INSTRUMENTATION FOR ULTRASONIC TESTING OF NONHOMOGENEOUS MATERIALS

M. TECH PROJECT REPORT

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ABSTRACT

This project was aimed at the design and fabrication of the instrumentation necessary for nondestructive testing of nonhomogeneous materials using ultrasonic techniques. As a first application, an instrument for testing of concrete using ultrasonic pulse velocity technique was developed. This is a proven technique and can be used for estimating the concrete strength, uniformity, etc at actual sites. Also detection of cracks and estimation of damages are possible using this instrument. Further, a technique for ultrasonic pulse attenuation measurement in concrete was investigated in this project. The necessary instrumentation for implementing this technique was developed and laboratory tests were conducted on specially cast concrete specimen. The validity of the results was studied by crosschecking attenuation variations with velocity variations in different specimen.

The combined measurement of ultrasonic pulse velocity and pulse attenuation on concrete structures can improve the reliability of nondestructive test results by a great amount.

Using similar instrumentation testing may be conducted on other nonhomogeneous materials like timber, F.R.P., ceramics, etc.

ACKNOWLEDGEMENTS

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I am unable to find words to thank my wife Swatee, daughter Anuva, parents and in-laws, who have always been my source of inspiration throughout this work.

Abhijit A. Kulkarni

LIST OF FIGURES

CONTENTS

CHAPTER 1

INTRODUCTION

1.1 AN OVERVIEW

A person buying a coconut may check it by tapping it with a hard object. An earthern pot may be checked for internal cracks by tapping it from outside. Both are simple examples of nondestructive testing (NDT) using sonic techniques. In engineering applications, nondestructive tests are performed using several different techniques: sonic, ultrasonic, optical, radiographic, magnetic, electrical, etc. The best choice of a particular technique usually depends on the application under consideration.

Conventionally, acoustic waves of frequency in the audible range (20 Hz - 20 kHz) are referred to as sonic waves, whereas those having frequency above the audible range, i.e. above 20 kHz, are referred to as ultrasonic waves [16].

During the past 50 years numerous applications of ultrasonics in engineering and medicine have been reported. Rapid advances in electronic instrumentation and microprocessor technology have made it possible to perform detailed analysis of the acquired data before displaying the results.

When applying ultrasonic methods in NDT, usually these waves are passed into the specimen under test and the waves emerging out of it, either by reflection or through transmission, are observed to study the internal irregularities and faults [16]. Careful interpretation of the results obtained is necessary to form correct conclusions about internal flaws. Hence some experience and training is necessary on the part of the user.

Generation of ultrasonic waves is possible by applying electrical excitation to a piezoelectric or magnetostrictive transducer. The excitation may be continuous or pulsed type, depending upon the testing method used. These waves are then coupled into the object under study. Suitable coupling mediums like jelly, grease, soap or water are used to improve the coupling efficiency. Various methods are used for studying the behaviour of these waves when they emerge out of the specimen under study. Some commonly used methods are the pulse-echo method, continuous excitation method, resonance method, through transmission method, etc. The piezoelectric transducer can also be used as a receiver which converts the received waves into proportional electrical signals. Signal processing techniques may be employed for analysing these waveforms to extract the necessary information about the internal structure of the object [15]. The specimen may be scanned in different directions to obtain sufficient information for forming an image of the internal flaws.

These methods have widespread applications in testing of metals, castings, joints, composite materials, etc, and in checking internal defects and cracks as well as for studying stresses under load [16].

1.2 PROJECT OBJECTIVES

This project is aimed at developing the instrumentation necessary for NDT of nonhomogeneous and composite materials using ultrasonic techniques, and checking its usefulness in field applications.

As a first application an instrument for NDT of concrete structures will be developed. This instrument will use the through transmission method for ultrasonic pulses to estimate the time taken by the pulse to travel in a given thickness of concrete. The ultrasonic pulse velocity (UPV) estimated in this manner can be directly related to the compressive strength of the concrete [1,2,3,5,7,12,13,18]. Tests can be performed for studying the formation of cracks by studying the variations in the time of travel at various points on the same concrete slab [1,3,5,16].

Further, a technique for measuring the ultrasonic pulse attenuation (UPA) in concrete will be investigated and presented here. The UPV measuring instrument will be suitably upgraded so that it can also be used for measuring the ultrasonic pulse amplitude using this technique. Hence the attenuation suffered by the pulse during travel can be estimated. Tests will be performed on specially prepared laboratory specimen as well as at actual construction sites to verify the results obtained using this instrument.

While the ultrasonic pulse velocity (UPV) technique is well established, the ultrasonic pulse attenuation (UPA) technique is not much in use in concrete testing. In a "Combined Method of NDT of Concrete" the additional information obtained by attenuation studies can be used for improving the reliability of these strength estimations from UPV technique [3,7,18,29].

1.3 OUTLINE OF THE REPORT

This report describes the use of ultrasonic techniques in concrete testing and goes on to describe the design of the instrument developed for this purpose, and test results with this instrument.

Chapter 2 discusses the background behind concrete testing, its necessity, and various destructive and nondestructive methods used for concrete testing, along with the ultrasonic methods and the instrumentation used in them.

Chapter 3 presents the ultrasonic pulse velocity (UPV) measurement technique for concrete testing, methods of its application, and methods for interpreting test data.

Chapter 4 presents the ultrasonic pulse attenuation (UPA) measurement technique. The concept of measurement and the tradeoffs considered in implementation of the instrument are discussed in this chapter.

Chapter 5 describes the design and fabrication of instrumentation for UPV and UPA techniques.

Sixth chapter presents data obtained in laboratory tests and at sites during actual field tests. The validity of the results obtained by UPV and UPA tests is discussed.

The concluding chapter summerizes the work done so far in building the instrument. The future scope of work in UPA measurement is discussed. Also, the possibility of application of such instrument in the NDT of other nonhomogeneous materials is discussed at the end.

The test reports of UPV tests conducted at actual construction sites are attached in Appendix I. These reports highlight the utility of the instrument in civil engineering practice.

Appendix II presents a brief analysis of the various circuits designed and implemented in this project.

CHAPTER 2

NONDESTRUCTIVE TESTING OF CONCRETE - A PREVIEW

2.1 THE NEED FOR TESTING CONCRETE

Concrete is the most widely and commonly used material in all construction industry and thus requires some effective tool for day-to-day quality checks [1,2,3,10,11]. All important concrete structures are required to be checked for defects and quality from time to time. In construction of high rise buildings, water towers, bridges, dams, etc, tests are performed at various stages for monitoring the quality of concrete. Even in mass production of prefabricated units, quality control of day-to-day production is essential.

Checks have to be carried out for detecting cracks, voids, and testing uniformity as well as for strength estimations [1,3]. In existing structures, testing of concrete may be required to estimate the safe life of the structure or to estimate the damages due to weather, vibrations, fire, freezing and thawing, chemical attacks, etc [2,3,5,12,25,26].

2.2 METHODS OF TESTING CONCRETE

The methods used for concrete testing can be catagorized into two groups as destructive methods and nondestructive methods.

2.2.1 Destructive Methods

Most conventional testing methods use destructive tests for strength checking on a sample of concrete removed by cutting a core at site or on a cube cast by using the same mix of concrete as that used at the actual site [5,13]. The strength of concrete is checked by applying external compressive or flexural force on it. However core cutting is rather a long and costly process and may damage the original structure. Also the inherent difficulty of determining the quality of concrete 'in-situ' (at actual site) lies mainly in the fact that the test cube samples are not true samples of the mass of the concrete but are merely specially prepared samples of the concrete mix. If a concrete slab has been poorly compacted, it is possible to obtain a poor quality concrete from a good quality mix and in such a case strength tests on relatively well compacted cubes from the same mix would not represent the general quality of the concrete in the slab [13]. Thus the test cube sample does not represent the actual concrete in structure. Another main disadvantage is also the delay in obtaining test results on cubes, which require standard curing time of 28 days before the compressive strength can be checked. Further, it is not possible to take a large number of cube/cylinder samples on a given concrete. Hence, even if the cube/cylinder crushing strengths were considered to represent accurate values, they have less significance from statistical point of view than the results of nondestructive methods, which can be applied on large number of samples without damaging the concrete [29].

2.2.2 Nondestructive Testing (NDT) Methods

The preceding discussion about destructive testing methods brings out the necessity to perform in-situ tests for checking out the quality and service behaviour of concrete [12,13]. Hence during recent years efforts were concentrated on performing NDT of concrete to measure in-situ some parameter which may be related theoretically or empirically to compressive strength. Various NDT tests can be broadly classified as nonsonic and sonic tests.

The nonsonic tests attempt to measure some property of concrete like hardness, resistance to penetration by projectiles, rebound number, etc, from which an estimate of its strength is obtained [2,5,18]. Several tests like rebound hammer test, pull out test, Windsor probe test, etc are performed for estimating these parameters. Since these are indirect methods, careful analysis of the observed data as well as visual site inspection by experts is necessary before drawing conclusions about the concrete quality.

The sonic tests mostly performed on concrete are the pulse transmission tests. The most established pulse transmission test involves measuring the velocity of longitudinal ultrasonic pulse in the concrete under test [1,3,12,18] and this technique has found widest acceptance for NDT of concrete in several countries. Its main advantage is that velocity can be easily measured at several locations on the concrete surface and estimation of the overall quality is possible. Also this method is comparatively easy to apply and less time consuming. Several reports have been published in the USA [6], UK [12,13,14], USSR [31] & recently in

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India [17,25,26,27] on the usefulness of this technique for NDT of concrete. Despite wide ranging views about the interpretations of the results obtained for providing acceptance criteria for a given concrete, it is generally agreed that very high velocities are indicative of very good concrete and very low velocities are indicative of poor concrete [18]. It is further agreed that periodic or systematic changes in velocity are indicative of similar changes in the quality of the concrete. The pulse transmission test can also be used to study the attenuation of ultrasonic waves, which is indicative of porosity of the concrete under test. However, this method has not been used much for field testing as yet.

Other type of sonic tests may be performed to determine the fundamental longitudinal, transverse and torsional frequency of a specimen [18]. The dynamic Young's modulus of elasticity (dynamic E) and dynamic modulus of rigidity (dynamic G) can then be calculated. From these values, the Poisson's Ratio 'u' can be calculated using the relationship,

$$u = E/(2G) - 1 \qquad (2.1)$$

Methods for relating dynamic E with the compressive strength (σ) have been suggested [10]. However the major drawback of this technique is that it can be applied to small size specimens and has little value in studying the behaviour of concrete in-situ.

2.2.3 Combined Methods of NDT

The correlation between the NDT measurements and the compressive strength of the concrete are influenced by the concrete composition, hardening conditions, humidity, temperature, reinforcement, etc. As these factors influence the correlations in different ways, the simultaneous utilization of different NDT methods increases the amount of information on tested concrete and can help in estimation of concrete in-situ in better perspective, thereby improving the reliability of evaluation.

In general, a combination of two or more NDT methods may be used [18]. e.g.,

a) Longitudinal UPV with rebound index (Sonreb, or Rebultra method).
b) Longitudinal UPV with pullout force.
c) Longitudinal UPV with attenuation of ultrasonic pulse.

More than 70% of the existing applications make use of the combination of UPV with rebound index. Combinations of three methods are seldom. They include the longitudinal UPV and the rebound index in combination with either the pullout force or the pulse attenuation methods.

Recently a number of attempts have been made to use the above mentioned combinations [18,29]. Although mathematically the degree of accuracy of predicted strength increases only slightly with the number of methods used, the advantage is that the reliability of this assesment is greatly improved.

2.3 INSTRUMENTATION USED FOR ULTRASONIC PULSE VELOCITY MEASUREMENT IN CONCRETE

The use of ultrasonic pulse velocity [UPV] technique in concrete testing is believed to have its origin with Obert in USA in 1940 [18]. Tests were made on concrete replacement pillars in mines and involved the use of two geophones connected to two high gain amplifiers and light sources, and a camera with a moving strip. The geophones were fitted on concrete pillar about 7 m apart vertically. A hammer blow was struck at the base of the pillar and at the same time the camera lens was opened and the moving film strip exposed. The transit time of the impulse in travelling from one geophone to the other was determined by measuring the distance between the two signals on the film, the speed of motion of the film having been controlled carefully. The velocity could then be calculated.

In 1946 the Hydro-Electric Power Commission of Ontario, Canada, developed an instrument for examining cracks in monolithic concrete structures [6,18]. This instrument was called the 'Soniscope'. This device consisted basically of a pulse generator using piezoelectric crystals, a similar pulse receiver and electronic circuits to actuate the pulse generator and to amplify the received signal. Visual display of the transmitted and the received pulse was given on a CRT on which the time interval between the two could be measured using a calibrated scale. The Soniscope was used considerably in the United States, and Canada and several improvements were made in the original design in the forthcoming years. Around the same time an instrument called as 'Ultrasonic Concrete Tester' was developed at the Road Research Laboratory, Harmondsworth, England . This instrument worked on similar principles as the Soniscope and its usage and results obtained have been described at length by Jones [12,13].

The Ultrasonic Concrete Tester differed from the Soniscope primarily in that whereas the Soniscope used ultrasonic pulses of around 20 kHz for transmission, the latter used pulses of around 100 to 200 kHz. These changes improved the accuracy of measurement on smaller specimen but restricted the maximum path length to around 2 m which was much less compared to path lengths of around 15 m possible with the Soniscope. Similar instruments were also reported to be used in the USSR [31] for quality control of concrete.

Today's ultrasonic concrete testing equipments are based on similar principles. However, more compact instruments using digital displays for indicating the elapsed time are available commercially [16]: notable among these being the instrument called as 'PUNDIT' (Portable Ultrasonic Nondestructive Digital Indicating Tester), developed in Holland. Other manufacturers of similar equipment are Steinkamp (Germany) and James Electronics (USA).

These instruments are battery operated and are suitable for being used at building sites. They are supplied with probe sets of various frequency ranges between 20 kHz to 200 kHz. The required probe frequency can be selected by considering the measuring distance (path length) and the accuracy desired. A 10 MHz time marker permits a reading accuracy of 0.1 usec in measuring range from 0.1 usec to 999.9 usec. Another range permits readings accurate to 1 usec up to 9999 usec [16].

2.4 NONDESTRUCTIVE TESTING OF CONCRETE IN INDIA

In India, NDT techniques are as yet not widely used for concrete testing. Some use of Rebound Hammer is made by a few practicing engineers. However the use of the UPV technique for NDT of concrete appears to have been limited to research institutions only. Some amount of work in the use of this technique has been reported earlier from IIT Bombay [17]. Also successful use of this technique in some major field applications has been reported in some isolated reports published by individual researchers. Notable among these being the reports by Patwardhan [25,26,27] which describe the use of UPV methods for estimating damages to concrete due to fire. However apart from these reports very little use of UPV technique appears to have been made for concrete quality estimation in general construction activity. The use of UPA technique is still in a very preliminary stage. The major deterring factor appears to be the non-availability of proper instruments manufactured locally while the imported ones remain prohibitively expensive.

CHAPTER 3

ULTRASONIC PULSE VELOCITY TECHNIQUE

3.1 ULTRASONIC TESTING OF NONHOMOGENEOUS MATERIALS

Various NDT techniques including ultrasonics are adopted frequently for testing of homogeneous materials like metals, alloys, castings, etc [16]. It is possibile to sense various properties of the homogeneous material, like electrical resistance, magnetic, optical, and radiographic effects, etc, and to relate these with the required information about the material under test. In case of nonhomogeneous materials, such parameters are difficult to ascertain.

In ultrasonic techniques, the reflections of the incident waves are generally studied to draw conclusions about internal structure of the material under test [16]. However in case of nonhomogeneous materials like concrete, timber, fiber reinforced composites, etc, strong attenuation of the incident waves results due to scattering effects at interfaces of various particles and attenuation of pulse energy due to voids. Also multiple reflections produce so many disturbing echoes of uncontrollable direction and origin that the echo method can be applied very rarely. Hence normally one uses the two probe method with pulse transmission when testing these materials. Also variable nature of measured parameters necessitates considerable expertise and experience for accurate interpretation of results [2,10].

3.2 ULTRASONIC PULSE VELOCITY TESTING OF CONCRETE

The quality of concrete is taken to be based on its ultimate strength in compression or flexure. Although these parameters do not define the quality of concrete, they provide a good indication of it [12]. Hence it is always necessary to estimate strength and uniformity of concrete compaction at various locations. It is also important to detect cracks and to estimate the depth of these cracks if they are found to be present. The ultrasonic pulse velocity [UPV] techniques can be used effectively for these purposes [1,3]. Determination of density of concrete using UPV technique is uncommon since the pulse velocity has hardly any correlation with the density of the concrete.

The heterogeneous nature of concrete limits the range of ultrasonic frequency used for concrete testing to about 200 kHz [1,3,5,16]. Higher frequency waves undergo excessive attenuation and hence cannot be used when the probing distance exceeds 1 m. The use of low frequencies results in the absence of any directional effect of the probes. Hence it is possible to couple at arbitrary points on different surfaces of the specimen inclined to each other as shown in Fig. 3.1. The fastest wave received in this way is then always the direct longitudinal wave which is detected first by the receiver. This is followed by the transverse and surface waves which, depending upon the shape of

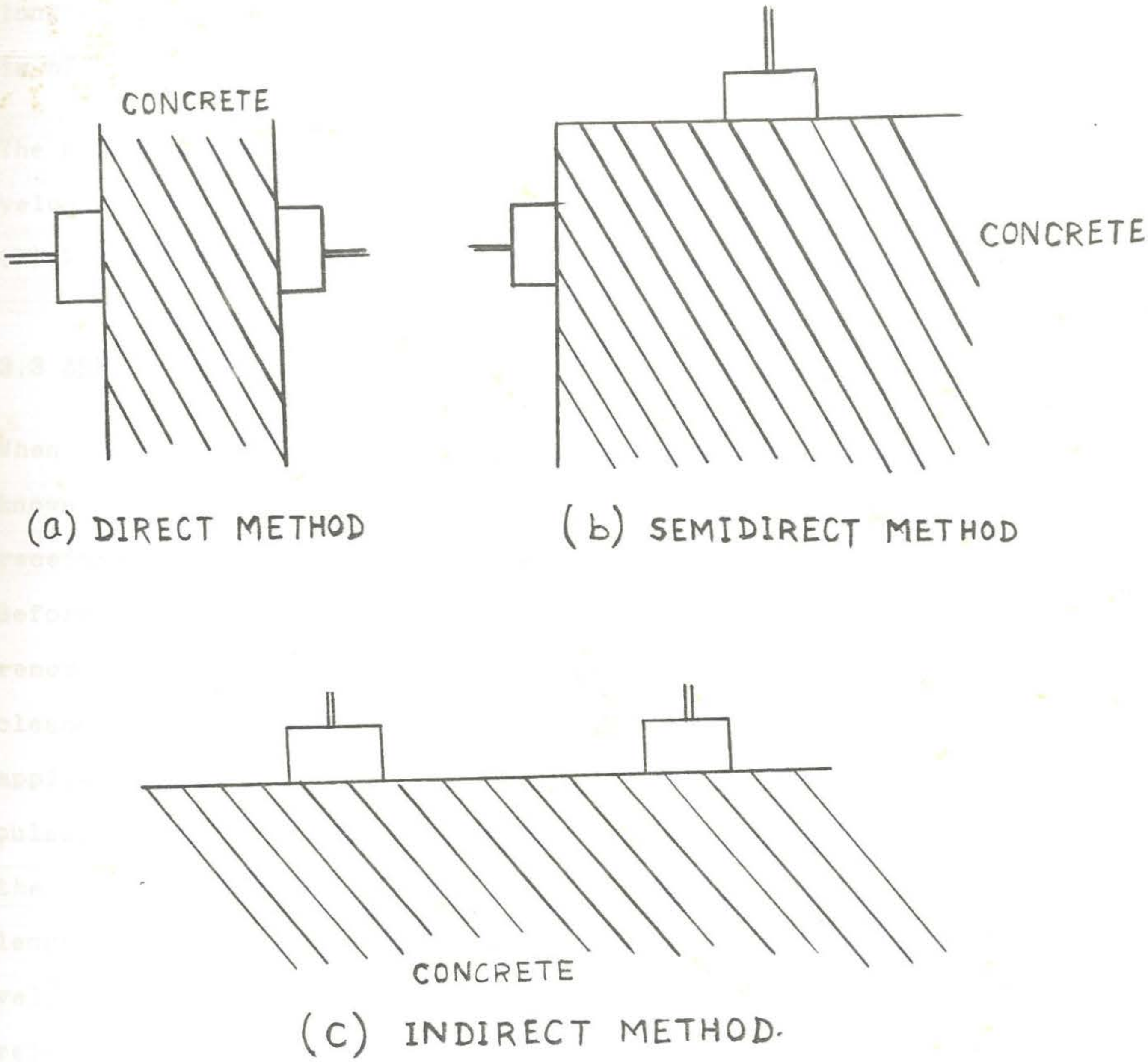

Fig. 3.1 : Direct, Semidirect and Indirect Methods of Coupling Probes.

Source : Bungey J.H. [4]

the specimen, may however already be disturbed by the reflected longitudinal waves. Thus the velocity of direct longitudinal wave is of interest when using UPV technique.

The presence of reinforcement has a slight influence on the pulse velocity only if the sound beam happens to be coaxial with very thick reinforcing rods above 20 mm in diameter [16].

