THE CLASSIFICATION OF SLURRIES AND OTHER SUSPENSIONS USING ULTRASONIC TECHNIQUES

BY

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SYNOPSIS

The attenuation of ultrasonic waves travelling through a liquid containing a suspension of solids is highly dependent on frequency. At low frequencies, where the wavelength is long compared to the particle size, the particles move with the wave with some phase lag which gives rise to a loss component. At high frequencies, where the wavelength can be made comparable to, and ultimately less than the particle diameter, there is still some movement but most of the energy is lost to the wave by scattering.

In this work, is attenuation used to characterize the suspension, and is treated in terms of these two components. Absorption which is the conversion of energy into heat and scattering from the actual particles. The former is expressed as loss (dB) per wavelength and increases with frequency, while the latter, in the short wavelength scattering zone simply obstucts the wave.

This work is directed at examining the feasibility of using ultrasonics to determine the concentration of relatively large (0.7mm) resin particles in slurry where the rock particle size is 0.02mm or less. Thus the attenuation per wavelength in slurry is expected to change slowly with frequency whereas the scattering from the resin will be small at say 100 kHz (λ = 15mm) and large at 2 MHz (λ = 0.75mm). Initial work was carried out on resin alone and this established the strong wavelength-dependent phenomenon.

Extensive work was then carried out on slurries up to the density limit used (600 kg / m^3). An array of transducers covering a wide frequency range was mounted to enable each to transmit across the suspension receive a return reflected signal, the amplitude of which could be measured and transferred to a computer. Electronic design and computer control gave a system allowing a wide frequency diversity together with signal averaging and analysis. The vigorous stirring required to maintain the suspension results in rapid fluctuations in attenuation. The characteristics of the fluctuations were dependent on stirring rate but the attenuation level was dependent on the slurry alone.

Technological developements were:

a) A wide band receiver and pulse detector which is common to all frequencies.

b) A frequency diversity enabled switching between the frequencies at a 2 kHz rate to be carried out.

c) Spectrum analysis of signal fluctuations up to a few hundred Hertz.

d) By using overtone frequencies, a single transducer can give a limited attenuation spectrum.

Phenomena observed, some of which are well known and understood are:

a) The linear dependence of attenuation on slurry density.

b) The profile of attenuation change during slurry settlement reflects the particle size distribution.

c) The long and short term attenuation changes which occur when initially dry rock powder becomes saturated with water.

d) A frequency dependent attenuation in resin consistent with Rayleigh's law.

e) A large signal fluctuation observed during settlement indicated a verticle velocity gradient. This suggests that the ultrasonic wave velocity is density dependent.

f) When resin is present in dense slurries, effects were observed which indicate that the resultant attenuation is not simply the sum of the seperate attenuations.

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LIST OF SYMBOLS

a - transducer radius

a_x - attenuation per unit distance

B - near / far field boundary

d - particle diameter

D - density

f - frequency

ℓ - (unit) litres

- (variable) length

λ - wavelength

ρ - reflection coefficient

Q - quality factor

σ - cross sectional area

CHAPTER ONE

INTRODUCTION

Ultrasonic frequencies in the megahertz region can be used for the classification of suspensions of slurry and resin particles in water. This is of interest in the RIP (resin in pulp) gold extraction process and this project aims at developing an instument to aid measurement and control of this process.

The slurry is obtained from the Rand Mine Projects (RMP) in Johannesburg, South Africa and mainly consists of quartz. The slurry has a large proportion of the gold extracted from it, but due to the inefficient processes in the past, a gold content of 1 gram of gold per ton of slurry is present. It is presently economic to extract the remaining gold. This can be achieved using an activated charcoal method (CIP - carbon in pulp) or the RIP process which forms the basis of this work.

The gold bearing slurry particles from mine dumps are typically 20 microns in diameter. In the RIP process, the particles are washed into the first of six large silos, each 30m high and 10m in diameter. Cyanide is added to dissolve the gold, subsequently an ion exchange process occurs causing the gold to adhere to the resin particles. The slurry is pumped consecutively through the silos in the opposite direction to that of the resin. The slurry with the lowest gold content, located in the sixth silo therefore comes into contact with pure resin to achieve the most efficient extraction possible. The gold bearing resin particles are removed from the slurry and sent for smelting to extract the gold. The process control is aided by a knowledge of the slurry and resin particle concentrations in each silo. This work aims at establishing the ultrasonic characteristics of these two media separately, and then combining the results to obtain a method of characterizing a mixed suspension.

Ultrasonic tone bursts are launched into the medium by a transducer operating in transmit/receive mode. The burst echo from a suitable reflector is processed using electonics developed for this work. The two main phenomena apparent were the attenuation of the signal and its fluctuation about the mean. Both phenomena are dependent on the frequency of the tone in each burst, giving three parameters from which the suspension may be classified, namely:

- attenuation
- fluctuation
- frequency

Only two parameters are necessary, and the effects of the suspension determine which should be used. The degree of attenuation is a function of the scattering and absorption of the propagating wave by the particles in the medium. Chapter two discusses the expected effects for a single particle and extends the analysis to many randomly distributed particles. The wavelength dependence of scattering and absorption is characterized by the Rayleigh and geometric regions. Rayleigh scattering occurs when the wavelength is larger than the particle and geometric scattering when it is smaller than the particle.

A dual frequency system was chosen with frequencies of 1 and 3 MHz, giving wavelengths in water that enclose the nominal resin particle diameter of 0.7mm. Good scattering discrimination can be achieved by a comparison of the Rayleigh and geometric effects. The slurry however is homogeneous at both these frequencies and causes negligible scattering but substantial attenuation due to absorption. These different frequency dependent effects of the slurry and resin media are the basis for the characterization of the suspension.

High attenuation of the 3 MHz signal makes the above technique impractical in dense suspensions Experimental evidence showed the fluctuation of the reflected signal amplitude about its mean to be different for slurry and resin. This is considered a suitable characterizing parameter for the suspension.

The measurement system evolved to its present form as a result of the information gained in earlier trials. The system comprises a tone burst echo system wherein a single transducer is driven alternately with tone bursts at the two chosen frequencies. The path through the suspension is the same for both channels, therefore improving on the accuracy of comparisons made with the multi-transducer system. The latter relies on the statistical average of the suspension along each path being constant.

A computer is used to analyse the above measurements. The system is described more fully in chapter five. The results plus those from the previous multi-transducer system are discussed in chapter six.

CHAPTER TWO

ULTRASONIC WAVE PROPAGATION IN RANDOM MEDIA

2.1 Acoustic scattering and absorption of particles in suspensions

The characterization of slurries and other suspensions is to be achieved by analysis of the effects of the suspension on ultrasonic waves. These effects, based on attenuation, scattering and velocity changes have been recorded by many authors[1,2,3] and are similar for acoustic, optic, radio and micro waves. Firstly the case of a plane wave impinging on a single particle will be considered, and this will be extended to include many randomly distributed particles in a measurement cell.

The ultrasonic wave travelling through the random medium, on encountering a particle is both scattered and absorbed. Absorption is due to viscosity[5] and is the result of frictional losses caused by the particle vibrating with a lower amplitude and different phase than the medium. Scattering is the reflection of the wave from the particle, considered as a fixed inhomogenity, and together with absorption result in a power loss from the propagating wave. These effects are analysed in terms of the cross sectional area of the particle, which is considered to be the main controlling parameter.

The relevant cross-sections are:

σ_g - The geometric cross-section of the particle
σ_s - The effective scattering cross-section
σ_a - The effective absorption cross-section

σ_s and σ_a are directly related to the scattering and absorption of the incoming wave. These two phenomena are dependent on the size, shape (and hence orientation) of the particle. For the purpose of this work, the shape is known to have negligible effect, and particles are therefore regarded as simply analysable regular spheres. The mean scattering reflection coefficient (ρ) expresses the ratio of the reflected and incident wave amplitudes, and will be a different constant for each different type of scatterer. The power of the wave is proportional to its amplitude squared, giving the reflected power as a function of ρ^2. In these experiments as far as possible, particles of uniform size were used and ρ is therefore taken as constant. The suspensions contained either resin particles with a nominal diameter of 0.7mm or a quartz slurry 20 microns in size.

The size of the particle has the dominant effect, and gives rise to two principal types of scattering, dependent on the wavelength (λ) of the incident wave[9]. These are characterized as follows (see FIG 2.2):

Rayleigh scattering : $\lambda >> d$ (particle diameter)
Geometric scattering : $\lambda << d$

The proportion of scattered and absorbed power from a particle is a function of the effective cross-section of the particle. It has been shown[1] that σ_s and σ_a are related to wavelength.

When $\lambda >> d$, σ_s is inversely proportional to the fourth power of the wavelength, and proportional to the square of the volume of the scatterer. Increasing the wavelength therefore causes a marked decrease in signal strength. σ_a however is inversely proportional to the wavelength and directly proportional to the scatterer's volume. The energy absorbed per wavelength is constant, and a doubling in frequency would double the energy absorbed per unit time.

So called resonance scattering occurs when the particles are of the same order of magnitude as the wavelength, and is also referred to as stochastic scattering. This region has a square power frequency dependence.

When $\lambda << d$, geometric scattering takes place with σ_s and σ_a approximately equal to σ_g. The scattering and absorption is independent of wavelength in this region.

These phenomena indicate that the key to suspension characterization is a multi-frequency technique, utilizing the Rayleigh and geometric scattering effects. The signal removed from the plane wave is proportional to the sum of σ_s and σ_a, known as the total effective cross-section of the particle:

$$\sigma_t = \sigma_s + \sigma_a$$

In the region $\lambda << d$, σ_t approaches twice σ_g. The resulting power loss from the wave (proportional to $\sigma\rho^2$) is twice that expected. A measure of attenuation by the particle can be obtained with the knowledge of σ_t. The cross-sections for σ_t and σ_s are illustrated in FIG. 2.1, and have been normalized to σ_g. σ_a is not included for reasons of clarity, but can easily be calculated as the difference between σ_t and σ_s. The normalized curve σ_s/σ_g therefore also represents the energy scattering characteristics of the Rayleigh, stochastic and geometric regions.

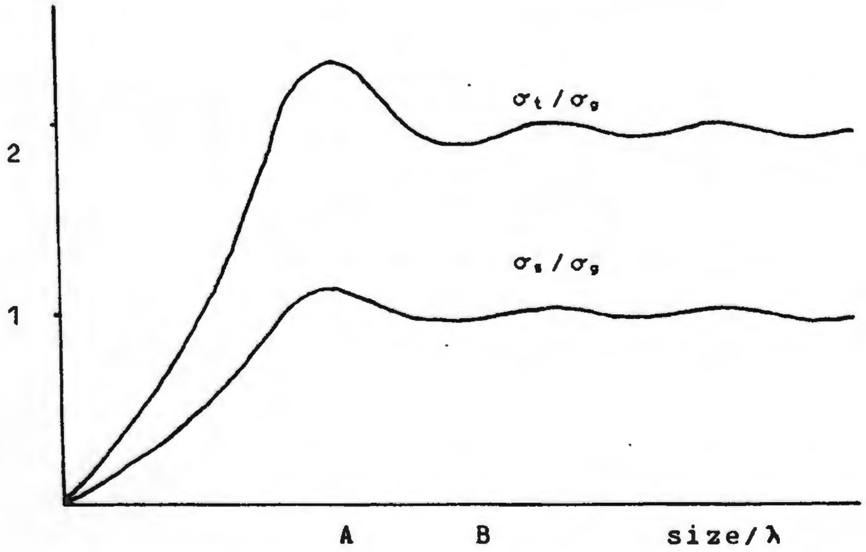


FIG. 2.1 The normalized cross-sectional areas of a scatterer as a function of the wavelength of an incident plane wave. The region below point A is where Rayleigh scattering, which is proportional to $(1/\lambda)^4$, occurs. At point A, the particle diameter is equivalent to the wavelength and the resonant peak is observed. Decreasing λ to point B is accompanied by decreased scattering. Beyond this point, the geometric region with scattering largely independent of λ is found.

The calculations of σ_s and σ_a are similar to those for electromagnetic waves, but the formulae for scattering vary slightly. An electromagnetic wave consists of transverse electric and magnetic waves, and extends across the range from ultra-violet to microwaves. Mie's formulae were developed for the scatterer being a dielectric or a conductor. The dielectric is characterized by a uniform electrostatic field across it, where as in the conductor the field is restricted to the outer layer and is known as the skin effect. Eddy currents set up in the conductor cause scattering in all directions and result in a greater power loss from the impinging wave than occurs with a dielectric. Ultrasonic waves are comparable to the dielectric case of electromagnetic waves with a pressure variation replacing the electric field.

2.2 Scattering of randomly distributed particles

The scattering effect of a single particle leads to the solution for the scattering of many particles in a random distribution. When the particles are sufficiently seperated, allowing each one's scattering effect to be analysed without reference to the others, then independent scattering occurs. The seperation required for independent scattering is three times the radius of the particle[2]. Even with this seperation, interference may be evident because of the phase relation of the scattered waves. Independent scattering assumes these phases to be unrelated, and the principle of superposition can be applied to determine the total signal power scattered from the particles. Any phase effects will average out for these random signals.

When the number density of scatterers encountered by the ultrasonic wave is high, multiple scattering will take place. This occurs when a scattered wave encounters inhomogenities resulting in further scattering of the wave (FIG. 2.2), an effect for which a simple mathmatical relation does not exist.

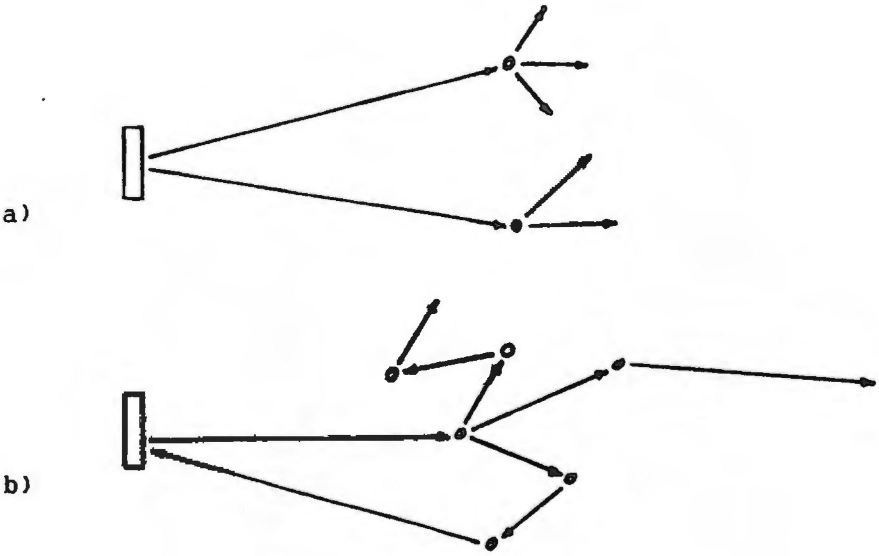


FIG. 2.2 a) First order scattering and
b) Multiple scattering of ultrasonic waves off several particles, illustrating both the increase in the signal reaching the transducer and particle screening.

Multiple scattering increases as the particle number density and the depth to which the wave penetrates increase. A simple but conclusive test for multiple scattering is given by Van de Hulst[2]. If the scattered power increases linearly with the increase in the number of scatterers, then negligible multiple scattering occurs and the particles can be regarded as independent scatterers. This was the case with the resin and slurry compositions used experimentally.

The part of the suspension to be measured is contained in the measurement cell, the volume of which is determined by the beamwidth of the propagating wave and the time slot over which measurements are made.

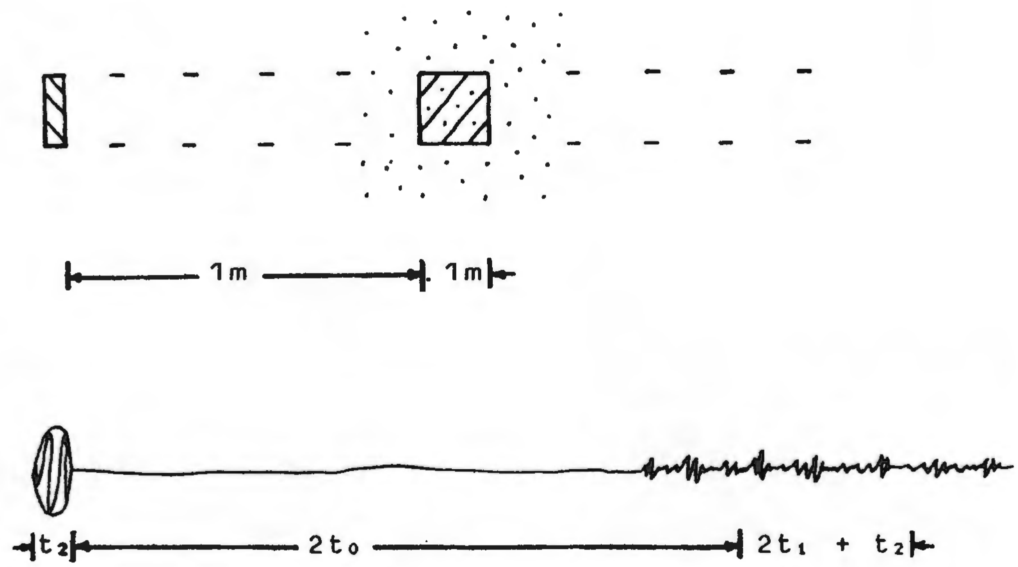


FIG. 2.3 A typical measurement cell and associated backscattered wave.

The spreading of the beamwidth is neglected and is taken as constant regardless of the cell's position in the suspension. The diagram illustrates a cell 1m from the transducer and 100mm long. The time for the wave to reach the cell is:

t_0 = distance/velocity of sound in water

= $1\text{m}/1480\text{ms}^{-1}$

= 676 μs

The time to traverse the cell is:

t_1 = 0.1m/1480ms-1

= 67.6 μs

The pulse burst duration is given as t_2. The part of the oscillogram representing the cell is $2t_0$ from the beginning of the trace with a length of $2t_1 + t_2$.

The particle number density is an important factor in determining the scattering and absorption of a wave propagating through the medium. Three distinct categories exist that can be summarized as follows:

Single scattering and absorption

- this is the fundamental case, which is dependent on the effective cross-sections σ_s and σ_a of the particle, and the power of the impinging wave.

Independent scattering and absorption

- this is the relevant category for this work. Each particle is considered seperately as in single scattering and absorption, and then the results are superimposed to obtain the total effect. Scattering and absorption are linearly related to density.

Multiple scattering and absorption

- occurs when the particles are less than three times their radii apart. A complex integral solution is necessary to define the wave pattern.

2.3 The propagation of waves through randomly dispersed particles in suspension

The propagation of ultrasonic waves through both homogeneous and inhomogeneous media has been the subject of much research[4,5,6]. The main two quantities characterizing this propagation are sound velocity and the attenuation coefficient, which are dependent on phenomena taking place at the surface of the particles in the fluid.

When the size of the particles in suspension is much smaller than the wavelength, then the medium is regarded as homogeneous[4]. Signal power will be absorbed and scattering will be negligibly small. This is because the small particles have low inertia and consequently vibrate with the suspending medium, which maintains the characteristics of a fluid. An increase in particle concentration increases the viscosity and density of the fluid and will increase the absorption of the ultrasonic signal but decrease its velocity through the medium. In non-homogeneous media, the sound velocity and attenuation are affected similarly to that in homogeneous media although scattering will now be present. In both media, the attenuation coefficient is the more sensitive quantity.

The attenuation of all signals- optic, acoustic and radio, travelling through a medium suffer an exponential loss of energy due to a variety of mechanisms. The fractional amplitude loss can be expressed as:

$$dA/A = -kx$$

intergrating gives:

$$A_x = A_0 \exp(-kx)$$

The attenuation a_x expressed in the normal form of decibels per unit distance is shown as:

$$dB = 20 \log(A_0/A_x) = a_x x$$

Alternate expressions used include $a(\lambda)$, the attenuation per wavelength with:

$$a(\lambda) = \lambda a_x$$

The attenuation a(λ) is proportional to the energy loss angle. For many simple sources of loss such as stress, strain and hysteresis it is independent of frequency. In investigations performed in this work, by expressing attenuation in this manner, the more subtle forms of loss such as scattering are readily identified.

Assumptions have been made concerning the impinging wave and the particles in suspension. In practice, the wave is not a perfect plane, and similarly, the particles are not perfect spheres. Chivers[6] states that the interpretation of acoustical measurements in inhomogeneous media can essentially only be answered numerically for the experimental situation under consideration. This work is essentially experimental in nature and is speciffically concerned with the classification of slurry and resin particle suspensions based on the results obtained from the measurement system.

The use of a reference signal in water eliminates any wave shape or spreading effects in the near and far fields, and ensures that any change in signal is due to the suspension alone. The attenuation of slurry is far greater than that of water, so the reference waveform is taken to represent zero attenuation of the signal. The experimental system and analysis techniques used are discussed in chapter 4.

CHAPTER THREE

ULTRASONIC TRANSDUCERS

3.1 The characteristics of ultrasonic transducers

An ultrasonic transducer is a device used to convert electrical energy into an acoustic wave and acoustic energy into an electrical signal. The electric effect is universal at the frequencies used in this work. A lead zirconate titanate (PZT) transducer in the form of a disk approximates to a vibrating piston at frequencies determined by its thickness. These are the planar, thickness resonant modes and the transducer is driven at one of these frequencies. It can be modelled electrically at resonance, as seen in FIG 3.1 below.

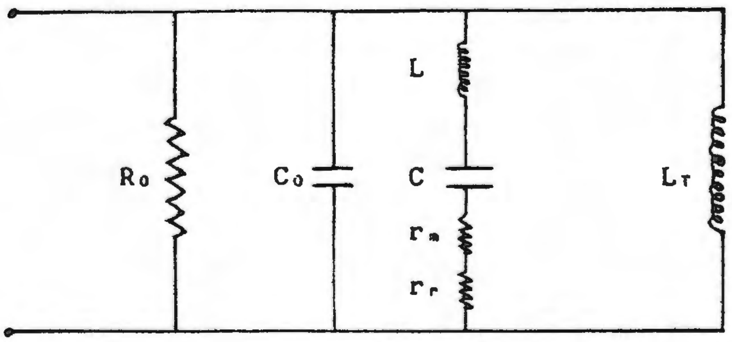


FIG. 3.1 The equivalent circuit of an ultrasonic transducer, operating as a vibrating piston at its fundamental thickness mode resonance.

C_0 - bulk capacitance
R_0 - leakage resistance
L, C - mechanical resonant components
r_r - radiation resistance
r_m - mechanical or mounting resistance
L_T - tuning inductance

For best performance, the ratio r_r/r_a should be a maximum. Low r also improves the efficiency of the transducer, raises its Q and narrows its bandwidth. The ratio C/C_0 is a measure of the energy conversion efficiency of the material. This favours PZT rather than quartz for ultrasonic transducers.

The acoustic field of an ultrasonic transducer is divided into two regions, the near and far fields. The acoustic pressure magnitude in these regions can be determined using Huygen's principle. This assumes each point in a wave to be the source of a new wave. The sum of all these wavelets describes the pressure contours created by the transducer. Interference is extensive within the near field, which is known as the Fresnel diffraction region. The far field is characterized by spreading and is the Fraunhofer region[7]. Disk-shaped transducers vibrating with simple harmonic motion have the approximate field boundaries illustrated in FIG. 3.2.

