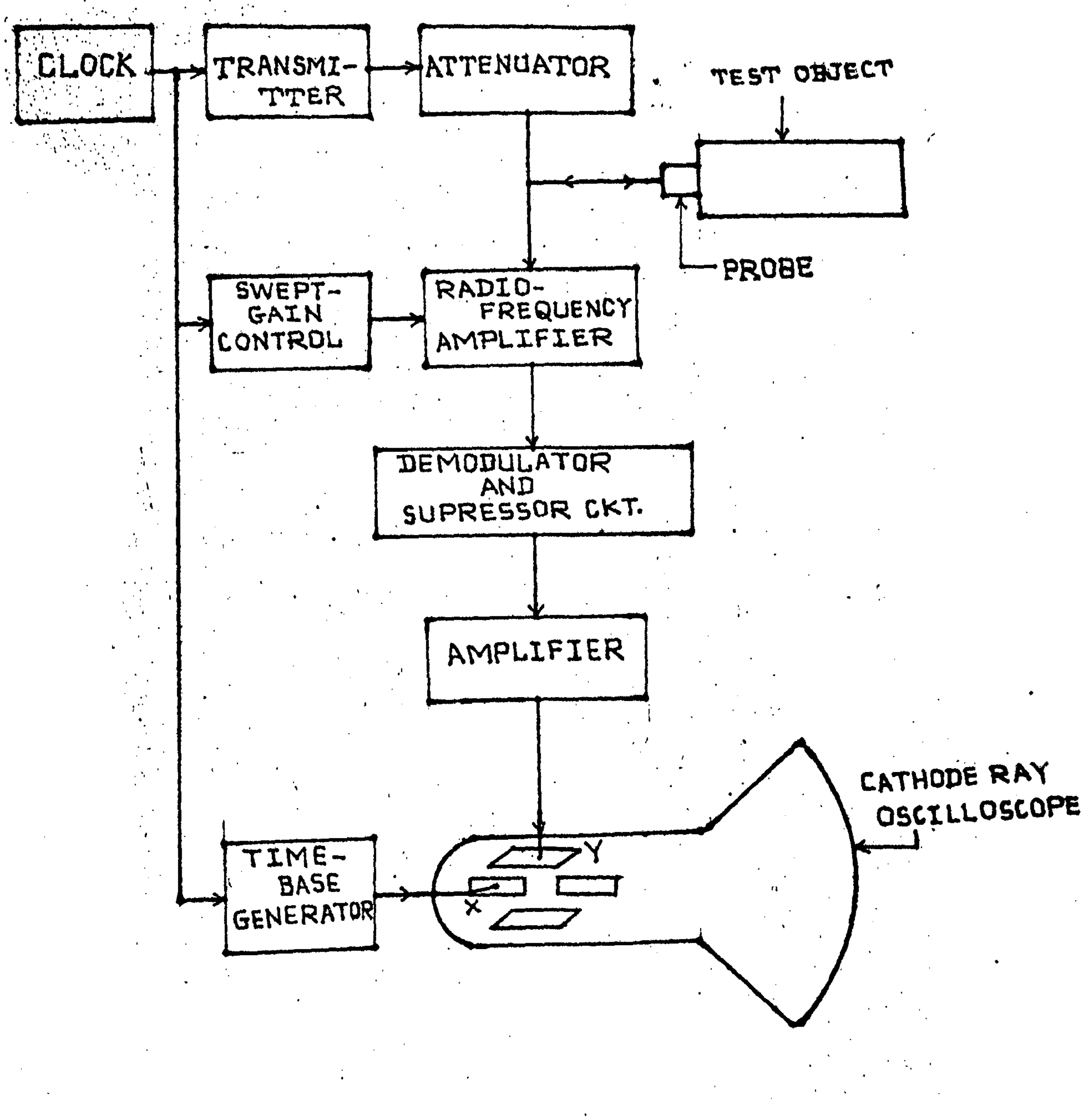
CALIBRATION CURVE



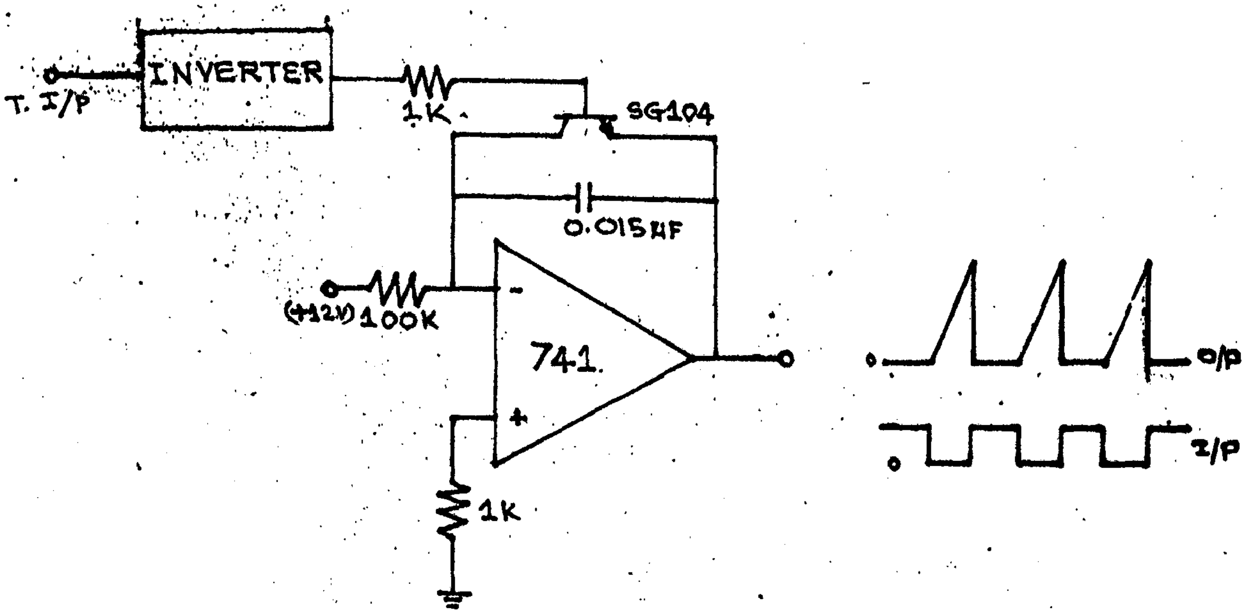
3.1 BASIC PULSE-ECHO METHOD



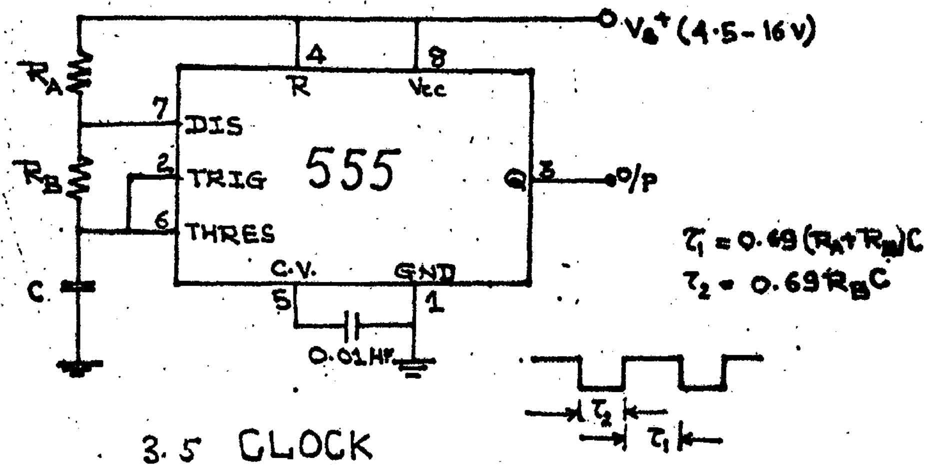
3.2 SCHEMATIC SCREEN PICTURES OF PULSE-ECHO METHOD



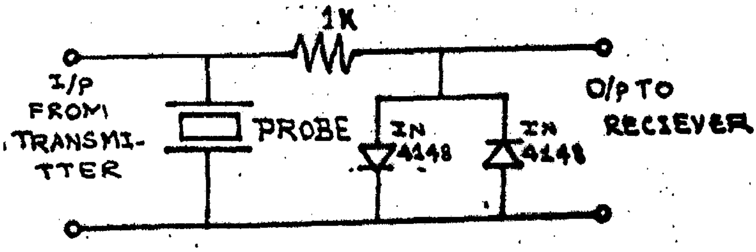
3.3 PULSE-ECHO SYSTEM.