3.3 APPLICATION METHODS

When performing UPV test of concrete on RCC column members of known width or thickness (path length), the transmitter and receiver transducers are held firmly on opposite faces [1,3,5]. Before application, the unevenness of the contact surfaces is removed by scrubbing with carborundum grinding stone and they are cleaned of dust. The surfaces as well as the transducers are applied with low viscosity grease. The transmitter transmits pulses through the concrete section which in turn are received by the receiver. The time taken by each pulse to traverse the path length is recorded by the instrument in microseconds. The pulse velocity in the given concrete is then calculated by using the relation,

$$V \ (\text{km/sec}) = \frac{\text{path length (mm)}}{\text{time} \ (\text{usec})} \tag{3.1}$$

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3.4 CALCULATION OF CONCRETE PARAMETERS FROM ULTRASONIC PULSE VELOCITY

The pulse velocity of concrete is related to the properties such as elastic modulus and strength. The detailed procedure for calibration and use of ultrasonic method for strength determination etc has been described in [1] and [3].

The ultrasonic pulse velocity 'V' in concrete has been empirically found to be related [1,3,5] to the elastic modulus 'E' and the crushing strength 'σ' of the concrete as the following,

$$V \propto (E)^{1/2} \tag{3.2}$$

$$V \propto (\sigma)^{1/4} \tag{3.3}$$

As per IS 456, 1978 [10], the following relations can be assumed for calculations,

$$E = 5700\ (\sigma)^{1/2} \tag{3.4}$$

&

$$F_{cr} = 0.7\ (\sigma)^{1/2} \tag{3.5}$$

where, E (dynamic elastic modulus), σ (crushing strength), and F_{cr} (flexural cracking strength) are expressed in N/mm^2.

Concrete is a heterogeneous material consisting of various phase componants such as aggregates, sand, cement, and water. Thus it has different properties in orthogonal directions. Hence if ultrasonic velocities are found in all the three directions, it is possible to evaluate the Poisson's ratio for concrete.

According to Jones [12], if the Poisson's ratio is known and if the modulus of elasticity is to be computed from the pulse velocity, then the relationship generally recommended is,

$$E = V^2 p (1 - u^2) \qquad \text{for pavements} \qquad (3.6)$$

$$E = \frac{V^2 p (1 + u)(1 - 2u)}{(1 - u)} \qquad \text{for mass concrete} \qquad (3.7)$$

where,

E = dynamic modulus of elasticity

V = longitudinal pulse velocity

p = mass density

u = Poisson's ratio

The properties of concrete, particularly the strength and modulus of elasticity are dependent upon water-to-cement ratio, aggregate-to-cement ratio, maximum size of aggregates, type of cement, type of aggregates, porosity, etc. Thus it is essential to correlate ultrasonic pulse velocity (UPV) with the particular concrete and thus there is no standard graph for UPV v/s strength of concrete. Hence IS 456, 1978, Clause 16.0 [10] states that NDT on concrete be carried out by experienced and expert qualified engineers only.

3.5 EXAMPLES OF PRACTICAL APPLICATIONS

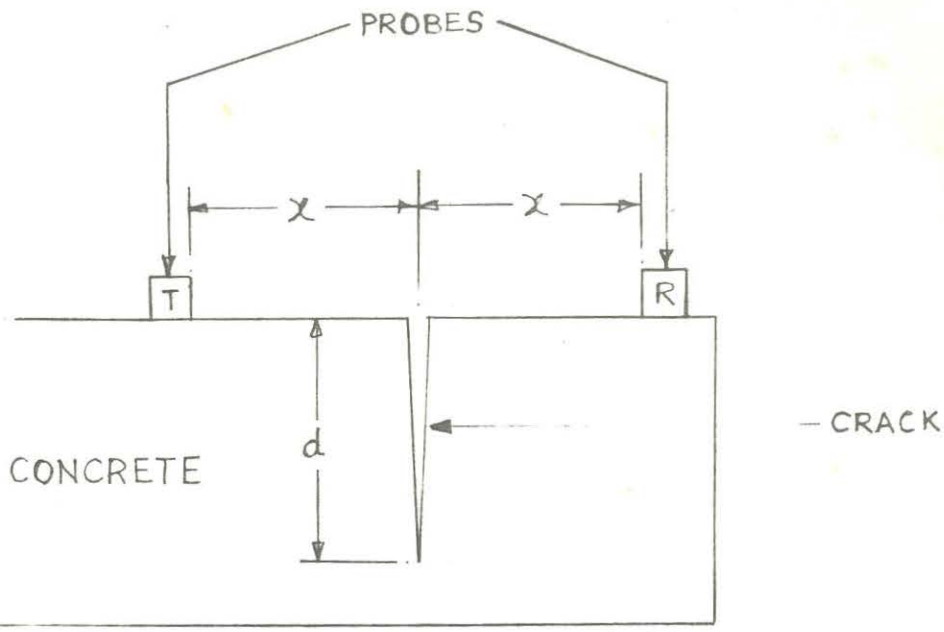
As per BS 1881, Section 203,1986 [3], UPV method may be used for applications like evaluation of strength of concrete, uniformity of concrete, quality control during construction, investigations and survey for prestressed structures, estimation of damages due to fire or due to environmental impacts, deterioration of concrete due to chemical attack or due to chloride ingress near sea shore, etc.

In case of fire damages [25,26] or deterioration of concrete due to chemical attack, the pulse velocity reduces depending upon the severity of the attack and thus by knowing base UPV on unaffected region it is possible to estimate the damages.

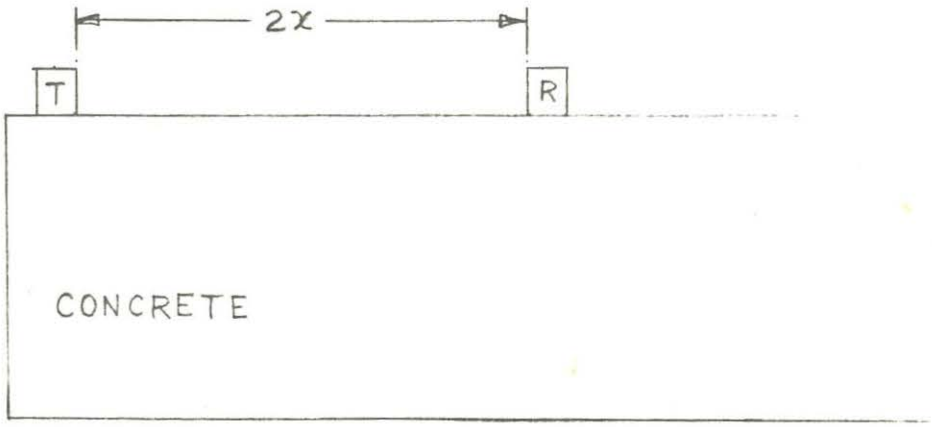
In case of determination of depth of crack in concrete the method employed can be explained with the help of Fig. 3.2. The depth of crack (d) can be found from the relation [1,3,16],

$$d = x\,[(Tc/T)^2 - 1]^{1/2} \qquad (3.8)$$

In case of massive structures, it is necessary that concrete be uniform and evenly compacted. For example in turbo generator foundations in power plants uneven quality of concrete may lead



T_C = TRANSIT TIME AT CRACKED CONCRETE.



T = TRANSIT TIME UNCRACKED CONCRETE.

$$\text{DEPTH OF CRACK} = d = x\sqrt{\frac{T_C^2}{T^2} - 1}$$

Fig. 3.2 Estimation of Crack Depth in Concrete

to vibrations due to imbalance which can lead to failure of the structure in due course of time. In such cases UPV is measured in close grid locations & corrective actions are advised wherever low UPV is observed.

Thus it is very essential that appropriate instrumentation for ultrasonic pulse velocity technique be developed . Apart from construction industry, this type of instrument can also find wide ranging applications in testing of timber, fiber reinforced composites, etc. However exact application techniques for these materials need to be studied.

CHAPTER 4

ULTRASONIC PULSE ATTENUATION TECHNIQUE

4.1 ATTENUATION OF ULTRASONIC WAVES [16,24]

The amplitude of an ultrasonic wave decreases gradually while travelling in materials under test. This occurs mainly due to spreading of wave, scattering, and absorption. These phonomena can be explained as follows,

a) Spreading of Wave - The sound beam originating from a probe can be visualized as a spherical wave, which spreads as it travels in a homogeneous material. The sound pressure along its path decreases as the wave travels away from the probe in the far field.

b) Scattering - Scattering results due to the nonhomogeneous and anisotropic nature of the material under test. An otherwise homogeneous material may be nonhomogeneous for ultrasonic waves if the grains are oriented at random. Thus the sound velocities are different in different directions due to the difference in elastic properties. Such materials are called as anisotropic materials. A nonhomogeneous material contains boundaries on which the acoustic impedance changes abruptly because two materials of different density or sound velocity meet at these interfaces. For example concrete is an agglomeration of various materials like sand, aggregates, cement, etc, which have different elastic properties. Thus an ultrasonic wave travelling in concrete gets scattered at various interfaces between these constituents. The scattering effect is negligible when the grain size of the material is very small compared to the wave length. In the case of grain sizes of one-thousandth to one-hundredth of the wave length, scatter is very less. However it increases very rapidly as the grain size increases. The increase is approximately as the third power of the grain size.

The scatter coefficient (α_s) has been shown to be related to various factors as the following [16],

$$\alpha_s \propto F_A D_k^3 f^4 \qquad (\text{for } D_k \ll \lambda) \qquad (4.1)$$

and

$$\alpha_s \propto F_A (1/D_k) \qquad (\text{for } D_k \gg \lambda) \qquad (4.2)$$

where,

F_A = factor due to anisotropy

D_k = grain size

f = frequency of ultrasonic wave

λ = wavelength of ultrasonic wave

c) Absorption - This effect is due to direct conversion of sound energy into heat, due to various complex physical processes. Absorption can be visualized as a sort of braking effect of the oscillations of the particles. Hence a rapid oscillation loses more energy than a slow oscillation, i.e. absorption increases with frequency.

The absorption coefficient (α_a) can be shown as [16],

$$\alpha_a \propto f \qquad (4.3)$$

The combined effect of scattering and absorption is termed as attenuation of an ultrasonic wave in the material under test. The combined attenuation coefficient (α) is then taken as the sum of the scatter coefficient (α_s) and the absorption coefficient (α_a).

If the sound wave is assumed to be a plane wave, then the decrease in sound pressure is only due to attenuation. If the sound pressure is measured at two points in the path of the wave, then the decrease in pressure can be represented mathematically as,

$$p = p_o e^{-\alpha d} \qquad (4.4)$$

where,

p_o = sound pressure at the beginning

p = sound pressure at a distance 'd'

$\alpha = \alpha_s + \alpha_a$ = attenuation coefficient

d = distance of travel

By taking natural logarithm of both sides of eqn. 4.4, we get

$$\alpha d = \ln (p_o/p) \text{ Nepers} \quad (4.5)$$

The attenuation coefficient (α) is therefore given in Nepers/cm. More commonly, decibel per metre (dB/m) is the unit used, where,

$$\alpha d = 20 \log (p_o/p) \text{ dB} \quad (4.6)$$

By this definition, ultrasonic attenuation is a measure of the relative amplitudes of a wave at two locations in the material under study. However, the attenuation coefficient (α) is a definite quantity for a particular mode of wave motion at a certain frequency in a given material under specific conditions. Absolute measurement of 'α' is possible by careful experimentation.

The principal reason for the interest in measuring ultrasonic attenuation on an absolute basis is the verification of physical theories which predict attenuation. The attenuation itself is often not of intrinsic interest. Rather, the attenuation is often a result of some physical or chemical phenomenon which is of interest, so that the attenuation provides a measurement for the inductive study of the phenomenon.

In most cases, relative measurement of attenuation is sufficient. However, care has to be taken to account for the errors introduced due to beam spreading and coupling variations between the transducers and the specimen.

4.2 ATTENUATION MEASUREMENT IN CONCRETE

The Ultrasonic Pulse Velocity measurement technique was presented in Chapter 3. This technique has been most widely used and accepted until now. Several instruments are available commercially for transit time measurement of ultrasonic pulse in concrete, from which the pulse velocity can be computed. However, in addition to UPV, the measurement of ultrasonic pulse attenuation can provide additional information about the specimen under test. In recent years combined methods of NDT of concrete have been used, which make use of the results obtained by two or more NDT techniques for improving the reliability of prediction of concrete strength [7,18,29].

Measurement of ultrasonic pulse attenuation can be combined with UPV to estimate the compressive strength of concrete with a greater degree of reliability than if pulse velocity alone had been used. The increased accuracy of prediction is due to the fact that the pulse velocity accounts for the elastic properties, whereas the pulse attenuation represents the inelastic properties [18].

Several problems associated with pulse attenuation measurement in concrete have been reported in literature, and these can be listed as the following,

a) The attenuation of ultrasonic wave is not defined as a unitary measurement, independent of path and the geometry of the specimen [7].

b) The results obtained may differ for different instruments and measuring techniques [18].

c) The attenuation of an ultrasonic wave is a function of its frequency. Hence the results obtained at various test frequencies will be different [29].

d) The coupling losses may vary during the course of testing.

Due to the difficulties in overcoming these problems, application of attenuation measurement technique for field testing has been very limited.

4.3 ATTENUATION MEASUREMENT TECHNIQUE

The technique for ultrasonic pulse velocity (UPV) measurement presented in Chapter 3 is well established. However, the ultrasonic pulse attenuation (UPA) measurement technique has not been much reported in the past. The aim of this project is to develop a technique, which can be standardized for attenuation measurement of ultrasonic pulse in concrete, and to design an instrument for application of this technique alongwith the UPV technique. The basic desirable features of the UPA technique are enlisted as follows,

a) Even if it is not possible to measure attenuation as an absolute quantity, the instrument should be capable of displaying the relative amplitudes of ultrasonic pulses, from which the attenuation can be visualized.

b) For a given set of equipment and probes, operated at a fixed pulse energy and at a fixed amplifier gain, repeatable readings of pulse amplitude should be obtained for successive readings taken on identical or same sample of concrete, i.e. the readings obtained should be reproducable.

c) The readings should be relatively unaffected by slight variations in coupling conditions. This is important because it is almost impossible to obtain exactly similar coupling each time.

d) The readings should be independent of the geometry of the specimen, i.e. for a given concrete, for a particular path length, the pulse amplitude measured should be independent of the lateral dimensions of the concrete block.

e) The instrument to be developed for this technique should be portable so that application for field testing is possible.

Mostly the use of an oscilloscope has been reported for measurement of the pulse amplitude [7,18]. The conventional amplitude measurement technique used in the testing of homogeneous materials uses an envelope detector circuit, which enables the user to measure the peak of the envelope corresponding to the maximum amplitude of the received pulse. The reduction in the amplitude of this peak is measured for estimating the attenuation.

However, this technique cannot be applied for measuring pulse amplitude in nonhomogeneous materials like concrete. As described in section 3.2, the use of low frequency ultrasonic waves, of the order of 100-200 kHz, for concrete testing no longer permits sharply collimated sound beams as is customary in the testing of metals [18]. The contact face of the probe is of the order of the wavelength (at 100 kHz, λ=40mm) and radiates other wave modes besides longitudinal waves of appreciable intensity. A strong surface wave may be present alongwith transverse wave. As shown in Fig. 4.1, the receiver probe receives these various waves in succession. The first wave to reach the receiver is always the direct longitudinal wave, which travels fastest. This is followed by the indirect longitudinal waves, which may have been reflected at the specimen boundries or may have been scattered within the specimen itself. The surface waves and the transverse waves are also picked up by the receiver probe. The sequence in which these waves follow cannot be predicted easily and depends upon the geometry of the specimen under test.

In the UPV technique, the time of travel of the direct longitudinal wave only is of interest. Similarly, it is clear that the attenuation of this wave alone can provide correct information about the concrete under test. If the presence of other waveforms is taken into consideration, then the readings of maximum amplitude may correspond to some other reflected waves or the surface waves. The results obtained can then be different for the same distance between probes if the dimensions of the specimen are changed. Hence only the amplitude variations of the

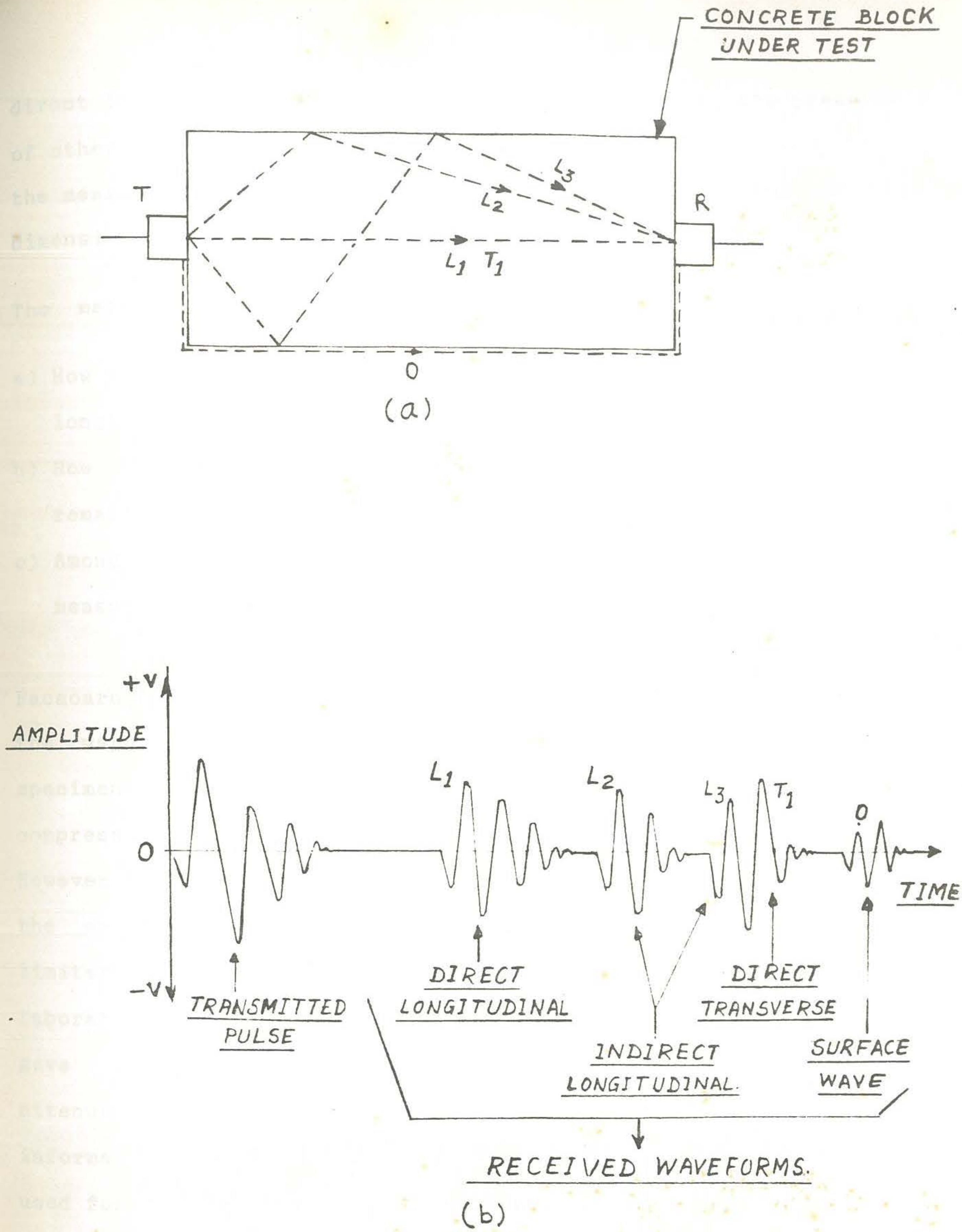


Fig. 4.1 : Testing Concrete by Pulsed Sound Transmission
(a) With transducers placed on opposite faces of a concrete specimen.
(b) Showing the first pulses of various waves.

Adopted from : Krautkramer J. & Krautkramer H. [16].

direct longitudinal wave should be measured, whereas the presence of other waveforms arriving in succession should be ignored. Then the measured amplitude of this wave is independent of the lateral dimensions of the specimen under test.

The main difficulty was about deciding the following factors.

a) How many of the first received cycles correspond to the direct longitudinal wave.

b) How to detect and how to segregate these cycles from the remaining ones.

c) Among these cycles, the amplitude of which one should be measured or should the peak amplitude among these be measured.

Facaoaru [7] has mentioned that measurement of the attenuation of the wavefront of an ultrasonic pulse transmitted in a concrete specimen can be used alongwith the transit time to estimate the compressive strength with a greater degree of reliability. However he has mentioned the use of an oscilloscope for observing the waveform to be measured. This itself puts a serious limitation on the applicability of such instrumentation beyond laboratory specimen. Although several papers published recently gave data about relating ultrasonic pulse velocity and attenuation with compressive strength of concrete, very little information was available on the technique and instrumentation used for ultrasonic pulse attenuation measurement in concrete and other nonhomogeneous materials.

It was decided to first observe the behaviour of ultrasonic pulses in various concrete specimen having varying compositions and lengths. For this purpose the Waveform Analyzer [mfg. by Analogic Inc., U.S.A.] was used. This analyzer is capable of sampling waveforms upto 100 MHz frequency and has facility for storing the waveforms, which can be recorded on a floppy disk.

Three different types of specimen were studied as follows,

a) Concrete specimen having rectangular and cubical dimensions.

b) Concrete specimen having cylinderical dimensions.

c) Siporex specimen having rectangular and cubical dimensions.