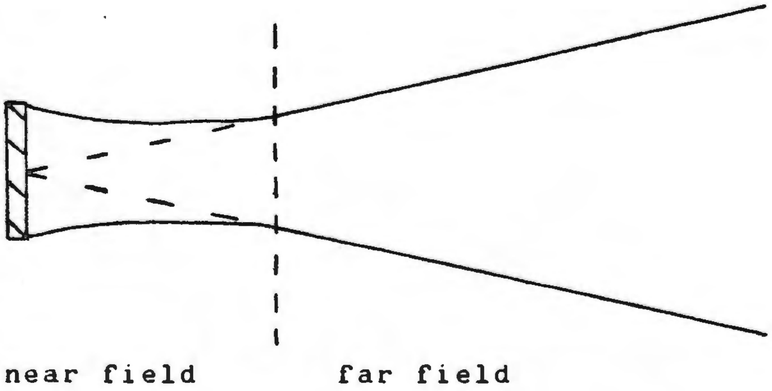


FIG. 3.2 The field boundaries of an ultrasonic transducer. Assuming the face vibrates as a piston, the field converges slightly (near field) then diverges to give a conventional beam spreading pattern in the far field.

Zemanek[7] gives a more accurate description of the acoustic field, and establishes its dependence on the relative transducer radius (a) and the wavelength (λ). The on-axis acoustic pressure magnitude in the near field for a transducer with a ratio $a/\lambda = 5$ is shown in FIG 3.3. The complex nature of the interference patterns is clearly seen, as is the beginning of the spreading region. The larger the radius to wavelength ratio, the more complex the field pattern.

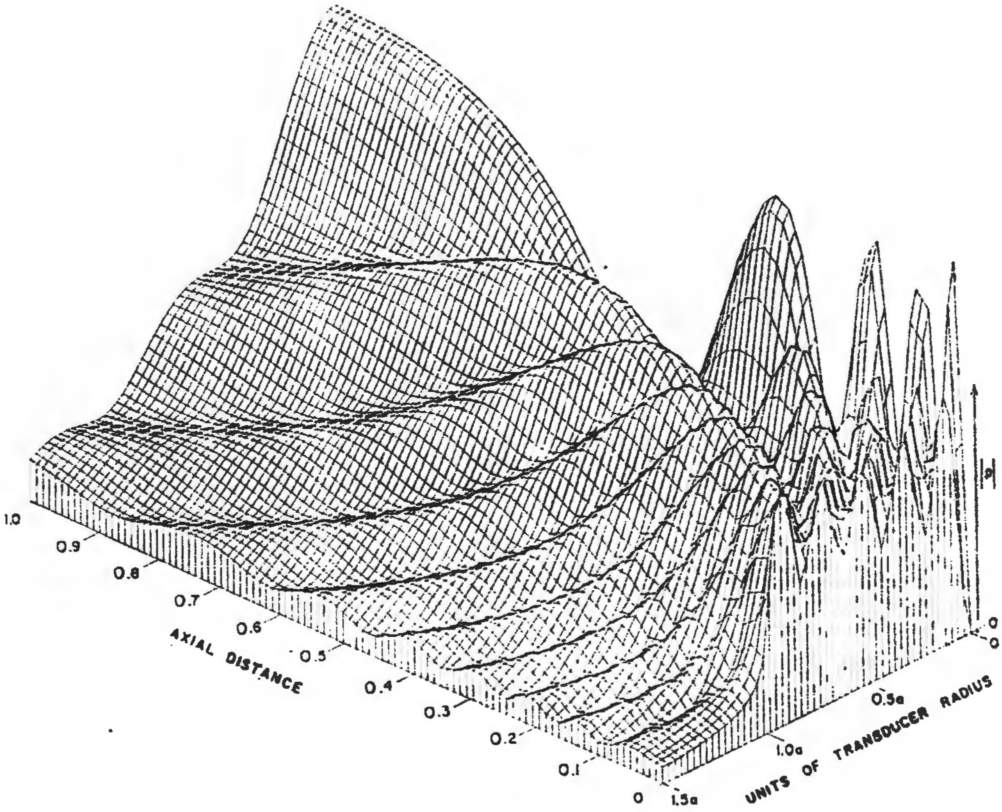


FIG. 3.3 The on-axis acoustic pressure magnitude for a transducer with $a/\lambda = 5$, showing the complex near field waveforms and the start of the spreading region.

The far field begins at a distance $Z = 0.75(a^2)/\lambda$ from the transducer. At this point the beam has its minimum diameter or "spot size". FIG 3.4 & 3.5 sketch the acoustic field contours and on-axis pressure for disk transducers.

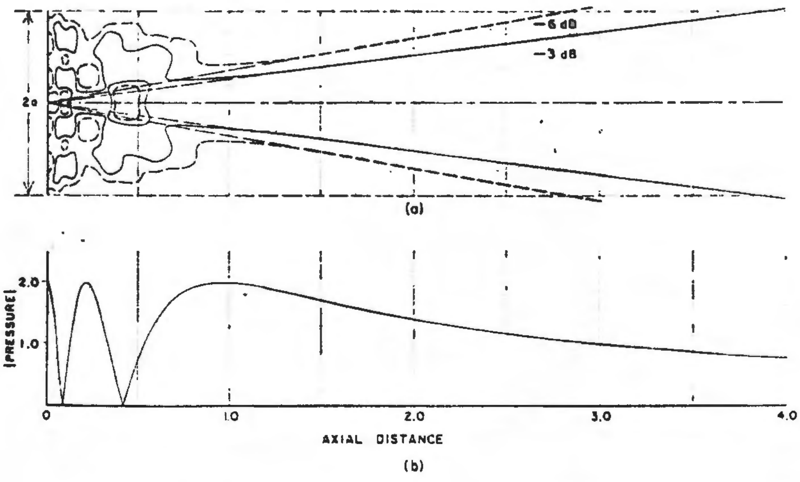


FIG. 3.4 a) The acoustic pressure and b) on-axis pressure magnitude of a transducer having $a/\lambda = 2.5$. Distance is normalized to a^2/λ, and pressure to the average pressure on the disk surface.

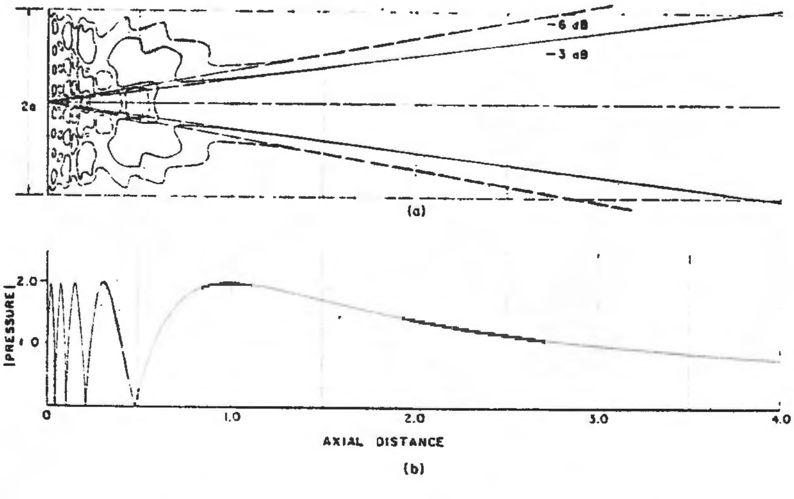


FIG. 3.5 a) The acoustic pressure and b) on-axis pressure magnitude of a transducer having $a/\lambda = 5.0$

The exact interpretation of results obtained in the near field is mathematically complex. For sonar applications only the far field is relevant but for attenuation and velocity measurements, the near field is generally used. Measured signal strength changes with distance due to attenuation and diffraction effects. For the highly attenuating media investigated the diffraction effects are held constant by using a fixed path system. All signal strengths are referred to water where the attenuation is relatively small.

The beamwidth of a transducer is needed to calibrate the measurement cell. FIG 3.6 gives a linear comparison of two different ultrasonic transducers, and illustrates the beamwidth dependence on frequency. This is strictly only true in the far field where spreading occurs, the near field being approximated by a cylinder with its radius equal to that of the ultrasonic, disk shaped transducer.

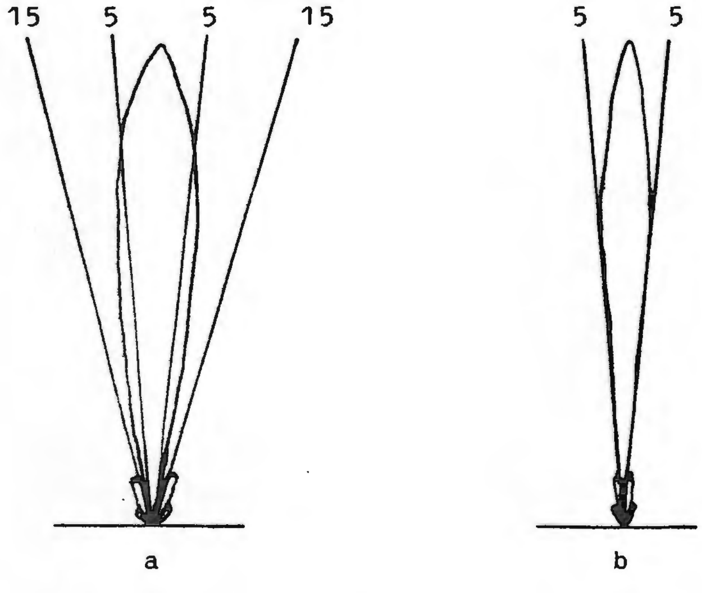


FIG. 3.6 Farfield acoustic beam patterns for a/λ ratios of a) 2.78 and b) 5.62

Pressure side lobes exist but are of the order of 20dB less than the main beam magnitude. The higher frequency transducer has a narrower beamwidth.

3.2 The preparation of ultrasonic transducers for use in measurement systems

Lead zirconate titanate (PZT), disk shaped transducers are used to launch ultrasonic waves into the suspension under test. They are thickness resonant and typically have a quality factor Q of 20 in water giving a 5% 3dB bandwidth. Each transducer should be electrically tuned to its natural mechanical resonance for efficient operation. This is usually done by means of a parallel inductor.

Transducers in the low megahertz range were mounted on bubble PVC using araldite. Properties of the backing materials that influence the damping and sensitivity of the transducer are its acoustic impedance and attenuation. This backing provides a low acoustic impedance relative to water which minimizes the radiation lost from the back of the transducer. In addition it is of advantage if the backing is highly attenuative to absorb all backward transmitted energy in a short distance[8].

The tuning requirements for the backed transducers should be determined from their resonant frequency and admittance characteristics. Two measuring techniques were employed:

i) The transducer was connected in series with a resistor and driven with a pulse burst (FIG 3.7). The frequency is adjusted until a large signal is obtained across the resistor, indicating the low impedance associated with the transducer at resonance. During the burst, the transducer stores energy and the output across the resistor is distorted. On completion of the burst, an initially large mono-tonic signal decays exponentially while the stored energy is dissipated. This decrement signal is at the transducer's resonant frequency and also gives a value for Q, calculated as:

$$Q = \pi n/(\ln(A_0/A_n))$$

where n is the number of cycles

A_0 is the amplitude of the first cycle

A_n is the amplitude of the second cycle

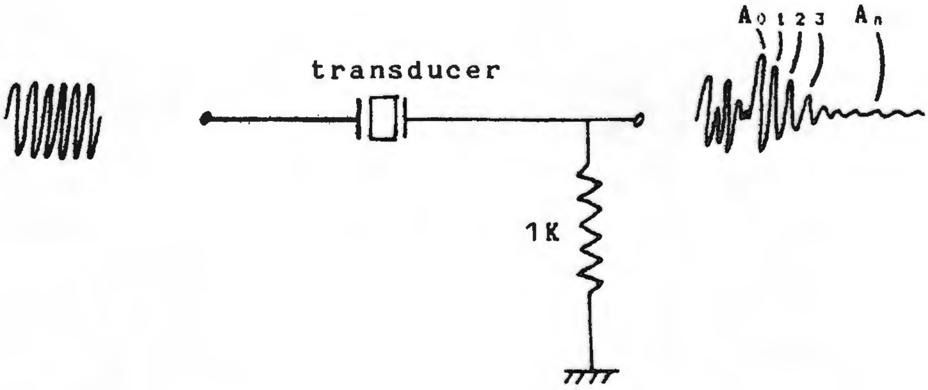


FIG. 3.7 The circuit for determining Q and resonance of an ultrasonic transducer from its pulse burst response.

The bulk capacitance of the transducer should be frequency independent and possible to measure without interference from the mechanical resonance. The tabulated capacitance values below were measured on a digital impedance meter at 1 KHz. These results enabled the tuning inductance to be calculated as:

$$L_T = 1/(2\pi f_0)^2 C_0 \quad \text{Henries}$$

Experimentally these calculated inductors proved to be inexact. It was found that the best tuning was obtained when the electric resonance was tuned to the second or third harmonic of the mechanical resonance.

f_0 (KHz)	rad. (mm)	C_0 (pF)	L_T (nH)	L_T (μH)
261	2.5	71	$5.3*10^6$	
544	10.0	1250	68000	460
1100	5.0	390	53600	324
2100	2.5	236	24000	
2100	5.0	943	6100	91
2200	10.0	4430	1200	16
4400	2.5	551	2400	
4400	5.0	2320	560	6.8
6300	2.5	669	954	
9800	5.0	4610	57	

FIG. 3.8 The parameters of the ultrasonic transducers include its:

mechanical resonance - f_0
radius
bulk capacitance - C_0
calculated inductance - L_T

and where applicable, the experimentally determined tuning inductance required.

ii) The admittance- or circle-diagram (FIG 3.9) was used as the second method for determining the transducer's parameters.

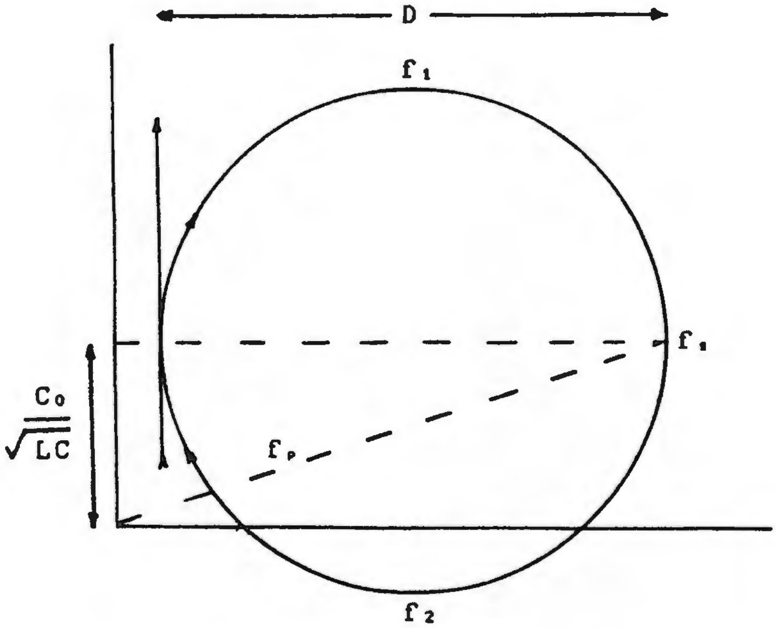


FIG. 3.9 The admittance diagram of a transducer in the complex plane is represented by a circle with the associated frequencies being:

f_s - mechanical resonance
f_p - parallel resonance
f_1, f_2 - 3 dB bandwidth frequencies

The circle diagram enables the equivalent circuit of the transducer to be calculated as follows:

$$R = 1/D$$

$$L = R/(f_1 - f_2)$$

$$C = 1/L(2\pi f_s)^2$$

$$BW = f_2 - f_1$$

$$C_0 = BW/(LC)\hat{}1/2$$

The transducer in the receiving mode is tuned using C_T and L_T, preserving both its resonant frequency and Q.

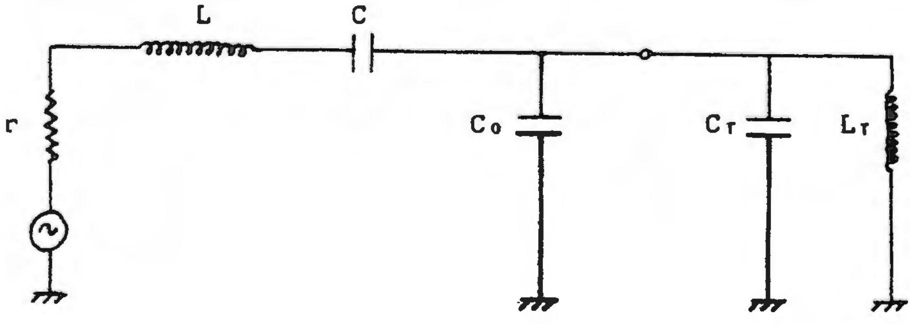


FIG. 3.10 The transducer equivalent circuit in the receiving mode, with electrical tuning.

The tuning capacitance C_T is calculated from the formula for bandwidth (BW)

$$BW = f_1 - f_2$$

$$L(C_T + C_0) = 1/(2\pi(f_1 - f_2))^2$$

and the tuning inductance is

$$L_T = 1/(2Pf_s)^2(C_T + C_0)$$

The circle diagram can be used as an interferometer, provided a wideband transducer is used. Standing waves are set up between the transducer and a parallel reflector, here 19mm away, in water. The frequency at which an integer number of nodes occurs is obtained from the diagram.

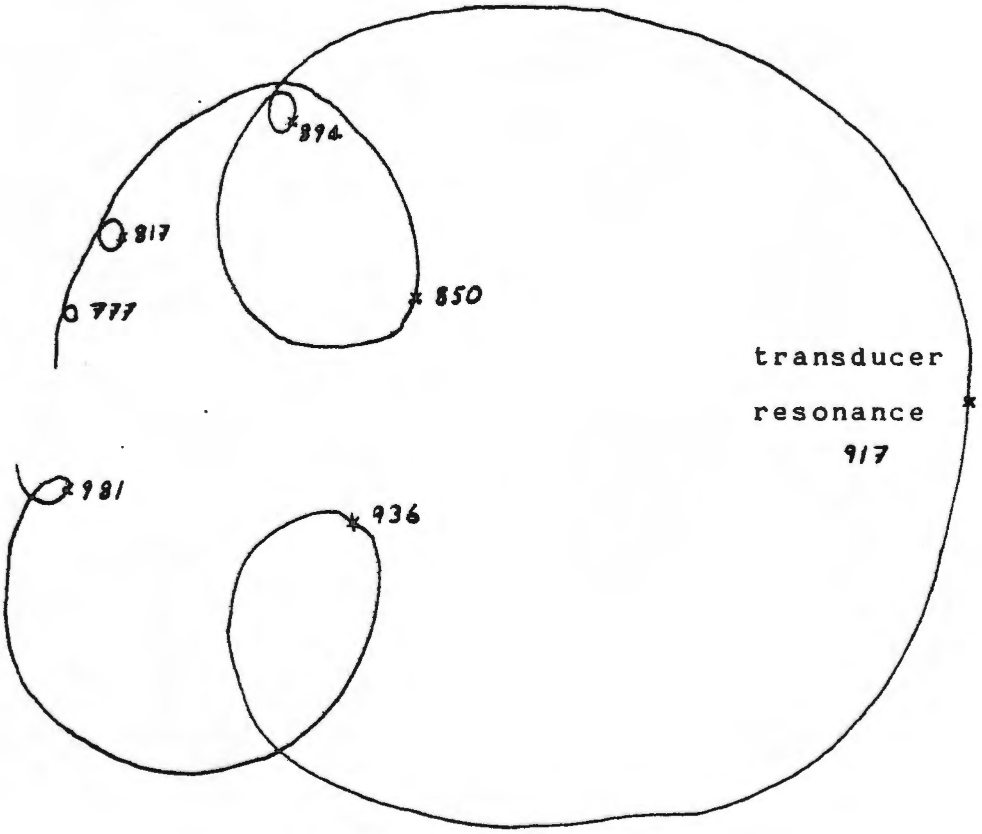


FIG. 3.11 The circle diagram of a 917KHz transducer in water with standing waves caused by a plate at a distance ℓ = 19mm. The number of nodes is designated $n = 2\ell/\lambda$.

Two simultaneous equations are obtained from the circle diagram giving:

$$\ell = n\lambda_n/2 = (n+4)\lambda_{n+4}/2$$

Substituting: wavelength = velocity/frequency

$$\lambda_n = v/f_n$$

a formula for n is obtained:

$$n = 4f_n/(f_{n+4} - f_n)$$

In the experiment,

$$f_n = 817 \text{ KHz}$$
$$f_{n+5} = 981 \text{ KHz}$$
$$n = 19.93 \text{ giving } n = 20$$

the ultrasonic velocity in water is calculated as:

$$v = 2f_n\ell/_n$$
$$= 1552 \text{ ms}^{-1}$$

This result indicates the usefulness of the technique, although if high accuracy is desired, presice values of ℓ, water temperature and atmospheric pressure are needed.

3.3 Pulse generation for the transducers

The transducers are power driven from n- and recently developed p-channel VMOS FETs operating in open drain mode. VMOS has the advantages of fast switching (no minority carrier stage) and high power gain. The circuit (FIG 3.12) receives interlaced pulses from digital circuitry which are then level shifted using transistors. The two FETs are alternatively driven into saturation, producing a quasi-sine wave.

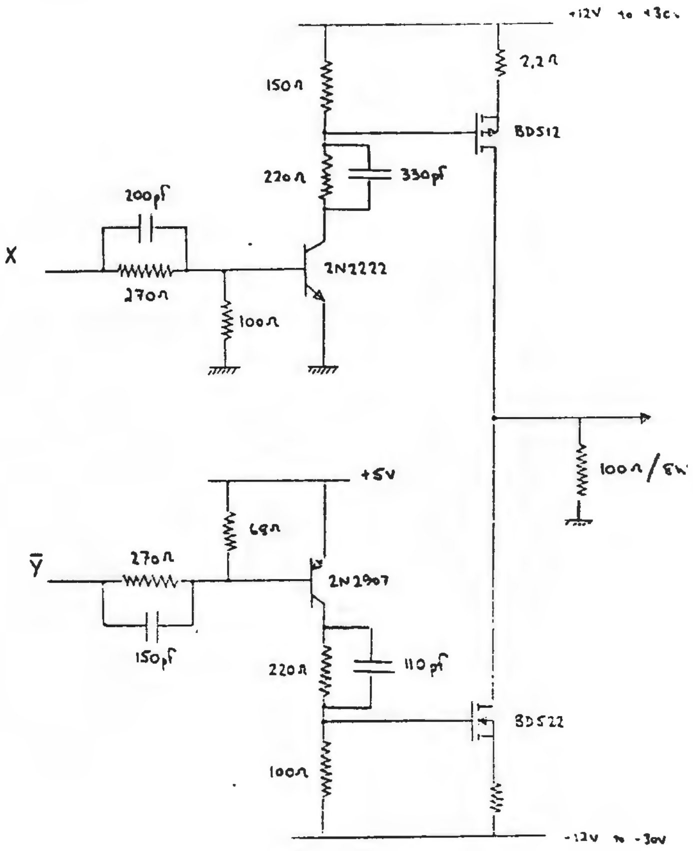


FIG. 3.12 The driving circuit for the transducers.

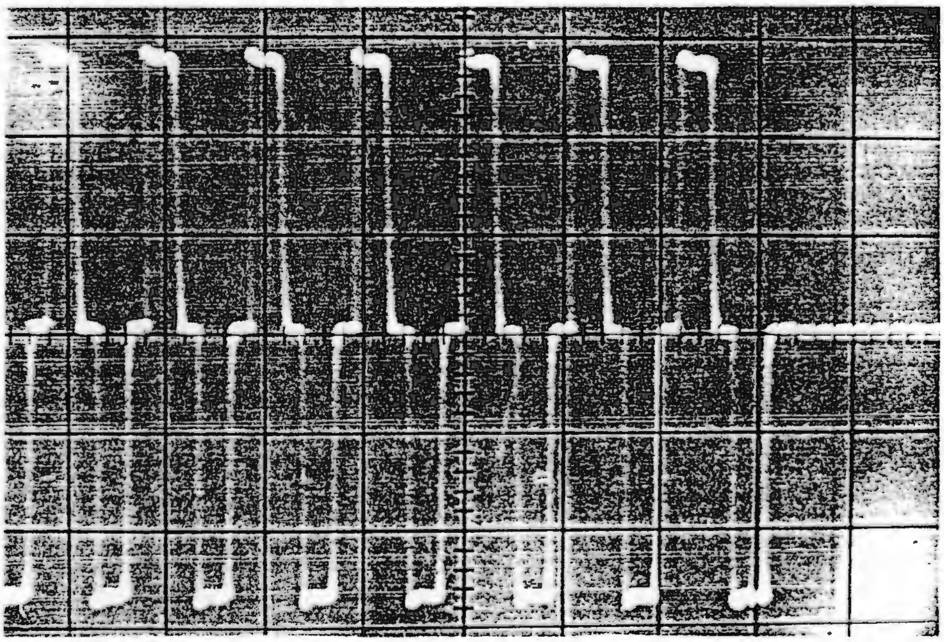


FIG. 3.13 a) This digital quasi-sine wave has the same frequency spectrum as an equal mark-space ratio square wave. The first overtone is the third harmonic with an amplitude equal to one third the fundamental.