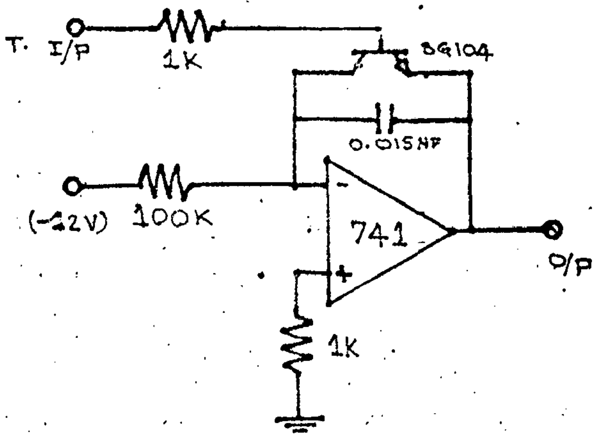
3.4 TIME BASE GENERATOR



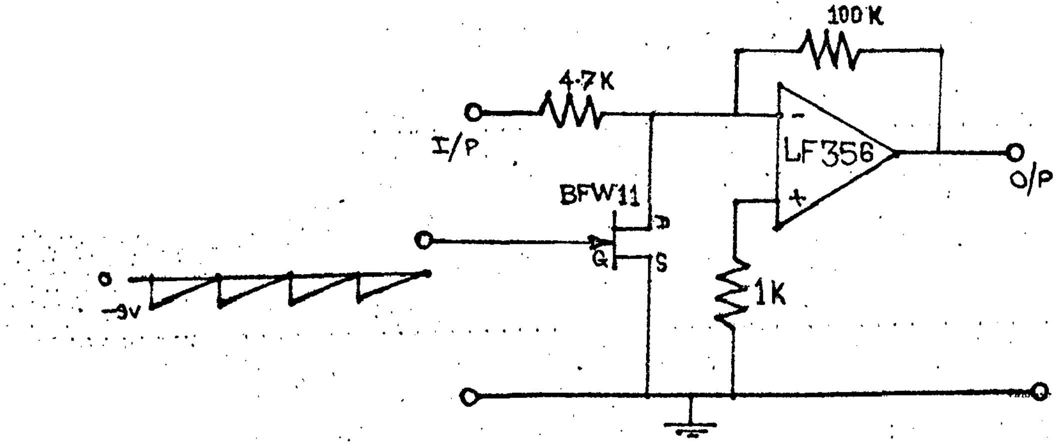
3.5 CLOCK



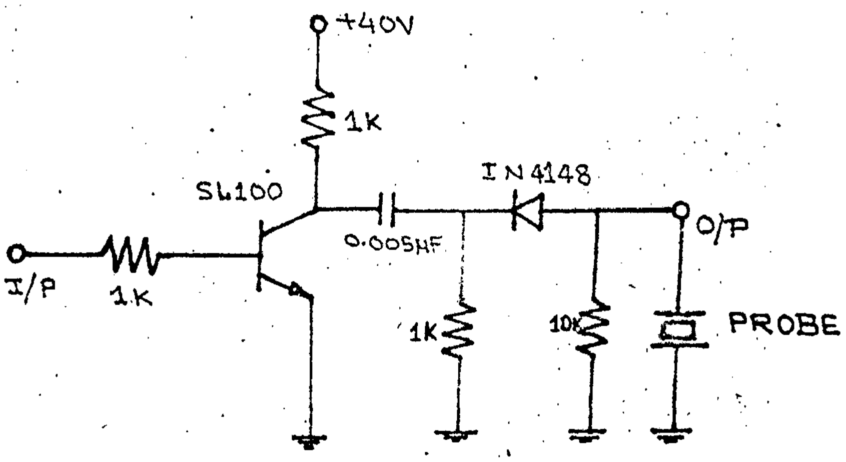
3.6 PROTECTION CKT.



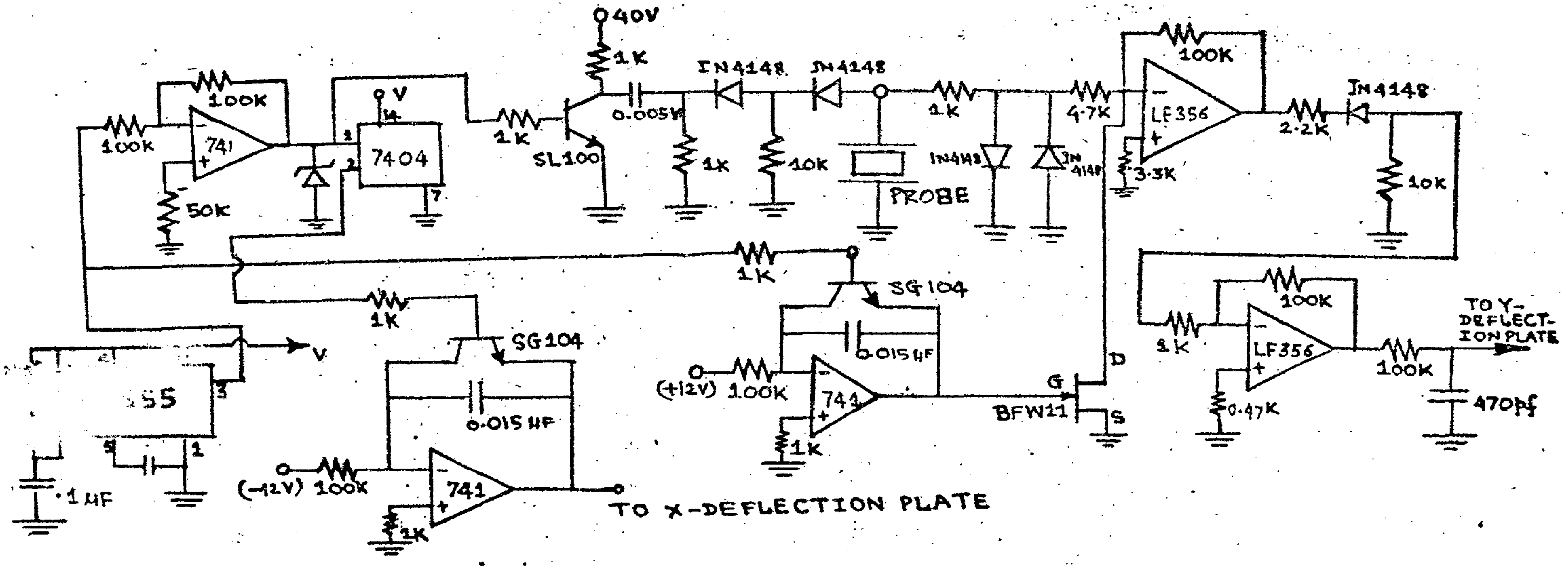
3·7 CKT. TO CONTROL 'SWEPT GAIN'