The concrete cubical and rectangular specimen were prepared as per the normal composition of concrete, having cement, aggregate, sand, etc, and were well compacted to minimize porosity. The porosity in these specimen was estimated to be of the order of 2%.

All the concrete cylindrical specimen were prepared in identical moulds, having same diameter and length. These were cast at the same time using the same concrete mixture, but having varying degree of compaction. This was deliberately done to introduce varying degree of porosity in the samples.

The siporex specimen did not contain any aggregate or sand. In general these appeared like a porous mass. The porosity of these was estimated to be of the order of 20%.

The instrument developed for UPV technique, which is described in chapter 5, was used, alongwith probes of 150 kHz frequency. Fig. 4.2 shows the set up used for the experiment. Efforts were made to maintain uniform coupling by applying uniform layer of grease of low viscosity on the contact surfaces. It was observed that although the transmitter probe was being pulsed by an electrical pulse of approximately only 2 microseconds, the total recieved signal lasted for nearly 8-10 milliseconds. The signals received by the receiver probe and amplified by the amplifier were digitized and recorded in each case and these are shown in Figs. 4.3 to 4.8.

From these recorded waveforms the following observations were made.

a) The first peak observed was always negetive going peak. This was followed by 2-3 cycles having consistant amplitudes and frequency. These were followed by other cycles which did not show any consistant pattern in various specimen. However it was also observed that for a given specimen the total signal received was generally similar, over repeated trials.

b) Minor variations in coupling caused by varying pressure of hands holding the probes did not cause much change in the amplitude and frequency of these first 2-3 cycles received. However, the following pattern was affected quite significantly by such variations.

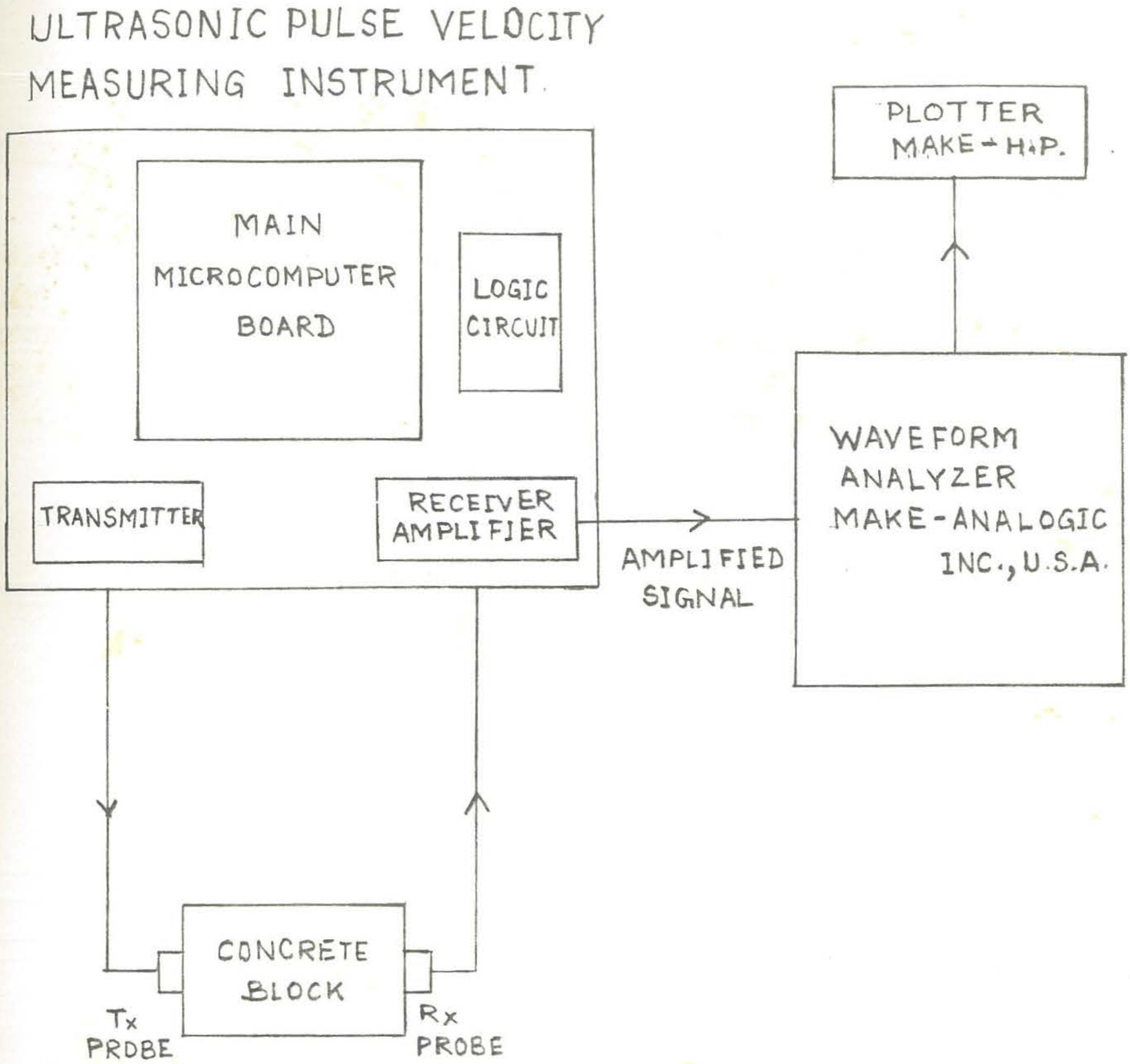


Fig. 4.2 : Experimental Set Up Used for Ultrasonic Pulse Attenuation Studies

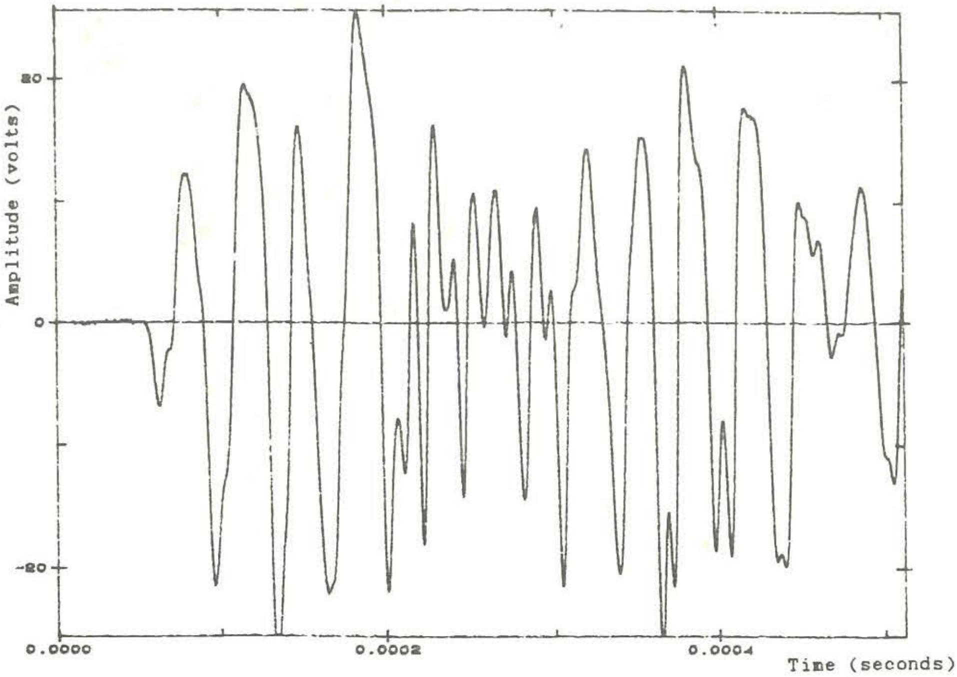


Fig. 4.3 : Waveform Recorded on Concrete Specimen
Size - 150 X 150 X 150 mm.
Path Length - 150 mm.

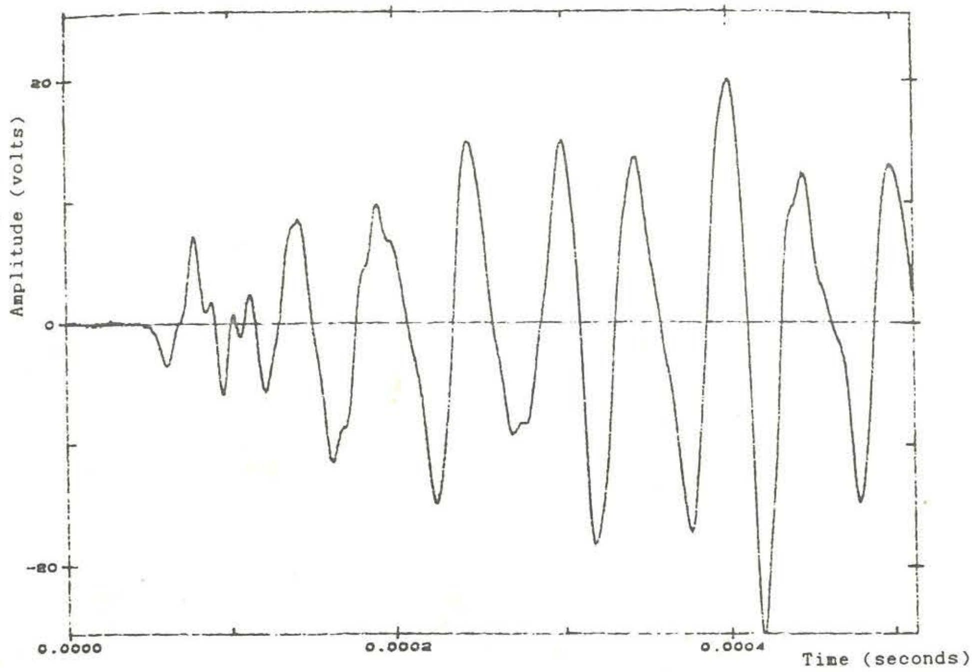


Fig. 4.4 : Waveform Recorded on Concrete Specimen
Size - 150 X 175 X 380 mm.
Path Length - 175 mm.

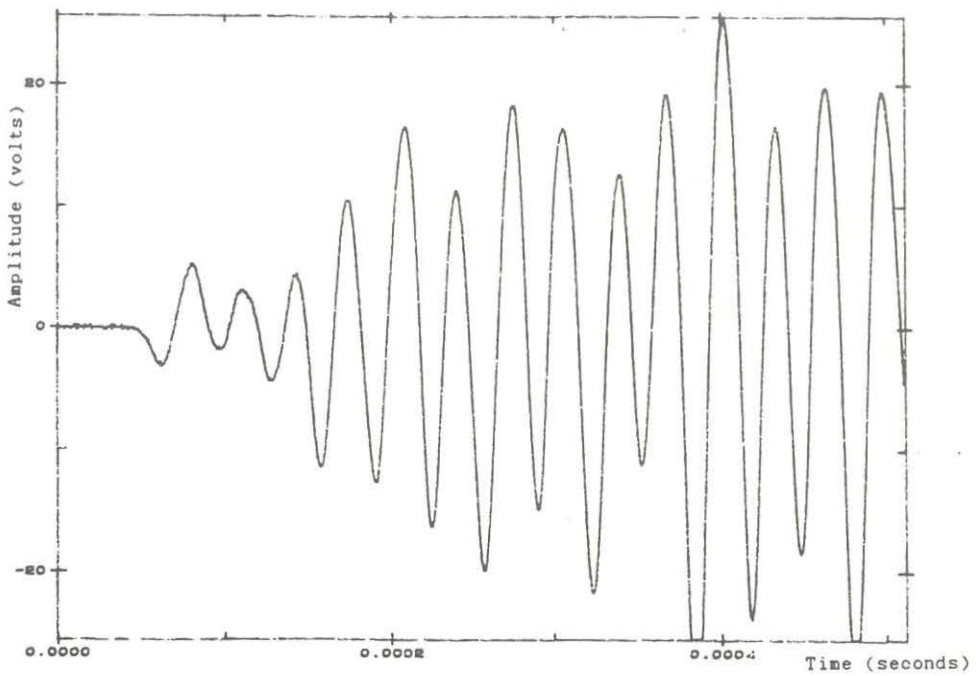


Fig. 4.5 : Waveform Recorded on Concrete Specimen
Size - 150 X 175 X 380 mm.
Path Length - 380 mm.

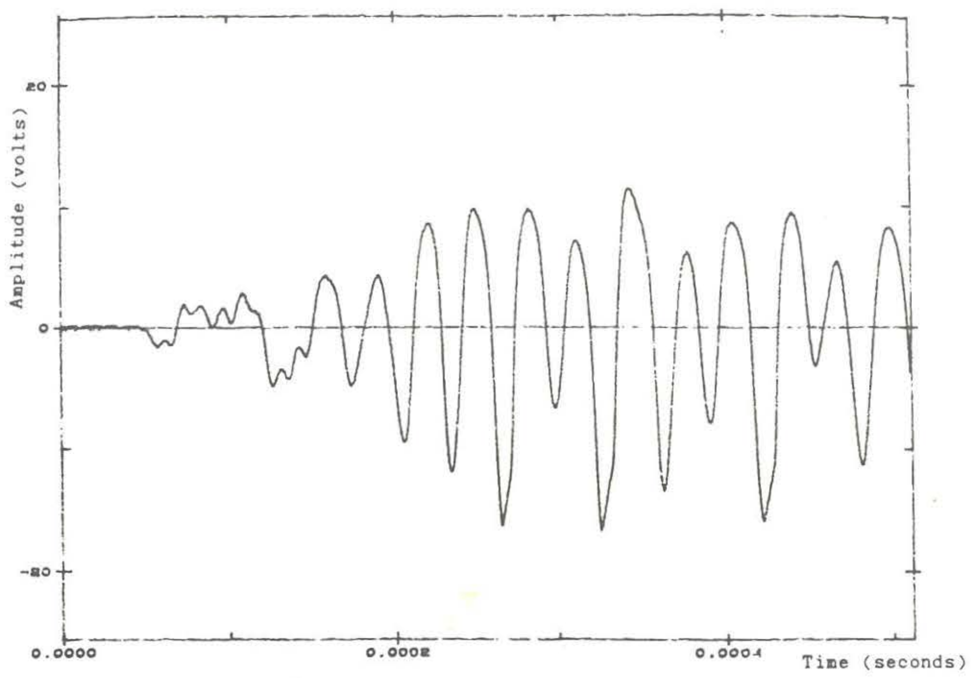


Fig. 4.6 : Waveform Recorded on Concrete Specimen
Size - 100 X 100 X 500 mm.
Path Length - 500 mm.

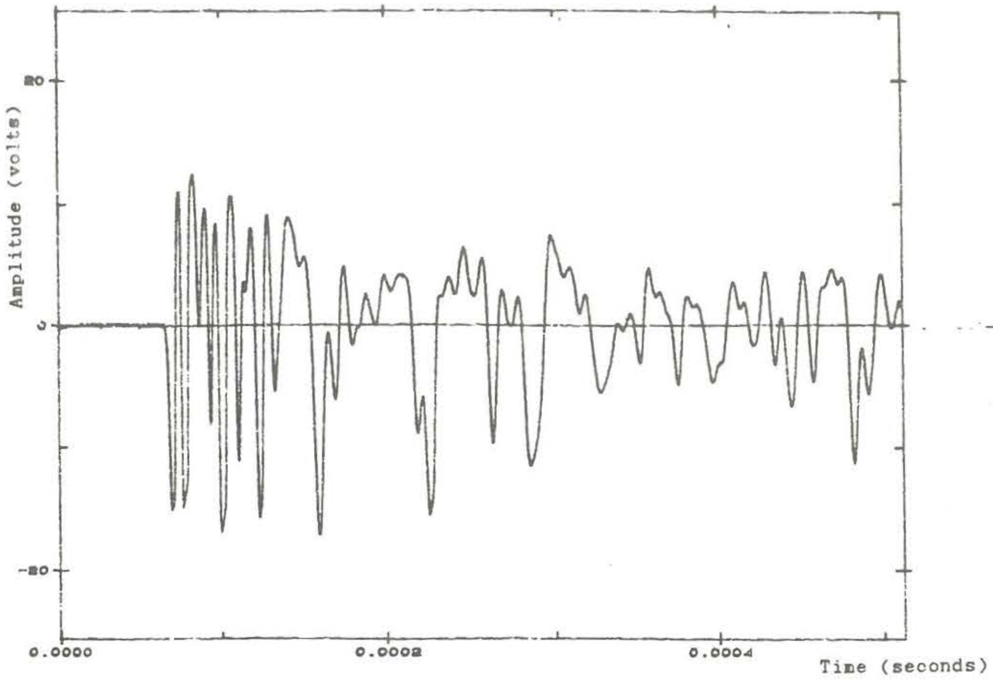


Fig. 4.7 : Waveform Recorded on Siporex Specimen
Size - 150 X 150 X 150 mm.
Path Length - 150 mm.

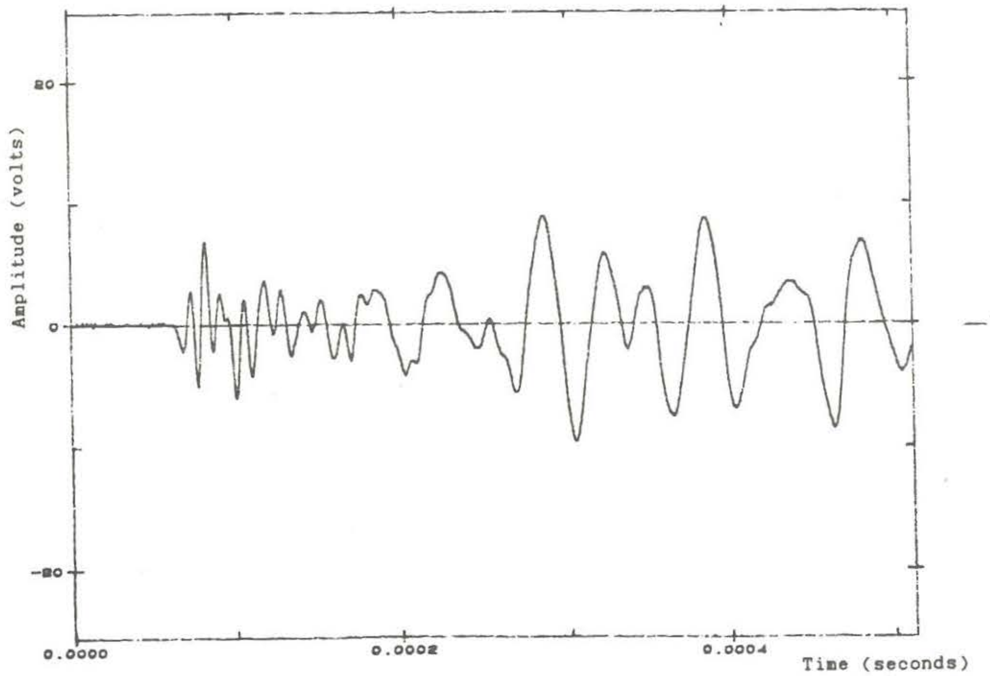


Fig. 4.8 : Waveform Recorded on Siporex Specimen
Size - 150 X 200 X 295 mm.
Path Length - 295 mm.

c) The decrease in the amplitude of the first 2-3 cycles received could be observed as the path lengths, in concrete of similar quality, were increased.

d) When only the first 2-3 cycles were seperated in each case, the frequency analysis of these showed that as the length of travel increased, the higher frequency componants were filtered out, as these suffered higher degree of attenuation than lower frequency componants. Also, since siporex didnot contain any aggregate, the signal received contained more high frequency componants than that received in concrete of same length, although the velocity in siporex was found to be nearly half of that in concrete.

e) For same path length and lateral dimensions, the amplitude as well as the velocity of the received signal was decreased as the porosity was increased. However, the amplitude variation was much more sensitive to porosity than velocity variations.

Based on these observations the following conclusions were drawn.

a) The first few received cycles correspond to the direct longitudinal wave, which travels fastest in the concrete specimen under test. It is the velocity and amplitude attenuation of this wave which is of interest.

b) The signals received subsequently are the reflected waves, transverse waves, surface waves, etc. These depend upon the geometry of the specimen. In smaller specimen, these waves get mixed up with each other and hence cannot be easily distinguished from each other upon their arrival at the receiver.

c) The grain size of siporex is much smaller than the wavelength of waves in the 100 kHz frequency range (λ = 40-50 mm approx. at 100 kHz in concrete), hence the scattering effect is much less. However, attenuation takes place due to increased porosity. This fact is also evident from the decrease in velocity. In concrete, the aggregate size is of the order of 20-30 mm. Hence, scattering effects are more predominantly observed, which results in increased attenuation of higher frequency componants.

Thus, in order to measure attenuation it was required to measure the variation in amplitude of the first 2-3 cycles received. This could be done very easily by observing the signal on an oscilloscope. However, since the aim was to avoid using an oscilloscope, it was necessary to find some other solution for this problem.