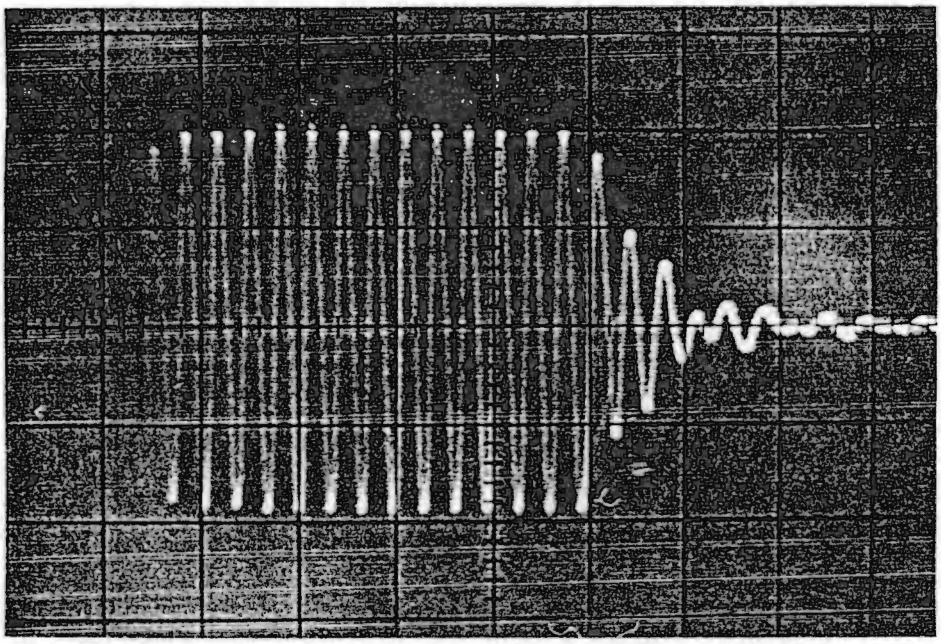


FIG 3.13 b) The actual output waveform produced when the driving circuit is coupled to the transducer. The selectivity of the system filters the drive to give a good sinusoidal signal burst.

The quasi-sine wave output (FIG 3.13) is acceptable because the high Q of the transducer ensures that only the fundamental frequency is used, producing the required sine wave burst into the suspension. The exponential decay, dependent on the Q of the transducer, is clearly seen. A similar exponential rising edge occurs, but is not visible on the oscillogram.

CHAPTER FOUR

EXPERIMENTAL TECHNIQUES, MEASUREMENTS AND RESULTS

4.1 Signal analysis of ultrasonic waves in suspensions

Ultrasonic waves travelling in an inhomogeneous suspension are scattered, absorbed and experience a change in velocity, all dependent on their frequency. Measurements are typically made using either a single transmit/receive transducer, or a seperate transmitter with one or more receivers. The ultrasonic wave can be continuous or pulsed. The method chosen comprises single transducers operating in a pulse-echo, multi frequency system. The quantities of interest are the mean and fluctuating amplitudes of the backscattered signal, and the attenuation of the wave propagating through the suspension.

A common measurement technique is to restrict the suspension to a container within the transducer beam[5,10,11,14]. Measurements are made in the far field to avoid the complex nature of the near field. Weight[12] however, obtained good results as close as 1.5 times the transducer radius (a=5mm, f=10MHz) away, suggesting the usefulness of this region, as was found later in this work, providing a suitable reference has been obtained.

The divergence of the beam within the measurement cell and the reflections inside the container are neglected. The pulse burst must be sufficiently long to obtain a steady amplitude output, and will depend mainly on the Q of the transducer.

In practice, a reference waveform is required with which the magnitudes and pulse shape of the returned signals can be compared. This can take the form of a reflected signal from a known surface, or the signals are correlated to the source. The latter method is only necessary when background interference (noise) is high. The received signal is spread in time, a feature dependent on the depth of penetration into the suspension, and detected energy will always be less than that of the source. A Fourier analysis of the signal is often performed, but in the frequency domain amplitude and phase are needed to characterize the signal, where as in the time domain amplitude is sufficient. Frequency analysis is only useful if it provides information unobtainable from the untransformed signal[13].

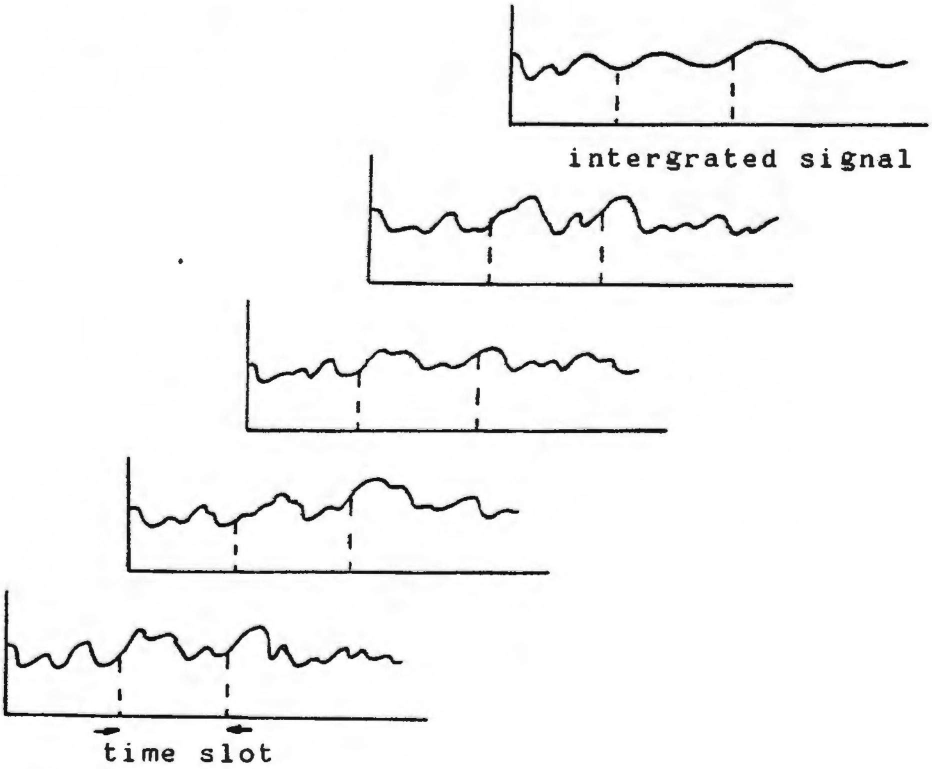


FIG. 4.1 An ensemble of signals defining a random process, with time slot integration used to examine the area of interest.

The randomness of the detected signals suggests the use of an ensemble. FIG 4.1 illustrates typical waveforms obtained from random data systems. Each one is individually useful in providing information about the fluctuations, and collectively they form an ensemble, used to determine the average properties of the data[13].

The ensembles obtained from the systems under consideration are ergodic, that is the average of the ensemble is time invariant. Such a system is said to be stationary, and lends itself to time slot integration. This enables any required measurement cell within the suspension to be analysed as a function of the backscattered signal magnitude. Analysis of the fluctuations normally requires the storage of the signals, the computation of their mean and a comparison of each waveform with the mean in terms of the magnitude and frequency of the deviation.

4.2 The initial measurement system

The reflection magnitudes from resin particles at various frequencies is to be determined. Using a-priori knowledge that the particles have a nominal diameter of 0.7mm, two transducers (numbers 3 and 8 in FIG 3.8 in chapter 3) were chosen because they were expected to give good scattering discrimination at their resonant frequencies. Their ultrasonic wavelengths in water are 1.50mm and 0.33mm, and will respectively be Rayleigh and geometrically scattered. The high Q of the transducers ensures that this is essentially a narrow band system.

The transducers are situated centrally at one end of a low, water filled, 1m by 3m tank. A container for the suspension is constructed from a strong rectangular plastic bucket by cutting windows in two opposite sides, and covering them with a thin plastic with a ρc close to that of water. The container which appears transparent for ultrasonic waves is placed in the beam of the transducers. A signal burst generator[16] provides the required number of pulses and their duration per burst to the two transducers, which are driven simultaneously to ensure inspection of the random composition of the medium at the same instant at both frequencies. The backscattered pressure waves from the sample are amplified and envelope detected, as illustrated by the block diagram:

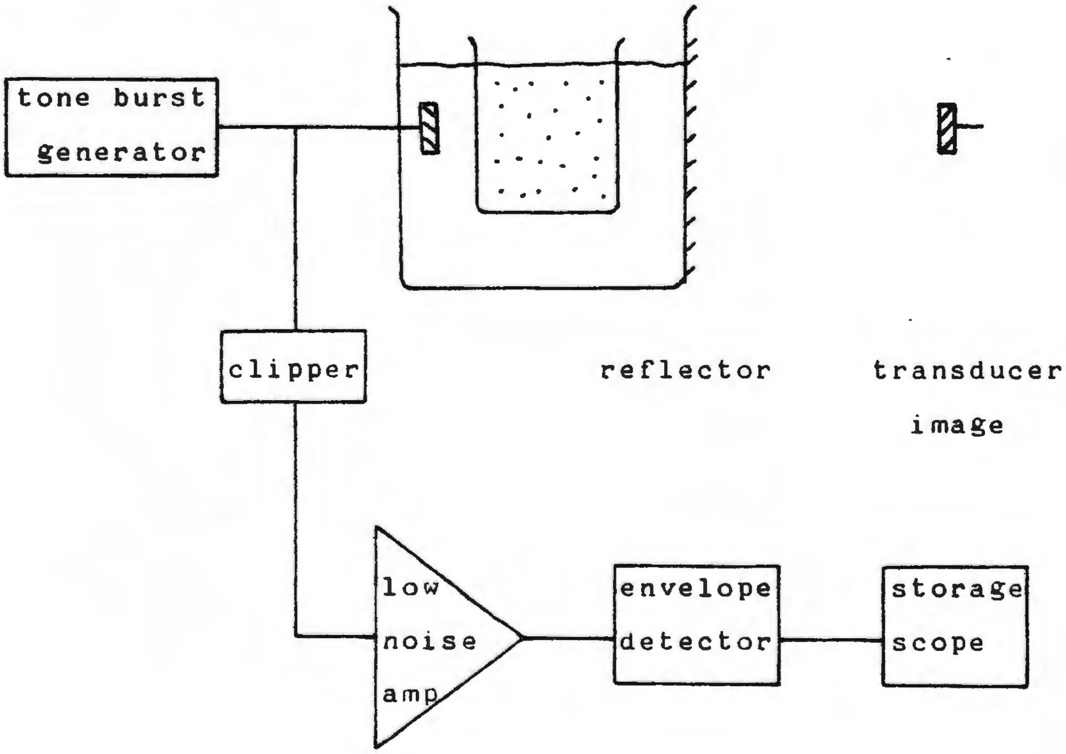


FIG 4.2 The block diagram describing the ultrasonic measuring system.

The amplifiers and envelope detectors (in appendix A) were designed specifically for each transducer. Tuned circuits are used in the amplification stage to eliminate noise from the system, especially cross talk between the transducers. An overall gain of 26dB is obtained, providing easily measured signals at the output. The envelope is taken to enable ensemble traces to be plotted.

FIG 4.3 describes the reflections characterizing the system, and the strong signal from the end of the tank confirms the low loss from the ultrasonic waves through the container windows W_1 and W_2. Time slot integration is applied between these two points to obtain measurements from only the suspension.

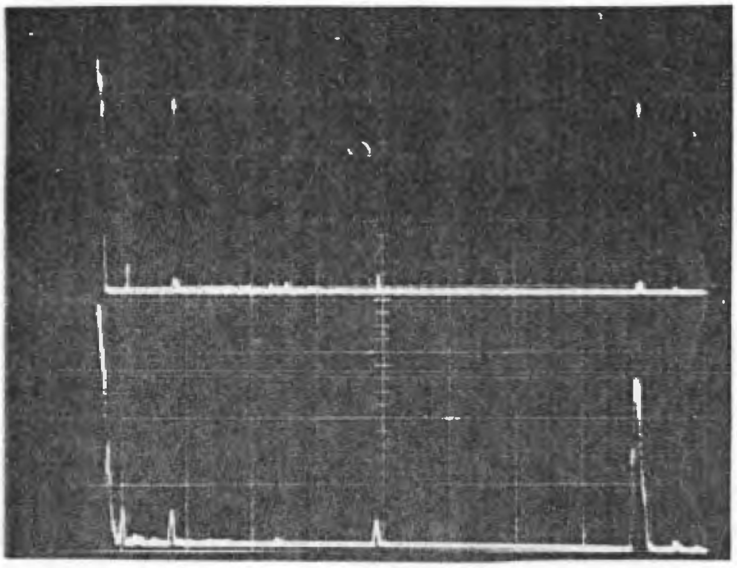


FIG. 4.3 A typical oscillogram of the 4.6 (upper) and 1.1 MHz ultrasonic signals characterizing the measurement system. Each trace has been amplified and envelope detected, and is described by the letters B, W, M, and T.

B - tone bursts driving the transducers
W_1, W_2 - echoes from the container windows
M_1, M_2 - multiple echoes from the container
T - the far wall of the testing tank

The tone bursts are 60 volt peak-peak quasi sine waves each of 20 cycles. The power transmitted at 1.1 MHz is therefore four times that at 4.6 MHz. This has to be taken into consideration when calculations are made based on these measurements. The large echo from the rear of the tank confirms that the attenuation of the thin plastic windows is small. This reflection (T) serves as a useful indication of the amount of signal lost due to scattering, attenuation and also, outside the near field, inverse square law spreading.

4.3 Results

The backscatter from the resin particles is investigated using the returned signals from the suspension. The reflection from the end of the tank can also be used to determine the effects of the particles. The reference signal was taken to be the slightly scattered signal from the water in the container in random motion (FIG 4.4). Signals from inhomogeneties such as specks of dust are visible, especially on the 4.6MHz trace.

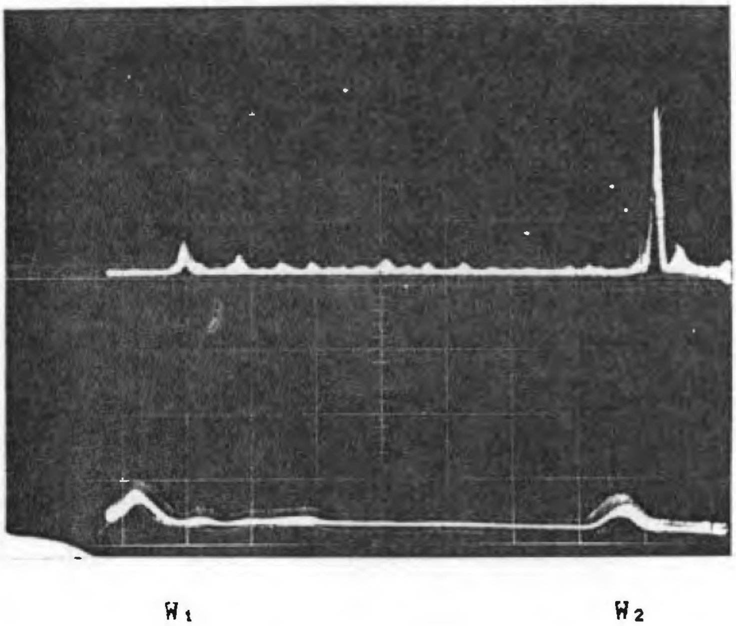
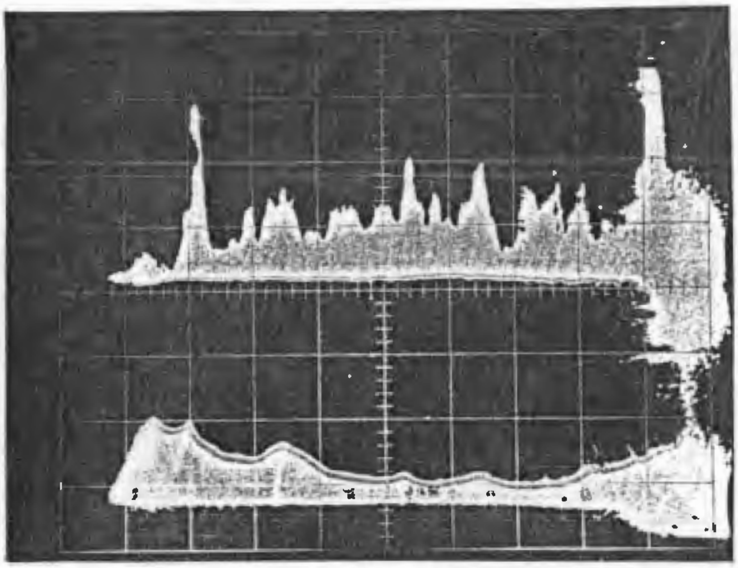


FIG. 4.4 The reference signal, taken in water, for the ultrasonic measurements. The upper trace is at 4.6 MHz and the lower at 1.1 MHz. W_1 and W_2 represent the signal echoes from the container walls as seen in the previous photograph. The time slot integration technique was applied with W_1 to W_2 being the time slot, and the random returned signals from the medium were integrated over a period of five seconds. The water was agitated to provide a turbulent medium. The effect of this can be seen, particularly on the 4.6 MHz trace. These signals are negligible and the signals obtained with this system can confidently be taken as from the suspension alone.

A suspension of resin particles in water was produced, having a concentration of approximately 1000 particles per litre. FIG 4.7 a) and b) are the integrated backscattered signals over a five second time interval. The geometric scattering of the 4.6MHz signal is clearly larger than the Rayleigh scattering at 1.1MHz.



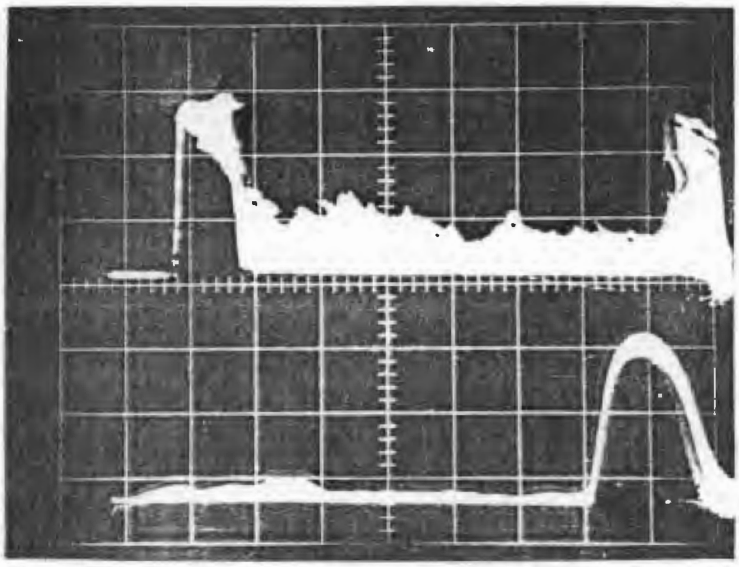


FIG. 4.5 The backscatter of resin particles at 4.6 (upper) and 1.1 MHz. The top photograph is obtained when the tone bursts each contain 20 cycles, and the bottom one has bursts of equal duration. The latter transmits the same power per channel into the system and therefore gives an improved comparison of the two frequencies. The difference between the large geometric and small Rayleigh scattering is observed.

The difference (D) in backscattered signal power is predicted to be

$$D = 20\log_{10}[4.6\text{MHz}/1.1\text{MHz}]^4$$
$$= 48\text{dB}$$

This large difference has been confirmed and indicates the usefulness of the multiple frequency techniques for detecting and classifying particles. These results provide motivation for large scale computer controlled measuring and analysis.

The experiments described above establish that the backscattered signal from the resin used in mining industry (0.7mm diameter) increases by a large factor as the wavelength becomes smaller than the particle diameter. This is geometric as opposed to Rayleigh(f^4) scattering which occurs when the wavelength is large. As the grains in mining slurries are very small, an instrument to measure resin concentration appears feasible.

It was decided to use a system where a reflected echo rather than the scattered signal is measured. In effect the signal remaining instead of the scattered signal is determined. The echo is a measure of signal loss due to both attenuation in the slurry and resin scattering. The actual resin concentration is expected to be obtained from the attenuation spectrum. The backscattered signal to echo ratio still remains an option although the scattered signals have very variable structure and are not readily measurable.

The conventional experimental arrangement for pulse echo signals was shown in FIG 4.2. A tone burst is transmitted, specularly reflected and received back at the transducer. In effect the receiver is the image of the transmitter in the reflector. Precise alignment of the reflector is necessary and this is carried out by adjusting the reflector tilt to make the echo amplitude a maximum.

Water is used as the zero attenuating reference. In a typical experiment, a tank containing pure water with facilities for stirring is used. The average echo level is recorded, usually with continuous stirring. Slurry is then added and the particular experiment is carried out. Stirring then ceases and when the suspension has settled, the zero attenuation reference can be checked. Similar measurements are made with resin which allows a comparison of the two materials. This technique with results is used in chapter 6.

CHAPTER FIVE

THE ELECTRONIC CIRCUITRY AND COMPUTER SOFTWARE

5.1 The experimental procedure

Attenuation of ultrasonic waves in slurry increases with an increase in frequency. It is therefore desireable to use the lowest possible frequency, while maintaining scattering discrimination. Experiments indicated the 500KHz to 5MHz range to be best, with 2MHz being the key frequency. The use of a single wideband transducer and amplifier is advantageous:

- signals at both frequencies then have the same amplification and are easily compared.
- the identical part of the suspension is measured. The ultrasonic beam clearly follows the same path, and the suspension can be regarded as stationary if tone burst repetition frequency is sufficiently high.
- over-all electronics reduced.

A wideband transducer was not available so a narrowband transducer was used at its fundamental frequency and at an overtone. A tuned amplifier is unnecessary because the transducer has a high Q, eliminating all unwanted frequencies.

The basic measuring system comprised:

- the suspension under test
- a single transducer alternately launching tone bursts at the two chosen frequencies
- synchronised detection and signal processing
- computer storage and analysis of data.

Initially transducers 2, 3, 6 and 8 of table 3.8 were used with separate receivers and driven from the quad channel signal burst generator. The results of these measurements were stored on disk using a desktop computer and are to be found in chapter six. The system described here is the single transducer operated at two frequencies in the pulse burst mode.

The transducer (radius 5mm) was mounted in a circular hole in an aluminium plate using silicon rubber. The plate had a sealed air gap behind it to provide the desired attenuative backing. The associated electronics is described in section 5.2 and the use of the Apple IIE computer is in section 5.3.