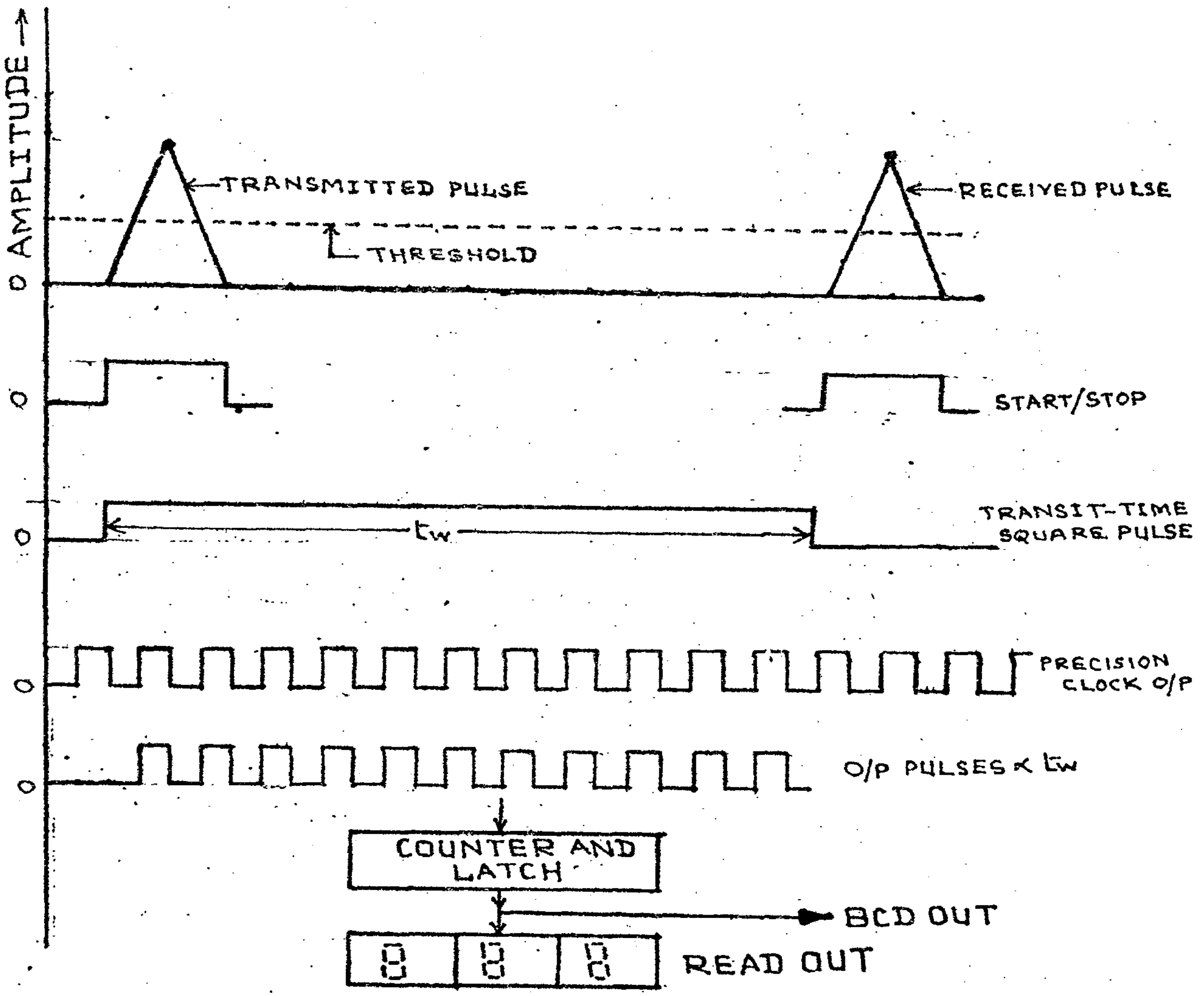
3.8 SWEPT GAIN CONTROL



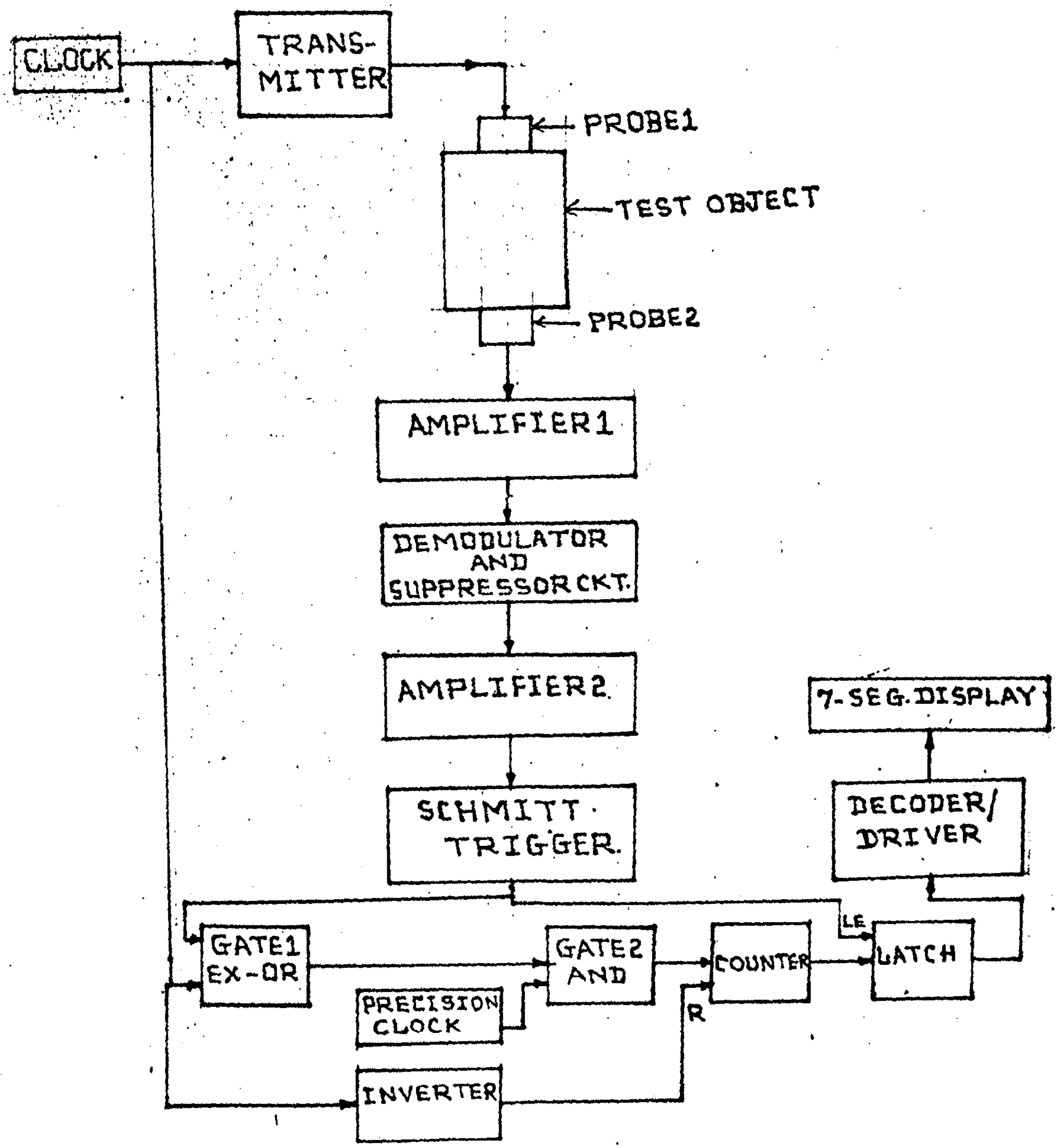
3.9 TRANSMITTER



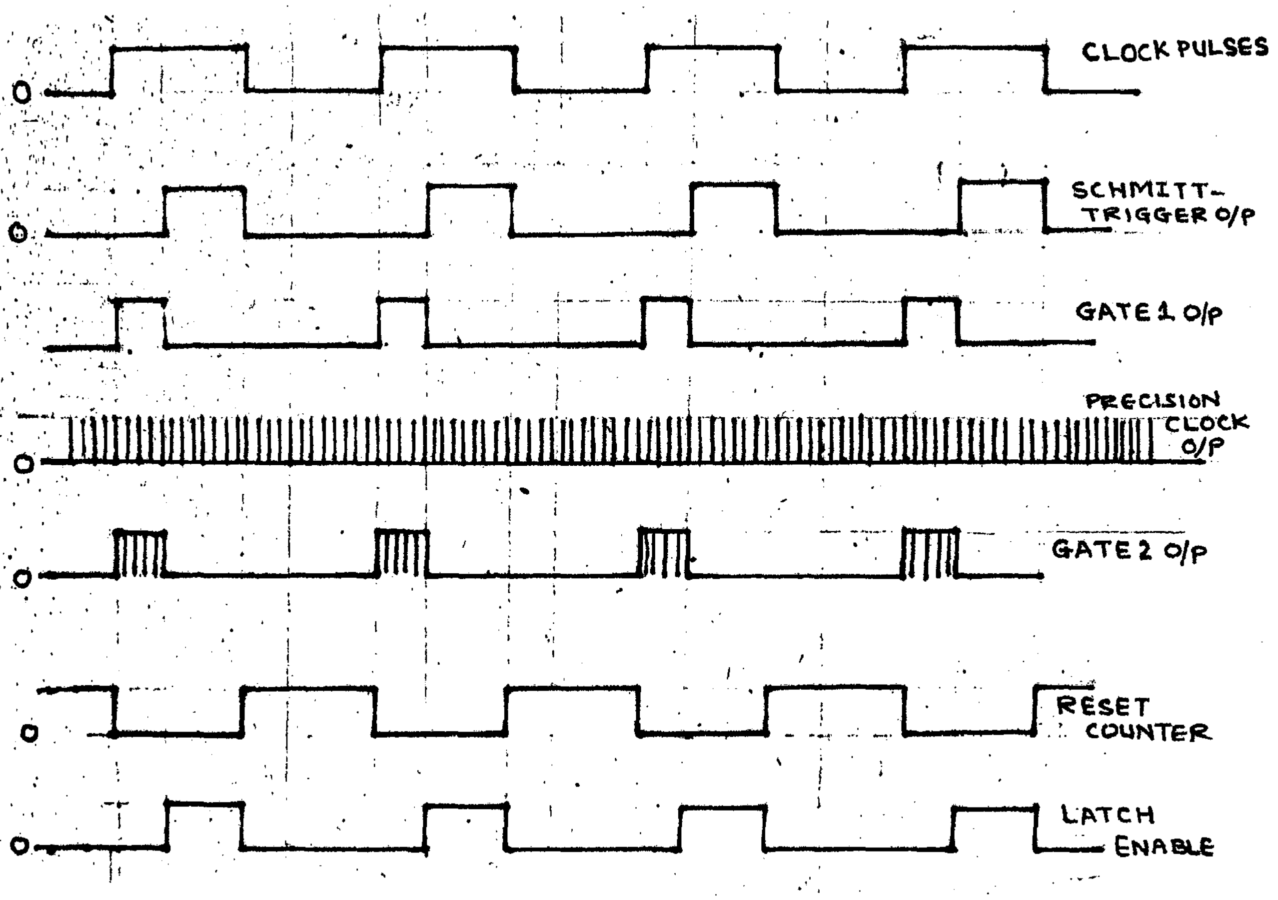
3.11 COMPLETE SCHEME OF PULSE-ECHO SYSTEM



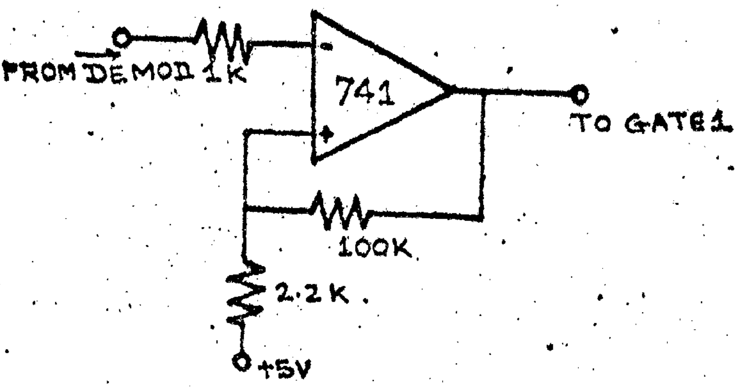
3.12 DIGITAL TRANSIT-TIME MEASUREMENT



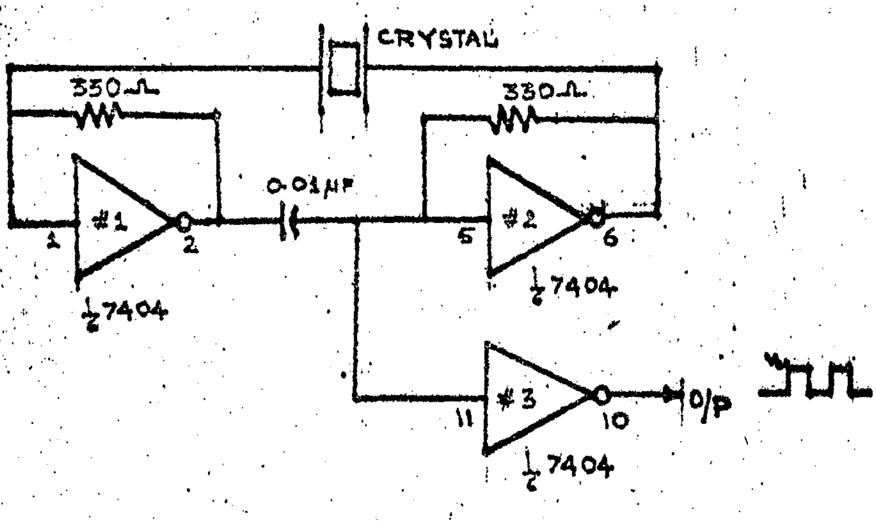
3.13 TRANSIT-TIME THICKNESS-GUAGE.