The plots of the signals received in concrete specimen showed that the duration for which these initial cycles could be seen before getting lost in the reflected waves arriving subsequently, was approximately minimum 100 microseconds for an average concrete cube of dimensions 150 X 150 X 150 mm. This time increased if the dimensions were larger. Since, this size of cube is generally the smallest sample encountered in concrete testing,

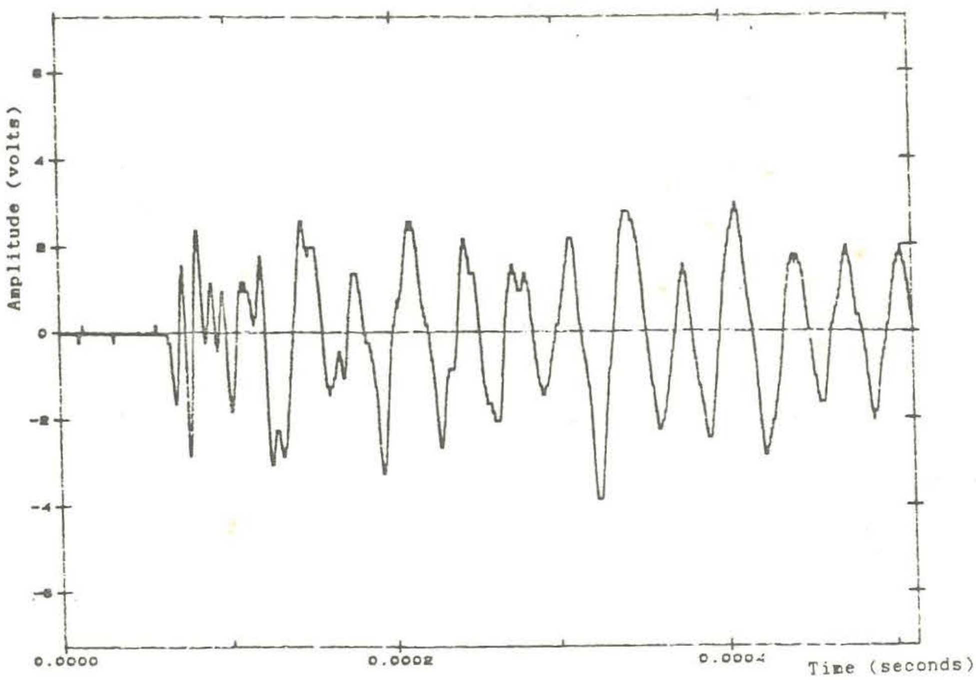


Fig. 4·9 : Waveform Recorded on Concrete Specimen
Size - 100 X 100 X 500 mm.
Path Length - 100 mm.

any technique applicable on such cube can be easily adopted on other larger specimen in field testing. Hence it was decided that the incoming waveform should be sampled for a period of 100 microseconds after its arrival and its peak occuring during that period should be measured irrespective of the fact that it is positive or negetive going.

It was evident that this approach would limit the applicabilty of this technique to samples larger than the average cube size. This is clearly seen from Fig. 4.9, from which it is seen that for concrete speciman of 100 mm width, the reflections start arriving around 70-80 microseconds after the arrival of the first pulse. Also, this technique may not be applicable in specimen having lateral dimensions less than 150 mm since the waves can get mixed with each other in less than 100 microseconds upon arrival at the receiver. However, as stated earlier, such specimen are very rare in actual practice.

CHAPTER 5

DESIGN OF THE INSTRUMENTATION FOR ULTRASONIC PULSE VELOCITY AND ATTENUATION MEASUREMENT TECHNIQUE

5.1 CONCEPT FORMULATION

After studying the various efforts made in the past and the types of instruments used by various researchers for applying ultrasonic techniques for testing of concrete [6,12,13,16,18,25, 32,33] it was decided that initially an attempt should be made to develop an instrument for ultrasonic pulse velocity [UPV] measurement on concrete. Such instruments have been widely used and reported in the past. The commercially available instruments are capable of giving an accuracy better than 1 us in measuring the transit time of the ultrasonic pulse in concrete and the maximum path length over which the measurement can be made is around 5 metres. In order to achieve the above performance it was decided that the transmitter and the receiver part of the instrument should be designed to have a broadband response so as to enable the user to choose the probes of various frequencies between 20 kHz & 200 kHz depending upon the range and accuracy requirements. It was decided to design a microprocessor based instrument so that additional functions can be easily added to the existing instrument by expanding the system hardware and by adding the necessary software. This proved to be a great advantage since the development of the instrument was done in stages during this project.

The desirable features for UPV measuring instrument may be summarized as following:

1] Accuracy of transit time measurement : Ø.1 us

2] Maximum path length over which measurement can be made on concrete : Around 5 m.

3] Operating frequency range of probes : 2Ø to 2ØØ kHz.

4] Operation possible on mains supply as well as on DC storage battery.

This instrument was designed and constructed during the first stage of the project. The instrument was tested successfully in laboratory as well as in field.

Since very little information was available on the technique and the type of instrumentation used for measurement of attenuation of ultrasonic waves in concrete, the instrument developed for UPV technique was used for conducting the experiments, as described in Chapter 4, for deciding the technique for ultrasonic pulse attenuation [UPA] measurement on concrete. It was decided to carry out the circuit design required to implement this technique and to add it as an additional facility to the existing instrument.

Throughout this project the aim was to develop an instrument which is portable and can be carried for field testing at sites.

5.2 CIRCUIT DESIGN

The block diagram of the finally combined instrument for UPV and UPA measurement on concrete is as shown in Fig. 5.1. The microcomputer board is used for controlling the overall sequence of operations of the system. This board is based on the 8748 single chip microcomputer and additionally a 8255 peripheral interface adapter (PIA) and 8254 timer have been added to enhance the capabilities of the CPU.

At the beginning of each measurement cycle the microprocessor initiates a starting pulse of approximately 2 us duration through the 8255 PIA and monoshot. This pulse energizes the transmitter ciruit so that a high energy pulse is applied to the piezoelectric transducer connected to the transmitting port. The transmitter transmits a brief burst of ultrasonic waves into the concrete specimen under test. The receiving transducer generates an electrical signal corresponding to the received ultrasonic wave. This is a very weak signal, of the order of a few hundred uV, and is amplified by the receiver amplifier.

The transit time measurement is carried out by a flip-flop FF1 and the 8254 timer. The brief pulse that initiates the transmitter also sets flip-flop FF1, which is subsequently reset when the leading edge is detected at the receiver amplifier output. Thus, the pulse at the output of FF1 corresponds to the transit time. The counting of 10 MHz clock pulses by the 8254 timer is thus enabled for the duration of pulse transit time. The zero adjustment circuit is provided for compensating the internal delays of the probes and the delays due to cable length of the transmitting and receiving probes.

Amplitude measurement is possible by holding the peak of the first few cycles, corresponding to the direct longitudinal wave, using the peak detector ciruit. This is done by using an analog switch (AS1) for gating the required signal in to the input of the peak detector. This switch is directly controlled from the control lines of the microprocessor. At the beginning of each measurement cycle the microprocessor initializes the peak detector to zero and enables the input to it by switching ON AS1 before initiating the starting pulse. The microprocessor then waits for FF1 to be reset by the leading edge of the received wave and then turns OFF the switch AS1 after a fixed duration of time (approx. 100 usec). The peak detector thus holds the peak amplitude of the cycles arriving during the first 100 usecs. This measured amplitude needs to be passed through an analog to digital converter (ADC) so that the microprocessor can read it. This is achieved by applying the output of the peak detector to a voltage to frequency converter (VFC), which converts it into equivalent frequency output. This is applied to the CLK input of counter 2 of 8254. The microprocessor now enables the GATE input of counter 2 for exactly 100 msec. The count value obtained thus represents the maximum amplitude of the longitudinal wave cycles.

The microprocessor reads these values of transit time and amplitude. The required result is displayed depending upon the

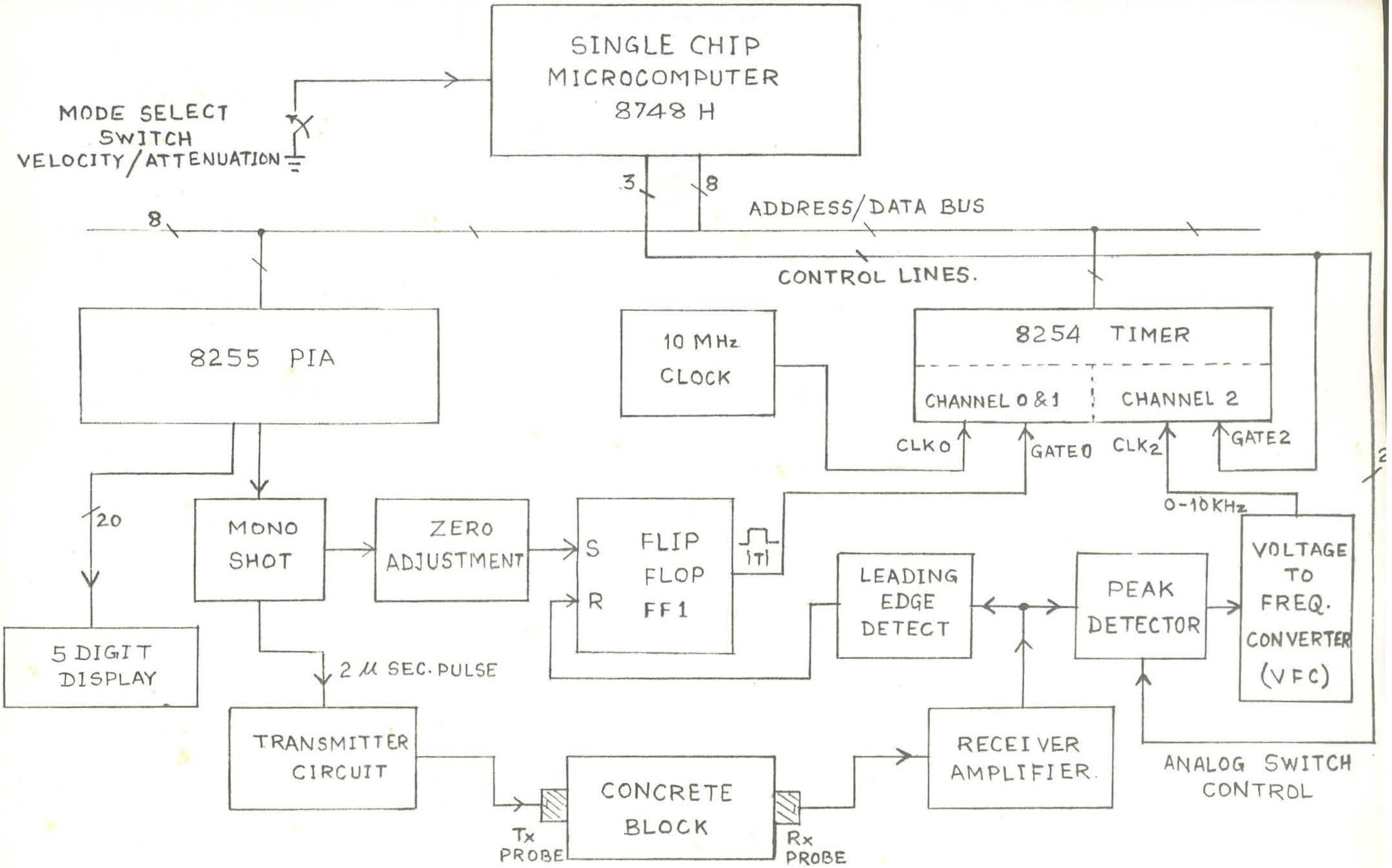


Fig. 5.1 : Block Diagram of the Instrument

position of the mode selector switch. Thus either the transit time or the amplitude is displayed after each measurement cycle.

In case the receiver is unable to detect the pulse, the microprocessor detects overflow of the counter and displays overrange in the transit time mode or zero in amplitude display mode. This process is repeated to obtain the next reading.

In the following subsections, various circuit blocks will be further described.

5.2.1 The Probes

Piezoelectric crystal probes of resonance frequency 150 kHz were used for this project, as suggested by [1,3]. The probe body is made of steel in order to provide ruggedness and to prevent damage due to the rough concrete surface. In order to obtain maximum sensitivity, it is desirable to have a matched pair of probes having identical resonance frequencies.

The probes were connected to the transmitter & receiver terminals using shielded cables to prevent noise being introduced due to external electromagnetic interferences.

5.2.2 Transmitter Circuit

The transmitter circuit is used to generate a high voltage pulse of short duration to energize the piezoelectric crystal transducer. The higher the voltage of the pulse applied to the transducer, stronger is the sound wave generated by it. Generally a practical limit is set by the voltage ratings of the transistors or SCR's used for generating this pulse and also due to the interference caused by this pulse to other circuits. It was found that a pulse of 300 to 400 V applied for a short duration (2 usec. approx.) was sufficient to produce the required results. Hence it was decided to apply a 400 V pulse to the transmitting crystal. The circuit used for this purpose is as shown in Fig. 5.2.

A DC/DC converter module (mfg. by Praag Systems) was used to generate the requisite 400 V DC from the 5 V DC available on the card. The module is capable of delivering approximately 1 W power at 400 V DC output. The capacitor C2 across its output is provided for filtering the DC output. The resistance R1 connected across the capacitor helps in discharging the capacitor once the power is switched off.

Transistor T1 is normally OFF, hence capacitor C3 is normally charged to V_H = 400 V through resistance R2. The base of T1 is connected to the collector of transistor T2, which is driven by the $\overline{Q1}$ output of monoshot MM1 to be described later in Section 5.2.5. Since $\overline{Q1}$ is normally high, T2 is normally ON.

Upon application of a triggering pulse by the microprocessor the monoshot output $\overline{Q1}$ goes low for the time period set on the monoshot (which is approx. 2 us in our case). This results in T2 switching OFF and thus switching ON T1 momemtorily. Capacitor C3

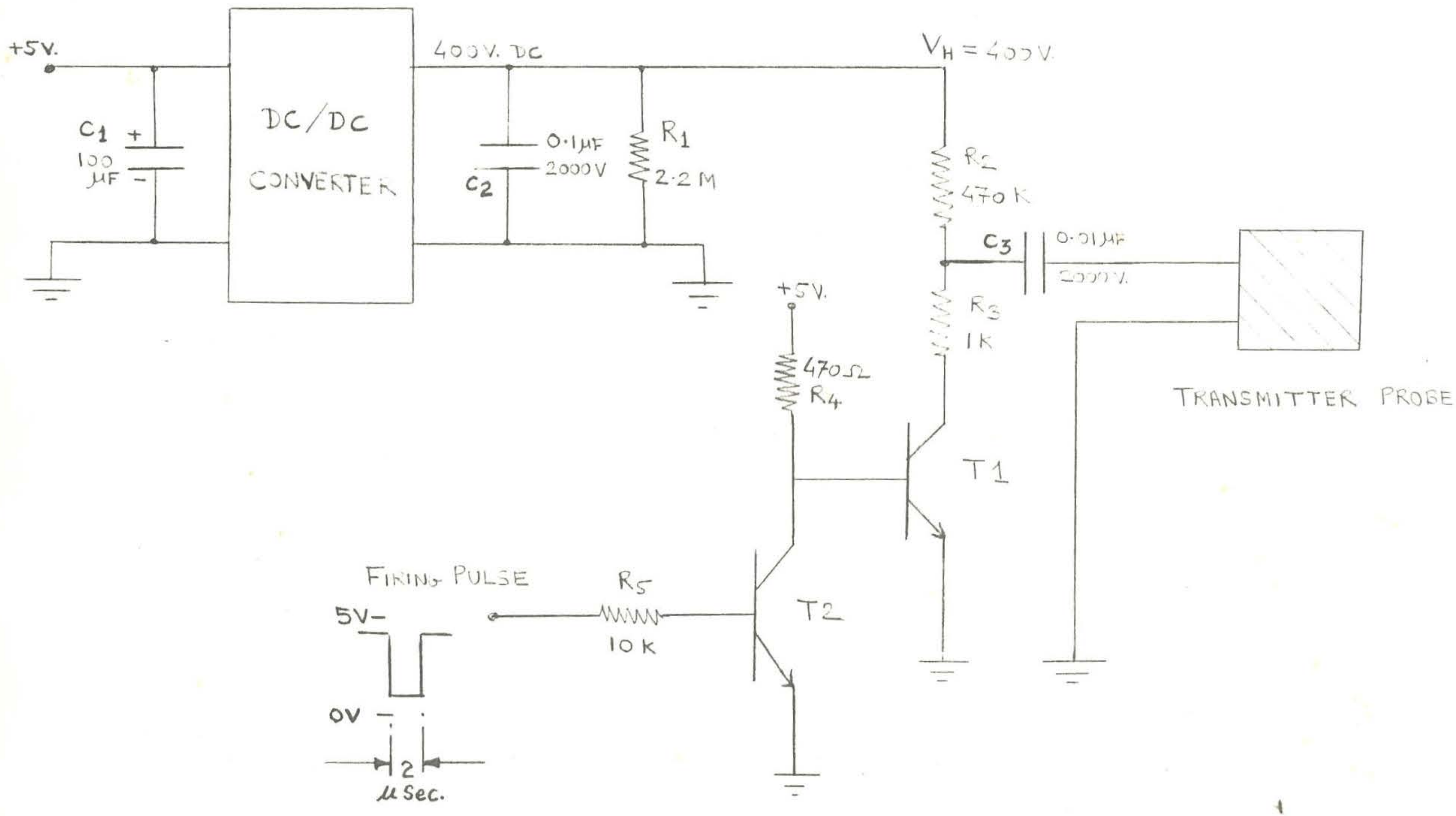


Fig. 5.2 : Transmitter Circuit

discharges through resistance R3 which decides the rate of discharge. This results in the application of a negetive going pulse of voltage $-V_H$ to the piezoelectric transducer thus resulting in the transmission of a burst of ultrasonic waves. This burst is normally referred to as the ultrasonic pulse. The frequency at which this pulse is repeated is referred to as the pulse repetition rate (PRR).

Transistor T1 is required to have a sufficiently high Vcemax, and BU5Ø8 having Vcemax = 7ØØ V [3Ø] has been selected for this purpose. Transistor T2 is basically provided as a driver for driving the base of T1, and SL1ØØ was used for this purpose.

5.2.3 <u>Receiver Circuit</u>

The receiver circuit consists of an amplifier for amplifying the received voltage signals from the receiving probe, a precision rectifier, and a comparator for detecting the leading edge of the received signal. The output of the comparator is converted in to a TTL level signal to be used to reset flip-flop FF1 for transit time measurement.

The receiver circuit is shown in Fig. 5.3. The input from the receiver piezoelectric transducer is coupled through the high pass filter formed by C1 and R1 [19], to the input of the source follower formed by a low noise FET T1 (2N4338). The output of this follower is AC coupled into the transistor amplifier stage formed by transistor T2 (BC147), where a gain of 2Ø is provided.

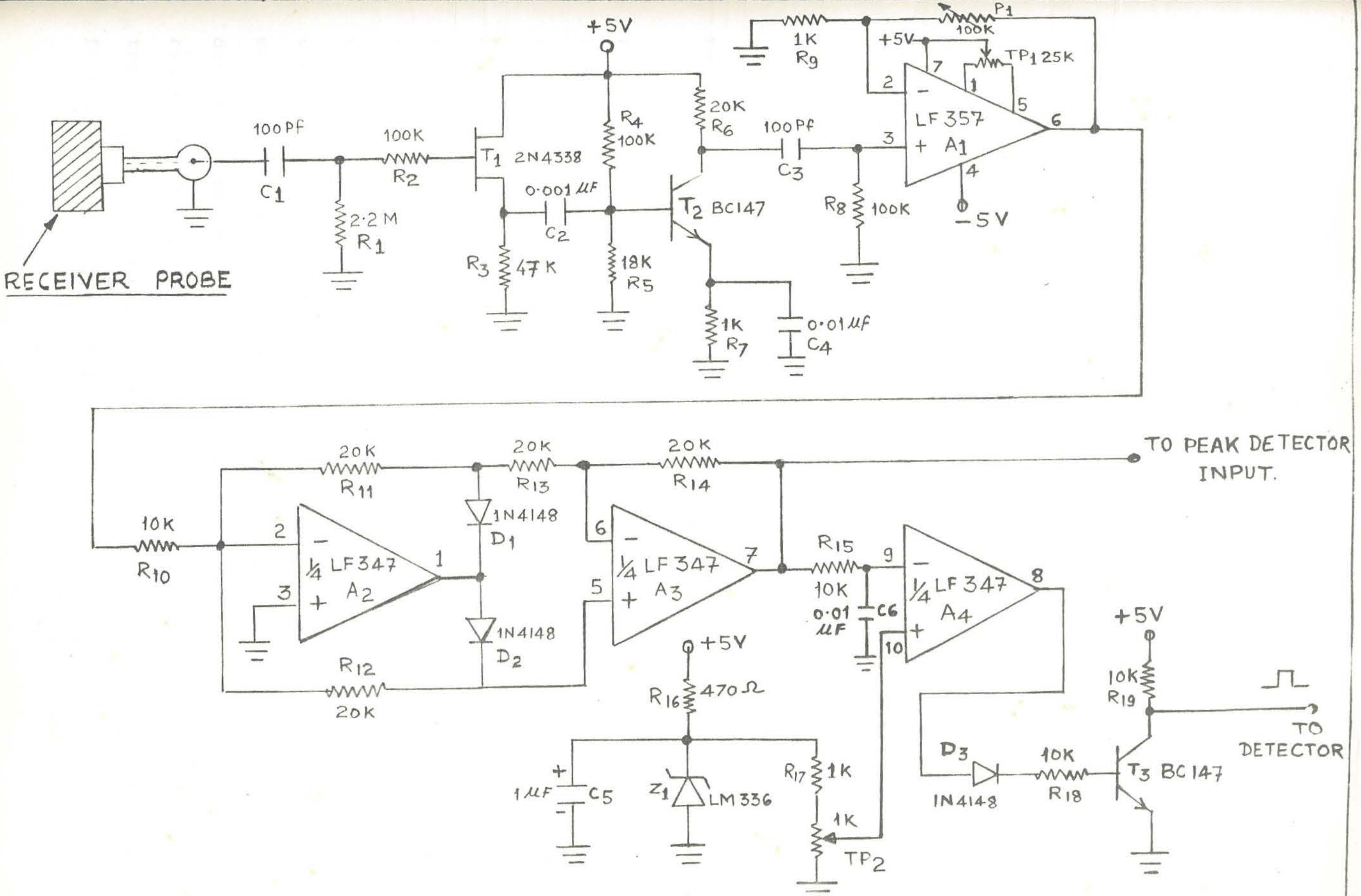


Fig. 5.3 : Receiver Circuit

Again, bipolar amplifier stage is used to reduce noise. The output of this amplifier is AC coupled into the input of opamp A1 (LF 357), connected in the non-inverting amplifier configuration. The gain of this stage is adjustable from 1 to 101 by potentiometer P1, which is provided on the front panel of the instrument. Since the gain is quite high it is necessary to null the offsets of the opamp A1 to avoid errors in the output. Trimpot TP1 is provided to null the offsets.