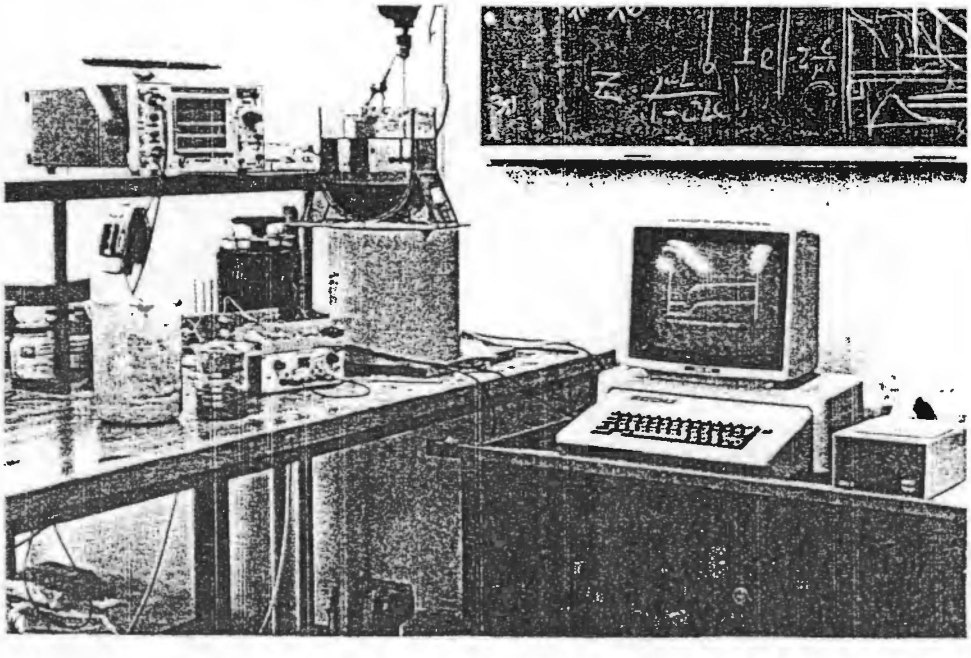


FIG. 5.1 The suspension classification system showing the measurement, signal processing and analytic sections. The measurements are made in the 2.5ℓ container using an ultrasonic transducer. The suspension is maintained with the hand drill and stirrer and is speed controlled using the variac. The tone burst generator, amplifiers, envelope detector and sample and holds are in the aluminium box. The outputs go to the oscilloscope and the micro computer for analysis.

The transducer was tested on the circle diagram plotter which indicated the presence of many weak resonances and two strong ones. These were the 917KHz and 2908KHz as illustrated in FIG 5.2, which is perfectly suited to resin particle measurement.

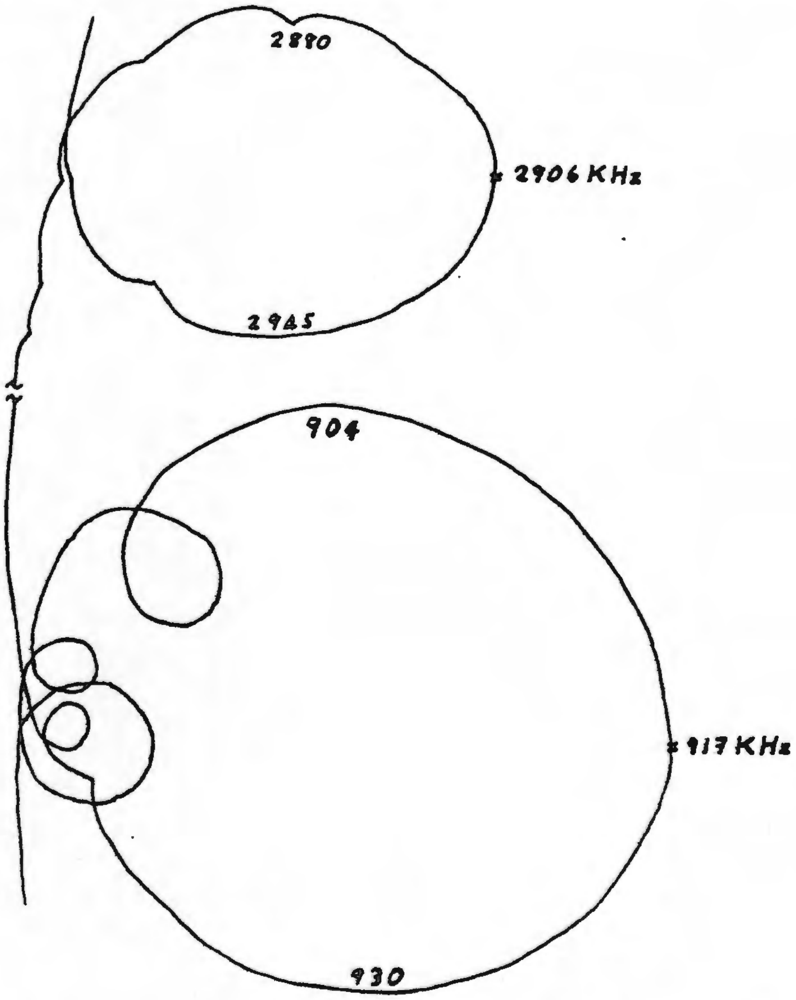


FIG. 5.2 The circle diagram in the complex plane for the transducer mounted in the aluminium plate. The mechanical resonances occur at 917 and 2908 KHz.

The transducer is mounted in a small 2.5 litre container (80x200x210mm) in which the suspension is maintained using a variable speed hand drill with a propeller-type stirrer. To eliminate the near field effects as far as possible, the attenuation will be measured using the reflected signal from the container wall as a reference. The near/far field boundary (B) for the two frequencies is usually taken to be of the order of $a^2/\lambda = a^2f/v$. It is in fact the rather indeterminate point from which spreading commences and the beam type radiation model becomes valid.

1MHz $\quad B = (5mm)^2.1MHz/1500ms^{-1}$

$\quad = 16.7$ mm

3MHz $\quad B = (5mm)^2.3MHz/1500ms^{-1}$

$\quad = 50.0$ mm

The reflector is mounted 80mm away and is therefore just into the far field where some fall in signal due to spreading will occur. An Apple IIE based "aScope" is available for signal analysis and provides computed information not immediately apparent from the oscilloscope viewed signals.

5.2 The signal generator, detector and processor

Electronic circuitry was designed specifically for the single transducer, dual frequency system. The requirements are:

- pulse burst generater - alternating between two frequencies, but retaining single frequency option.
- detection and amplification of burst echo
- envelope detection of echo
- time-slot measurement with sample and hold
- computer output

The block diagram of the system is given in FIG 5.3 and the electrical circuit diagram is in appendix A.

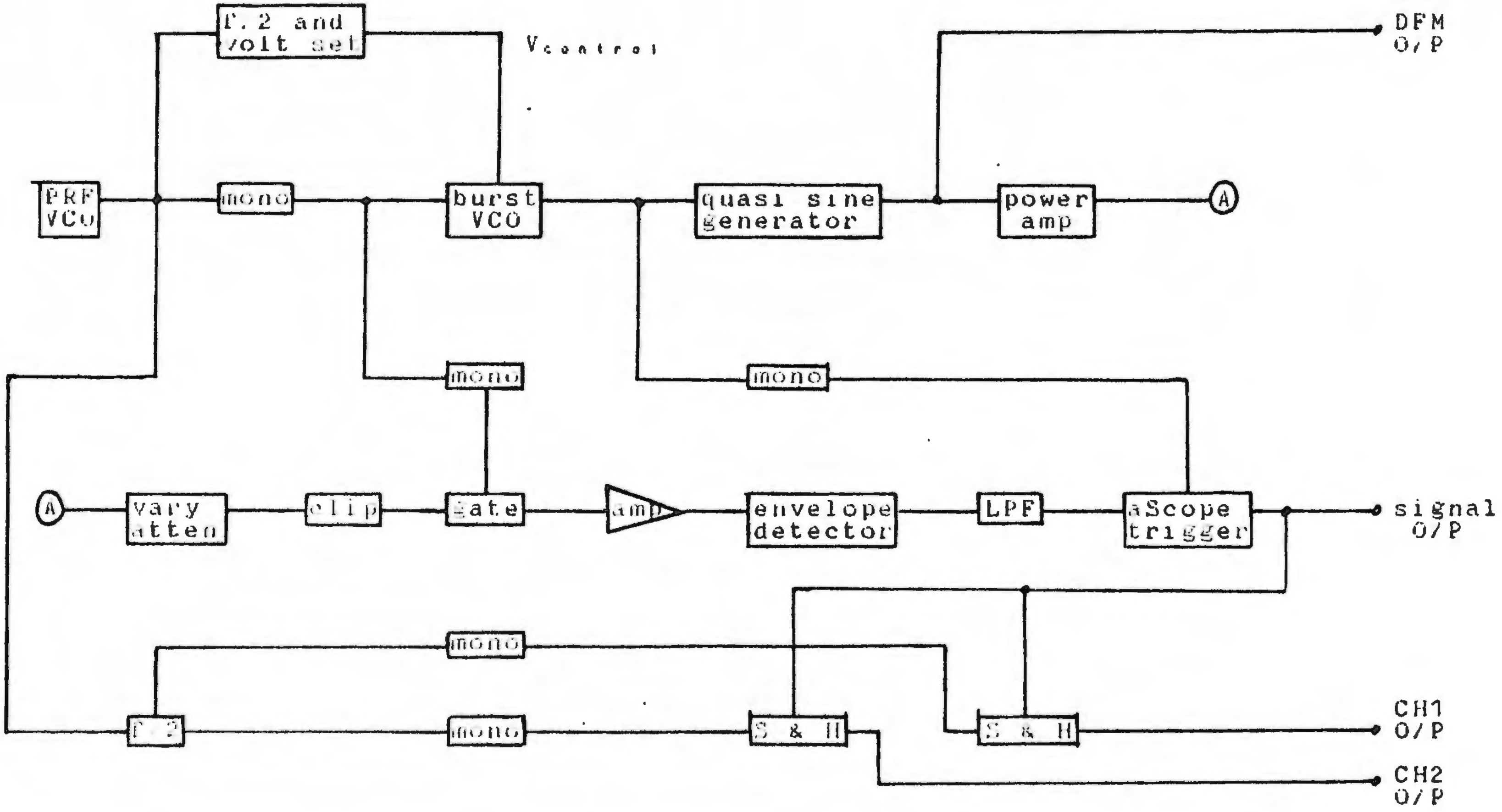


FIG. 5.3 The block diagram of the electronics.

The repetition frequency of the tone bursts launched into the suspension is determined by a trigger pulse generated by the voltage controlled oscillator VCO_1. It is set at approximately 2KHz to allow multiple reflections within the tank to subside before transmitting another burst. The pulse repetition frequency (PRF) of VCO_1 after being halved is also used to switch the output burst from the VCO_2 between two preset frequencies, which are double the resonant frequencies of the transducer. This is achieved using a potential divider and TTL logic to alter the control voltage of VCO_2.

A monostable determines the length of the burst that is sent to the quasi sine wave generator which produces a low voltage waveform, now at the correct frequency. VMOS FETs amplify the burst as in chapter 3 but here to only $30V_{p-p}$ across the transducer.

The detected signal is attenuated to a level suitable for processing and is clipped to prevent any saturation of the amplifiers. The detector input is disconnected using a gate during burst transmission for the same reason.

Wideband integrated circuit (IC) amplifiers are used to increase and envelope detect the signal which is optimised by the post envelope low pass filter. The use of logic controlled switched resistors in the amplifier's feedback gives a convenient gain control. The part of each signal of interest is latched using alternatively triggered sample and hold ICs and these are then measured by the computer. Typical signals in the electronics are seen in FIG 5.4.

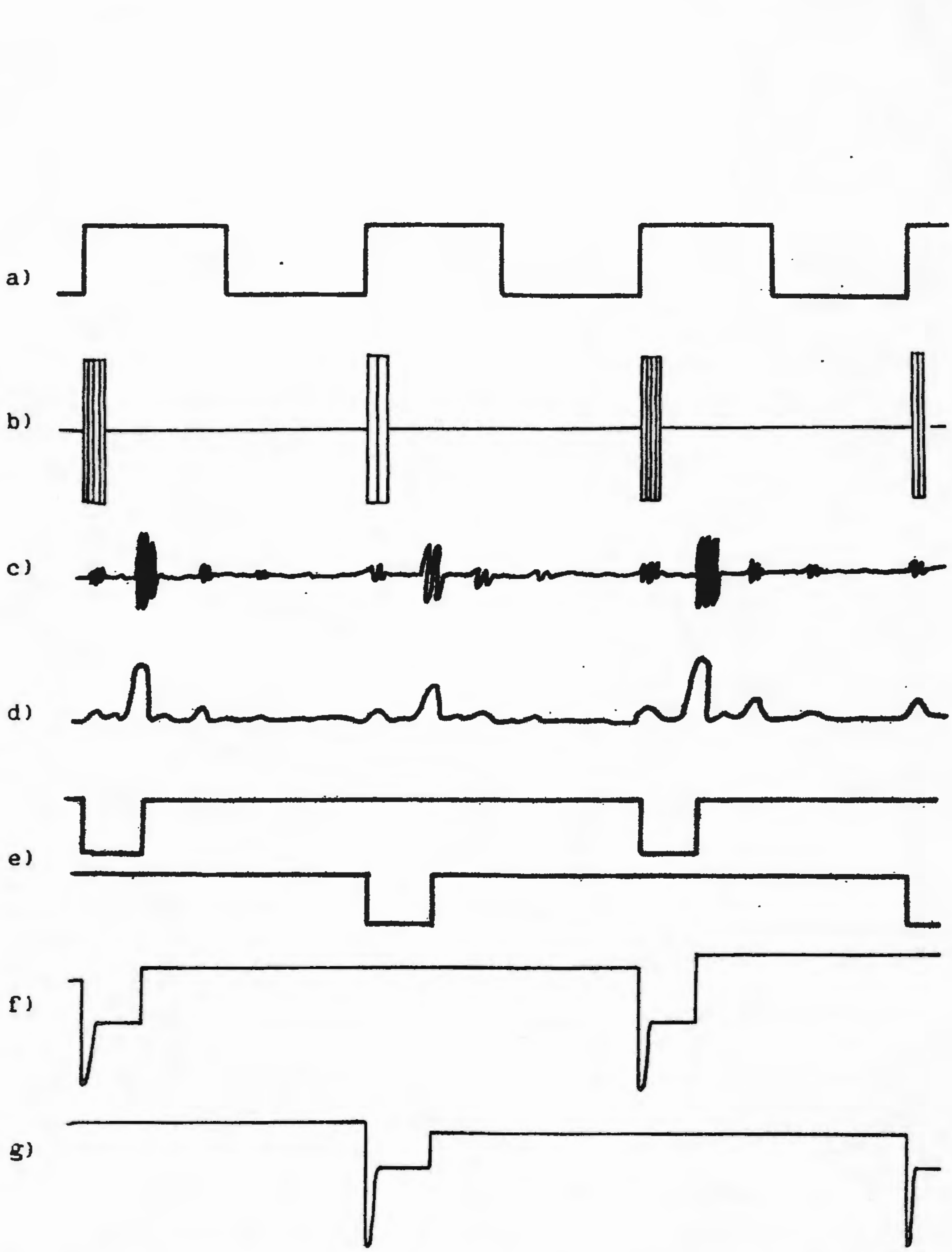


FIG 5.4 The sequence of electronic signals present during measuring.

a) The PRF triggering the tone bursts and the monostables.
b) The two different tone bursts alternately launched into the suspension.
c) The detected signal from the suspension.
d) The envelope of the detected signal.
e) A monostable for each channel sets the point at which the received waveform is to be sampled. Synchronous triggering is required to ensure each tone burst is always detected on the same channel.
f) The sample and hold output for CH 1 and
g) CH 2, with the aScope trigger added.

The outputs from the circuitry are:

- two channels, sample and hold values
- digital frequency meter output for the transmitted frequency
- single channel output showing the amplified and envelope detected signal

The controls include:

preset adjustments	- frequency of the tone bursts
	- channel gain
	- sample and hold trigger
switches (SPST)	- transmit (tone bursts) or DFM output (continuous tone)
	- preset or variable frequencies
10 turn pot.	- variable frequency adjustment
switches (SPDT)	- tone f_1, f_2, or alternate
	- three gain settings
switch (SPMT)	- six attenuation settings

5.3. Use of the computer and aScope

The aScope is available for the Apple IIE desktop computer. It operates as a dual beam digital storage oscilloscope and can display, in real time, signals up to 25KHz. When measuring repetitive waveforms however, signals as high as 50MHz can be obtained using an iterative process. This would require 2000 scans. Each trace consists of 256 eight-bit words which are readily accessible for signal analysis.

The aScope is suitable for this measurement system which operates using the sample and holds at approximately 2KHz. The absence of an external trigger complicates operation, but the solution is to include a trigger pulse on the signal channels. A typical received signal from the random suspension is illustrated in FIG 5.5. Each point (256 total) represents one reading from the suspension.

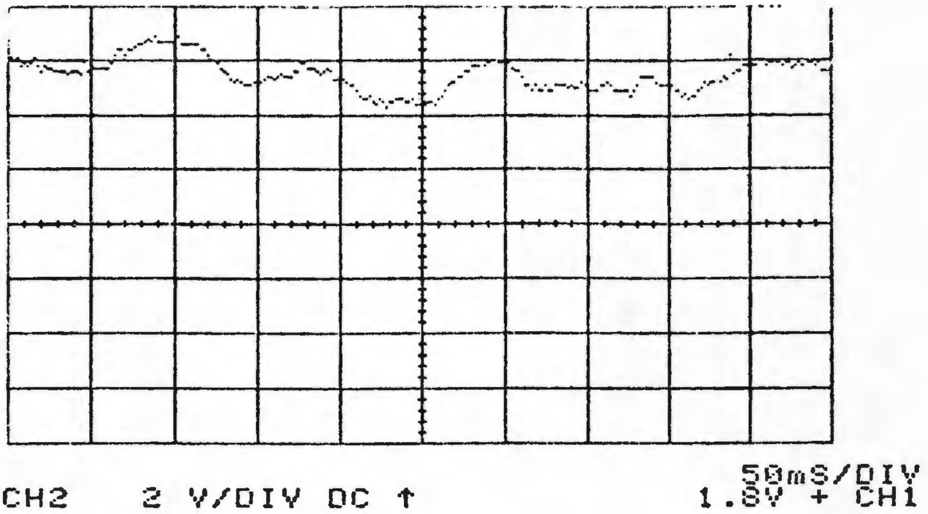


FIG 5.5 The fluctuation of a typical received signal due to the random motion of the suspension for the duration of 500ms.

The mean value and fluctuation of the trace are apparent and are easily calculated. The mean gives an indication of attenuation and the fluctuations give information on the random motion and velocity of the slurry. The computer is used to calculate these values, averaged over any desireable number of samples.

The control program for the measurement is written in modular form, with the following menu:

i) Ascope
ii) Basic
iii) Channel select
iv) Sampling points
v) Number of samples
vi) Initial setup storage
vii) Alter reference
viii) View reference
ix) Run measurement program
x) Continue run
xi) Save plot
xii) Load plot
xiii) View signals
xiv) Output plot to printer
xv) Fluctuations

The software listing is in appendix B while a brief description of each module is given below.

"Ascope" exits the program and calls the oscilloscope mode of the computer. All the normal functions are available from the keyboard, as illustrated in the appendix. The time base and vertical gain must be set in this mode before the control program can be used.

"Basic" exits the program and returns to the monitor.

"Channel select" selects both or either one of the aScope's beams.

"Sampling points" sets the time slot on each trace of the data to be analysed. The average of the points between the two markers is stored by the computer.

"Number of samples" sets the number of traces that will be averaged before the time slot averaging above is performed. This enables a trace to be made from the suspension containing very little random noise.

"Initial setup storage" saves the parameters set in iii, iv and v on disk and these values are automatically loaded each time the control program is run, eliminating the need to reset them each time measurements are to be made.

"Alter reference" averages 255 waveforms from the suspension to obtain a reference waveform consisting of 256 points. The suspension must not be altered during this time, and therefore the reference is normally taken in water for stability.

"View reference" is used to check the acceptability of the reference.

"Run measurement program" determines the attenuation of the suspension with respect to the reference. A trace of this attenuation is built up over a time, dependent on the number of samples required to be averaged. The fluctuation effects from the suspension are largely neutralised by the averaging process. During a measurement run, it is possible to return to the menu to alter iii through v and "continue run".

"Save plot" allows a measured trace to be viewed and then be stored on disk if required.

"Load plot" returns the specified trace from disk to the control program's memory.

"View signals" allows any traces to be viewed. This is normally used before saving a trace on disk or the plotter and after loading a trace from disk.

"Output plot to printer" makes a hard-copy of the required traces stored in memory.

"Fluctuations" is a module added to the original program for the purpose of analysing attenuation or signal traces. It determines the mean and its RMS fluctuation in either dBs or volts as required.

CHAPTER SIX

RESULTS AND DISCUSSION

6.1 Measurements in suspensions with transducers operated at their fundamental resonance

Measurements of attenuation and fluctuation were taken using four transducers (2, 3, 6, 8, FIG 3.8) resonant at 0.5, 1, 2 and 4 MHz. Care was needed to align them with the opposite wall in the suspension container to obtain the best possible reflected signal. A reference waveform is acquired from this pulse echo before measurements commence. It is usually taken in water but experiments indicate that a known density suspension reference is suitable, especially for dense media where attenuation is high. This is true because of the stationary nature of the results.

The media of interest are resin particles in water and slurry suspensions. This section gives details of the slurry measurements at 0.5, 1, 2 and 4 MHz. Section 6.2 deals with slurry and resin comparisons using a single transducer operated at 1 and 3 MHz. The initial analysis of mixed suspensions is performed in section 6.3.

The slurry particles are quartz rock in powder form and are approximately 20 microns in size. They are of random form with some porosity. The air has an acoustic impedance many orders larger than water and this results in very high scattering. Observations have shown that the attenuation decreases as the particles become saturated, suggesting that the air is removed from the surface of the particles. This would be necessary in the gold extraction process to enable the ion exchange to take place.

The attenuation of slurry is greater for the higher measuring frequencies and is predicted to have a square law dependence. The results from the aScope are plotted linearly although the co-ordinates are given logarithmic values (in decibels). The standard measuring technique is to take several readings from the reference medium before changing its composition. This indicates the reliability of the reference and renders possible any necessary corrections, such as a D.C. offset.

A comparison of the 2 and 4 MHz frequencies for a low slurry density is described in FIGs 6.1 and 6.2 and show the high sensitivity of the system. The density of the 520g dry weight slurry in the 17 litre solution used is given as:

$$\begin{aligned} D &= \text{weight/volume of the suspension} \\ &= (17 + .520)\,\text{Kg} \,/\, 17\ell \\ &= 1.031 \end{aligned}$$

This is approximately a twentieth of the density that is typically achieved in the gold extraction process. The effects noted here are used as a guideline for the characterisation of high density slurries. The dBs used throughout are for the signals as recorded. Because of the exploritory nature of the work it was not felt justified in claiming dBs per centimeter or dBs per wavelength.

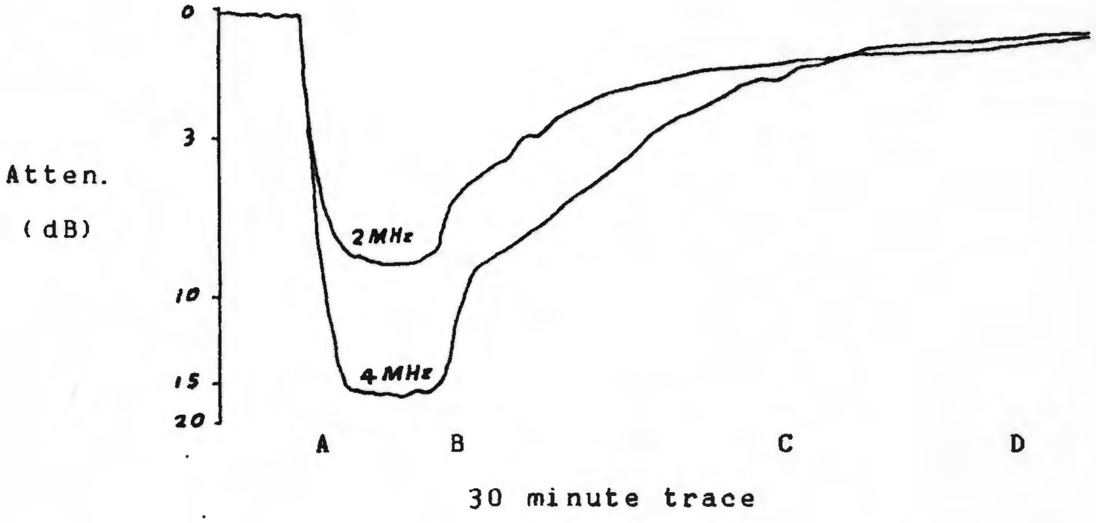


FIG. 6.1 An attenuation trace typical of slurry. Up to A, stirring of fresh water shows the zero reference attenuation. Wet slurry was then added and the suspension soon became stable. It is noted that the 4 MHz attenuation is virtually twice that at 2 MHz. At time B, the stirring stopped and the attenuation slowly returns to its zero value as particles of various sizes settle past the transducers. Some very fine particles are still present even after 20 minutes.