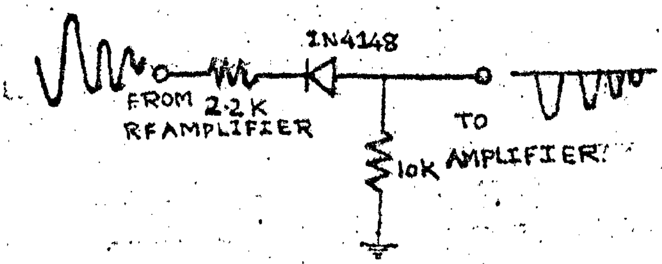
3.15 TIMING DIAGRAMS.



3.14 SCHMITT TRIGGER

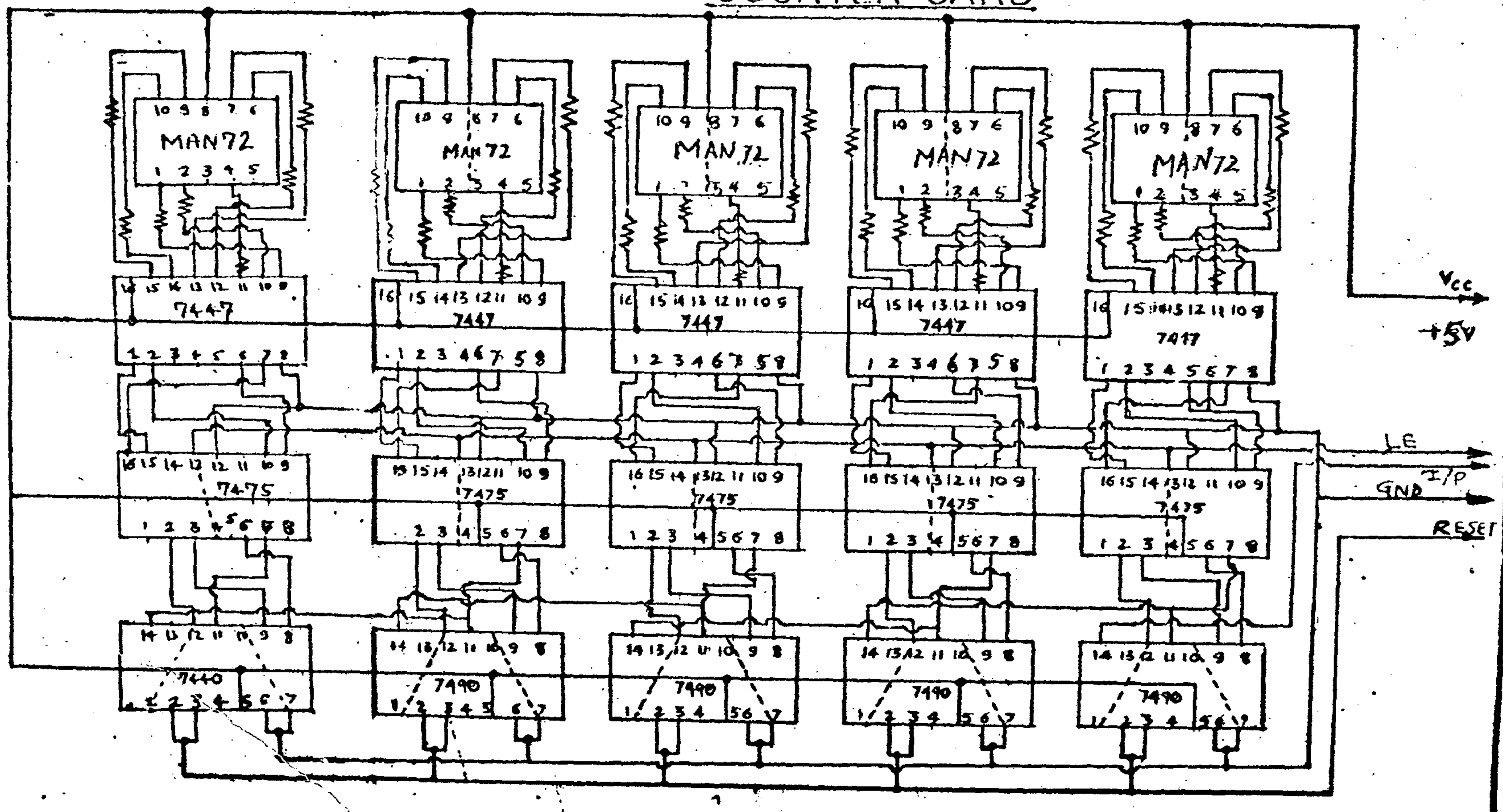


3.16 PRECISION CLOCK

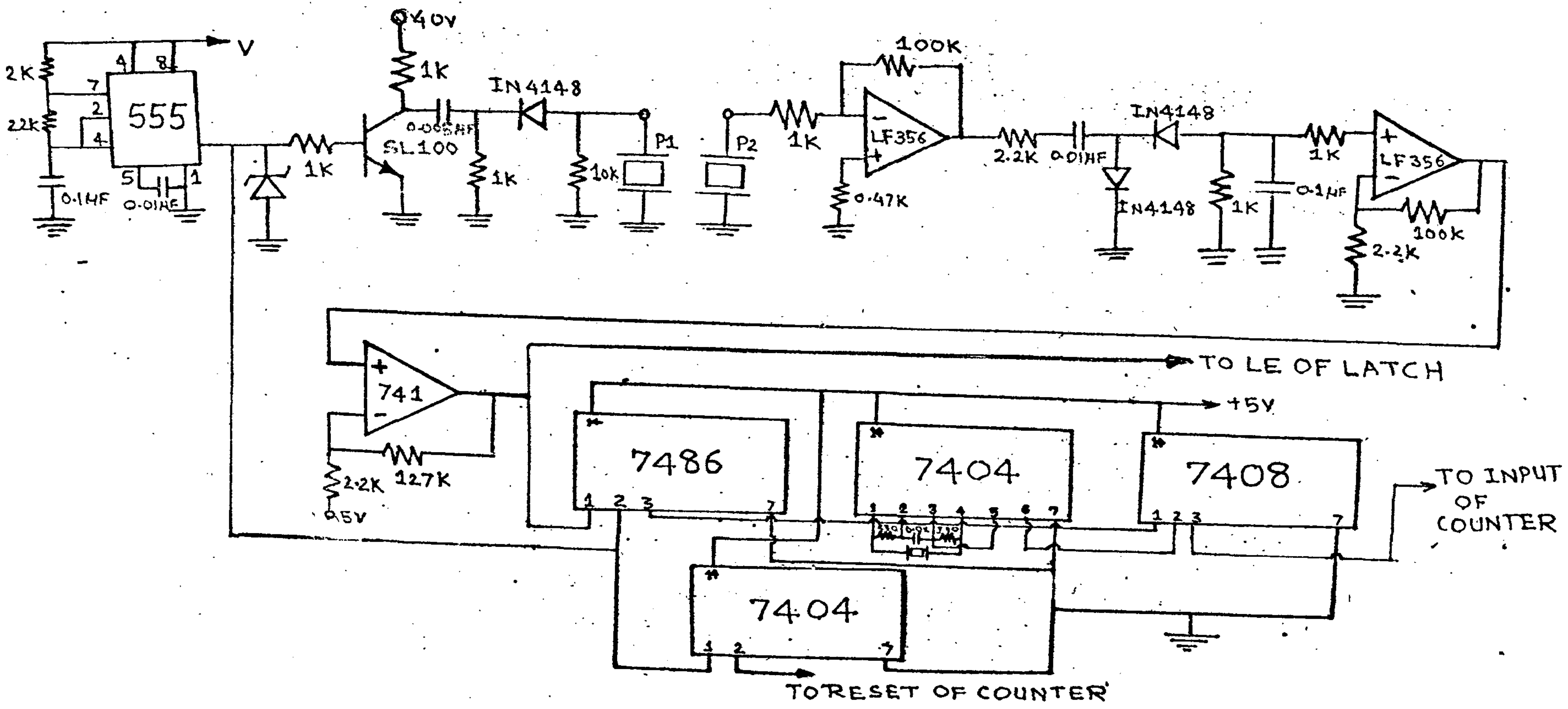


3.10 DEMODULATOR

3.18 COUNTER CARD



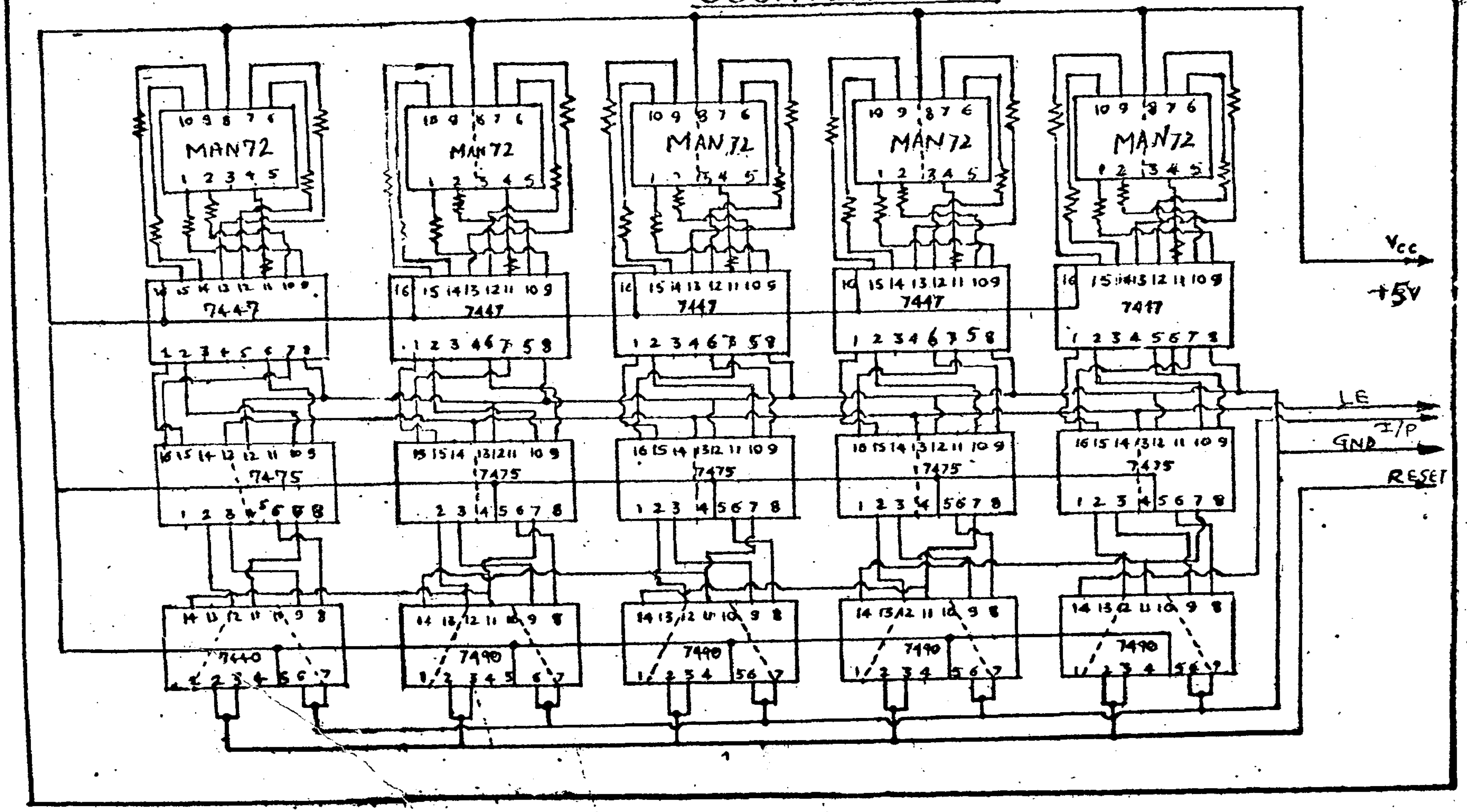
ALL RESISTENCES = 270Ω

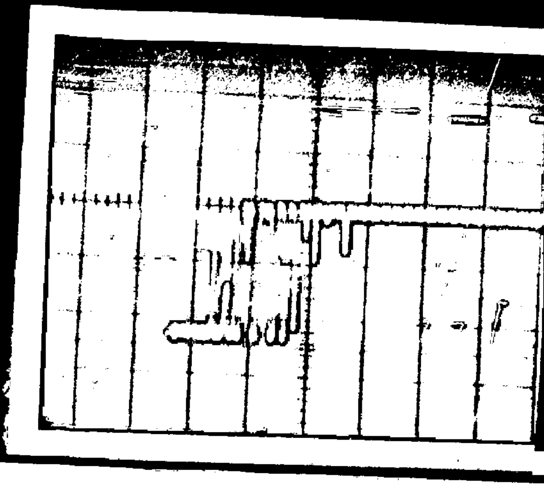


3.17 SCHEME OF TRANSIT-TIME THICKNESS GAUGE

3.18 COUNTER CARD

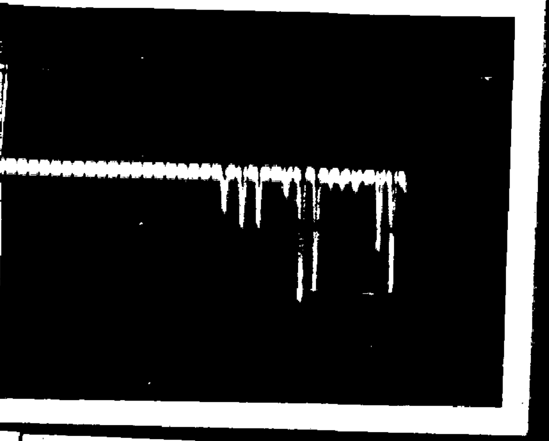
ALL RESISTENCES = 270Ω