The output of opamp A1 is a bipolar waveform. It is necessary to convert it into a unipolar waveform so that triggering occurs on the first leading edge of the received signal, may it be positive or negetive going. This is necessary to avoid errors in transit time measurement. Also, the maximum amplitude of the signal can be obtained by sampling the rectified signal only. Hence a precision full wave rectifier is formed by opamps A2 and A3 (two opamps of quad-opamp LF347) [22,23].

The rectified signal at the output of A3 is used for triggering the comparator A4 and also as input to the peak detector circuit. The reference voltage for adjusting the threshold for triggering the comparator A4 is generated using a stable temperature compensated zener (LM336-2.5 V) [23]. The trimpot TP2 is used to set the threshold voltage high enough so that spurious triggering due to noise does not occur. The output of the comparator is rectified to convert it into a unipolar pulse which drives the transistor T3 to produce a TTL level pulse for resetting the flip-flop FF1 on logic card.

The operational amplifiers used are LF357 and LF 347 [22,23]. The choice of these opamps was mainly governed by the high gain-bandwidth product (16 MHz and 4 MHz respectively). Since our input signal frequency is in the range of 20 - 200 kHz, these op-amps are adequate.

5.2.4 Peak Amplitude Measurement Circuit

The peak amplitude measurement circuit, shown in Fig. 5.4, consists of a peak detector, which is used to hold the maximum level of the signal sampled, and a voltage to frequency converter (VFC) stage, which converts this voltage level into a proportional frequency signal, which with the help of the 8254 timer is used as an A-D converter.

The peak detector is formed of opamps A5 & A6 (LF357). The rectified signal at the output of opamp A3 on the receiver card is applied at the input of peak detector. Analog switches AS1 and AS2 are used for gating the signal at the input and for initializing the peak detector, respectively. Solid state CMOS analog switches are used for this purpose (CD4066). These switches are directly controlled from the output port 1 of microprocessor as shown.

Initially switch AS1 is open i.e. OFF and AS2 is closed i.e. ON. This is the initialization stage and results in capacitor C2 discharging through AS2. The output of peak detector is thus set to zero volts.

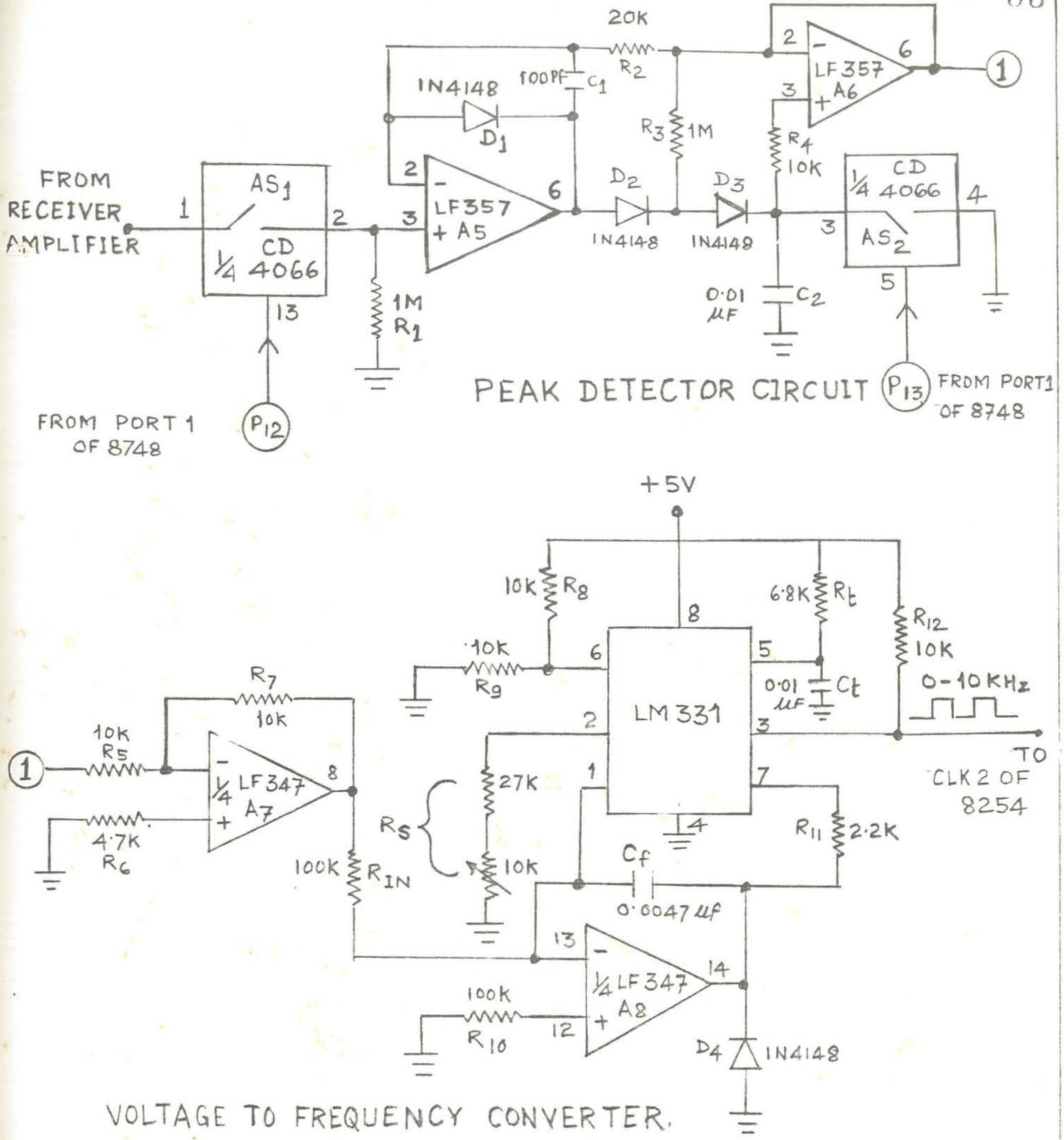


Fig. 5.4 : Peak Detector and Voltage to Frequency Converter Circuit for Pulse Amplitude Measurement.

At the beginning of each measurement cycle, AS1 is closed and AS2 is opened. AS1 is kept in the closed state till 100 usec after the received signal is detected by the time measurement circuit and flip-flop FF1 is reset. Thus the peak amplitude of the signal received during this period is held by the peak detector. A low leakage polyester capacitor is used as C2 to minimize errors due to charge leakage.

This peak detector circuit is a low drift type [22]. The low drift is achieved due to the fact that during hold, nearly zero volts is maintained across diode D3 and thus very low leakage current can flow from C2. Opamp A6 is a FET input opamp with low input bias current [23].

The output of the peak detector is inverted by opamp A7 and applied to the VFC stage formed by IC LM331 and opamp A8 [22,23]. The frequency output of the VFC is related to the input voltage by the following relation [23],

$$F_o = \frac{-V_{in} * R_s}{2.09 * R_{in} * R_t C_t} \qquad (5.1)$$

The componant values have been chosen such that R_s can be adjusted to obtain Fo = 0 to 10kHz for Vin = 0 to -4V.

The VFC output is connected to the CLK2 innput of the 8254 timer/counter.

5.2.5 Logic Circuit & Clock Generation

This additional logic circuit, shown in Fig. 5.5, is used to generate the starting pulse of 2 usec and to obtain a gating pulse of exactly the same duration as the transit time of the ultrasonic pulse in the concrete under test. Additionally, a zero adjustment facility is provided for initial calibration of the instrument before beginning any measurement. The necessity of zero adjustment is explained as follows.

Ideally when the transmitter and receiver transducers are joined face to face with a coupling medium like grease, the transit time measured should be zero microseconds. However it was observed that due to the internal construction of the transducers, the ultrasonic wave transmitted has to travel a finite distance within the transducer itself. This results in the display of some nonzero time interval (10 - 20 us approx.) even when the distance between the transmitter and receiver is zero. Also, depending on the length of the wires used for connecting the probes, the delay in transmission of the transmitted and the received pulse may be required to be compensated. Hence a monoshot (MM2) is provided with an adjustable pulse width by providing potentiometer (TP2) which is referred to as the zero setting potentiometer. The use of this can be explained with reference to the circuit shown in Fig. 5.5 as the following.

The START command pulse from the microprocessor triggers the monoshot MM1 on its negetive going edge. The TP1 and C1

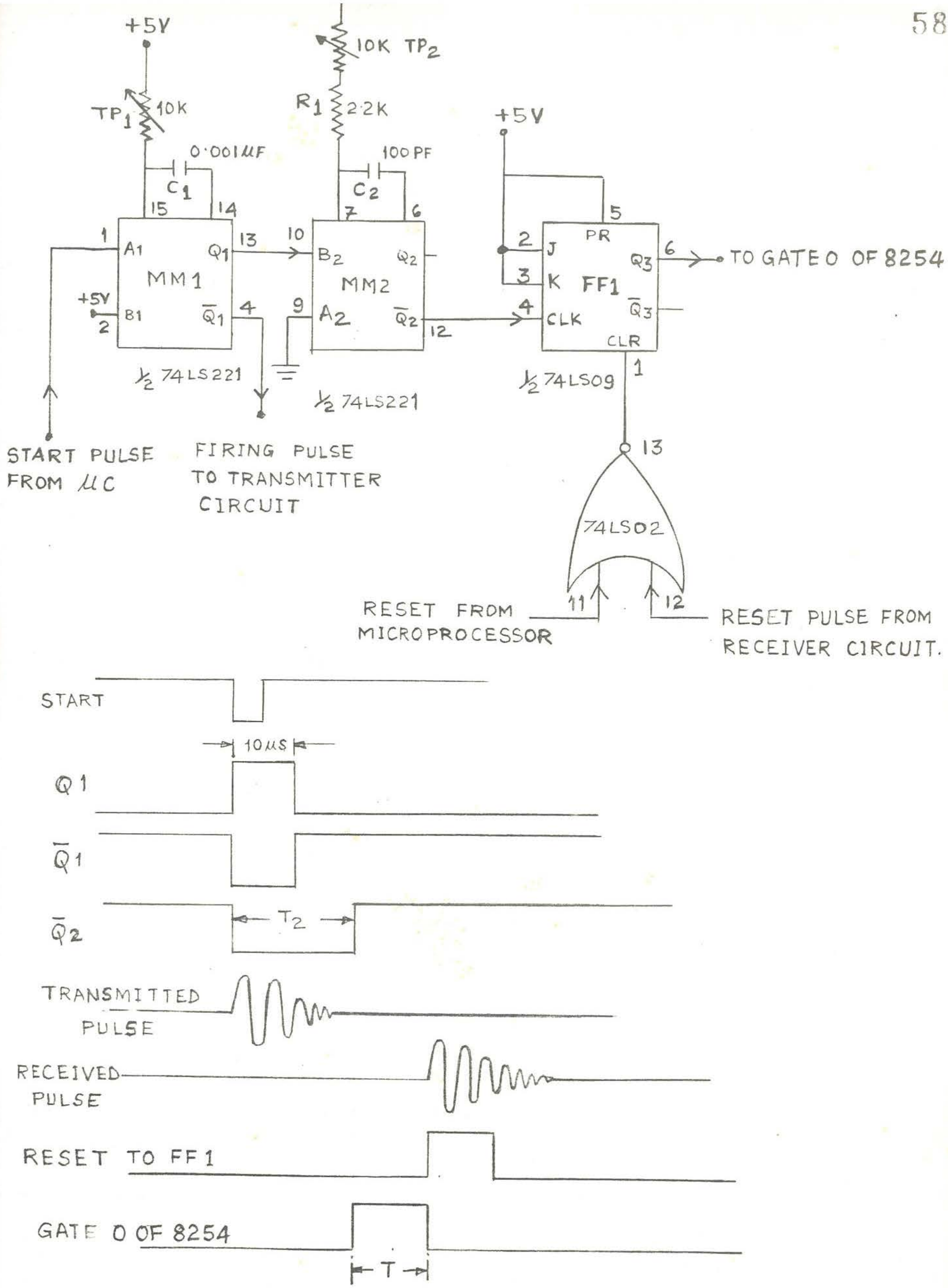


Fig. 5.5 : Logic Circuit and Timimg Diagrams for Transit Time Measurement

componants are chosen to obtain a pulse width of approx 2 us by adjusting TP1. The Q1 output of MM1 triggers monoshot MM2 on its positive going edge, whereas the $\overline{Q1}$ output is used to provide a 2 us pulse for energizing the transmitter. The pulse width of the monoshot MM2 is adjustable with potentiometer TP2, which is the zero adjustment potentiometer. The $\overline{Q2}$ output of monoshot MM2 is applied to the CLK terminal of FF1, due to which the flip-flop gets set on the positive going edge of $\overline{Q2}$. The amplified pulse from the receiver is used to reset the flip-flop by pulling the CLR input low.

The monoshot MM2 is used for delaying the setting of FF1 to compensate for the error introduced due to the delays introduced due to the probes, wires, and transmission and receiver circuits. For zero adjustment, the probes are joined together firmly by applying a suitable coupling medium like grease or soap. The potentiometer TP2 is turned till the duration of the output pulse from flip-flop FF1 at Q3 output is observed to be just going to zero. (This can be done normally by adjusting the potentiometer till the display starts reading zero us.) The zero adjustment has to be done each time when the set of probes being used is changed or when probe wires of different length are used.

The output Q3 of the flip-flop FF1 is applied to the GATE input of the 8254 Timer/Counter on the microprocessor board [9]. The 10 MHz clock is generated using the multivibrator circuit realized using NOR gates of 74LS02 [21] as shown in Fig. 5.6. This clock is applied to the CLOCK input of 8254. Thus the counting is

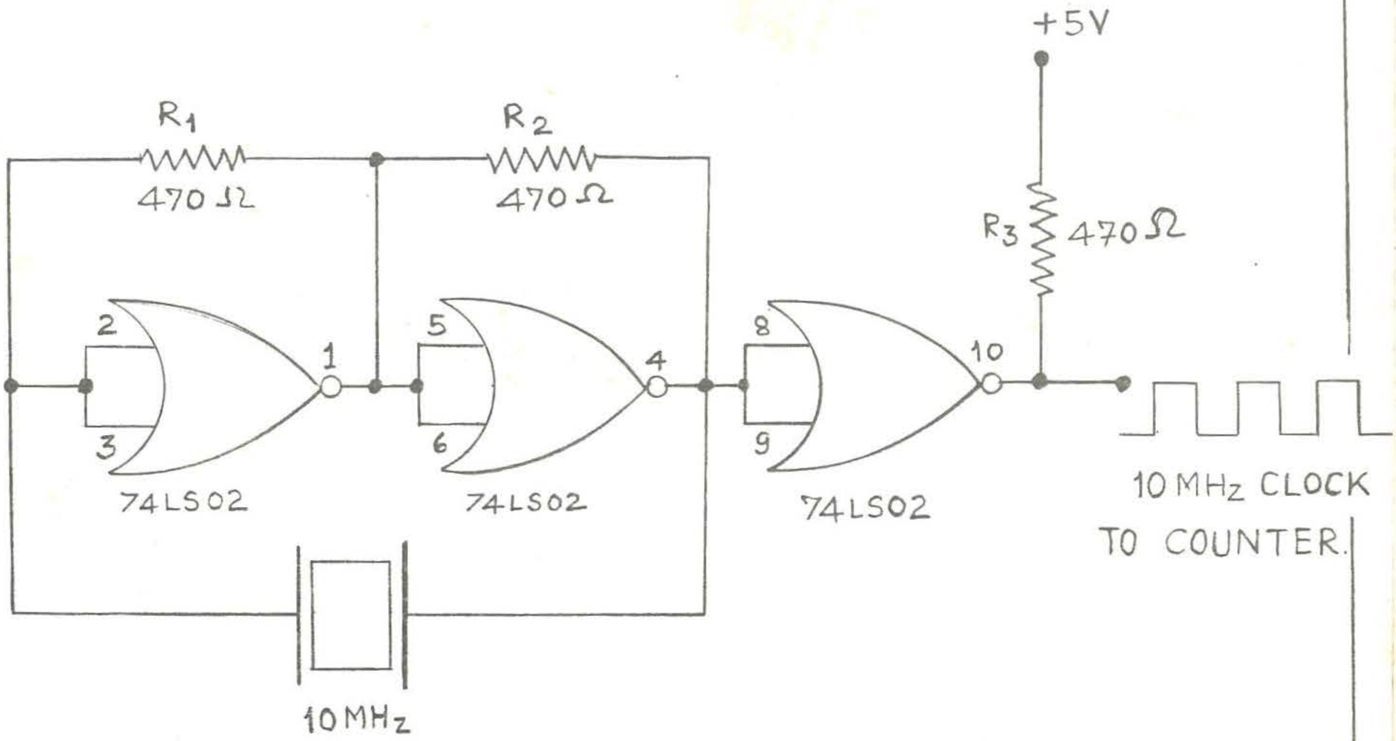


Fig. 5.6 : Clock Generator Circuit

enabled only as long as the GATE signal is high. The microprocessor reads the counted value upon sensing the resetting of FF1. This value can be displayed directly as the elapsed time in us.

5.2.6 The Microprocessor Board

The microprocessor board used in this application is a special purpose board designed to be used in this project. The circuit schematic diagram is shown in Fig. 5.7. This board is built around the Intel MCS 48 family of single chip microcontrollers [8], and interface with several peripheral ICs is provided by using the expanded MCS 48 configuration. The choice of board design based on a single chip microcontroller helps in reducing the chip count, and is found to be sufficient for the current application which is not computation intensive. Also there is reduction in power consumption, which can be of great advantage in battery powered instrumentation.