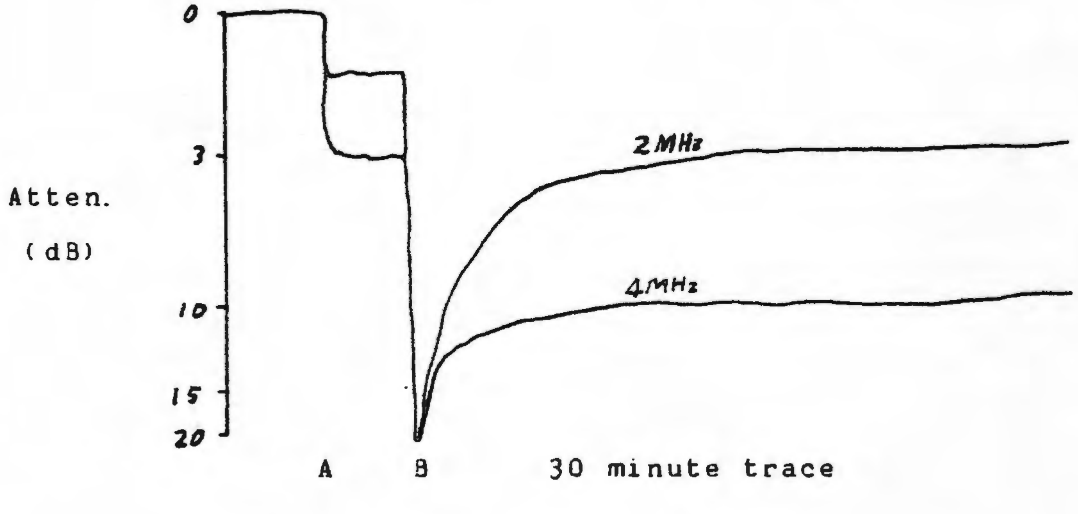


FIG. 6.2 Some of the settled slurry from the previous experiment was measured without stirring until point A. At time B, dry slurry was added causing extinction of signals. These returned as the powder became saturated. The attenuation ratio of the two frequencies is again in the approximate ratio of two to one indicating a constant loss angle.

Dry slurry additions initially make the suspension opaque to ultrasonic waves. The result is repeatable and occurs irrespective of the manner in which the dry slurry was inserted, namely sprinkled in as a fine powder or entered as lumps. After a short time the attenuation settles to that level which an equivalent wet slurry addition would have established.

The time taken for the signal to stabilize is thought to be dependent on the solubility of air into water and the surface shape of the particles, which could cause pockets of air to become trapped in cracks or other discontinuities. A sample of slurry was placed in a vacuum to eliminate as far as possible air from the particles, and then saturated with carbon dioxide which is readily dissolved into water. The addition of this sample to the suspension still revealed the disappearance of the signal echo and its characteristic return. This experiment therefore did not clarify the mechanism producing this phenomenon.

Typical results obtained for the determination of the attenuation dependence on slurry density are illustrated in FIG 6.3. As in most of the attenuation experiments, a water reference is used making the addition of equal amounts of slurry easily discernable.

The extrapolated curve does not pass through the origin in FIG 6.3a as might be expected. This is due to a residue of slurry and resin particles in the container which, when in suspension adds to the attenuation of the material under test.

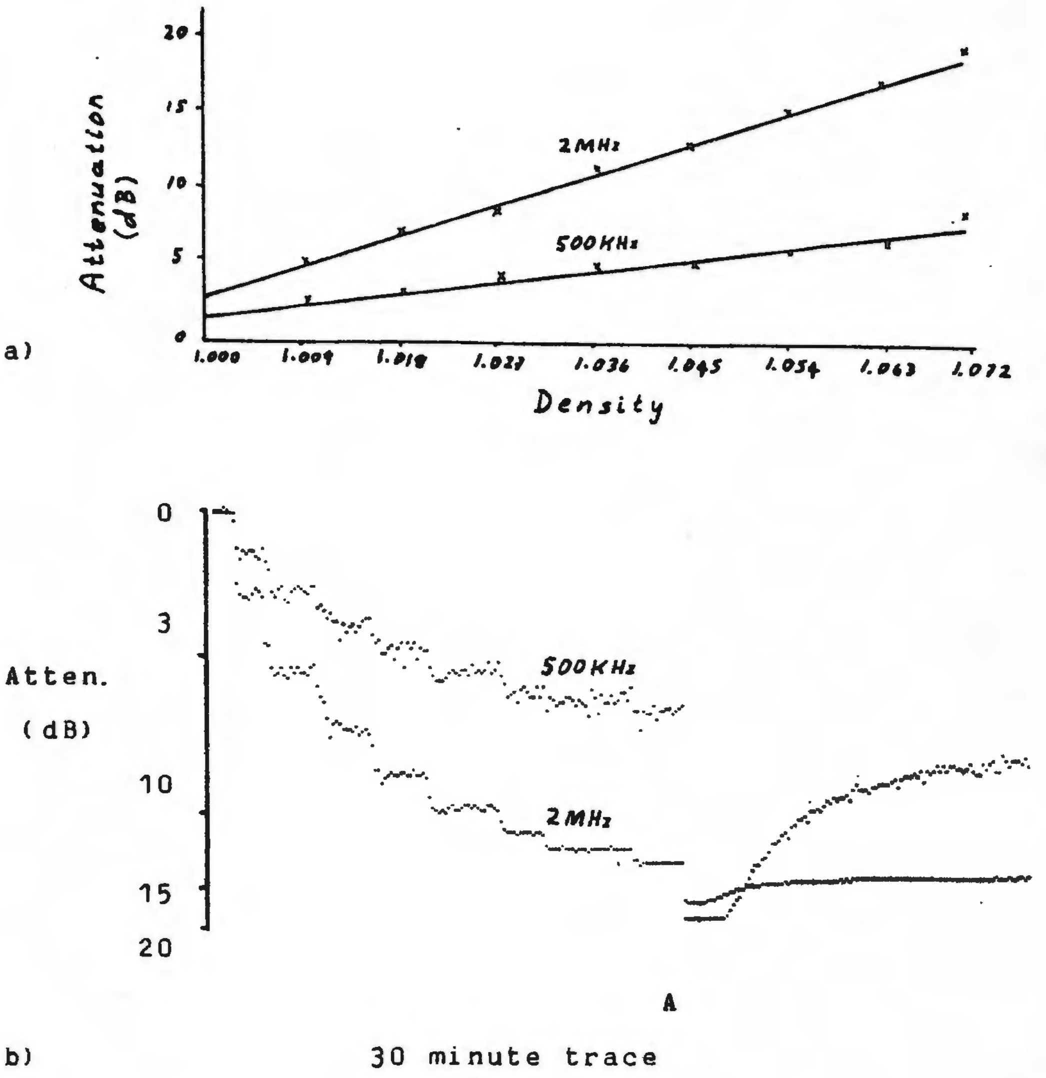


FIG. 6.3 Equal additions of slurry cause a linear increase in attenuation which is dependent on the measuring frequency. The 2MHz signal is attenuated three times the 500KHz signal as seen in a). The graph was obtained from b) which shows wet slurry additions except at point A where dry slurry caused the usual total loss of signal.

The reliability of the reference waveform obtained from signals propagating through a suspension was verified for low density concentrations. Attenuation measurements similar to those in FIG 6.1 were made at 1 and 2 MHz, using both water and slurry referenced signals. A comparison of the two approaches is illustrated graphically in FIG 6.4.

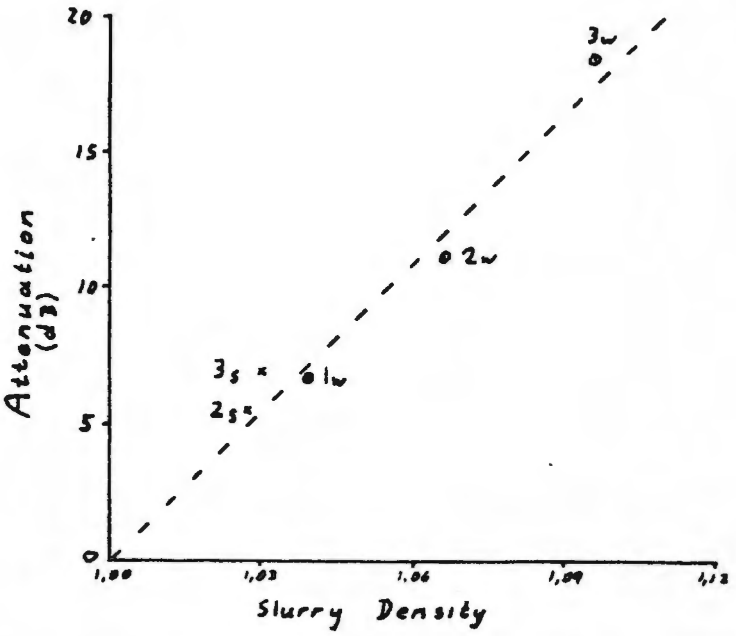


FIG. 6.4 Low density slurry is used to compare water (zero) and slurry referenced signals. Points 1_w, 2_w and 3_w are water referenced. Slurry referenced measurements were taken between each of these readings, and the suspension therefore was allowed to settle before each subsequent zero reading could be made. Points 2_s and 3_s were obtained by adding slurry to a stirred suspension , and correspond to the change in attenuation between 1_w & 2_w and 2_w & 3_w respectively. The correlation of the two techniques is evident, and further experiments confirmed the value of the slurry referenced signals.

An unexpected phenomenon was dicovered when slurry suspensions with densities greater than approximately 1.05 were allowed to settle. Instead of the previously observed exponential settling of the particles, the attenuation indicates that the suspension is being maintained. Observations revealed a clearly defined slurry/water boundary is formed which on crossing the transducers causes an immediate return of the signal. This is a settling characteristic of sufficiently high density suspensions.

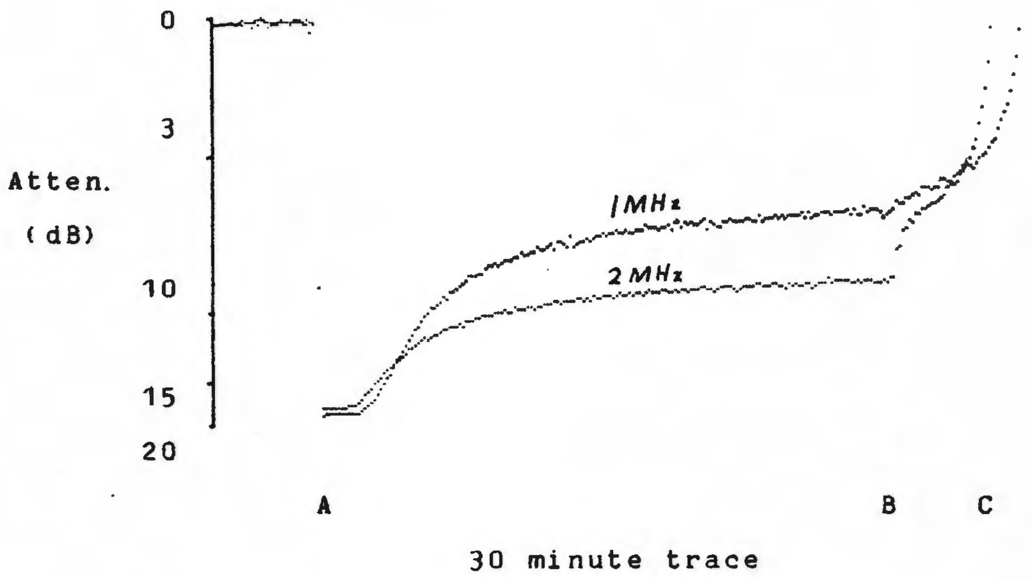


FIG. 6.5 1 and 2 MHz signals are averaged at 16 samples per point. A slurry reference is used and is checked to point A, where dry slurry is added. The characteristic recovery of signal is observed to B, where stirring ceased. The slurry is seen to settle until C where the slurry/water boundary passed the two transducers giving attenuation in water.

FIG 6.5 describes a slurry stirred into suspension until point B, after which it is allowed to settle. The immediate settling of the larger particles is detected by the increase of the 2 MHz signal. Shortly afterwards this signal is unexpectedly seen to rise before the 1 MHz trace. This is due to a clearly visible slurry/water boundary being formed by the suspension, which gradually moves down the tank. The 2 MHz transducer is mounted above the 1 MHz and therefore gives rise to the earlier increase of signal.

It is apparent in FIGs 6.6 and 6.7 that the attenuation and fluctuation of the received signal are dependent on the speed of the stirrer.

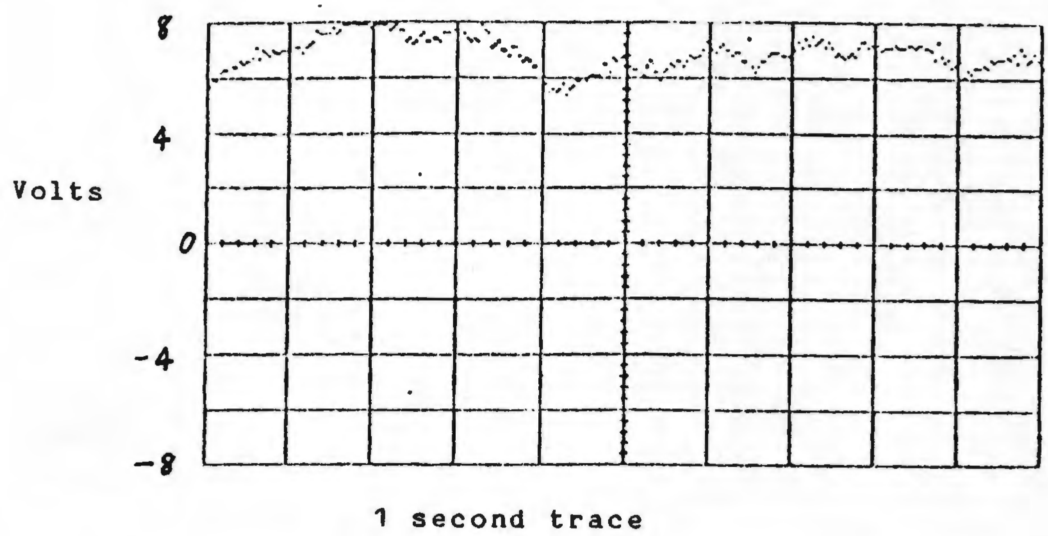


FIG. 6.6 The fluctuation of a pulse echo in a slurry suspension. The 2 MHz aScope display shows successive pulse heights (volts) for a time of one second (256 samples). Analysis shows the fluctuations to be 1.2 dB about a mean echo amplitude of 6.4 volts.

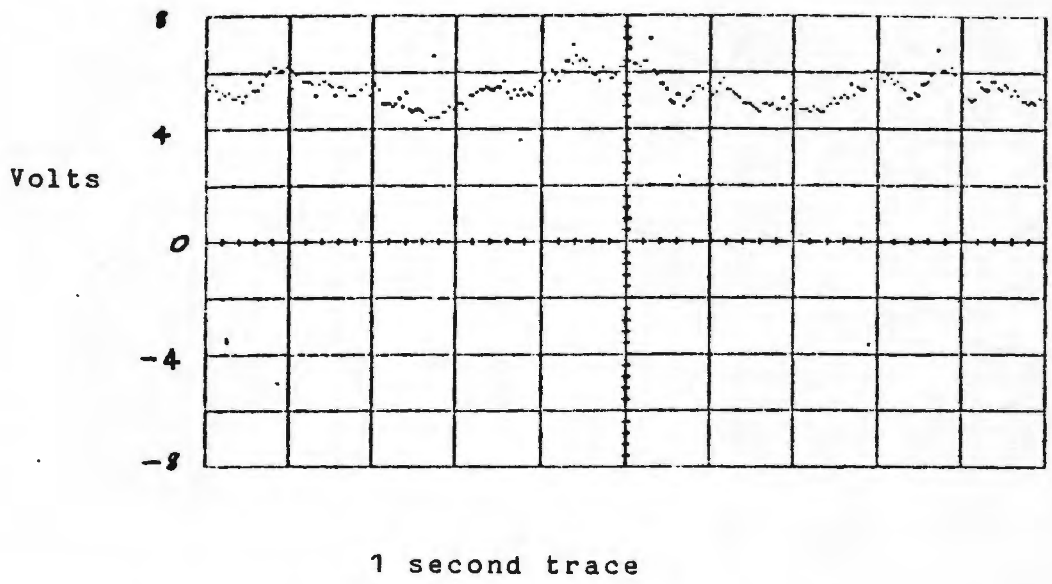


FIG. 6.7 The received signal with a considerable increase in stirring speed. The mean echo height fell by only 1.8 dB and the fluctuations remained at 1.2 dB. The two predominant frequencies in the fluctuations (2 and 10 Hz) increased only slightly.

Increased attenuation occurs with increased speed due to a more even suspension being obtained. Care is needed during experimentation to ensure that a uniform suspension is maintained to ascertain the reliability of the results.

The fluctuations are both frequency and amplitude dependent on speed. Spectral analysis confirmed this in part, as seen in FIG 6.8, the fourier transform of the amplitude versus time trace[17].

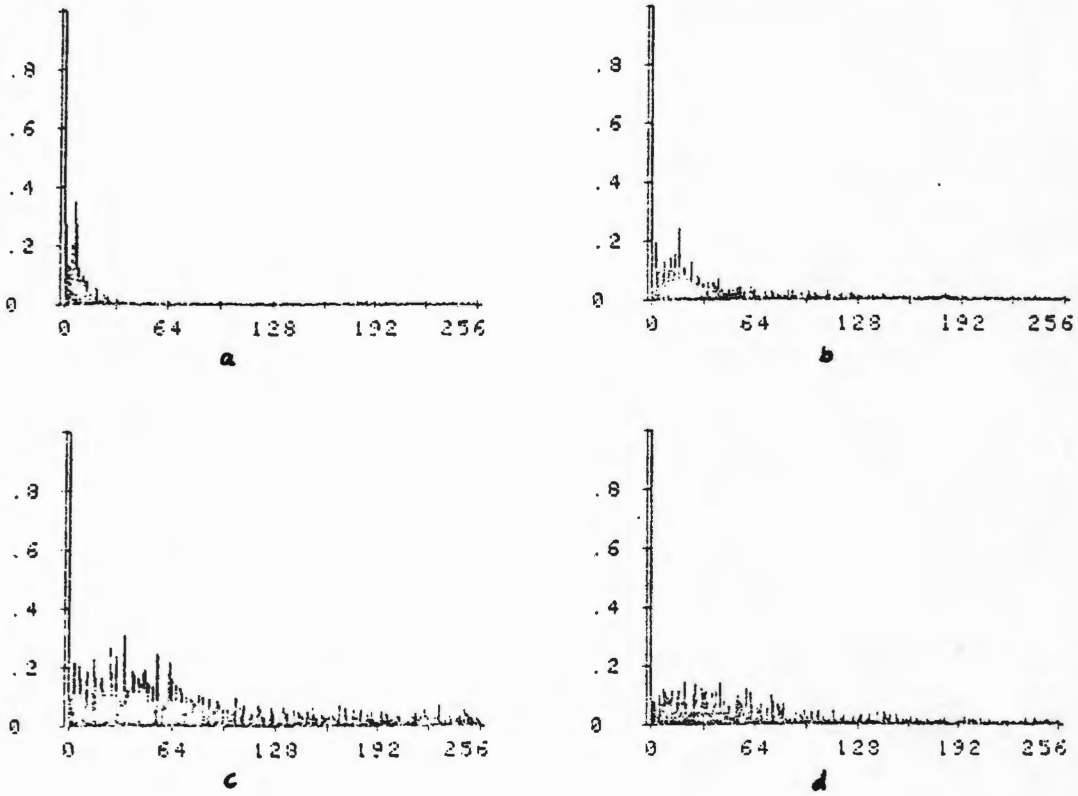


FIG. 6.8 The spectra of the detected signals' amplitude fluctuations at four slurry velocities. The variac controlling stirring speed was set at 30, 40, 60 and 70 volts. The corresponding spectral components are dominant at a) 7Hz, b) 15Hz, c) 30Hz and d) 40Hz. The frequency of the fluctuations is a characteristic of the motion, velocity and turbulence, of the slurry and not of the inherent slurry characteristics.

6.2 Results of the single transducer, dual frequency system

The measurement system as described in section 5.1 is used for the analysis of resin particles in water and slurry suspensions. The single transmit/receive transducer is alternately driven at the fundamental resonance of 1 MHz and then at the overtone frequency of 3 MHz. The pulse burst duration at each frequency is 0.040ms and the time between bursts is 2.0ms ensuring that any multiple reflections from the container walls will have died down. During this time, the suspension will have travelled less than 0.1mm and the received signal echoes at each frequency can be regarded as having propagated through paths with the identical suspension composition. Any difference in signal is therefore attributed to the change in the pulse burst frequency.

Experiments showed the 3 MHz signal to be useful only at low density suspensions, where as the 1 MHz echo is detectable in 1.6 density slurries over a distance greater than 160mm. Slurry densities are given as a weight to volume ratio (see sec. 6.1) and resin particle densities as a volume to volume ratio. The latter are measurable above 1.10 densities, which is the 10% by volume typically used in practice.

The resin and slurry give time variant signals due to the water absorbant properties of the two materials. Dry particles added to the suspension initially cause the suspension to be opaque for ultrasonic signals. The echoes reappear and reach a plateau after about an hour. This plateau rises gradually over a period of days apparently exponentially, with a rapid increase in the first hour and marginal change after several days. Measurements of resin and slurry therefore require knowledge of the materials history if an accurate value of density is to be obtained from the attenuation measurements.

Distortion of the wavefront causes fading, which is the reduction of signal due to phase effects. This distortion is proportional to frequency and is dependent on the turbulence and micro temperature structure of the medium. An ultrasonic wave passing through a warm region would increase in speed, and therefore tend to disperse. Similarly, a cold region would focus the wave to a point. Huygen's principle, based on the consideration of each point on the wavefront as a wave source can be used to determine the distorted path.

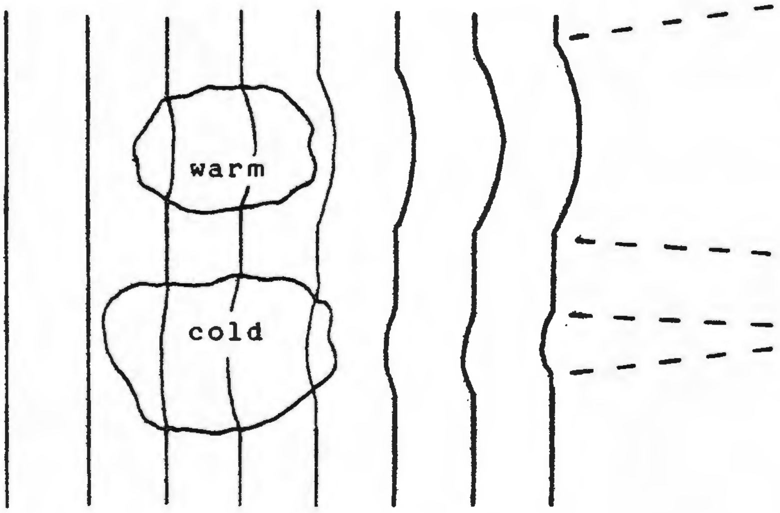


FIG 6.9 Distortion of a wave due to the presence of micro temperature stuctures.