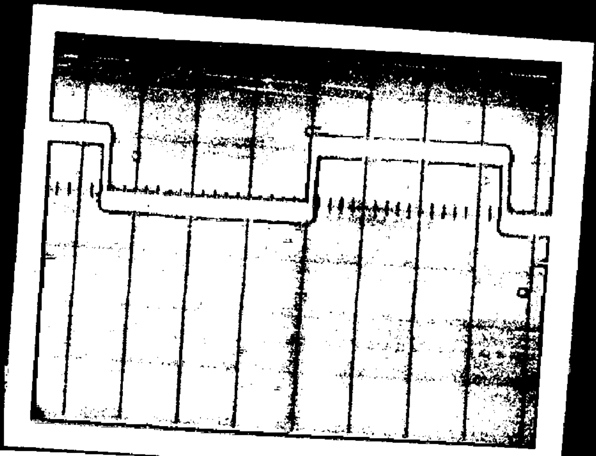
P1: Transmitted signal to brass bar (108 cm)

Scale: X axis - EXT
Y axis - 5v/Div.



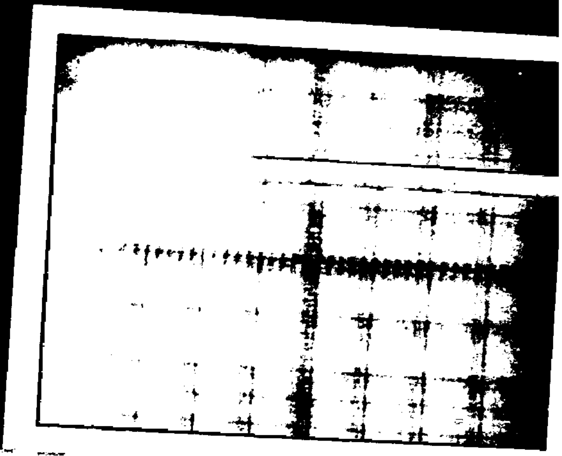
P2: Backwall echo for a brass bar (108 cm)

Scale: X axis - EXT
Y axis - 0.5 v/Div.



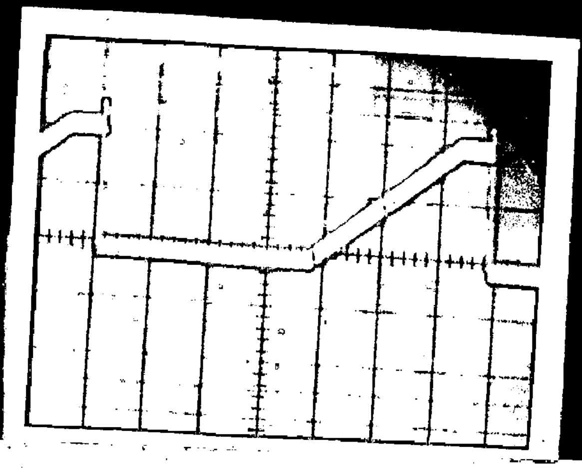
P3 : Clock signal with PRF = 285.7 Hz

Scale : X axis - 500 us/Div
Y axis - 5V/Div



P5 : Short duration pulses from transmitter (with probe not connected)

Scale : X axis - EXT
Y axis - 20 v/Div.