The 8748 microcontroller is used. It contains on-chip 1 K byte EPROM & 64 bytes of RAM. The program can be stored in the EPROM & the RAM can be used as a scratchpad memory during program execution. The board includes one 8255 PIA, one 8254 timer, one 8279 keyboard/display controller, and one 6116 CMOS RAM which has a provision for back-up battery so that data are not lost in case of power failure. The 8748 can operate in stand alone manner with limited number of input and output pins or depending on the

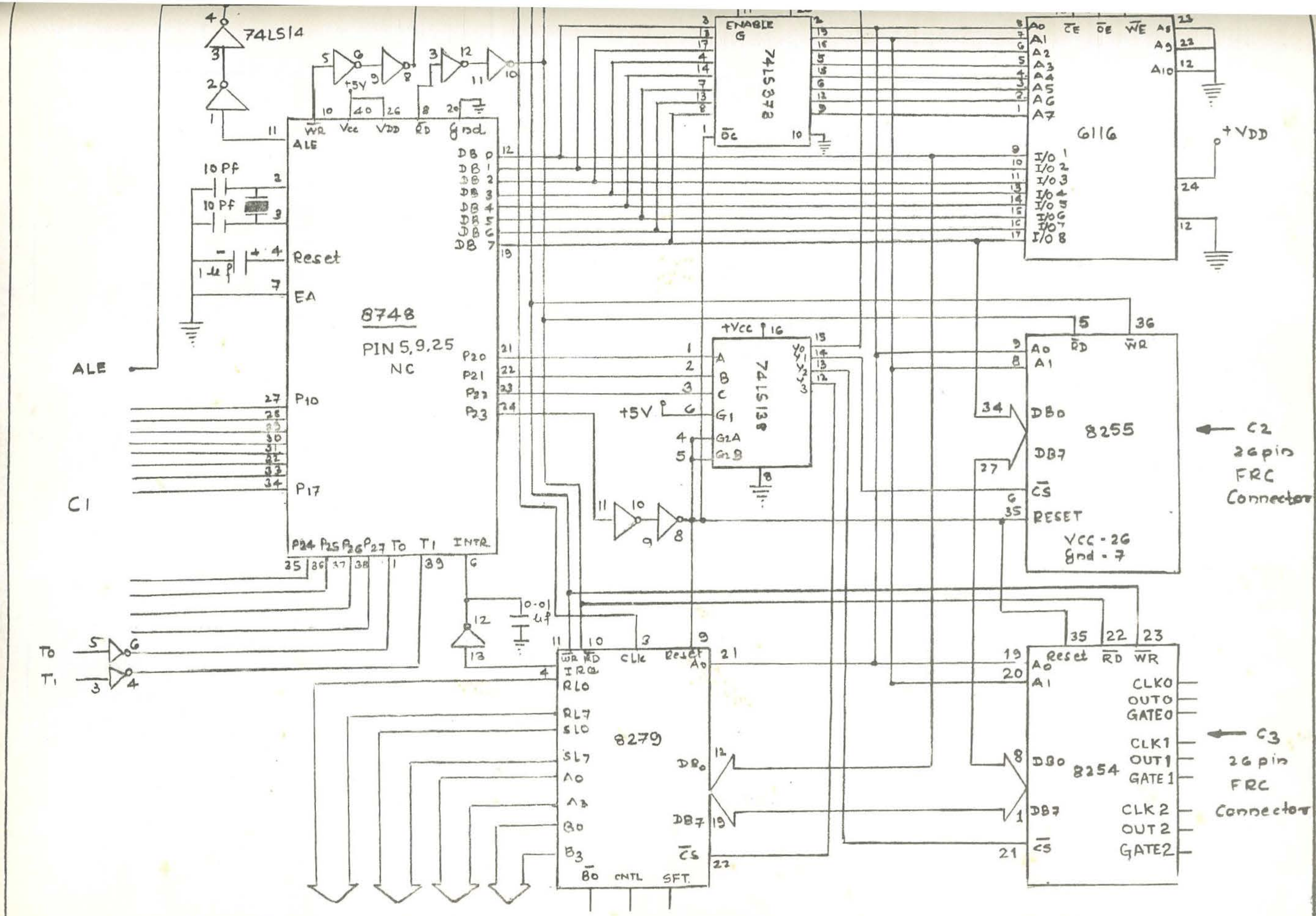


Fig. 5.7 : The Microprocessor Board

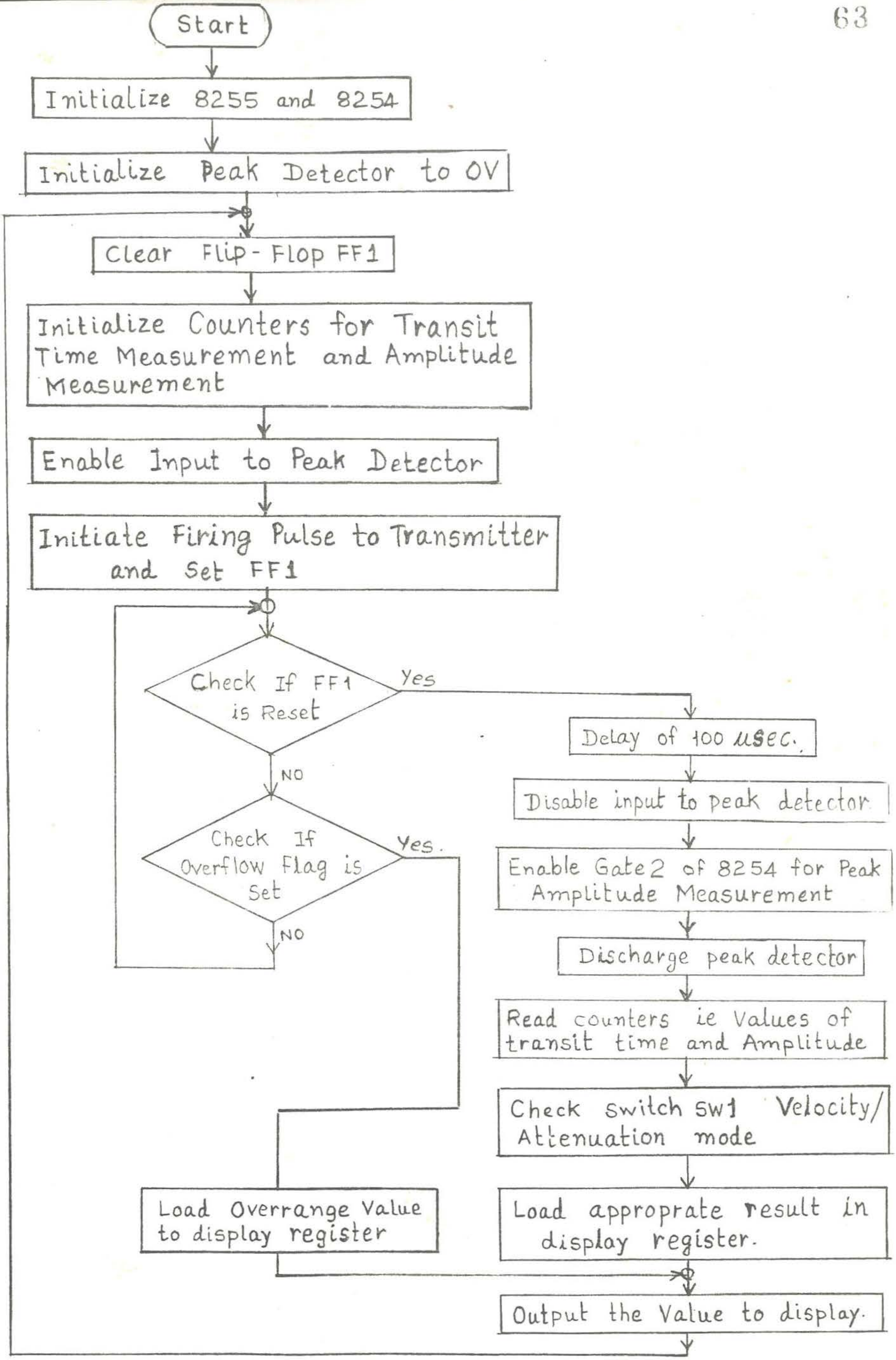


Fig. 5.8 : Software Flowchart

application requirements its capabilities can be enhanced by adding the necessary peripheral chips. The board was designed by the author to serve as a general purpose board. For the present application the 8254 timer is used for counting the 10 MHz clock pulses and for counting the frequency input from VFC. The display interface is through the output ports of the 8255 PIA.

The software was written in the assembly language of MCS 48 family of microcontrollers. The flowchart is as shown in Fig. 5.8.

5.2.7 Display Circuit

The display card uses CD4511 BCD to seven segment decoder IC's [21]. The value to be displayed is provided in BCD form at the output of 8255.

5.3 FABRICATION AND ASSEMBLY

Initially the design of the instrument for UPV measurement was completed. Since the transmitter generates a considerable amount of RF noise, this section was well shielded away from the rest of the circuits by fitting a metallic cover over it. The receiver, being highly susceptable to external noise, was also covered with a metallic cover. The PCB's were fitted on an aluminium chassis and wired. Good quality connectors were used for interconnections in order to prevent breakdowns due to loose contacts. After successful field trials of this instrument, the design of the pulse amplitude measurement circuitary was undertaken in the second stage of the project. This was designed as an additional feature to the existing design. The circuit was tested for its stability and reading accuracy in the laboratory. The results obtained on specially prepared laboratory specimen were found to be encouraging. Also, field trial was taken at one site only. The results obtained are presented in Chapter 6.

5.4 DESCRIPTION OF THE INSTRUMENT

Operating Modes (Switch Selectable)	: a) Transit Time Measurement b) Pulse Amplitude Measurement
a) Time Measurement	
Range	: 0000.1 to 9999.9 usec
Resolution	: 0.1 usec
b) Amplitude Measurement	
Range	: 000.0 to 100.0 %
Resolution	: 0.1 %
Display	: 5 digit 7 segment 1/2" LED display (green colour)
Ultrasonic Frequency Range	: 20 - 200 kHz
Timebase	: 10 MHz (Crystal controlled)
Pulse Repetition Rate	: 5 pulses/sec
Power Supply	: 230 V AC mains

CHAPTER 6

TEST RESULTS AND DISCUSSIONS

6.1 INTRODUCTION

The instrument designed and fabricated during this project can be used for the measurement of the transit time (usec) and amplitude (%) of an ultrasonic pulse in concrete. From these measurements the ultrasonic pulse velocity (UPV) and ultrasonic pulse attenuation (UPA) can be computed. The results obtained can be used in the combined method of estimation of the compressive strength of concrete by using nondestructive techniques [7,18,29]. The following section describes the testing procedure to be employed with this instrument. Also, the test results obtained with this instrument on some specially prepared concrete specimen and in a few field trials are presented and discussed in Section 6.3.

6.2 TESTING PROCEDURE

1) Clean the contact surfaces of the concrete block to be tested and grind them smooth with a carborundum grinding stone.

2) Apply a low viscosity couplant (e.g. petroleum jelly) on these contact surfaces of the concrete block and also on the surfaces of the transmitter and the receiver probes.

3) Switch ON the instrument and join the two probes together. Adjust the zero setting potentiometer to read 0000.0 usec on the instrument in the velocity mode.

4) Keeping the probes coupled together, check that the instrument reads amplitude of 100.0% in the attenuation mode. Adjust the gain potentiometer if necessary.

5) Now, apply the probes firmly on the two sides of the specimen and take readings of the transit time (usec) and amplitude (%) by keeping the selector switch in the velocity and attenuation modes respectively.

6) The velocity can now be computed from the transit time and the path length in the concrete block. The attenuation can be studied from the percentage variations in amplitude as a relative measurement.

While performing amplitude measurements, the following precautions are necessary to be observed.

1) If the specimen size is small, i.e. of the order of 200-300 mm length, then the pulse received is very strong. Hence it may be necessary to reduce the gain in order to avoid saturation of the amplifier.

2) A set of amplitude readings should be taken at a fixed amplifier gain only, so that these can be compared.

3) All the observations for relative amplitude measurement should be necessarily performed with the same set of probes.

6.3 TEST RESULTS

The instrument made for UPV measurement was portable and could be used at various sites for checking concrete quality in-situ. The results obtained at two sites are presented in Section 6.3.1. After adding the facility for UPA measurement the instrument was not fully portable, hence only limited site testing was possible to check the results of the combined method using velocity and attenuation measurement. These results are presented in Section 6.3.2.

6.3.1 Ultrasonic Pulse Velocity (UPV) Tests

UPV TEST 1

The test for checking repeatability of the velocity measurement using the instrument was carried out on a rod of aluminium alloy having diameter of 50 mm. The rod was cut in lengths of 100, 300, and 500 mm. The end surfaces were filed smooth to ensure proper coupling between the probes and the rod. The transit times recorded by the instrument on these lengths of the rod were noted and the velocity was computed in each case.

TABLE 6.1

Material used for testing :

Aluminium Rod (Diameter - 50 mm)

Probe Frequency - 100 kHz

Sr. No.	Length l (mm)	Transit Time t (usec)	Velocity V = l/t (m/sec)
1	100	16.8	5952
2	300	50.3	5964
3	500	84.2	5938

The results presented in Table 6.1 indicate that the velocity remains nearly constant when readings are taken over various lengths of the same specimen. However, the velocity of ultrasonic waves in aluminium is reported as 6200 m/s [16]. Hence it was concluded that the aluminium rod used for carrying out the testing may be actually made of an alloy, due to which the average velocity is reduced.

UPV TEST 2

The results obtained using probe sets of 27 kHz, 54 kHz, 100 kHz, and 150 kHz frequencies were studied by taking transit time readings on concrete cube and cylinderical specimen.

TABLE 6.2

Specimen	Path Length (mm)	27 kHz	50 kHz	100 kHz	150 kHz
		Probe Frequency			
		Time (usec)			
Concrete cube Size - 150X150X150 mm	150	39.2	39.2	39.2	39.2
Concrete Cylinder Size - d - 150 mm l - 300 mm	300	64.6	64.6	64.6	64.6

The results presented in Table 6.2 show that the readings obtained at various probe frequencies are same.

UPV TEST 3

The instrument was carried to construction sites for checking the performance under actual field testing conditions. The testing was performed by M/s Composites Combine Technical Consultants, Bombay. The test reports are attached in Appendix I.

(These reports are attached with the kind permission of M/s Composites Combine Technical Consultants, Mulund, Bombay.)

UPV TEST 3 (A) - TEST REPORT 1

This report presents the concrete testing performed at M/s Vikram Ispat Ltd., Alibag. The ultrasonic pulse velocity (UPV) test was carried out for estimating the strength and for detecting the uniformity of concrete. The section where UPV was observed to be lower than other sections was weaker due to the presence of porosity. The report shows that the UPV has improved after suitable repairs were carried out on the weaker portions.

UPV TEST 3 (B) - TEST REPORT 2

This test report presents the UPV observed on a machine foundation at M/s Kesar Petro-Products Ltd, Chiplun. The average UPV was found to be 4157 km/s. Hence the concrete was certified to be acceptable. The report also gives the estimated strength calculated on the basis of the UPV observed to be 365 kg/cm^2.

6.3.2 Combined Tests - Ultrasonic Pulse Velocity (UPV) and Ultrasonic Pulse Attenuation (UPA) Tests

The results presented in Section 6.3.1 confirmed the reliability of the instrument for UPV tests. Tests were performed for verifying the consistency of the results obtained by UPA method. For this purpose readings of both, UPV and UPA methods, were taken on each sample and the results obtained were studied.

COMBINED TEST 1

Five cylinderical specimen of concrete were cast in the laboratory in identical moulds of diameter 150 mm and length 300 mm. These were cast at the same time using one concrete mixture but the degree of compaction was varied in each case. The purpose was to prepare specimens having varying percentage of porosity, while all other parameters remained same. These samples were cured in water for 28 days so that the concrete mixture was properly set. The density and percentage porosity were estimated by measuring the dry weight and the water absorption by each cylinder. These results are shown in Table 6.3 (A). Readings were taken for pulse velocity and pulse amplitude and were tabulated as given in Table 6.3 (B).

The plots of amplitude (%) v/s velocity (m/sec) and amplitude (%) v/s porosity (%) are shown in Figures 6.1 and 6.2 respectively. Results presented here agree with the results obtained by Facaorau [7].

TABLE 6.3 (A)

Volume of each cylinder - 0.0053 m^3

Sample No.	Weight (kg)	Density (kg/m^3)	Porosity (%)
C1	13.705	2585	1.1
C2	13.260	2501	4.2
C3	11.955	2255	13.3
C4	11.715	2209	15.6
C5	10.350	1952	25.5

TABLE 6.3 (B)

Length of Cylinder = Path Length (l) = 300 mm.

Velocity = V = l/t (m/sec) where, t = transit time (usec)

Sample No.	Porosity (%)	Transit Time t (usec)	Velocity V (m/sec)	Amplitude (%)
C1	1.1	64.6	4644	84.5
C2	4.2	72.3	4149	81.2
C3	13.3	92.0	3260	72.3
C4	15.6	103.5	2898	54.9
C5	25.5	117.0	2564	14.0

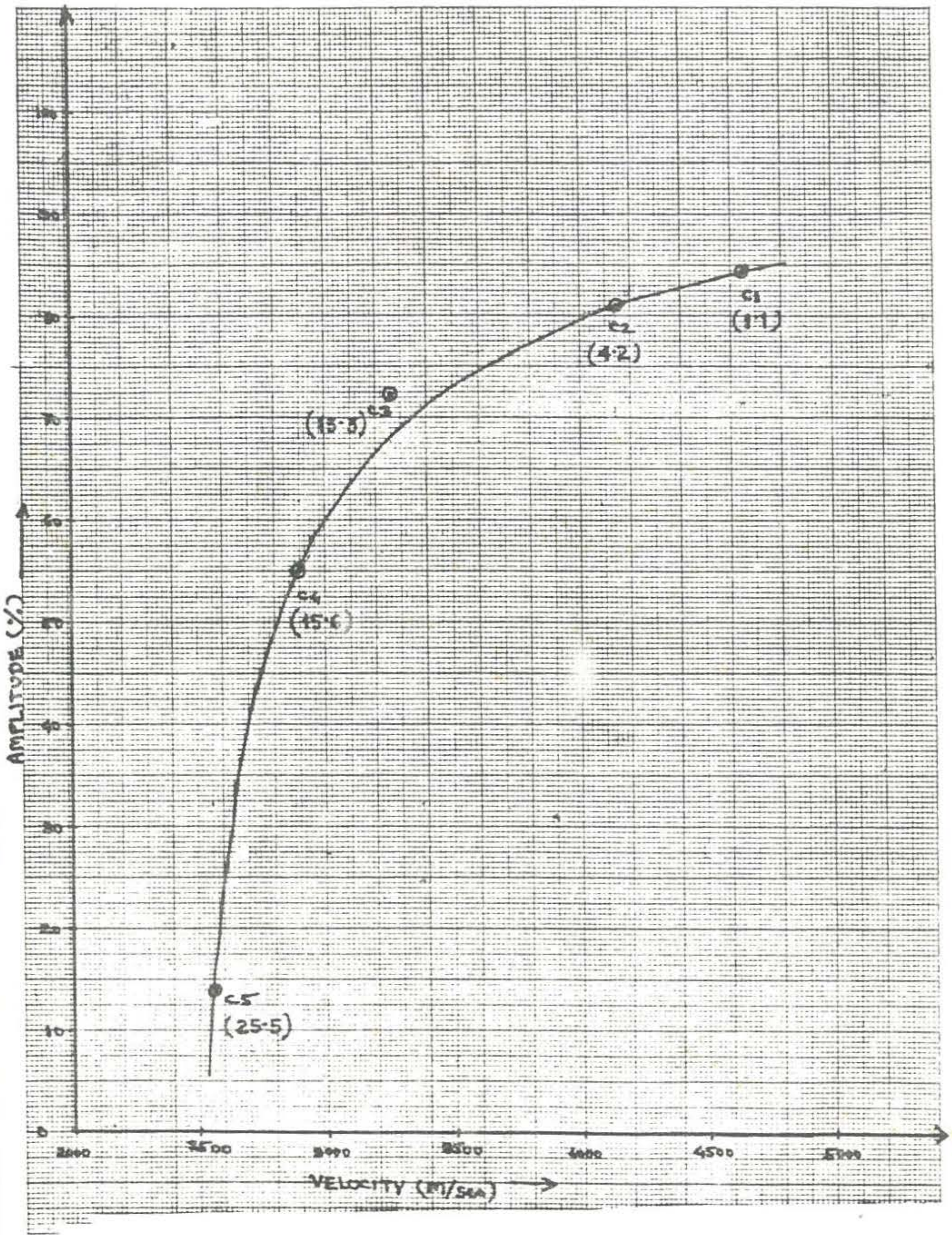


Fig. 6.1 : Plot of Velocity v/s Amplitude Observed on Five Identical Concrete Cylinders Having Varying Degree of Porosity. The Values in Brackets Show the Porosity (%).

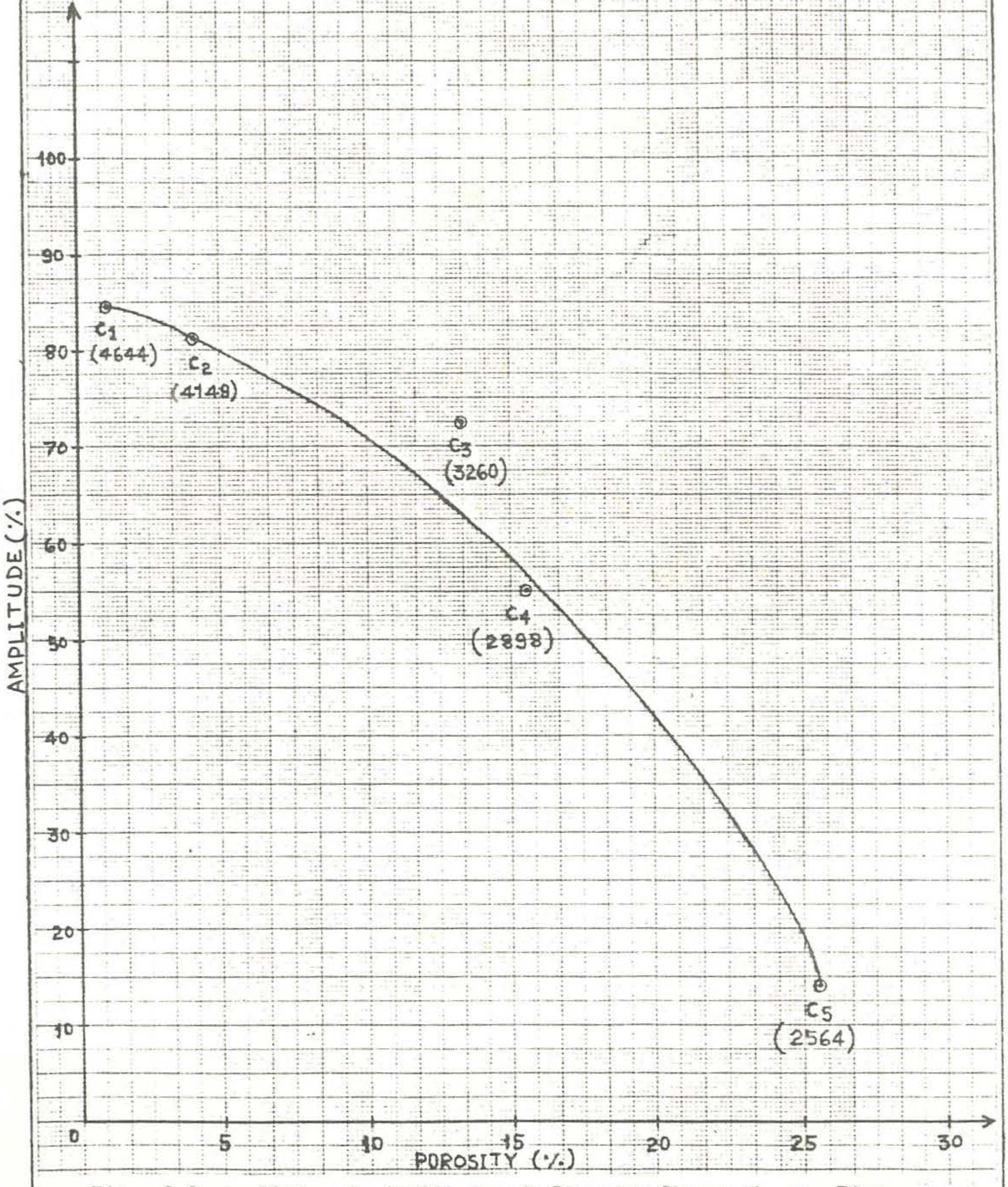


Fig. 6.2 : Plot of Amplitude v/s Porosity Observed on Five Identical Concrete Cylinders Having Varying Degree of Porosity. The Values in Brackets Show the UPV (m/sec) Observed.