Classification of slurry began with dry slurry additions to water. A reference was taken in still water, after which stirring began and the effects of turbulence were noted. They were negligible and therefore all changes with respect to the reference when particles are added are a property of that material. The difference between calm and turulent water is noted in FIG 6.10. Micro temperature effects could also cause errors in the results and to discover the extent of these effects, measurements were made on water at room temperature which then had boiling water added to it. This produced interfaces of the two waters in the path of the beam and was seen to have negligible effect. This means that micro temperature structures in a suspension under test will make no significant change to the ultrasonic signal.

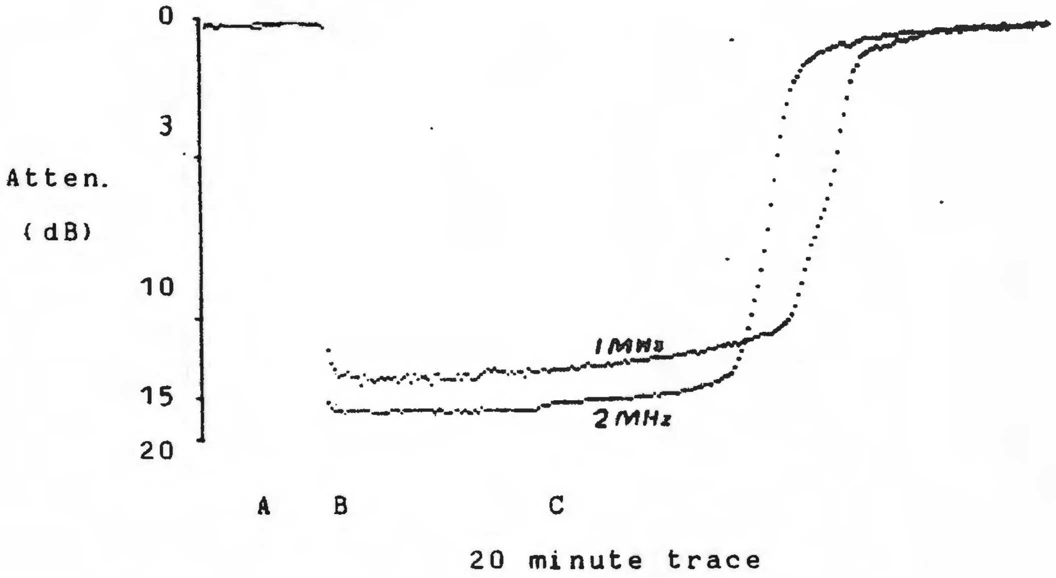
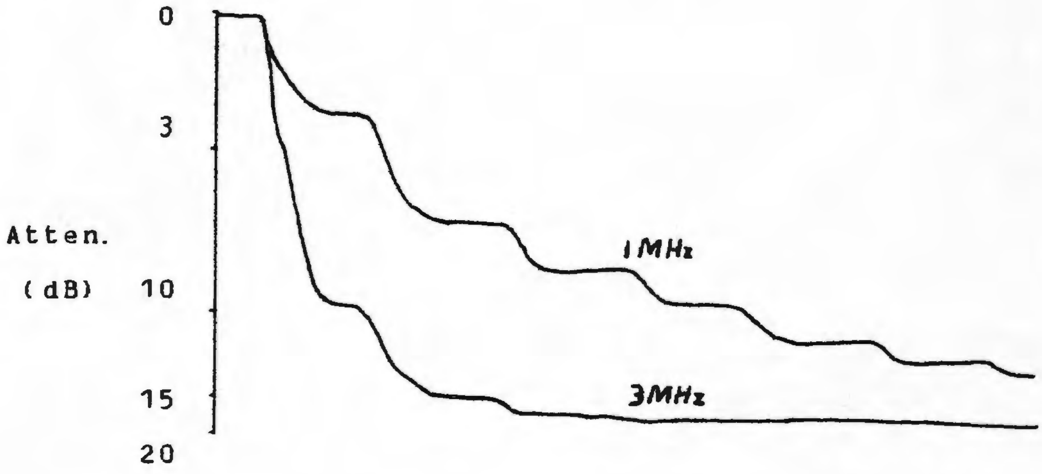


FIG. 6.10 A typical trace measured in a slurry suspension. The reference was taken in water and is directly compared to the readings up to point A to show the short term stability of the system. Stirring to B indicates the negligible effect of turbulence. A 1.01 density slurry by weight was created and stirring ceased at C. The suspension settled slowly and a sudden increase in signal occured when the slurry/water boundary crossed the transducers.

When historically identical samples of slurry or resin particles are added consecutively to a suspension, then the attenuation is exponentially dependent on density. Given this, the density determination of either individual medium is elementary, once its effect on attenuation has been established. More complex is the analysis of suspensions that contain particles saturated for varying lengths of time. Typical results of measurements made on slurry are illustrated in FIG 6.11. The graph in FIG 6.12 was obtained from these readings.



30 minute trace

FIG. 6.11 Attenuation of the 1 and 3MHz signals when 100g soaked slurry per addition is mixed with the 2 litre suspension. The linear plot reveals the exponential nature of attenuation with respect to density.

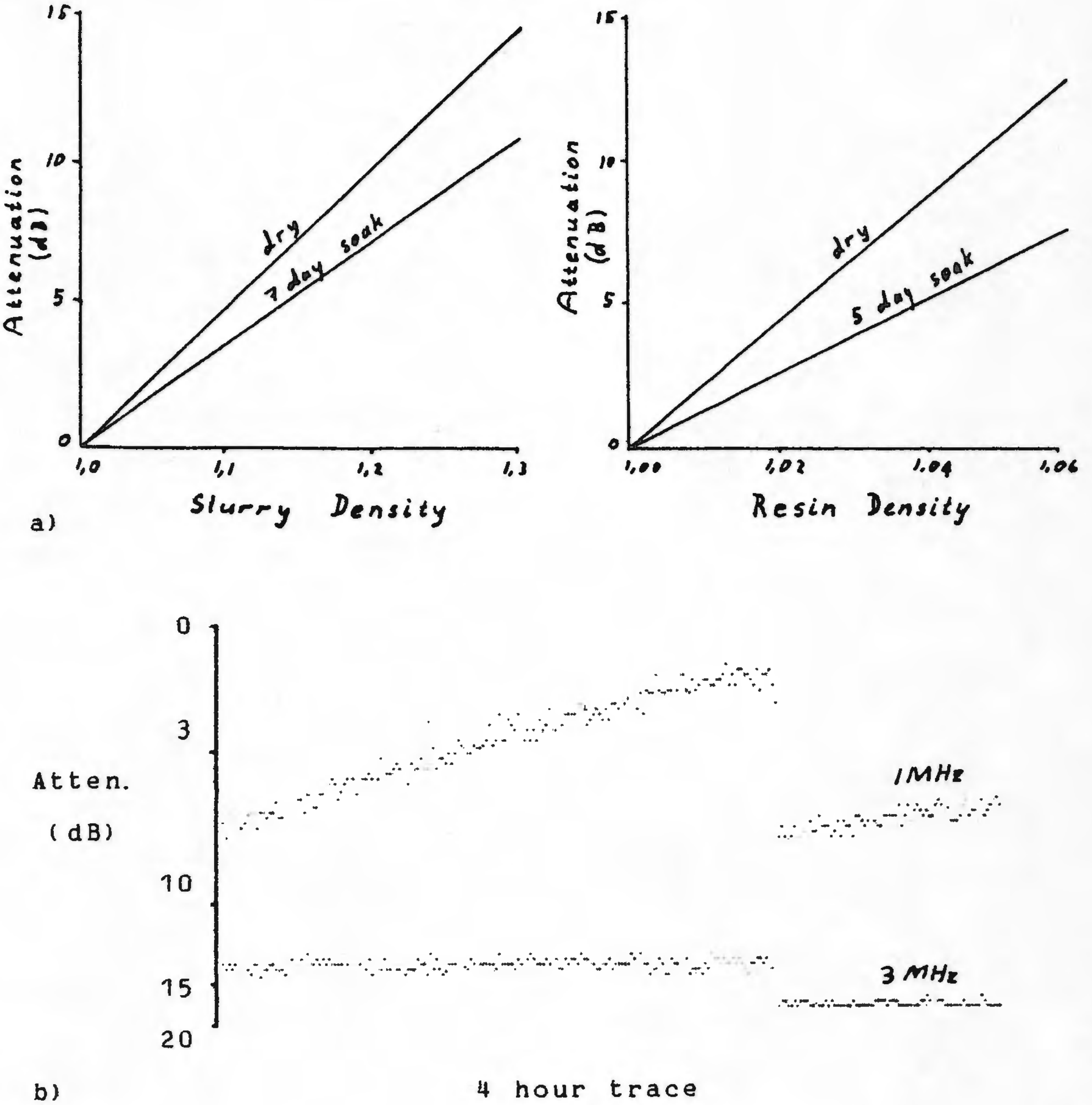


FIG. 6.12 The attenuation dependence of 1MHz signals on density and soaking time in a) slurry and resin, and b) Resin becoming saturated.

The resin particles exibit a similar change with time, as seen in the graph. They do not however cause the complete loss in signal when entered dry as does slurry. Typical signals for resin particles having undergone different periods of soaking are illustrated in FIG 6.13, from which the previous graph was compiled.

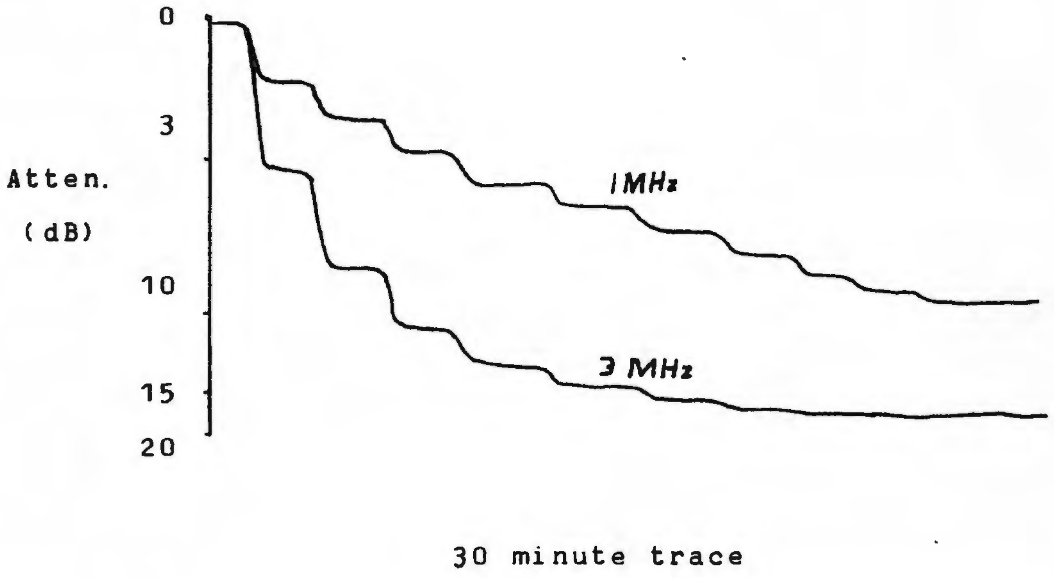


FIG. 6.13 Attenuation of 1 and 3MHz signals through a 2 litre suspension with 12.5ml additions of resin particles.

A comparison of the attenuation at different frequencies is given below for resin at 1 and 3MHz. This method is the so called loss angle, and gives an indication of attenuation per wavelength. For example, a resin density of 1.04 gave attenuation at 1 and 3MHz as 2.2 and 8.3 dBs respectively. Each value is normalized with respect to its frequency, and the ratio of these two values gives the loss angle as:

$$\text{loss angle} = (8.3/3)/(2.2/1)$$
$$= 1.26$$

This indicates that the attenuation per wavelength is greater at the higher frequency for the chosen resin suspension.

Frequency discrimination for high density suspensions is difficult because of the large attenuation of the 3 MHz signal. The 1MHz echo is still suitable for use in suspensions typically found in practice and it would be convenient if it alone was sufficient for classifying the medium. Experimental analysis showed the fluctuation of the attenuated echo about its mean to be dependent on the medium, and to be different for slurry and resin particles.

FIG 6.14 gives the empirical results for the two seperate media. There is evidence of a second order effect which can be determined from the latter part of the graph. The first order effect is approximated by the tangent at the origin.

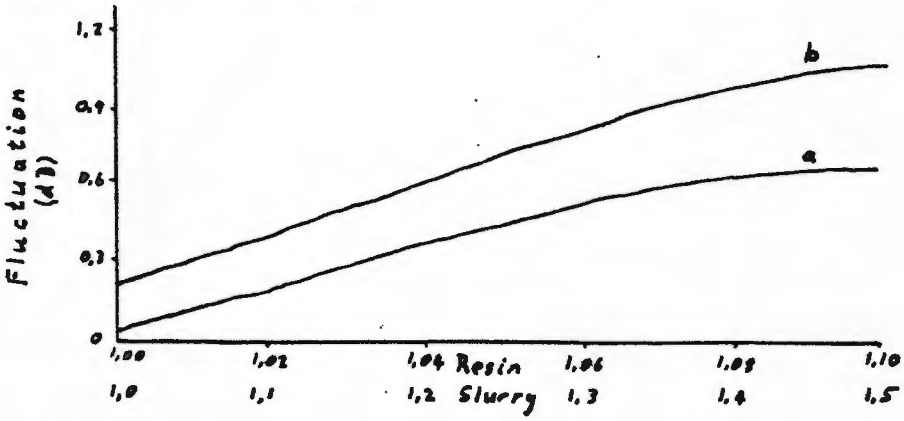


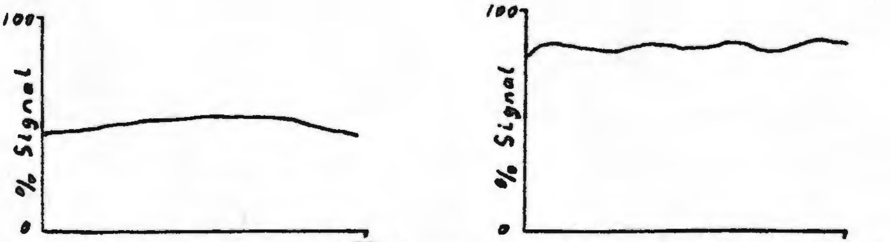
FIG. 6.14 The fluctuation caused by a) slurry and b) resin particles with respect to density.

When stirring stops, the fluctuations continue for a short while (15 - 45 seconds) before ceasing, which suggests that they are a turbulence phenomenon. Turbulence in water however does not produce this effect which means that it is also dependent on the suspension. It could be a wavefront distortion caused by the particles being in the near field, where the sound magnitude plot shows its complex nature. Interference from particles in this region could therefore further complicate the signal and cause the observed fluctuations. The use of a pin transducer would determine the extent to which particle interference in the near field effects the readings.

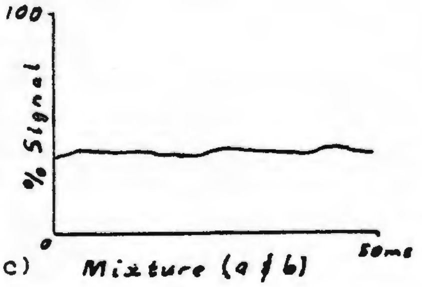
6.3 The applicability of the results to the characterization of suspensions

This section provides scope for future work. Initial measurements taken in mixed suspensions appear to behave as expected for attenuation and fluctuation. The attenuation is a first order effect for both slurry and resin and as an initial approximation for the mixed suspension attenuation, the logarithmic values for each individual medium are simply added. It is necessary to confirm that this is always true because the intermixing of the two media could result in less attenuation than expected.

The fluctuations are measured as the root mean square of the departure from the mean attenuation, and is therefore a second order effect. The mixed suspension fluctuations are approximated as the root of the sum of the individual squared values. Typical measurements are illustrated below.



a) Slurry (Dens. 1,2) b) Resin (Dens. 1,01)



c) Mixture (a & b)

FIG. 6.15 Fluctuations in the detected signal measured in a) slurry, b) resin and c) mixtures.

A comparison of these values is made with the graphs of the two seperate media in FIG 6.12. The materials used here were soaked for two weeks.

Slurry Density	Attenuation	Fluctuation
1.2	6.2	0.30
1.3	12.5	0.41
Resin Density		
1.01	1.1	0.30
1.02	2.3	0.39
1.03	3.7	0.45
1.04	4.9	0.65
1.05	6.2	0.75

Density		Predicted		Measured	
slurry	resin	atten.	fluct.	atten.	fluct.
1.2	1.01	7.3	0.42	6.57	0.41
1.2	1.02	8.5	0.49	7.97	0.43
1.2	1.03	9.9	0.54	9.14	0.53
1.3	1.03	16.2	0.61	11.52	0.55
1.3	1.04	17.4	0.77	13.28	0.64
1.3	1.05	18.7	0.85	14.27	0.65

FIG. 6.16 A comparison of the predicted and measured attenuation and fluctuation values of mixtures of slurry and resin. The predictions were derived from table a).

These values suggest the correctness of this approach but require to be substantiated by further experimentation.

The settling of the mixed suspension is of interest. When stirring ceases, there is an immediate small drop in signal before it is surprisingly attenuated to a value greater than that during stirring (FIG 6.17). This is followed by the settling of the resin particles which is represented by the sharply rising section of the trace. A plateau then follows which indicates the settling of the slurry. The mechanics of this settling always results in a layer of resin being sandwiched between two slurry layers on the bottom of the tank (FIG 6.18). The heavy slurry particles settle first, followed by the resin and then the light slurry producing the characteristic settling layers.

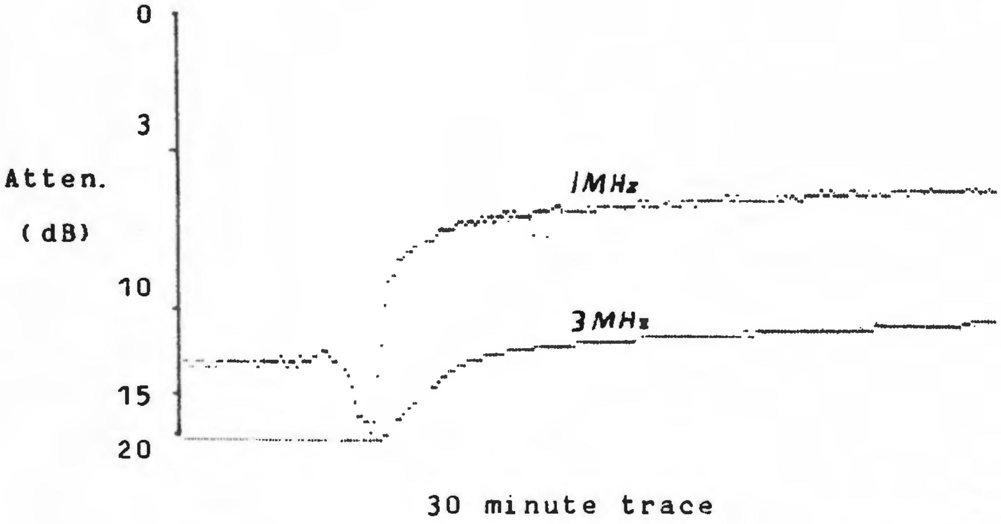


FIG. 6.17 The settling characteristics of a slurry and resin mixture measured at 1 and 3MHz. The 1MHz trace indicates heavy slurry particles settling, before a sudden increase in attenuation occurs as a result of the resin beginning to settle. An exponentially decaying plateau is reached when the fine slurry alone is left in suspension.

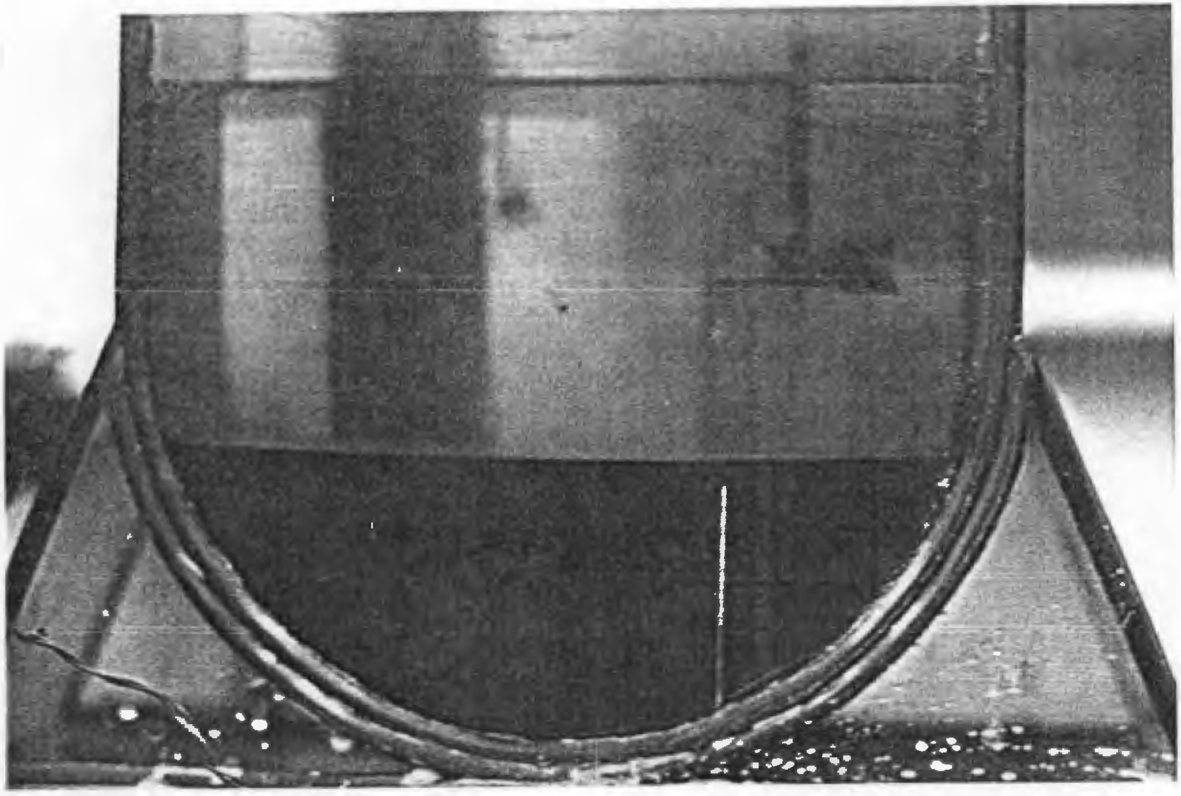


FIG. 6.18 The layered effect characteristic of the settling of resin and slurry mixtures.

The classification of slurry and resin suspensions has been studied in terms of the attenuation, fluctuation and frequency dependence of the two media. These depend on the scattering and absorption properties of the particles in suspension. The factors contributing to the change of the ultrasonic pulse echo are:

- particle size
- suspension density
- soaking time of the suspension
- velocity of the suspension

Mixed suspension effects could be approximated by a combination of the individual media effects. The settling of the suspension is of interest, especially in the case of a surry and resin mixture.

CHAPTER SEVEN

CONCLUSION

7.1 Characterization using attenuation and frequency

The attenuation (in dB) of ultrasonic waves propagated through a given homogeneous suspension increases linearly with signal frequency increments. This increased attenuation is best described as the loss angle, which gives the attenuation per wavelength as constant for homogeneous suspensions. Inhomogeneous media are characterized by the scattering effects of the individual particles which are significantly different for the Rayleigh and geometric regions.