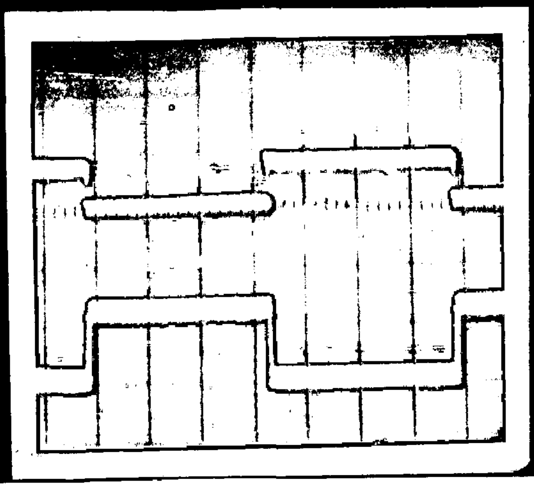


P4 : Input to X plate of CRO

Scale: X axis - 500 us/Div
Y axis - 5v/Div.

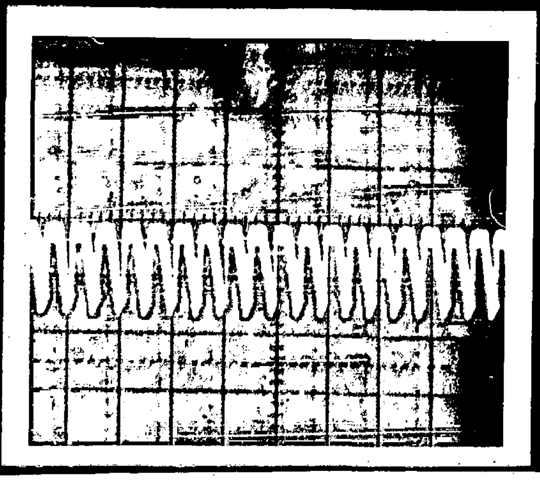
P6 : Signal transmitted via probe.

Scale: X axis - EXT
Y axis - 10v/Div.



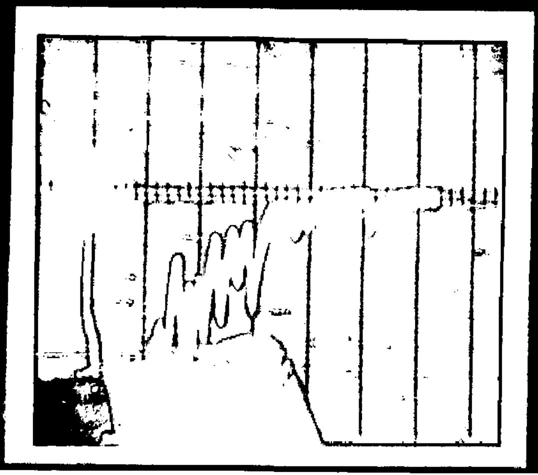
P7: Clock signal and its inverted output

Scale: X axis - 500 us/Div
Y1 axis- 5 v/Div.
Y2 axis- 0.5 v/div.



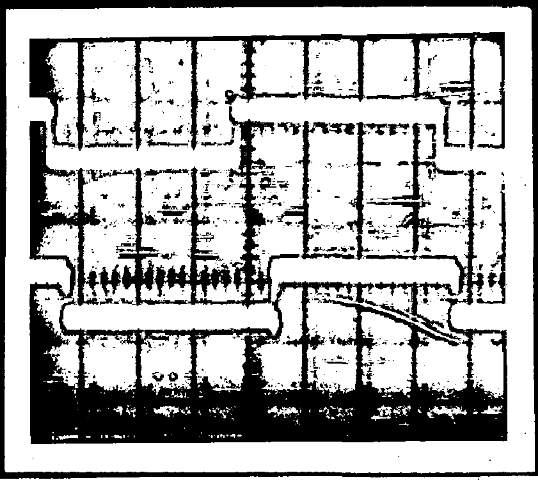
P10: Swept gain control signal for the system

Scale: X axis - 10 ms/Div.
Y axis - 5v/Div.



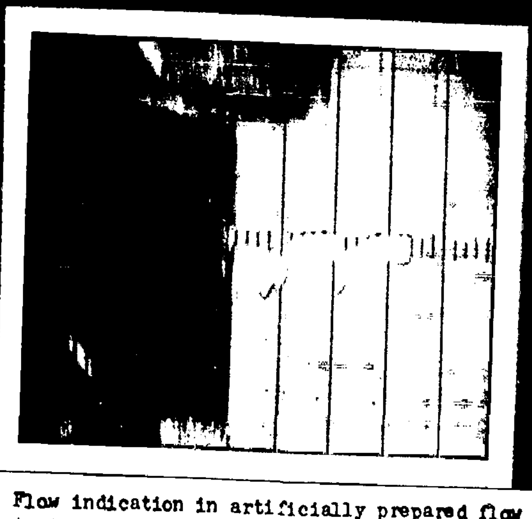
P9: Flow indication in artifically prepared flaw in test piece(flaw echo & backwall echo visible)

Scale: X axis - EXT
Y axis - 0.5v/Div.



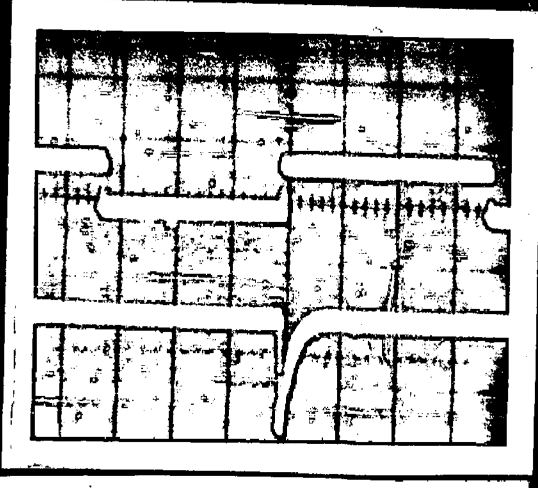
P11 : Trigger signal and schmitt Trigger output (for 108 cm brass bar)

Scale : X axis - 500 us/Div.
Y1,Y2 - 5v/Div.



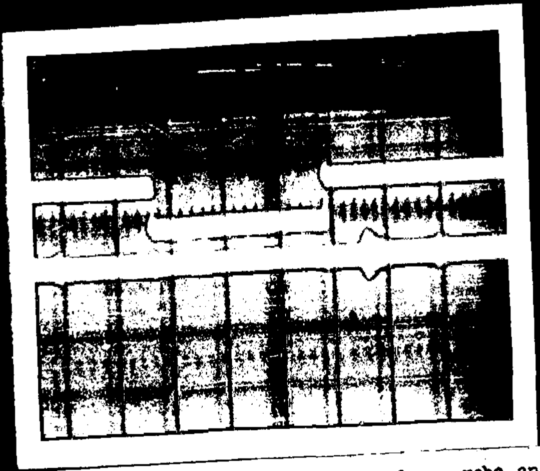
P8 : Flaw indication in artificially prepared flaw in test piece indicating transmitted signal alongwith backwall and flaw echoes.

Scale: X axis - EXT
Y axis - 0.5 v/Div.



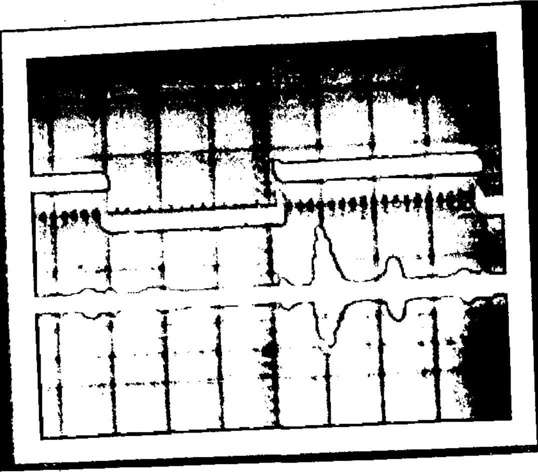
P12 : Transmitted signal to probe

Scale: X axis - 500 u s/Div.
Y1 axis -5v/Div.
Y2 axis -20 v/Div.



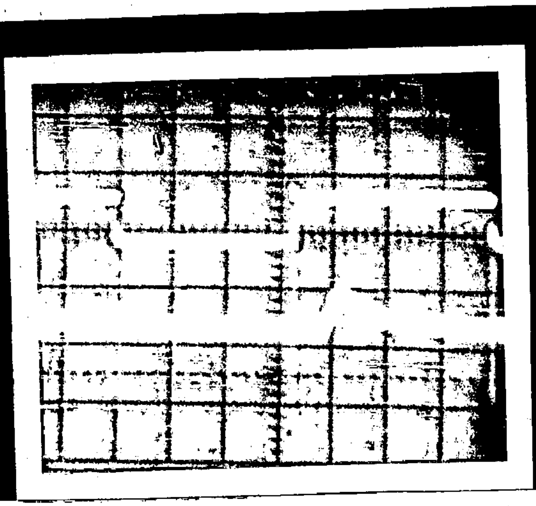
P13 : Received (unamflied) signal from probe and trigger signal

Scale: X axis - 500 us/Div.
Y1 axis -5v/Div.
Y2 axis -0.5v/Div.