Figs. 6.1 and 6.2 show that the amplitude as well as velocity of the ultrasonic wave decreases as the percentage porosity increases in concrete. However, the amplitude variation is much more sensitive to porosity variation as compared to the variation in velocity.

COMBINED TEST 2

Fifteen cubes of concrete were cast in standard moulds of 150X150X150 mm size, using freshly prepared concrete mix. These cubes were given numbers 1 to 15 and the transit times of ultrasonic pulses in these cubes were noted. These cubes were then pasted sidewise to each other in groups of 2, 3, 4, and 5 using epoxy adhesive (trade name - Monopol). Thus it was possible to obtain concrete blocks of lengths 150, 300, 450, 600, and 750 mm. from these cubes. These blocks were then used for carrying out velocity and attenuation studies on varying lengths of concrete.

The results obtained were tabulated as given in Table 6.4. The plot of Amplitude (%) v/s Path Length (mm) is shown in Fig. 6.3.

TABLE 6.4

Sr. No.	150X150X150 mm Concrete Cube Configuration and Individual Pulse Transit Times of Cubes (usec)	Path Length (mm)	Pulse Transit Time (usec)	Velocity (m/sec)	Pulse Amplitude (%)
	Both Probes Joined (Initial Settings)	0	000.0	----	93
1	$\boxed{1}$ 39.7 = 39.7	150	39.7	3778	77
2	$\boxed{2}\boxed{3}$ 44.1+39.8 = 83.9	300	85.3	3517	53
3	$\boxed{4}\boxed{5}\boxed{6}$ 39.2+40.1+39.4 =118.7	450	121.1	3716	47
4	$\boxed{7}\boxed{8}\boxed{9}\boxed{10}$ 40.1+39.4+38.9+40.1 =158.5	600	186.5	3217	6
5	$\boxed{11}\boxed{12}\boxed{13}\boxed{14}\boxed{15}$ 38.8+40.4+39.1+41.3+38.6 =198.2	750	203.9	3678	22

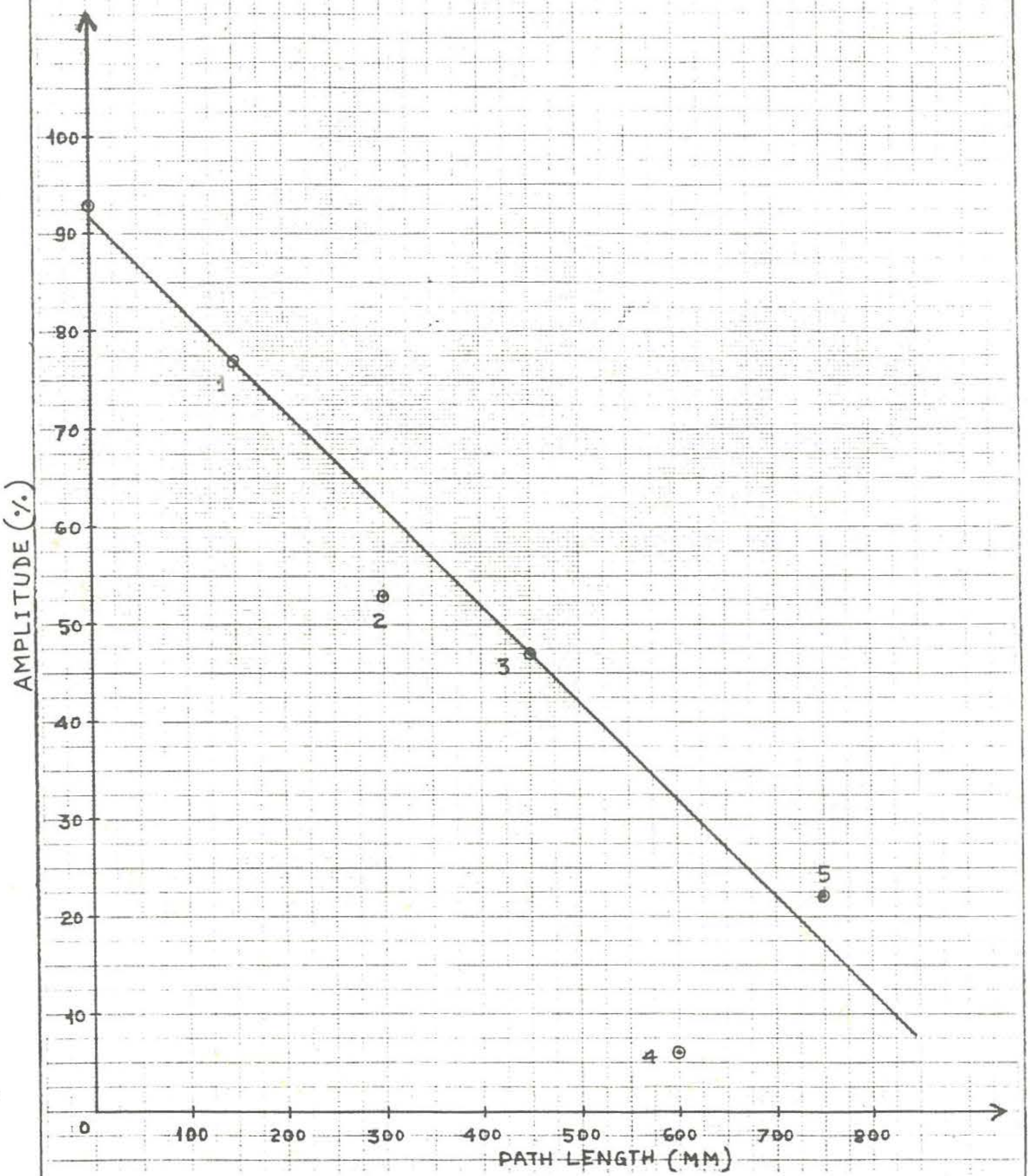


Fig. 6.3 : Plot of Amplitude v/s Path Length Observed on Five Identical Concrete Blocks of Different Lengths

The results presented in Table 6.4 were analysed and the following conclusions could be drawn.

1) The observations of pulse transit time and amplitude measurement were fairly consistent, except in case 4.

2) In cases 1,2,3, and 5, the total pulse transit time was expected to be equal to the sum of the individual pulse transit times of the cubes. However, it was observed that the total transit times of ultrasonic pulses in the blocks obtained by pasting these cubes always exceeded this sum by a few microseconds. It was reasoned out that this error was due to the interface of epoxy layers between the cubes. It was estimated that each interface introduced an error of approximately 2-3 microseconds in the transit time measurement. This error was reflected as an appearant decrease in the average pulse velocity in the blocks.

3) The graph of Amplitude (%) v/s Path Length (mm) showed that the amplitude of the pulse decreased almost linearly as the path length was increased.

4) From the graph of Amplitude v/s Path Length it was observed that the amplitude measured in case 2 was less than the expected value. Further, it was also observed that the average velocity computed in case 2 was 3516 m/sec, which was less than the normal value of around 3700 m/sec for other blocks. Thus it was verified that both measurements gave an

indication of the flaw in the block. It was noticed that the individual pulse transit times measured in cube 2 and 3 had been recorded as 44.1 usec and 39.8 usec respectively, which showed velocities of 3401 m/sec and 3769 m/sec in these cubes. Thus cube 2 showed considerable reduction in pulse velocity, which indicated that it was weaker in strength. Hence, the properties of the combined block obtained by joining cube 2 and 3 were not as good as other blocks.

5) In case 4, appreciable decrease in average pulse velocity was observed (3217 m/sec). Also, the graph of Amplitude v/s Path Length (Fig. 6.3) showed that the amplitude observed (6 %) was much less than the expected value. Hence, it was concluded that at least one or more cubes in the block contained flaw.

The velocities computed from pulse transit time readings on individual cubes of this block (cubes 7, 8, 9, and 10) were found to be in the range of 3700 m/sec, which did not give any indication of flaw. However, it was later found out that cube 9 had honeycombing and blowholes near the surface at it´s interface with cube 8. Since, the individual transit time measurement was made across the surfaces perpendicular to this surface, the path of the pulse was not affected by these flaws and hence the reading did not show any increase in transit time.

These observations indicate that the results obtained by pulse attenuation measurement technique are consistent with the results obtained by pulse velocity measurement technique. In fact attenuation measurement can be used to support the findings of the pulse velocity measurement and to improve the reliability of conclusions based on test results.

COMBINED TEST 3

Tests were performed on concrete blocks of mix. M-100 at the construction site of jetty at M/s Vikram Ispat Ltd., Alibag. The results obtained on two different test blocks were tabulated as in Table 6.6.

TABLE 6.6

Sample No.	Path Length l (mm)	Transit Time t (usec)	Velocity V (m/sec)	Amplitude (%)
Block A				
1	420	148.8	2822	61
2	930	301.8	3081	52
3	1610	774.4	2079	19
Block B				
1	600	235.0	2553	45
2	1800	762.0	2362	33
3	2250	922.1	2440	27

It is seen from these results that in case of block A reading no. 3 showed a sudden decrease in UPV which was also accompanied by a sudden decrease in amplitude. This was indicative of weaker concrete. It was found after investigations that microcracks had developed in that portion of block due to uneven loading.

In case of block B, where variations in UPV are not much, the decrease in amplitude is seen to be gradual with increase in path length.

CHAPTER 7

CONCLUSIONS & FUTURE SCOPE OF WORK

The objective of the project was to design and fabricate a portable instrument for in-situ testing of concrete using ultrasonic pulse velocity (UPV) and ultrasonic pulse attenuation (UPA) techniques.

The technique for UPV measurement is well established. The instrument for the UPV technique was designed and fabricated during the initial stage of the project. This instrument has been applied successfully for laboratory and field testing applications. The results obtained are repeatable and accurate enough to estimate the concrete parameters satisfactorily.

The technique for UPA measurement was not known at the beginning of the project. Hence a laboratory study was carried out to investigate a method for measuring the ultrasonic pulse amplitude in concrete. The necessary instrumentation for implementing this measurement technique was designed and added to the UPV measuring instrument. The instrument was then used for carrying out combined UPV and UPA tests on concrete. Both, UPV and UPA measurements, showed consistent results. Also, it was seen that the sensitivity of UPA to variations in porosity was more than the UPV.

These results indicate that, in addition to the velocity measurements, the instrument can also be used for relative attenuation measurements of ultrasonic pulses in concrete. However, this investigation is still in a preliminary stage. The applicability of the UPA technique needs to be assessed as well as proper analysis of the results obtained with the instrument should be made to verify the work presented here. The final aim shall be to conduct experiments for determining the value of attenuation coefficient (α) on a given type of concrete, so that the application of attenuation technique for field testing can become useful for in-situ testing like the UPV technique.

Also, in the existing instrument the work for incorporating additional features like data logging can be undertaken.

The possibility of using similar techniques for testing of other nonhomogeneous and composite materials can be studied and the instrument can be modified if necessary to enable its usage in such applications too. However it should be noted that similar to the study of concrete undertaken in this report, the case study for detailed investigation of each material needs to be undertaken to decide the exact application of NDT techniques using ultrasonics and interpretation of the results.

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APPENDIX I

TEST REPORTS

TEST REPORT 1

ULTRASONIC TESTING OF CONCRETE OF FOUNDATION P2-CO2 ABSORPTION SYSTEM AT VIKRAM ISPAT LTD., ALIBAG.

Ultrasonic test was carried out on a huge foundation at the above site. The concrete foundation was octagonal in plan with each side of 2085 mm (concrete path length 5050 mm as shown in Fig. A-1), and height 2500 mm. The concrete was of M-20 grade. It was necessary to establish the strength of concrete as well as uniformity. The ultrasonic pulse velocity (UPV) readings were taken at three levels a, b, and c as shown in Fig. A-1. Three UPV readings were taken on each face at every level (12 UPV readings were taken at each level and thus total 36 UPV readings were taken). The UPV values observed at each location are shown in Fig. A-2. The results were summerized as the following.

TABLE A-1

Location	No. of UPV Readings	Average UPV (m/sec)	Variation (%)
Top - a	12	3723	3.38
Centre - b	12	3728	2.90
Bottom - c	12	3353	5.86

The UPV more than 3600 m/sec indicated the acceptable strength of concrete of M-20 grade but the lower values indicated non-uniformity and porosity. Hence cement and epoxy grouting (22 bags of cement were required) and other repairs were carried out as per consultant's advice. A few UPV readings were repeated at the same locations (Fig. A-3). Following were the average results.

TABLE A-2

Location	UPV Before Repairs/Grouting	UPV After Repairs/Grouting
Top - a	3723	3844
Centre - b	3728	3754
Bottom - c	3353	3681

It may be observed that UPV has improved considerably after repairs. In case of UPV readings at Top (level-a), UPV was repeated only at 3 locations (12 UPV readings earlier). If only these 3 UPV readings are compared, then it will be found that there is no change of average UPV of 3844 m/sec before and after repairs. But at centre and bottom level, UPV has considerably improved.

In view of these test results the utility of the instrumentation can be viewed as the following.

a) The strength and uniformity of concrete can be thoroughly checked and porus or weak patches can be located, and confirmed.

b) After carrying out repairs of porus/non-uniform patches, the instrument can be used to check the adequecy of repairs by noting UPV readings at the same locations.

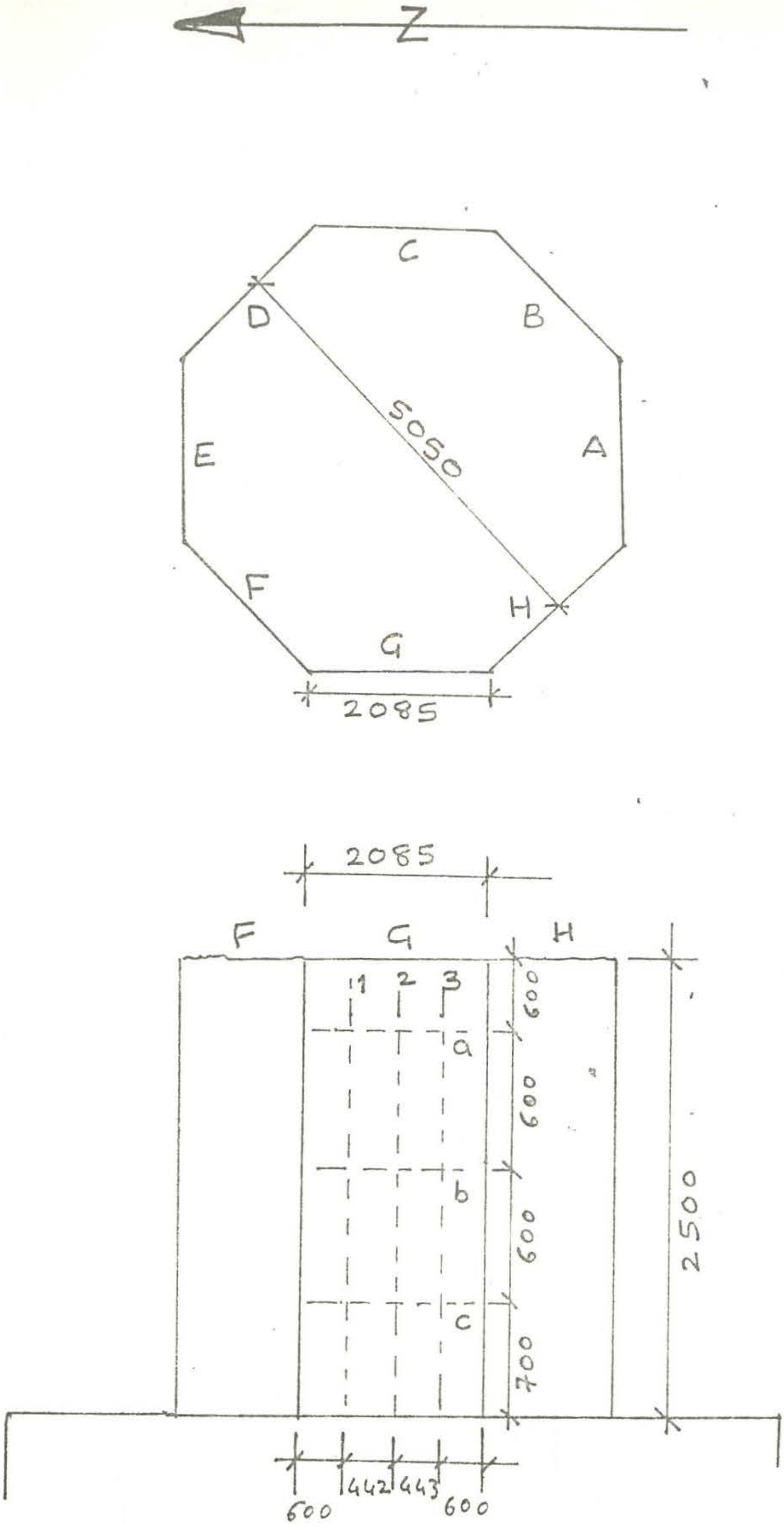


Fig. A-1 : Sketch Showing Dimensions of the Foundation at Vikram Ispat Ltd. The Test Locations are Marked on the Drawing.
(Courtesy : M/s Composites Combine Technical Consultants, Bombay.)

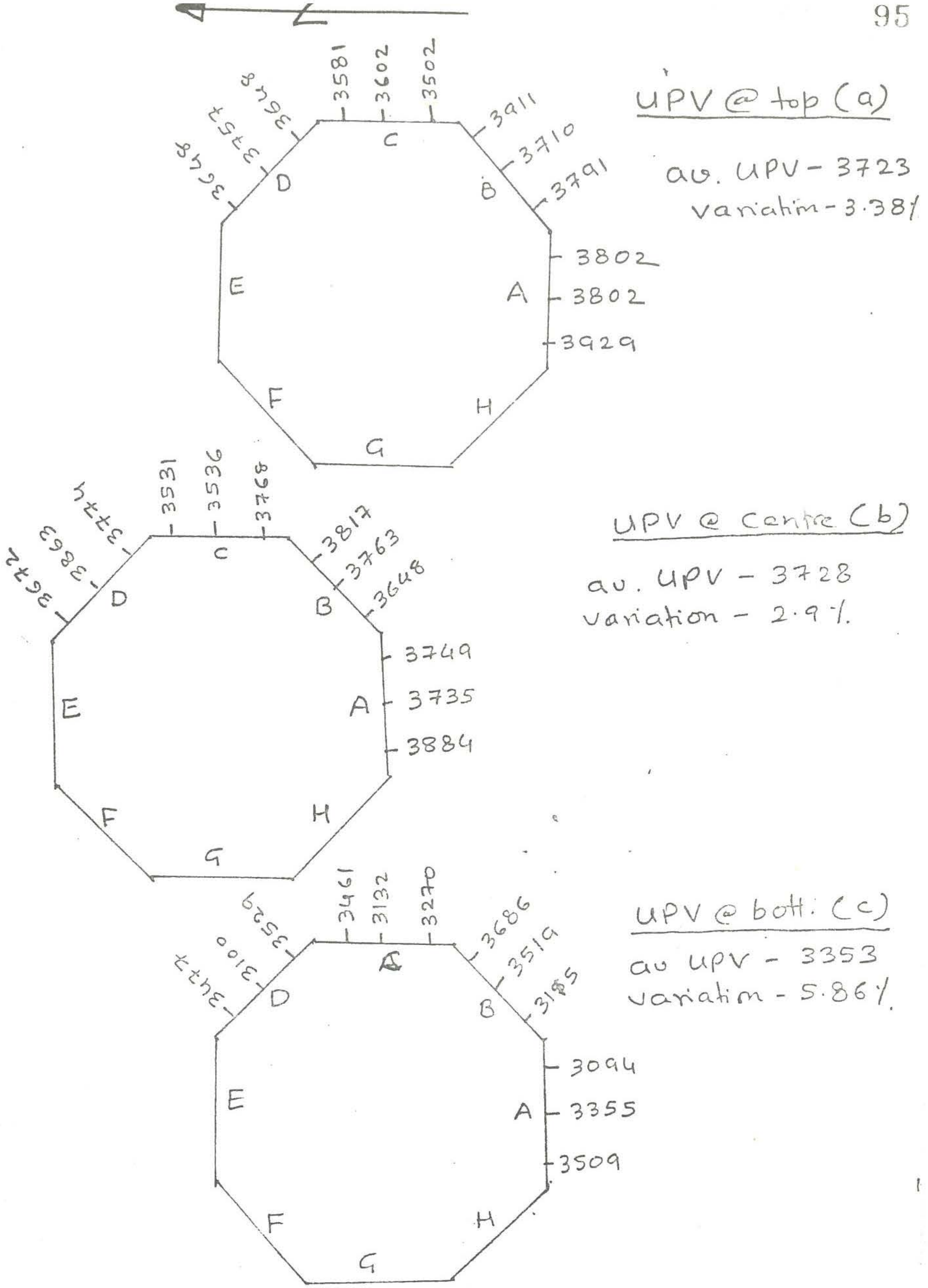


Fig. A-2 : Sketch Showing UPV (m/sec) Observed Before Carrying Out Repairs at Various Locations on the Foundation at Vikram Ispat Ltd.
(Courtesy : M/s Composites Combine Technical Consultants, Bombay.)