A change in density of the medium is accompanied by a corresponding change in the attenuation of the propagating wave, provided the added (or removed) particles are identical to those in the suspension. This appears trivial, but can be the source of great difficulty when it realized that the attenuation of slurry and resin particles is dependent on their soaking times. Experimental data reveals a logarithmic decrease in the attenuation with respect to time, and therefore the density of only historically known suspensions can be calculated from straight forward measurements of attenuation.

Initial measurements taken in suspensions left to soak for several days revealed not only the logarithmic decay in attenuation with time, but also evidence that each frequency is affected differently by the soaking time. The 3MHz signal was only slightly larger whilst the 1MHz signal was approximately 50% larger. This factor, once calibrated, could prove invaluable for density determination of slurry and resins, because the history of the suspension would no longer be a necessary parameter.

The attenuation (dB) of slurry and resin is characterized by the following factors:

Slurry
- Attenuation per wavelength is constant for a given suspension
- Attenuation increases linearly as the density increases
- Attenuation decreases linearly with the suspension's soaking time

Resin
- Attenuation per wavelength is constant for an homogeneous suspension
- Attenuation for inhomogeneous suspensions is wavelength independent in the geometric region
- Attenuation for inhomogeneous suspensions is proportional to the fourth power of frequency in the Rayleigh region
- Attenuation increases linearly as the density increases
- Attenuation decreases linearly with the suspension's soaking time

7.2 Characterization using attenuation and fluctuation

Fluctuation measurements taken in suspensions are dependent on the frequency of the propagating wave. A fluctuation versus frequency technique could therefore be used similarly to the above method. Such a system however would be pointless, because the two approaches would be identical except for the measured parameter, and fluctuation is more difficult to measure than attenuation. The fluctuations can however be used to replace the multi-frequency technique, and this is advantageous when dealing with high density suspensions. A mono-frequency system operated at the lowest possible frequency will give the greatest penetration into the medium. The trade-off with this technique is a lack of sesitivity because the fluctuations are frequency dependent. A compromise between the low frequency penetration and the high frequency fluctuations must be reached, and a tone burst of 1MHz is regarded as a suitable value.

The attenuation measurements in this system are identical to those in section 7.1, but only taken at a single frequency. To distinguish between resin and slurry suspensions, a second parameter is required from the backscattered signal. This is taken as the root mean square (RMS) value of the fluctuation in attenuation. These fluctuations are dependent on frequency which here is constant, the composition and density of the suspension and velocity at which it is moving. In a controlled or known enviroment a comparison of attenuation and fluctuation would reveal the density and composition of the suspension.

The fluctuation of the signal will also vary with soaking time, to an extent that has to be determined. If the attenuation and fluctuation are altered proportionally, which is likely, then the history of the suspension must be known before its density can be determined.

The use of the fluctuations is more applicable to resin measurements where the particles are far larger than in slurry. This is seen in the increased fluctuation amplitude about the mean attenuation of the signal. The motivation for this technique is in the analysis of high density, mixed suspensions. The effects of seperate resin and slurry suspensions on fluctuation are as follows:

- RMS fluctuation increases with increased frequency
- RMS fluctuation has a 2nd order dependence on density
- RMS fluctuation decreases with respect to the suspension's soaking time

7.3 Characterizing mixed suspensions

Two techniques used to characterize mixed suspensions are dual-frequency attenuation measurements and mono-frequency measurements of attenuation and fluctuation. The dual-frequency technique is suitable for low density media where signal penetration is high where as the mono-frequency technique is prefered for high densities where fluctuations in attenuation are significant and high frequency signals are heavily attenuated.

Attenuation versus frequency analysis of a mixed suspension requires a-priori knowledge of its composition. The slurry and resin particles are of the order of fourty times different in size, which enables two frequencies to be chosen to give good scattering discrimination. Both propagating signals have chosen wavelengths far larger than the slurry particles, but the 0.5mm and 1.5mm wavelengths encompass the resin particle size.

Discrimination between the slurry and resin densities using the dual-frequency technique can be achieved by establishing the effects of the two media. The total attenuation of each frequency burst is the logarithmic sum of the resin and slurry's individual attenuations. The power loss per wavelength in slurry is constant, and therefore the 3MHz tone burst is attenuated three times more than the 1MHz signal. The resin particle effects are independent of frequency at 3MHz and proportional to the fourth power of frequency at 1MHz. Establishing the exact relationship and combining it with the slurry effects provides the formula from which the individual densities of the two media in the suspension can be calculated.

The mono-frequency discrimination technique follows a similar method of obtaining a mathematical formula. The attenuation measurements are unchanged but the frequency is replaced by fluctuation analysis. Both the resin and slurry particles cause fluctuations that are calculated as RMS values. The slurry is regarded as homogeneous at the chosen 1MHz frequency and only causes slight fluctuations. The resin particles however, being of similar order of magnitude to the wavelength have a more significant effect. The total attenuation and fluctuation in a mixed suspension are the logarithmic sum of the individual attenuations and the RMS value of their fluctuations. This requires knowledge of the percentage attenuation to fluctuation for each medium.

Both techniques provide consistent results and further work along these lines is encouraged, to obtain the exact effects of the suspensions which will enable accurate classification.

7.4 Viability as an instrument

The developement of an instrument is feasible using the mono- and dual-frequency techniques. A single PZT disk shaped ultrasonic transducer could be used as a transmitter and receiver in both cases. The dual-frequency system requires either a wideband transducer or one with a suitable fundamental and overtone resonances. Tone bursts of 0.040ms duration are launched alternately into the suspension at the two predetermined frequencies (which can be identical). A reflector plate mounted in front of and parallel to the transducer provides the backscattered signal from which measurements are made. Before the process begins, a reference signal usually taken in water is set. Attenuation is calibrated relative to this reference, and fluctuation is calculated from the divergence of the signal from its mean.

The electronics used to implement the process is reasonably straight forward. The required tone bursts are generated by a VCO and then amplified to drive the transducer. The detected signals are amplified and envelope detected, then sent alternately to two sample and holds which is necessary for the dual-frequency technique. At present, a micro computer takes over at this stage to perform the calculations because of its versatility. The attenuation and RMS fluctuations could easily be measured electronically to provide a portable instrument. The characteristics of slurry and resin need to be more fully understood however before a truly accurate instrument could be produced.

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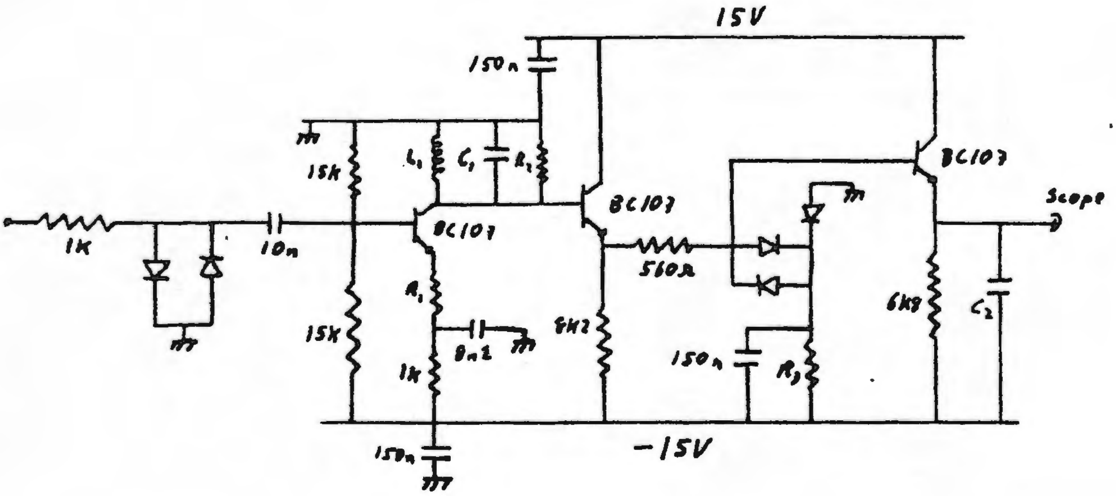
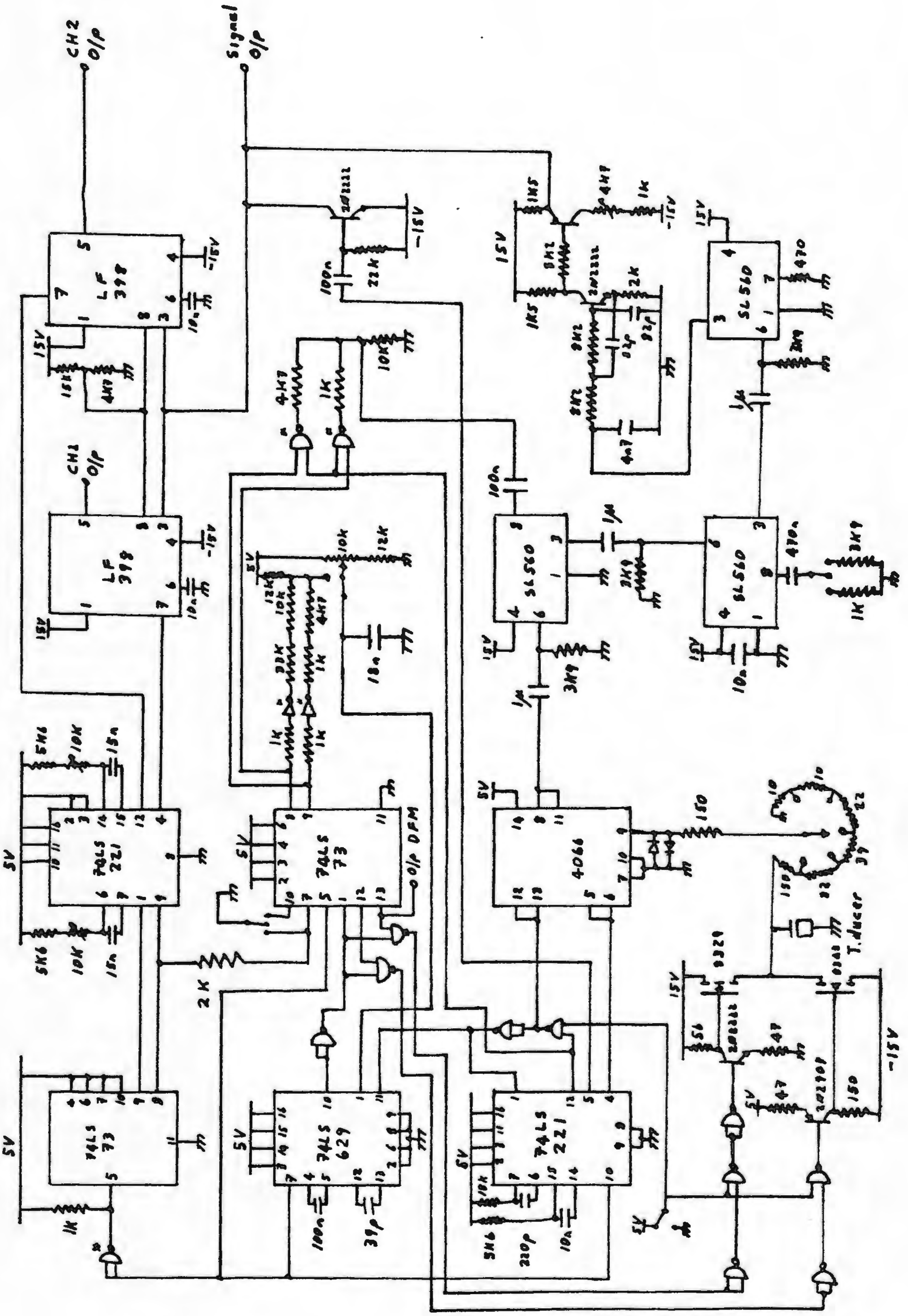
APPENDIX A

Electronic circuitry



The tuned amplifiers and envelope detectors used in the multi transducer measuring system. The two chosen frequencies are 1.1 and 4.6 MHz. The component values differing for the two circuits are:

	1.1 MHz	4.6 MHz
R_1	1 K	47 ohms
R_2	100 K	-
R_3	2.7 K	2.2 K
L_1	330 μH	46 μH
C_1	27 pF	22 pF
C_2	22 nF	8.2 nF



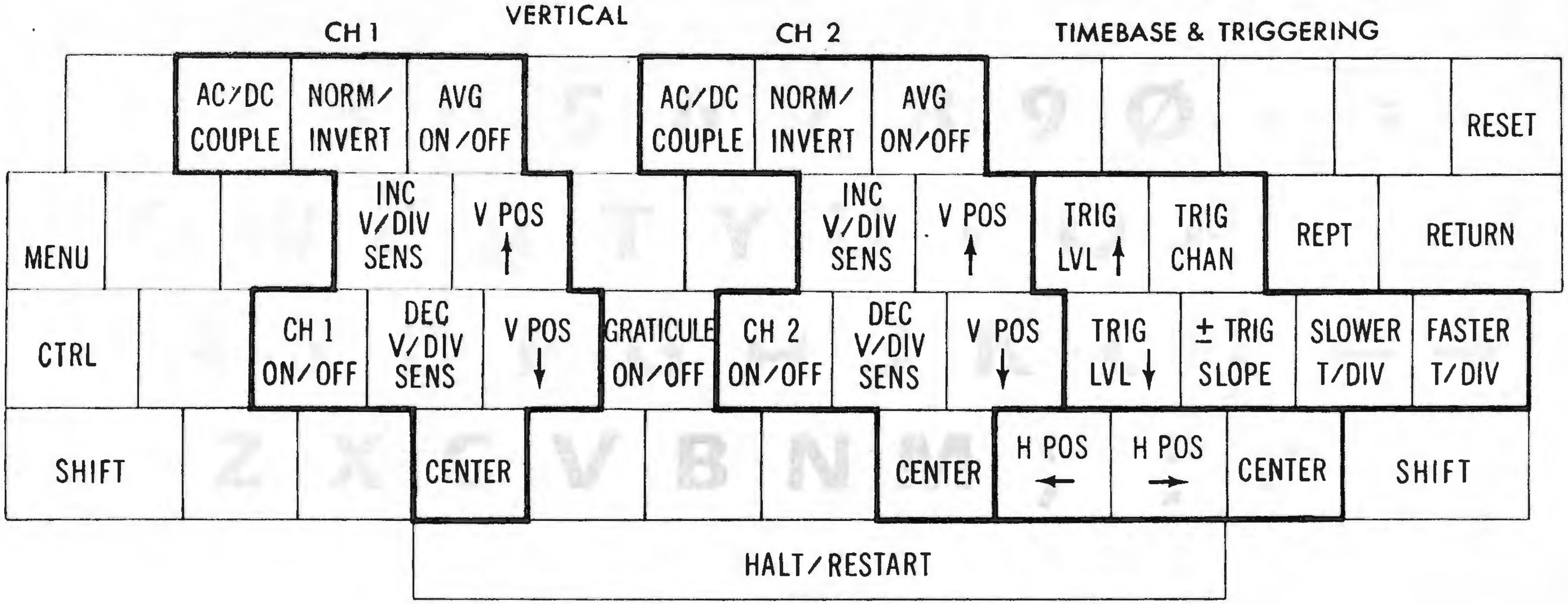
The complete electronics used in the single transducer transmit/receive tone burst echo system.

APPENDIX B

Computer software and aScope controls

MODEL 85 KEYBOARD CONTROL

CTRL-K UNLOCK KEYBOARD
CTRL-X USER SUBROUTINE
CTRL-R REF WAVEFORM ON



The aScope control key allocation for the computer.

```
10  DIM M(4),X(280),Y(280)
15  PRINT  CHR$ (4);"OPEN  STORSET"
20  PRINT  CHR$ (4);"READ  STORSET"
25  INPUT C1,C2,P1,P2,P3,P4,S1,R1,R2,Z$
30  PRINT  CHR$ (4);"CLOSE STORSET"
32  IF Z$ = "Julie" THEN 40
33  HOME
34  INVERSE : PRINT "INSERT DATA DISK"
36  NORMAL : PRINT "Press [RETURN]"
38  GET Z$: GOTO 15
40  POKE  - 27284,1: REM   CH1 AVE ON
45  POKE  - 27212,1: REM   CH2 AVE ON
65 M(1) = 2048
70 M(2) = 2816
75 M(3) = 3584
80 M(4) = 2560
85 SWHALT =  - 27287
90 DIGITIZER =  - 28432
95  HCOLOR= 7
100  TEXT
105  HOME
110  PRINT "Menu": PRINT
120  PRINT "A  Alter reference"
130  PRINT "B  Basic"
140  PRINT "C  Channel select (CH1-";2 - C1;"  CH2-";C2 - 1;")"
145  PRINT "I  Init set-up storage"
150  PRINT "L  Load plot"
155  PRINT "M  Continue run"
160  PRINT "N  Number of samples (";S1;")"
170  PRINT "O  Output plot to printer"
180  PRINT "P  Sampling points (";P1;"-";P2;"  ";P3;"-";P4;")"
190  PRINT "R  Run control program"
200  PRINT "S  Save plot"
205  PRINT "U  View signals"
210  PRINT "V  View reference"
220  PRINT "Z  Ascope"
225  PRINT : PRINT
230  GET Z$
240  IF Z$ = "A" THEN 800
250  IF Z$ = "B" THEN 9989
260  IF Z$ = "C" THEN 400
265  IF Z$ = "I" THEN 8800
270  IF Z$ = "L" THEN 2400
275  IF Z$ = "M" THEN 360
280  IF Z$ = "N" THEN 540
290  IF Z$ = "O" THEN 3000
300  IF Z$ = "P" THEN 600
310  IF Z$ = "R" THEN 1100
320  IF Z$ = "S" THEN 2000
325  IF Z$ = "U" THEN 4000
330  IF Z$ = "V" THEN 900
340  IF Z$ = "Z" THEN  CALL 34352
345  PRINT Z$
350  GOTO 230
```

```
325  IF Z$ = "U" THEN 4000
330  IF Z$ = "V" THEN 900
340  IF Z$ = "Z" THEN  CALL 34352
345  PRINT Z$
350  GOTO 230
360  GOSUB 9010
365  VTAB 22
370  POKE  - 16301,0
375  NEXT J
400  PRINT "CH1  0=off"
405  PRINT "     1=on"
410  GET Z
420  IF Z = 0 THEN 440
430  IF Z <  > 1 THEN 410
440 C1 = 2 - Z
450  PRINT "CH2  0=off"
455  PRINT "     1=on"
460  GET Z
470  IF Z = 0 THEN 490
480  IF Z <  > 1 THEN 460
490 C2 = Z + 1
495  GOTO 100
540  PRINT "No. of samples to average on signal?"
550  INPUT S1
560  POKE  - 27346,S1
570  GOTO 100
600  FOR I = C1 TO C2
610  PRINT "CH";I;" Start?"
620  INPUT P3
630  PRINT "CH";I;" End?"
640  INPUT P4
650  IF I = 1 THEN P1 = P3:P2 = P4
660  NEXT I
670  GOSUB 9000
680  POKE 49234,0: REM  TO PLOT
690  POKE SWHALT,128
700  CALL DIGITIZER
710  FOR J = C1 TO C2
720  FOR I = 0 TO 255
730 X(I) =  PEEK (M(J) + I)
740  HPLOT I,X(I)
750  NEXT I
760  IF J = 1 THEN  HPLOT P1,X(P1) TO P2,X(P2)
770  IF J = 2 THEN  HPLOT P3,X(P3) TO P4,X(P4)
780  NEXT J
790  GET Z$: GOTO 100
800  PRINT "
```

```
780  NEXT J
790  GET Z$: GOTO 100
800  PRINT "Averaging over 255 samples"
810  POKE  - 27346,255
815  POKE  - 16302,0
820  POKE SWHALT,128
830  CALL DIGITIZER
840  FOR I = 0 TO 255
845 X(I) =  PEEK (M(1) + I)
850  POKE (M(3) + I),X(I)
855 Y(I) =  PEEK (M(2) + I)
860  POKE (M(4) + I),Y(I)
870  NEXT I
880  POKE  - 27346,S1
900  INPUT "Zero ref start?";Z
905  GOSUB 9000
910  FOR J = C1 TO C2
920  FOR I = 0 TO 255
925 X =  PEEK (M(2 + J) + I)
930  HPLOT I,X
935  NEXT I
940  NEXT J
945  HPLOT P1,50 TO P2,50
950  HPLOT P3,110 TO P4,110
953 N = Z + 20
957  IF N > 255 THEN N = 255
960  HPLOT Z,156 TO N,156
995  GET Z$: GOTO 100
1100  GOSUB 9000
1110  POKE  - 16301,0: REM  MIXED
1115  HPLOT 260,10 TO 260,159
1120  HPLOT 0,10 TO 4,10 TO 4,159 TO 0,159
1125  VTAB 22
1130  PRINT "M(Menu)?"
1135  FOR I = 0 TO 255
1140 X(I) = 0:Y(I) = 0
1145  NEXT I
1150  FOR J = 5 TO 279
1160 A1 = 0
1170 A2 = 0
1180  POKE SWHALT,128
1190  CALL DIGITIZER
1200  IF C1 <  > 1 THEN 1310
1210  FOR I = P1 TO P2
1220 X =  PEEK (M(1) + I)
1230 X1 =  PEEK (M(3) + I)
1240 X = (X - X1) / (R1 - X1)
1250 A1 = A1 + X
1260  NEXT I
1270 X(J) = 149 * A1 / (1 + P2 - P1) + 10
1280  IF X(J) > 159 THEN X(J) = 159
```

```
1270 X(J) = 149 * A1 / (1 + P2 - P1) + 10
1280  IF X(J) > 159 THEN X(J) = 159
1290  IF X(J) < 0 THEN X(J) = 0
1300  HPLOT J,X(J)
1310  IF C2 <  > 2 THEN 1420
1320  FOR I = P3 TO P4
1330 Y =  PEEK (M(2) + I)
1340 Y1 =  PEEK (M(4) + I)
1350 Y = (Y - Y1) / (R2 - Y1)
1360 A2 = A2 + Y
1370  NEXT I
1375  PRINT  INT (A1 * 100 / (1 + P2 - P1));"%", INT (A2 * 100 / (1 + P4
      - P3));"%"
1380 Y(J) = 149 * A2 / (1 + P4 - P3) + 10
1390  IF Y(J) > 159 THEN Y(J) = 159
1400  IF Y(J) < 0 THEN Y(J) = 0
1410  HPLOT J,Y(J)
1420 Z =  PEEK ( - 16384)
1430  IF Z <  > 205 THEN  NEXT J
1440  GET Z$: GOTO 100
2000  PRINT "SAVE: A  Atten. result(only 256 pt.s)"
2010  PRINT "      C  CH1 & 2"
2020  PRINT "      R  Ref. CH1 & 2"
2030  PRINT "      B  Back to Menu"
2040  GET Z$
2050  IF Z$ = "B" THEN 100
2060  IF Z$ = "A" THEN 2140
2070  IF Z$ = "C" THEN U = M(1):V = M(2): GOTO 2100
2080  IF Z$ = "R" THEN U = M(3):V = M(4): GOTO 2100
2090  GOTO 2040
2100  FOR I = 0 TO 255
2110 X(I + 5) =  PEEK (U + I)
2120 Y(I + 5) =  PEEK (V + I)
2130  NEXT I
2140  GOSUB 9000
2150  HPLOT 0,10 TO 4,10 TO 4,159 TO 0,159
2160  FOR I = 0 TO 255
2170  POKE (3840 + I),X(I + 5)
2180  POKE (4096 + I),Y(I + 5)
2190 X =  PEEK (3840 + I)
2200 Y =  PEEK (4096 + I)
2210  HPLOT I + 5,X
2220  HPLOT I + 5,Y
2230  NEXT I
2235  PRINT : PRINT : PRINT : VTAB 22
2240  POKE  - 16301,0
2245  INPUT "SAVE(Y)?";Z$
2250  IF Z$ <  > "Y" THEN 100
2260  INPUT "File Name?";N$
2270  PRINT  CHR$ (4);"BSAVE";N$;",A$F00,L$1FF"
2280 F$ = "T" + N$
2300  INPUT "Description?";T$
2320  PRINT  CHR$ (4);"OPEN ";F$
```

```
2300  INPUT "Description?";T$
2320  PRINT  CHR$ (4);"OPEN ";F$
2330  PRINT  CHR$ (4);"WRITE";F$
2340  PRINT T$
2350  PRINT  CHR$ (4);"CLOSE";F$
2360  GOTO 100
2400  INPUT "File Name?";N$
2405  PRINT  CHR$ (4);"BLOAD";N$
2410 F$ = "T" + N$
2420  PRINT  CHR$ (4);"OPEN ";F$
2430  PRINT  CHR$ (4);"READ ";F$
2440  INPUT T$
2460  PRINT  CHR$ (4);"CLOSE";F$
2490  GOSUB 9000
2505  HPLOT 0,10 TO 4,10 TO 4,159 TO 0,159
2510  FOR I = 0 TO 255
2520 X(I + 5) =  PEEK (3840 + I)
2530 Y(I + 5) =  PEEK (4096 + I)
2540  HPLOT I + 5,X(I + 5)
2550  HPLOT I + 5,Y(I + 5)
2560  NEXT I
2570  VTAB 22
2575  POKE  - 16301,0
2580  PRINT T$
2590  PRINT "Save Ref(Y)? else Menu"
2600  GET Z$
2610  IF Z$ <  > "Y" THEN 100
2620  PRINT "LOAD in CH1 Ref:0  Nothing"
2630  PRINT "                1  CH1"
2640  PRINT "                2  CH2"
2650  GET Z$
2660  IF Z$ = "0" THEN 2730
2670  IF Z$ = "1" THEN U = 3840
2680  IF Z$ = "2" THEN U = 4096
2690  FOR I = 0 TO 255
2700 X =  PEEK (U + I)
2710  POKE M(3) + I,X
2720  NEXT I
2730  PRINT "LOAD in CH2 Ref:0  Nothing"
2750  PRINT "                1  CH1"
2760  PRINT "                2  CH2"
2770  GET Z$
2780  IF Z$ = "0" THEN 100
2790  IF Z$ = "1" THEN V = 3840
2800  IF Z$ = "2" THEN V = 4096
2810  FOR I = 0 TO 255
2820 Y =  PEEK (V + I)
2830  POKE M(4) + I,Y
2840  NEXT I
2850  GOTO 100
3000  GOSUB 9000
3010  HPLOT 0,10 TO 4,10 TO 4,159 TO 0,159
3020  HPLOT 260,10 TO 260,159
3030  FOR I = 0 TO 255
3040  HPLOT I + 5,X(I + 5)
```

```
3020  HPLOT 260,10 TO 260,159
3030  FOR I = 0 TO 255
3040  HPLOT I + 5,X(I + 5)
3050  HPLOT I + 5,Y(I + 5)
3060  NEXT I
3065  POKE  - 16301,0
3070  VTAB 23
3080  PRINT "Plot(P)  CH1 off(1)  CH2 off(2)  Menu(M)"
3082  GET Z$: IF Z$ = "M" THEN 100
3083  IF Z$ = "P" THEN 3120
3084  HCOLOR= 0
3086  IF Z$ <  > "1" THEN 3094
3088  FOR I = 0 TO 255
3090  HPLOT I + 5,X(I + 5)
3092  NEXT I
3094  IF Z$ <  > "2" THEN 3102
3096  FOR I = 0 TO 255
3098  HPLOT I + 5,Y(I + 5)
3100  NEXT I
3102  HCOLOR= 7
3110  PRINT : PRINT : GOTO 3080
3120  PR£ 1
3130  PRINT  CHR$ (9);"G"
3140  PRINT T$
3145  PRINT : PRINT : PRINT : PRINT : PRINT
3150  PR£ 0
3900  GET Z$: GOTO 100
4000  PRINT "View CH1(1) or CH2(2)?"
4010  GET Z$
4020  GOSUB 9000
4030  HPLOT 0,10 TO 4,10 TO 4,159 TO 0,159
4040  IF Z$ <  > "1" THEN 4080
4050  FOR I = 5 TO 279
4060  HPLOT I,X(I)
4070  NEXT I
4075  GET Z$: GOTO 100
4080  IF Z$ <  > "2" THEN 100
4090  FOR I = 5 TO 279
4100  HPLOT I,Y(I)
4110  NEXT I
4120  GET Z$: GOTO 100
8300  PRINT P1,P2
8800  PRINT  CHR$ (4);"OPEN  STORSET"
8810  PRINT  CHR$ (4);"WRITE STORSET"
8820  PRINT C1: PRINT C2: PRINT P1: PRINT P2: PRINT P3: PRINT P4: PRINT
     S1: PRINT R1: PRINT R2
8900  PRINT  CHR$ (4);"CLOSE STORSET"
8910  GOTO 100
8999  END
9000  CALL  - 28707: REM   ERASE
9010  POKE  - 16304,0: REM GR'S
9020  POKE  - 16302,0: REM FULL
9030  POKE  - 16297,0: REM HGR'S
9040  POKE  - 16300,0: REM PAGE1
9050  RETURN
9989  TEXT
9999  END
```