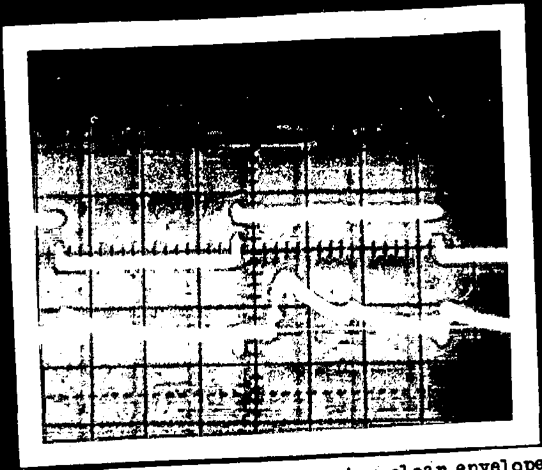
P14 : Amplified signal of P13 alongwith transmitted signal

Scale: X axis - 500 us/Div.
Y1 axis- 5 v/Div.
Y2 axis- 10 v/Div.



P15 : Demodulated signal alongwith trigger signal

Scale: X axis - 500 us/Div.
Y1 axis- 5v/Div.
Y2 axis- 0.2 v/Div.

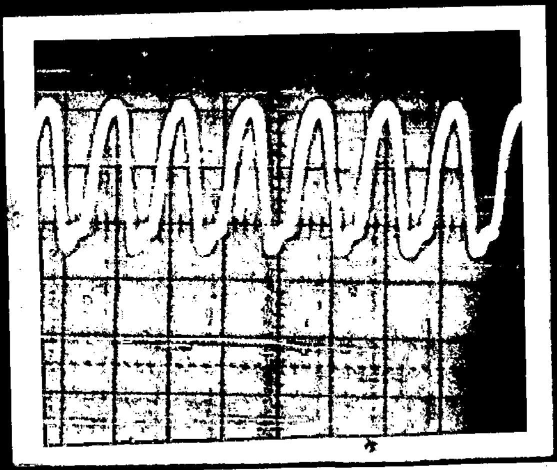


P16 : Demodulated signal showing clear envelope

Scale: X axis - 500 us/Div.
Y1 axis- 5v/Div.
Y2 axis- 10 v/Div.

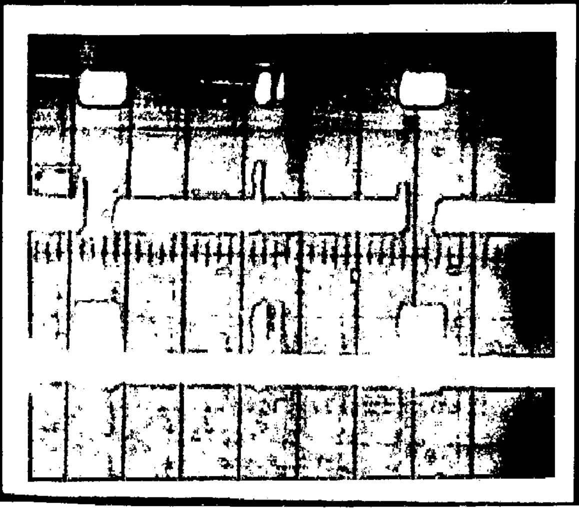
P17 : Output of Schmitt Trigger and demodulator

Scale: X axis - 500 us/Div.
Y1 axis- 5v/Div.
Y2 axis -10 v/Div.



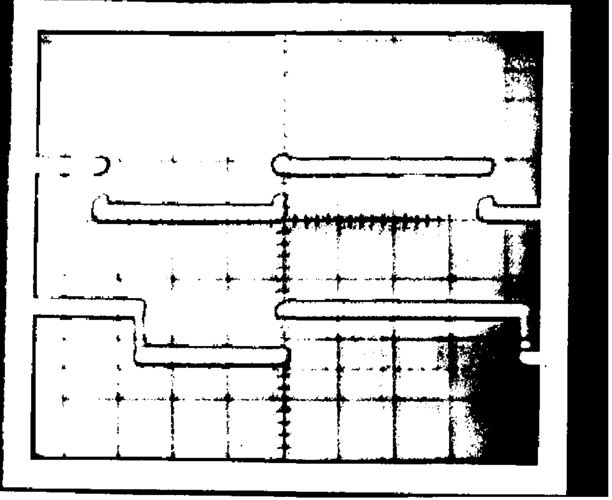
P18 : Output of a 4 MHz clock

Scale X axis - 0.2 us/Div.
Y1 axis - 2v/Div.



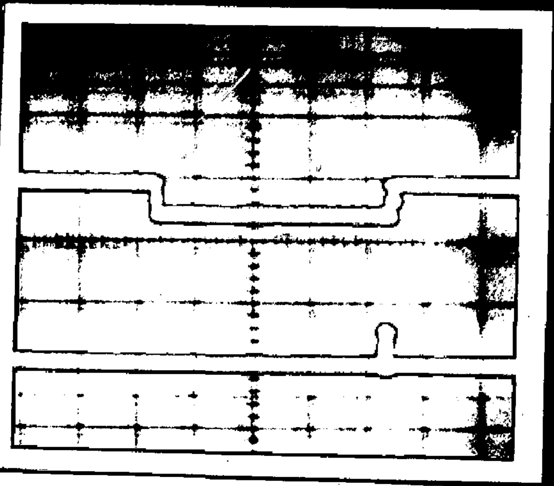
P19 : Output of EX-OR gate and the clock for brass rod (108 cm)

Scale X axis - 500us/Div.
Y1, Y2 axis - 5v/Div.



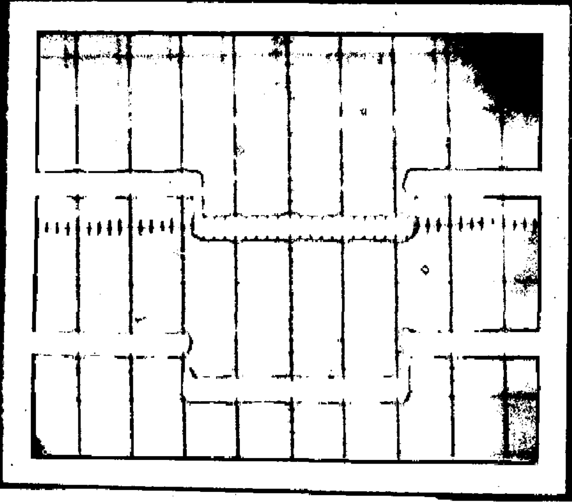
P22 : Output of Schmitt Trigger and the trigger signal for steel rod of 2.1 cm.

Scale : X axis - 500 us/Div.
Y1,Y2 axis - 5v/Div.

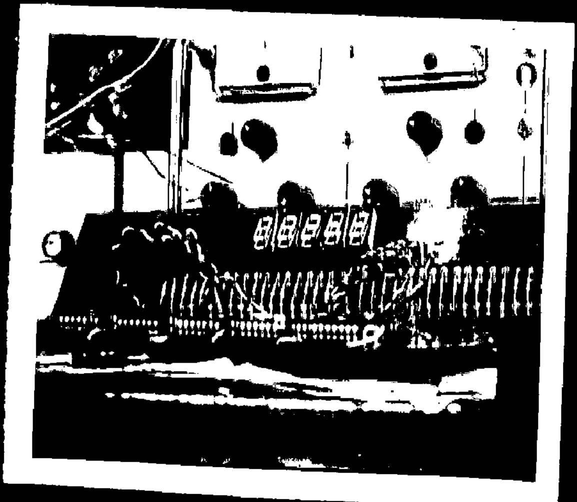


P20 : Output of the Schmitt Trigger and AND Gate

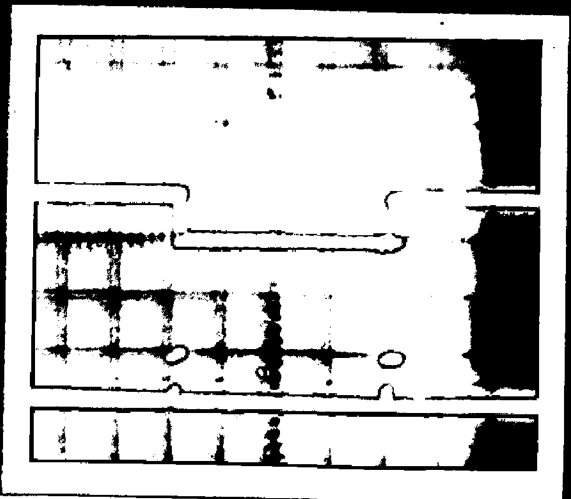
Scale : X axis - 1000 us/Div.
Y1,Y2 axis - 5v/Div.



P23 : Output of schmitt trigger and the Trigger signal f a rod of steel 10.8 cm Scale - X axis: 200 us/Div.
Y1, Y2 axis - 5V/Div.