UPV after repairs.

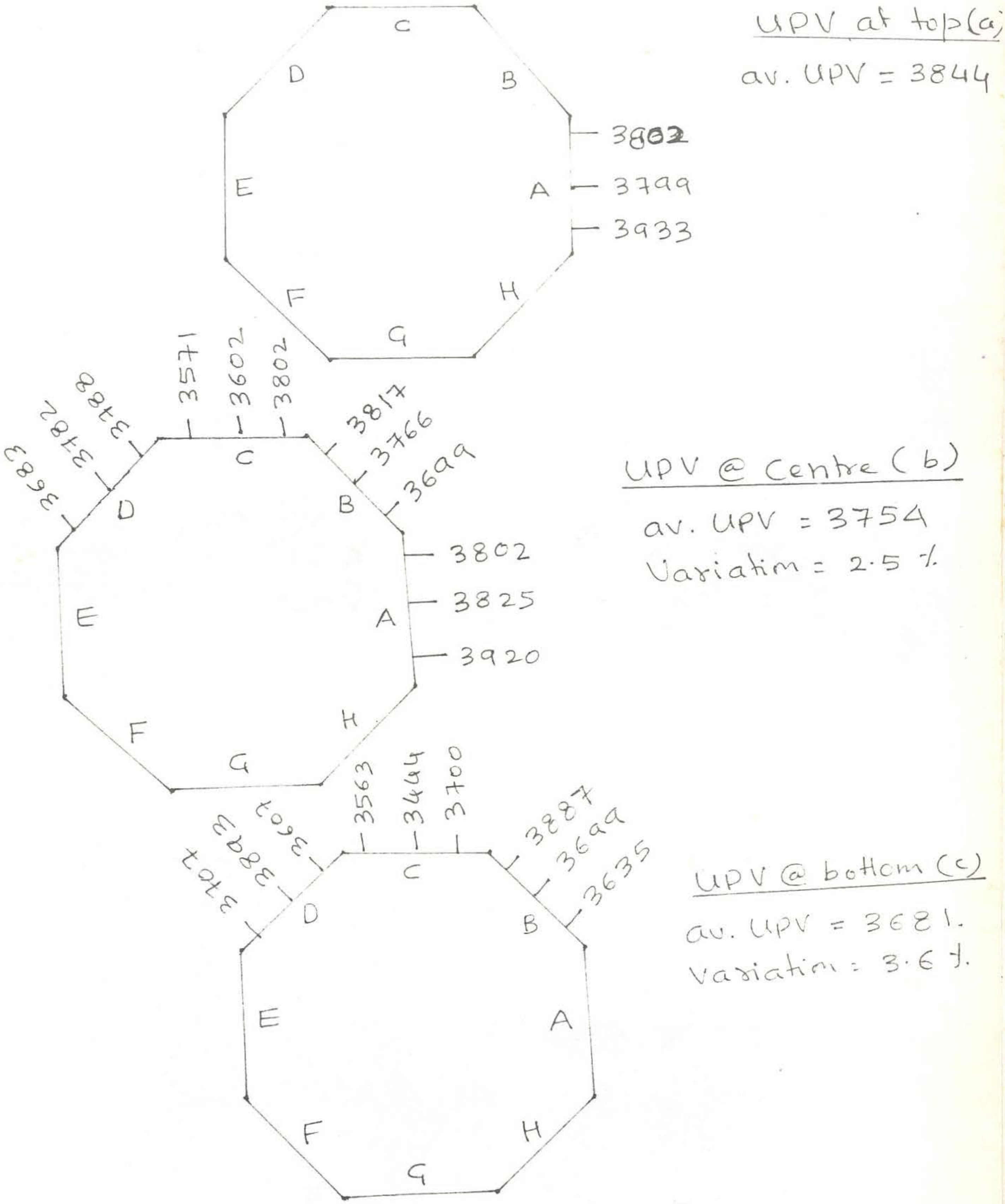
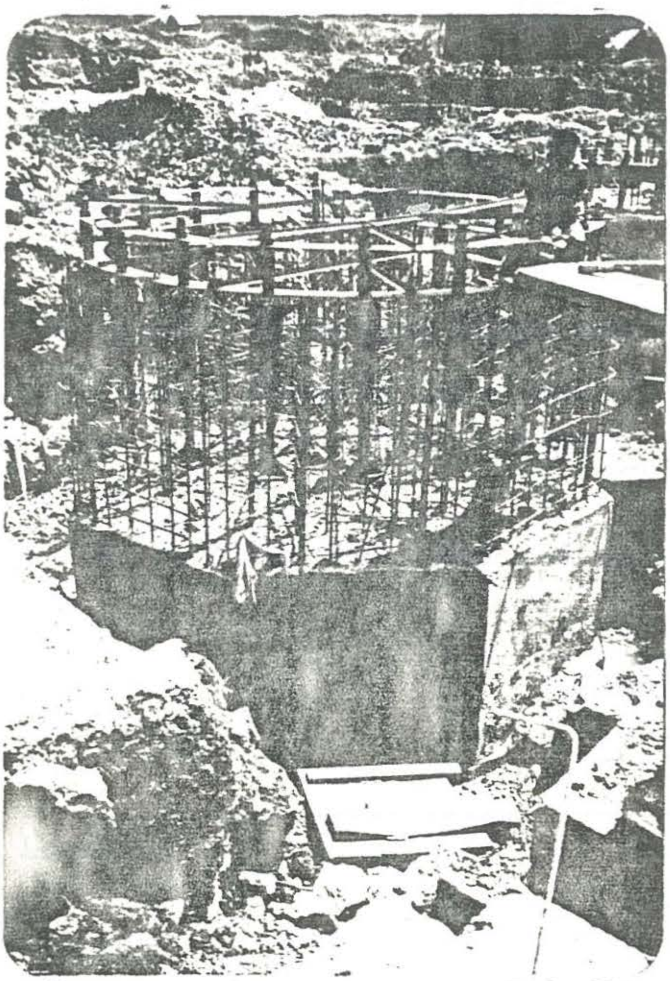
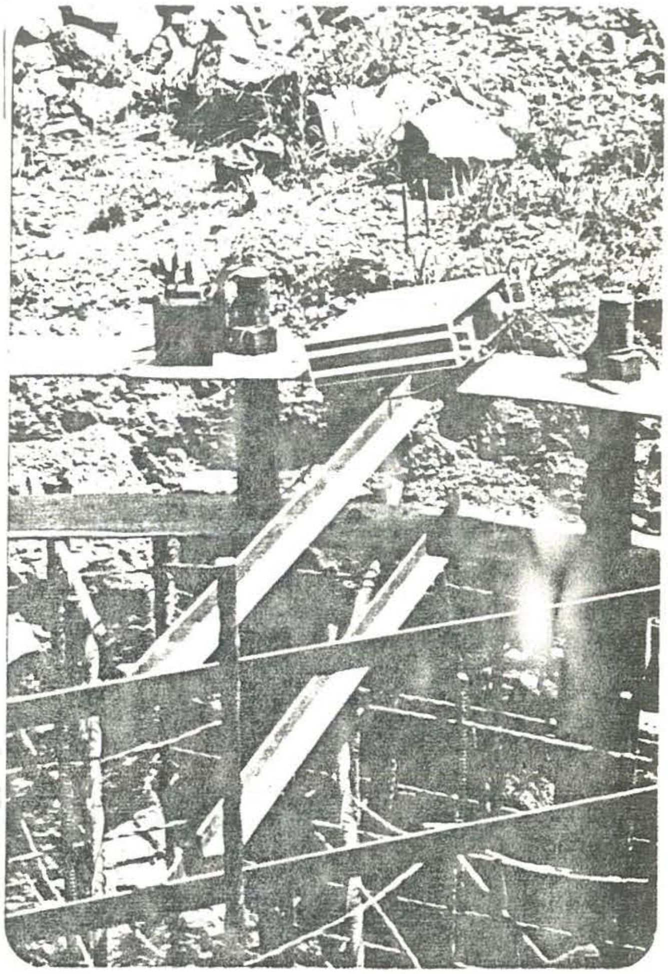


Fig. A-3 : Sketch Showing UPV (m/sec) Observed After Carrying Out Repairs at Various Locations on the Foundation at Vikram Ispat Ltd.
(Courtesy : M/s Composites Combine Technical Consultants, Bombay.)





Photographs Showing Testing Site at Vikram Ispat Ltd., Alibag.

(Courtesy : M/s Composites Combine Technical Consultants, Bombay.)

TEST REPORT 2

TESTING OF CONCRETE BLOCK FOR S-205 FOUNDATION AT KESAR PETRO-PRODUCTS LTD., CHIPLUN.

Ultrasonic tests were conducted on the above foundation at M/s. Kesar Petro Products Ltd., Lote, Chiplun.

The testing locations on the foundation were as shown in Fig. A-4. The results were tabulated as shown in Table A-3.

TABLE A-3

Location	UPV (m/sec)	Path Length (mm)
1.	4255	1000
2.	4385	500
3.	4132	600
4.	4000	2500
5.	4012	2500

Average UPV = 4157 m/sec

Based on these observations the concrete was recommended to be acceptable as M-350 grade (Estimated strength was 365 kg/cm^2).

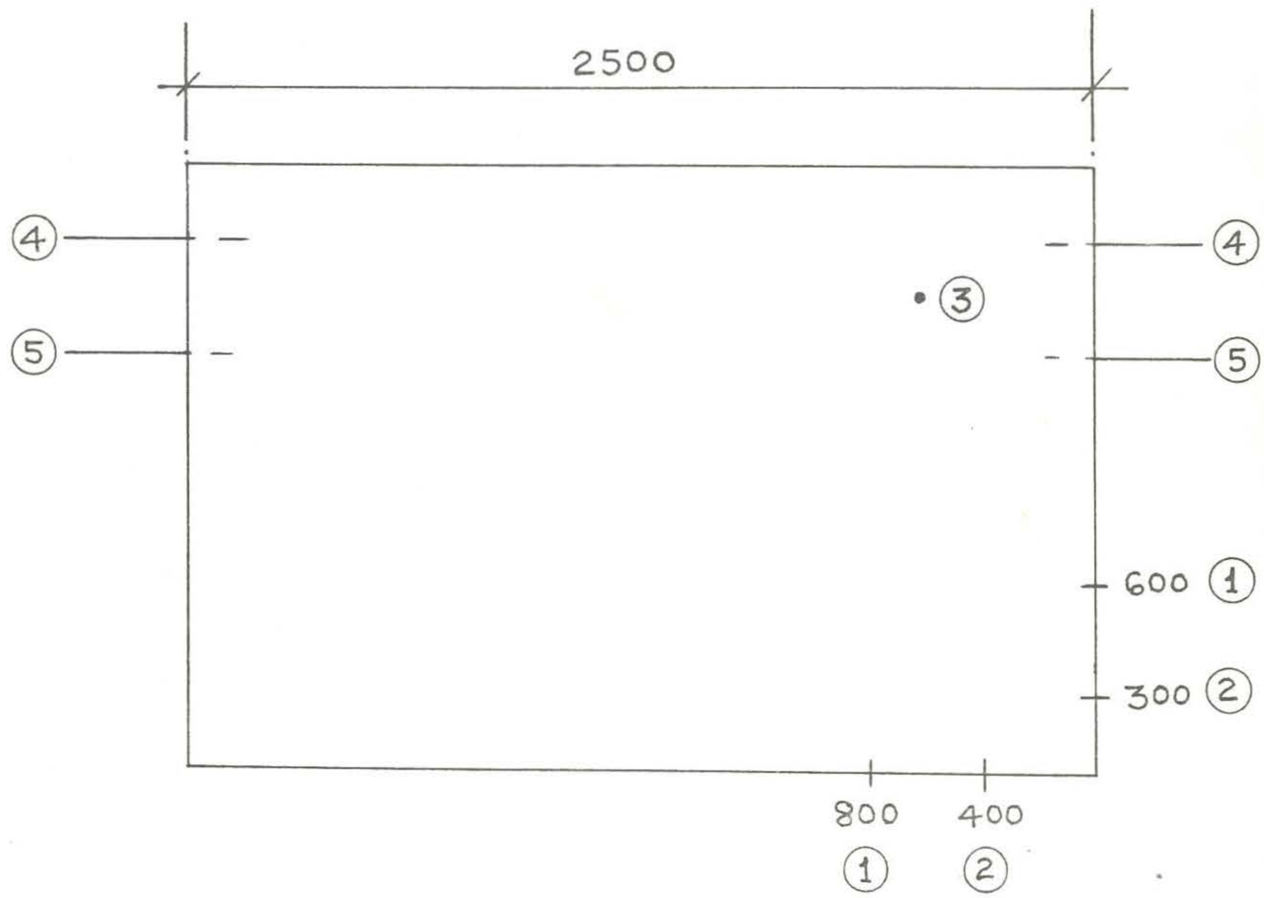
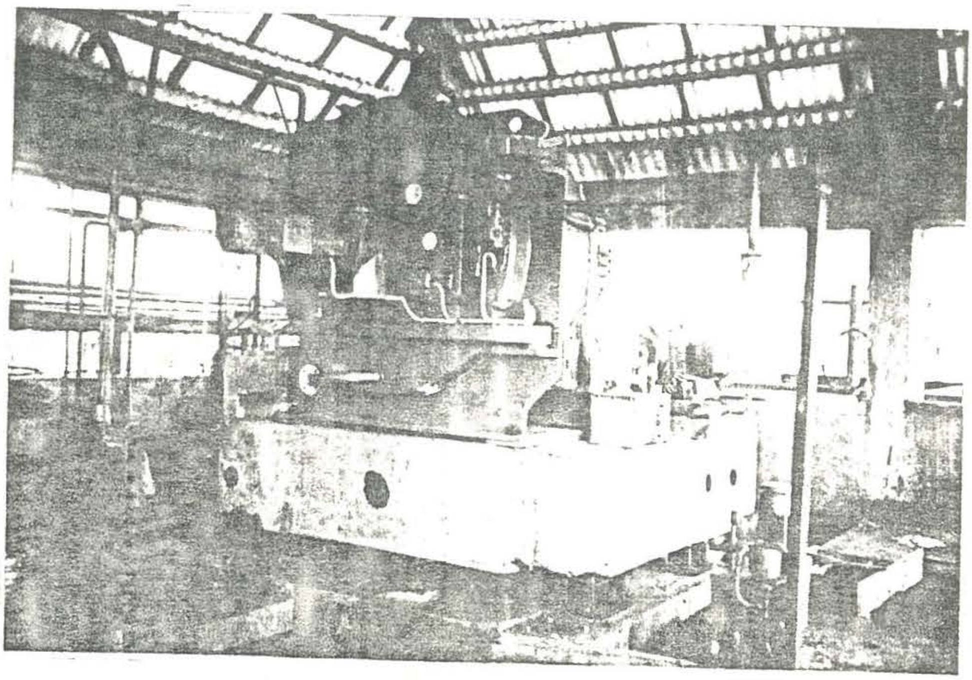


Fig. A-4 : Sketch Showing Dimensions of the Machine Foundation at Kesar Petro-Products Ltd. The Test Locations are Marked on the Drawing.
(Courtesy : M/s Composites Combine Technical Consultants, Bombay.)



Photograph Showing Testing Site at Kesar Petro-Products Ltd., Chiplun.

(Courtesy : M/s Composites Combine Technical Consultants, Bombay.)

APPENDIX II

CIRCUIT ANALYSIS

CIRCUIT ANALYSIS

The design of the instrument was presented in Chapter 5. A brief analysis of the various circuits used in this project is presented here. The following values have been assumed for all TTL gates and transistors.

High level output voltage of TTL gate (VOH) >= 2.4 V.

Low level output voltage of TTL gate (VOL) <= 0.4 V.

Base to emitter voltage of transistor (VBE) = 0.7 V.

Collector to emitter voltage of transistor in saturation (VCEsat) = 0.2 V.

Transmitter Circuit (Fig. 5.2)

Capacitors C1 and C2 are provided as filter capacitors at the input and output sides of the DC/DC converter. Resistance R1 is provided to discharge C2 after power is switched OFF. In normal conditions the current in R1 is 0.18 mA at 400 V DC. Hence the power loss due to R1 is 72 mW, which is negligible.

The base of T2 is connected to the Q1 output of monoshot MM1 (Fig. 5.5), which is normally high. Hence the base current of T2 is,

$$I_{b2} = (VOH - VBE) / R5 = (2.4 - 0.7) / 10k = 0.17 \text{ mA}$$

Thus T2 is driven into saturation (H_{FEmin} = 100). Hence T1 is turned OFF and capacitor C3 is charged to 400 V through R2.

T2 is switched OFF momentorily when a firing pulse is applied, thus switching ON T1. The base current of T1 is,

$$I_{b1} = (Vcc - VBE) / R4 = (5 - 0.7) / 470 = 9.1 \text{ mA}$$

This is enough to drive T1 into saturation and C3 is suddenly discharged through R3. This results in a collector current of maximum 400 mA in T1.

The charging time constant for C3 is 4.7 msec, whereas the discharging time constant is 10 usec only. This results in the generation of a sharp negetive pulse of approx. 400 V at the output, which is used to energize the transmitter probe.

Receiver Circuit (Fig. 5.3)

The input signal from the receiver probe is ac coupled through the high pass filter formed by C1 and R1. The cutoff frequency of this filter is,

$$F_{c1} = 1 / (2 \quad R1\ C1) = 723 \text{ Hz.}$$

The output of the source follower is again ac coupled to the base of T2. Neglecting the effect of R7 and C4, the Thevenin equivalent input resistance is Rin = R4 ¦¦ R5 = 15.25 kOhms.

Hence, the cut off frequency of the high pass filter formed by C2 and Rin can be computed as,

$$F_{c2} = 1 / (2 \quad Rin \; C2) = 10.43 \text{ kHz.}$$

The voltage gain of the amplifier formed by T2 can be written as,

$$Av = R6 / (R7 \;||\; C4) = \frac{R6}{R7} * \left[1 + (wR7C4)^{2}\right]^{1/2}$$

Thus it is seen that the gain is more at higher frequencies due to the effect of the bypass capacitor C4.

The collector of T2 is coupled to the noninverting terminal of opamp A1 through the high pass filter formed by C3 and R8. The cutoff frequency can be computed as,

$$F_{c3} = 1 / (2 \quad R8 \; C3) = 15.91 \text{ kHz.}$$

The gain of opamp A1 is adjustable between 1 to 101 by using potentiometer P1. Opamps A2 and A3 form a precision rectifier. The output of A3 is directly connected to the input of the peak detector circuit (Fig. 5.4), whereas it is passed through a low pass filter formed by R15 and C6 before applying to the input of comparator A4. The cutoff frequency is computed as,

$$F_{c4} = 1 / (2 \quad R15 \; C6) = 1591 \text{ Hz.}$$

This low pass filter is used as an envelope detector here.

The LM 336 is a 2.5 V. temperature compensated zener. The threshold of the comparator is set using trimpot TP2 and it´s value is adjustable between 0 to 1.25 V. The output of A4 is converted into TTL level pulse using transistor T3.

Peak Amplitude Measurement Circuit (Fig. 5.4)

The output of the precision rectifier is applied to the input of the peak detector through analog switch AS1. The input resistance of opamp A5 (LF 357) is very high, hence R1 = 1 MOhms is provided to discharge input capacitance when AS1 is open. The ON resistance of AS1 is typically 80 Ohms, which is negligible compared to 1 MOhms, hence the error in input is not significant. Capacitor C2 is charged to the highest level of the input signal and is not allowed to discharge by diodes D2 and D3. This peak detector circuit is a low drift type circuit as explained in Section 5.2.4. Analog switch AS2 is used to discharge C2 when initialization is to be done.

Opamp A7 is used to invert the output of the peak detector (which is a positive voltage). This is as per the voltage-to-frequency converter (VFC) requirements. The relation between the input voltage and output frequency is given by Eqn. 5.1.

Logic Circuit and Clock Generation (Figs. 5.5 and 5.6)

The output pulse timing of monoshot 74LS221 is given by,

$$T = 0.7\ RC$$

Hence, the output pulse width of MM1 is adjustable from 0 to 7 usec by using trimpot TP1. The output pulse width of MM2 is adjustable from 0.15 usec to 7 usec.

The 10 MHz clock generator circuit is shown in Fig. 5.6. The low value of R1, R2, and R3 (470 Ohms) is chosen to minimize the charging problems due to stray capacitances. Each TTL gate is required to sink approx. 10 mA current with a duty cycle of 50 %. Hence the effective value of sink current can be taken as 5 mA, which is within the maximum limit of 8 mA for LSTTL gates.

The Microprocessor Board (Fig. 5.7)

The expanded MCS 48 system has been implemented in this scheme. The DB0 - DB7 pins operate as a bidirectional data bus. The 8748 can provide a 11 bit address. The 74LS373 is used to latch the lower 8 bits of the address, whereas the 74LS138 is used to decode the upper 3 bits of address, which are used to select the peripheral chips. The various peripheral chips are provided to enhance the capacity of the 8748 microcontroller. The remaining ports of the microcontroller can be used as independent input/output lines.