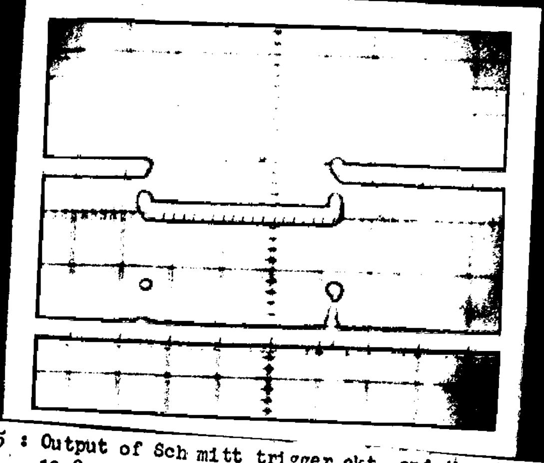


P21 : Display unit

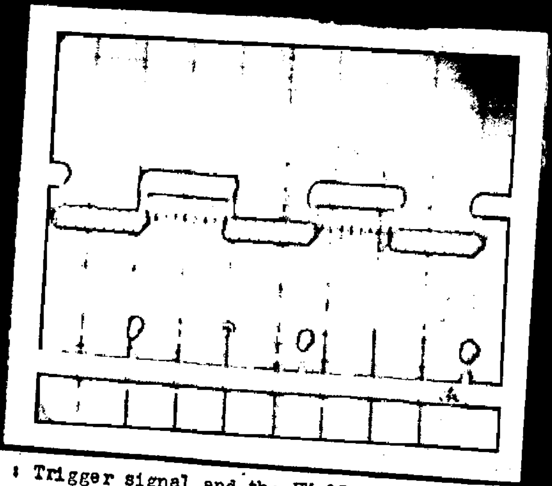


P24 : Trigger signal and the EX-OR gate output for steel rod of 10.8 cm.

Scale: X axis - 500 us/Div.
Y1, Y2 axis - 5V/Div



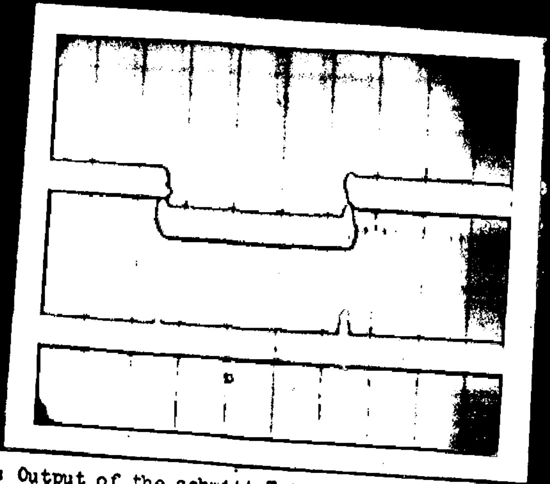
P25 : Output of Sch mitt trigger ckt. and the Ex-OR gate for 10.8 cm steel rod-scale as in P24



P26 : Trigger signal and the EX-OR gate output for a rod of steel 2.1 cms.

Scale - X axis : 200 us/Div.
Y1,Y2 axis- 5V/Div.

P28 : Complete experimental set up.



P27 : Output of the schmitt Trigger and the AND gate for a rod of steel 2.1 cm.

Scale -Xaxis - 200 us/Div.
Y1,Y2 axis - 5v/div.

CHAPTER - 4

CONCLUSIONS AND DISCUSSIONS

The basic purpose to develop ultrasonic pulse-echo system and ultrasonic transit time thickness gauge is to make an effort to explore the diagnostic area of ultrasonics in industrial non-destructive testing applications. Two instrumentation schemes have been designed, developed and tested by the author.

The developed pulse-echo system is more versatile than previously available systems. The use of transisters, printed circuits and integrated circuits have improved the sensitivity and resolving power of ultrasonic pulse-echo system. In the developed system, the voltage level required for deep penetration is much less than any other pulse-echo system. This allows the examination of extremely thick sections. Besides this the problems arising out of high voltage level have been completely removed. Suggested scheme has inbuilt depth compensation. It compensates the drop in sensitivity with increasing distance due to attenuation in the material and the beam spread. Hence the echo height obtained is larger which is found suitable for further data processing. Selection of the amplifiers of proper band width has reduced the noise problems. Higher sensitivity permits detection of minute defects. The system has faster response and hence rapid inspection is possible. It uses only single probe operation and hence additional cost of using another probe is saved or complexity involved in using transmitter-receiver probe assembly is not involved. The system is compact, light and it has more reliability.

An ultrasonic pulse transit-time thickness gauge has also been developed. The digital indication in this system improves readability. The conversion of transit-time into BCD form facilitates further extension of the scheme for process control purposes. It has an accuracy of 0.001 inch and good repeatability. The incorporated counting method eliminates the error arising out of additional time constants encountered in the integration method. The system has high speed of response. It can even be operated on battery and is portable. It is, therefore, convenient for field testing. Further, due to operational simplicity it can be handled by unskilled worker also. It is capable of accepting wide variety of probes for every kind of measuring situation one is likely to encounter.

Both these instrumentation systems thus developed are economical and amenable for large scale production.

Test conditions which may limit the application of ultrasonic systems thus developed usually relate to one of the following facts.

1. Unfavourable sample geometry,for example, size, contour, complexity and defect orientation.
2. Undesirable internal structure, for example, grain size, structure porosity,inclusion content, or fine, dispersed precipitates.
3. Coupling and scanning problems.

SCOPE FOR FUTURE WORK

In the present work on pulse-echo system stress has been given to developed A -Scan visual display. However for rapid and continuous testing in factories, processing of the test data in the form of digital signal is desirable and necessary for most documentation purposes. Hence there is a scope to develop auxillary system for electronic data processing.

Microprocessor based data aquisition systems for A-scanner as well as for pulse transit-time thickness gauge can also be developed.

REFERENCES

[1] Ensminger D., 'Ultrasonics', Marcel Dekker, INC; New York, 1973.

[2] Frederick J.R., 'Ultrasonic Engineering', John Wiley and Sons, Inc;New York, 1965.

[3] Frock B.G., 'Some Effects of Curved Entry Surfaces on the Calibration of Ultrasonic Systems', Materials Evaluation, Vol. 38, No.4, April 1980, pp. 35-39.

[4] Goldman R.,' Ultrasonic Technology,' Reinhold Publishing Corporation, New York, 1962.

[5] Krautkramer J, and Krautkramev H., 'Ultrasonic Testing of Materials', Springer Verlag Berlin Heidelberg, New York, 1977.

[6] Katsuhiro Kawashima and McClung R.W., 'Electromagnetic Ultrasonic Transducer for Generating and Detecting Longitudinal Waves', Materials Evaluation, Vol.34, No.4, April 1976, pp. 81-82.

[7] LoPilato S.A., 'Will the Real velocity Please Stand UP', Materials Evaluation, Vol. 35, No.8, August 1977. pp. 35-38.

[8] Lynnworth L.C., Patch D.R. and Mellish W.C., 'Impedance Matched Metallurgically sealed Transducers', IEEE Trans. on Sonics and Ultrasonics, vol. SU-31, No.2, March, 1984, pp. 34-37.

[9] Malvino A.P. and Leach D.P., 'Digital Principles and Applications', Tata McGraw-Hill Publishing Company Ltd. New Delhi, 1981.

[10] Mongy M. and Khafagy A.H., 'Abnormal Snock Peak in Steel', Acoustica, Vol. 47, March 1981, pp. 27.

[11] Mukhopadhyay P., 'Special Lectures on Noise in Electrical/Electronic Circuits', Measurement and Instrumentation activity, Department of Electrical Engineering, University of Roorkee, Roorkee, November 1985.

[12] McEnroy J.M., et. al., 'Ultrasonic Properties of Transducer Backing', Ultrasonics, Vol. 22, No.2, March 1984, pp. 57-60.

[13] Okyere J.G and Cousin A.J., 'The Design of a High voltage Pulse Generator for Ultrasonic Pulse-echo Applications', Ultrasonics, Vol.3, No.17, March 1979, pp. 81-84.

[14] Ramanan K.V., 'Functional Electronics', Tata McGraw-Hill Publishing Company Ltd., New Delhi, 1984.

[15] Rao V.V. and Srinivasan T.M., 'Design of Ultrasonic Transducers for Pulse-echo Applications', International Conference and Exhibition on Ultrasonics (ICEU-80) by National Physical Laboratory, New Delhi, 1980 pp.16.

[16] Rasmussen J.G., 'Ultrasonic Surface Waves-Prediction of Fatique Failure', Materials Evaluation, Vol.20, No.2, February, 1962 pp. 103-104.

[17] Smith A.L., 'Ultrasonic Testing Fundamentals', Materials Evaluation, Vol. 36, No.5, April 1978, pp. 22-31.

[18] Stenton, et.al., 'A Report Guide to Ultrasonic Testing Literature', Army Materials and testing Literature, Army Materials and Mechanics Research Centre (AD-689455), Vol. 6, Rep. AMMRC-MS-69-03, April 1969, pp.22-23.

[19] Sinha V.K. and Khanna K.M., 'Ultrasonic Testing- The present and Future', Vol. 38, No.6, June 1980, pp.14-15.

[20] Smith A.L., 'Ultrasonic Testing Fundamentals', Materials Evaluation Vol. 36, No.7, June 1978, pp. 37-41.

[21] Thissen J.M., et.al., 'Optimisation of Ultrasonic Transducer', Ultrasonics, Vol. 23, No.1, January 85, pp. 41-46.

[22] Van Valkenburg H.E., 'Present Trends in Ultrasonic Testing', Materials Evaluation, Vol. 21, No.3, March 1963, pp. 178-182.

[23] Wobschall D., 'Circuit Design for Electronic Instrumentation, McGraw-Hill Book Company, New York, 1979.

[24] Wells P.N.T., 'Biomedical Ultrasonics', Academic Press, London, 1977.

[25] Yoneyama H., et.al., 'Ultrasonic Testing of Austenitic Stainless Steel Weldments by means of Transmitter-Receiver type longitudinal Wave Angle-Beam Probe', Materials Evaluation, vol.40, No.5, April 1982, pp. 554-558.