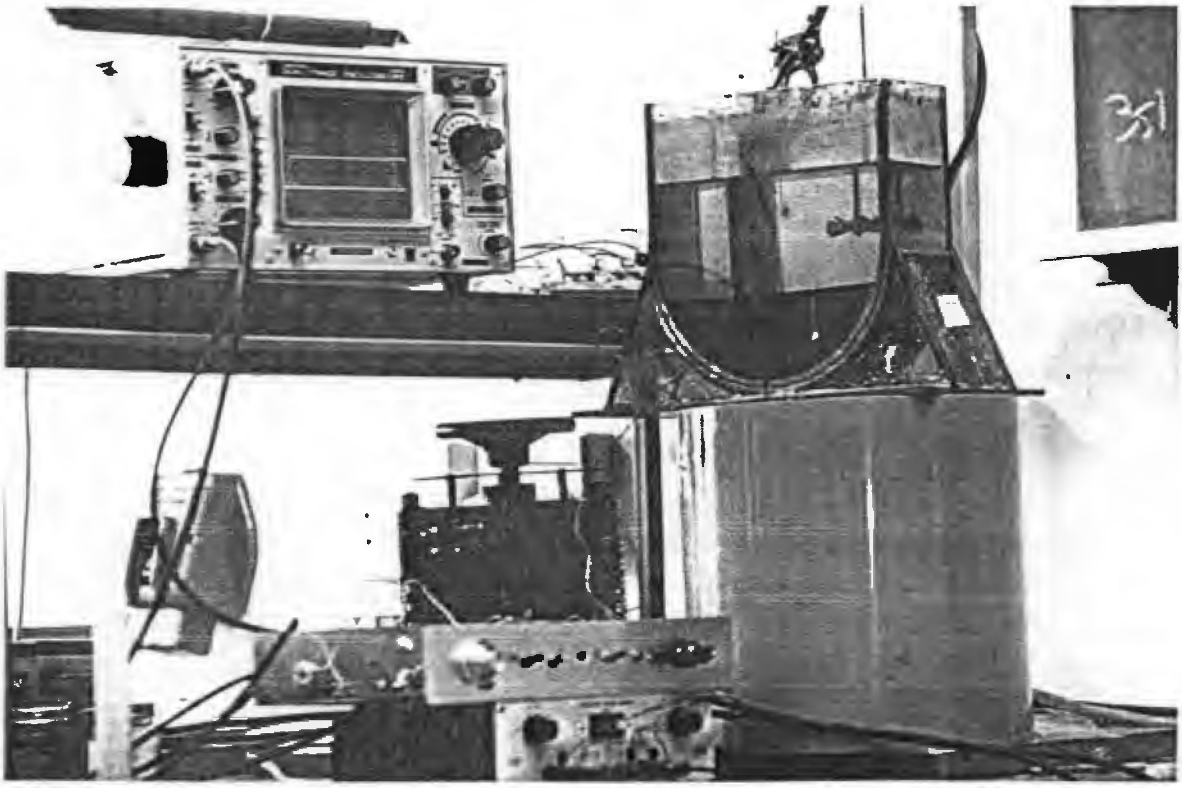
```
5000  PRINT "Signal(S) or Attenuation(A)?       "
5004  GET Q$
5006  IF Q$ <  > "S" THEN  IF Q$ <  > "A" THEN 5000
5008  GOSUB 9000
5010  GOSUB 9120
5015 J = 125:I = J: HPLOT I,0 TO I,159
5020  FOR K = 1 TO 2
5030  PRINT "Arrows to position ";K;"  ENTER to enter"
5040 Z =  PEEK ( - 16384)
5045  POKE  - 16368,0
5050  IF Z = 136 THEN J = J - 1: GOTO 5500
5060  IF Z = 149 THEN J = J + 1: GOTO 5500
5070  IF Z <  > 141 THEN 5040
5073 K(K) = I
5076 J = J + 10:I = J
5080  NEXT K
5115 X1 = 0:Y1 = 0
5120  FOR I = K(1) TO K(2)
5123  IF Q$ = "S" THEN  GOSUB 5900
5126  IF Q$ = "A" THEN  GOSUB 5800
5130 X1 = X1 + X3
5140 Y1 = Y1 + Y3
5145  NEXT I
5150 X1 = X1 / (K(2) - K(1) + 1)
5160 Y1 = Y1 / (K(2) - K(1) + 1)
5170  PRINT : PRINT "MEAN       "; INT (X1) / 1000,, INT (Y1) / 1000
5175 X2 = 0:Y2 = 0
5180  FOR I = K(1) TO K(2)
5183  IF Q$ = "S" THEN  GOSUB 5900
5186  IF Q$ = "A" THEN  GOSUB 5800
5190 X2 = X2 + (X3 - X1) ^ 2
5200 Y2 = Y2 + (Y3 - Y1) ^ 2
5210  NEXT I
5220 X2 =  SQR (X2 / (K(2) - K(1) + 1))
5230 Y2 =  SQR (Y2 / (K(2) - K(1) + 1))
5240  PRINT "STD DEV   "; INT (X2) / 1000,, INT (Y2) / 1000
5250  GET A$
5300  GOTO 100
5400  END
5500 Z =  PEEK ( - 16384)
5501  POKE  - 16368,0
5502  IF Z > 127 THEN X =  PEEK ( - 16336)
5505  HCOLOR= 0
5510  HPLOT I,0 TO I,159
5520  HCOLOR= 7
5530  HPLOT J,0 TO J,159
5535  HPLOT I,X(I - 5)
5540  HPLOT I,Y(I - 5)
5545 I = J
5550  VTAB 22
5553  IF Q$ = "A" THEN  PRINT "      dB","      dB"
5555  IF Q$ = "S" THEN  PRINT "      V","      V"
5558  VTAB 22
5560  IF Q$ = "A" THEN  GOSUB 5800
5562  IF Q$ = "S" THEN  GOSUB 5900
5565  PRINT  INT (X3) / 1000, INT (Y3) / 1000
5570  GOTO 5040
```

```
5550  VTAB 22
5553  IF Q$ = "A" THEN  PRINT "      dB","      dB"
5555  IF Q$ = "S" THEN  PRINT "      V","      V"
5558  VTAB 22
5560  IF Q$ = "A" THEN  GOSUB 5800
5562  IF Q$ = "S" THEN  GOSUB 5900
5565  PRINT  INT (X3) / 1000, INT (Y3) / 1000
5570  GOTO 5040
5800 X3 = 20000 *  LOG (1 - (X(I - 5) - 10) / 149) /  LOG (10)
5810 Y3 = 20000 *  LOG (1 - (Y(I - 5) - 10) / 150) /  LOG (10)
5820  RETURN
5900 Z =  PEEK ( - 27236) / 3
5910 X3 =  ABS ( INT ((Z -  INT (Z)) * 10) - 1) * 10 ^ ( INT (Z) - 6) *
     (127 - X(I - 5)) / 32
5920 Z =  PEEK ( - 27164) / 3
5930 Y3 =  ABS ( INT ((Z -  INT (Z)) * 10) - 1) * 10 ^ ( INT (Z) - 6) *
     (127 - Y(I - 5)) / 32
5950  RETURN
6000  END
8800  PRINT  CHR$ (4)"OPEN  STORSET"
8810  PRINT  CHR$ (4)"WRITE STORSET"
8820  PRINT C1: PRINT C2: PRINT P1: PRINT P2: PRINT P3: PRINT P4: PRINT
     S1: PRINT R1: PRINT R2: PRINT J$
8900  PRINT  CHR$ (4)"CLOSE STORSET"
8910  GOTO 100
8999  END
9000  CALL  - 28707: REM   ERASE
9010  POKE  - 16304,0: REM GR'S
9020  POKE  - 16301,0: REM  MIXED
9030  POKE  - 16297,0: REM HGR'S
9040  POKE  - 16300,0: REM PAGE1
9050  HPLOT 260,10 TO 260,159
9060  HPLOT 0,10 TO 4,10 TO 4,159 TO 0,159
9070  VTAB 22
9080  PRINT : PRINT : PRINT : PRINT
9090  RETURN
9120  FOR I = 0 TO 255
9130  IF X(I) > 159 THEN 9160
9140  IF X(I) < 0 THEN 9160
9150  HPLOT I + 5,X(I)
9160  IF Y(I) > 159 THEN 9190
9170  IF Y(I) < 0 THEN 9190
9180  HPLOT I + 5,Y(I)
9190  NEXT I
9200  RETURN
9989  TEXT
9999  END
```

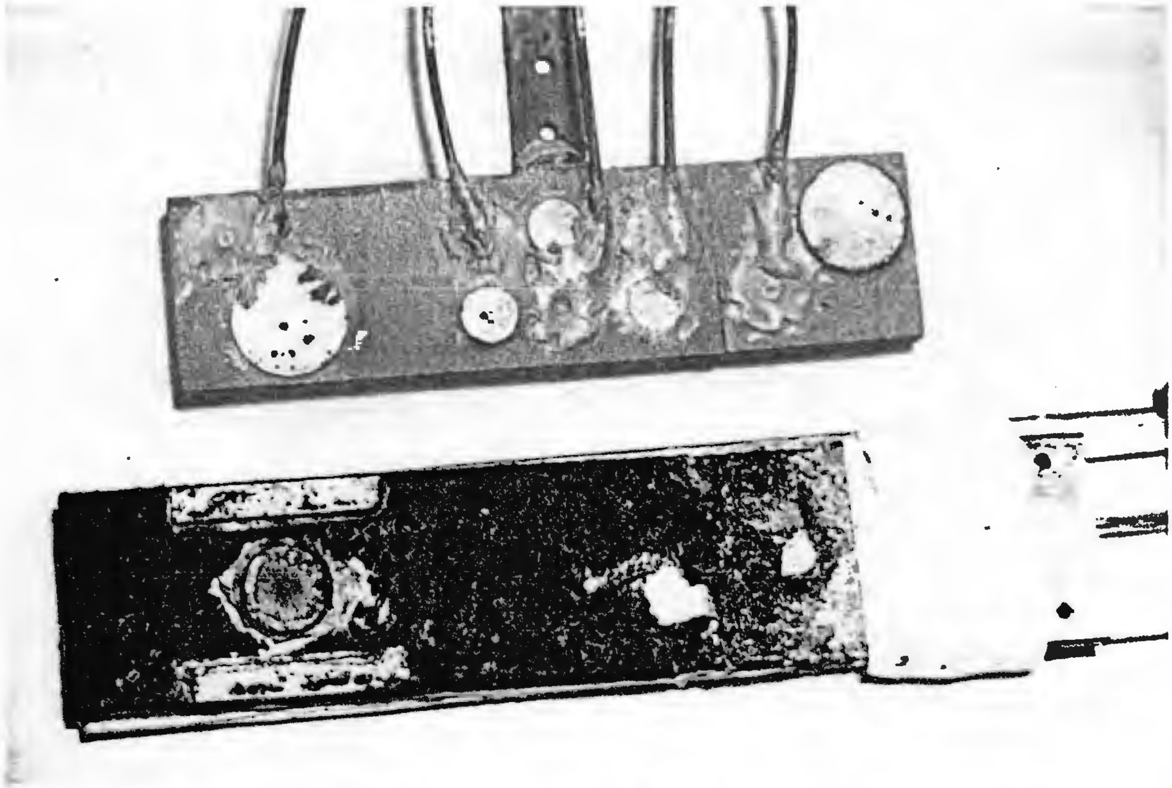
APPENDIX C

General photographs

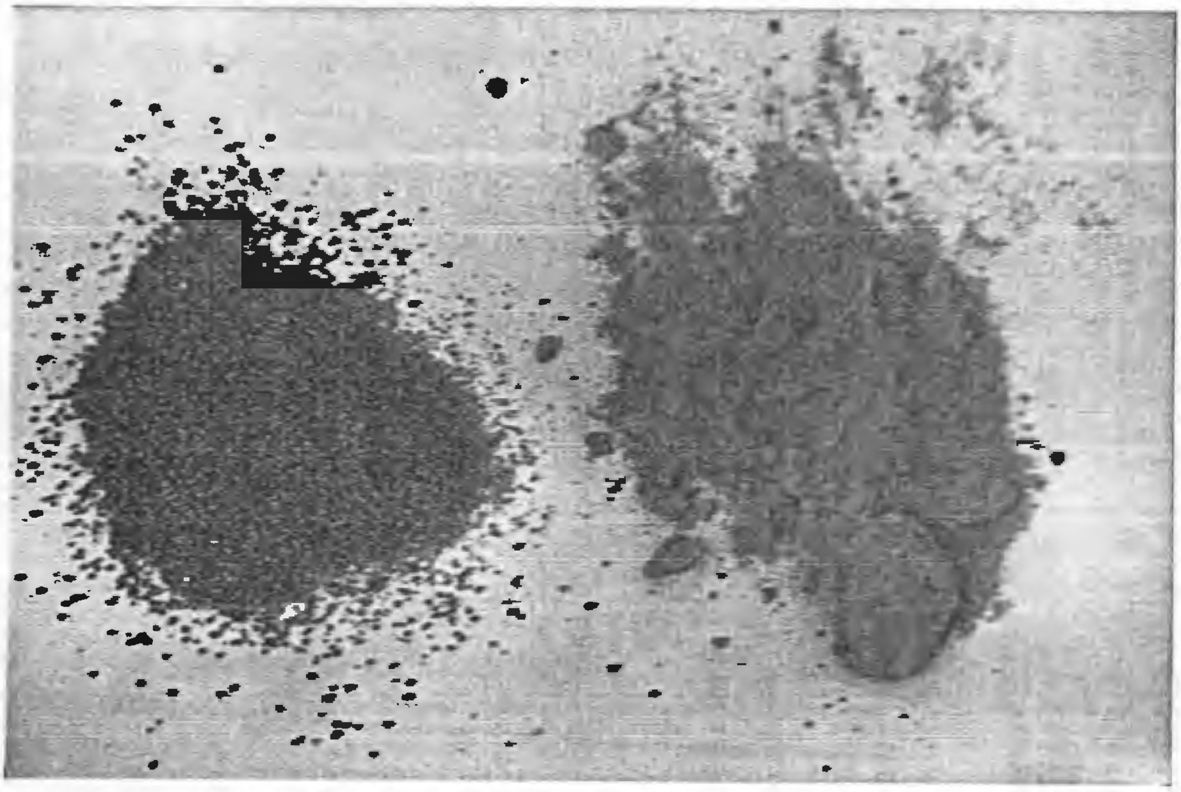
The initial measuring system comprising the quad- tone burst generator, 5 transmit/receive transducers, a storage and a standard oscilloscope and a computer.



The final classification system.



The 5 transducers used initially (top), and the single transducer mounted in an aluminium plate. Note the tarnishing presumed to be a chemical effect caused by the resin or chemicals (cyanide) added to the slurry.



Resin particles and slurry powder used experimentally.

APPENDIX D

Data sheets

PLESSEY
Semiconductors

SL560C

300 MHz LOW NOISE AMPLIFIER

This monolithic integrated circuit contains three very high performance transistors and associated biasing components in an eight-lead TO-5 package forming a 300 MHz low noise amplifier. The configuration employed permits maximum flexibility with minimum use of external components. The SL 560C is a general-purpose low noise, high frequency gain block.

FEATURES
(Non-simultaneous)

- Gain up to 40 dB
- Noise Figure Less Than 2 dB (R_S 200 ohm)
- Bandwidth 300 MHz
- Supply Voltage 2-15V (Depending on Configuration)
- Low Power Consumption

APPLICATIONS

- Radar IF Preamplifiers
- Infra-Red Systems Head Amplifiers
- Amplifiers in Noise Measurement Systems
- Low Power Wideband Amplifiers
- /Instrumentation Preamplifiers
- 50 ohm Line Drivers
- Wideband Power Amplifiers
- Wide Dynamic Range RF Amplifiers

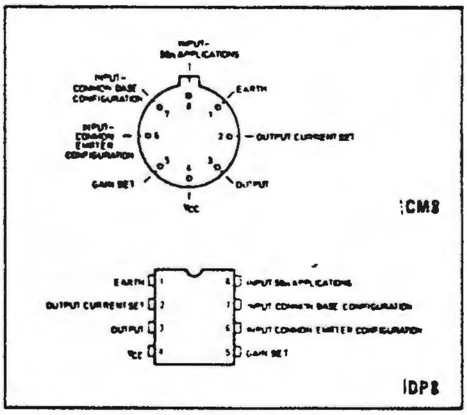


Fig. 2 SL560C circuit diagram

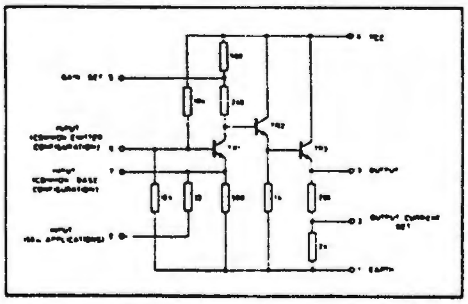
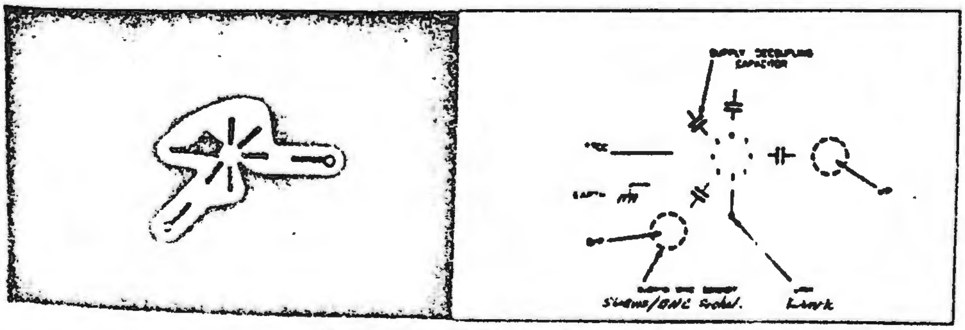


Fig. 1 Pin connections (viewed from beneath)



PC layout for 50Ω line drive (Fig 6)

ELECTRICAL CHARACTERISTICS

Test Conditions (unless otherwise stated):

Frequency 30 MHz
Vcc 6V
Rs = RL = 50Ω
TA = 25°C
Test Circuit: Fig. 6

Characteristic	Value			Units	Conditions
	Min.	Typ.	Max.		
Small signal voltage gain	11	14	17	dB	
Gain flatness		±1.5		dB	10 MHz — 220 MHz
Upper cut-off frequency		250		MHz	
Output swing	+5	+7		dBM	Vcc = 6V } See Fig. 5
		+11		dBm	Vcc = 9V } See Fig. 5
Noise figure (common emitter)		1.8		dB	Rs = 200Ω
		3.5		dB	Rs = 50Ω
Supply current		20	30	mA	

CIRCUIT DESCRIPTION

Three high performance transistors of identical geometry are employed. Advanced design and processing techniques enable these devices to combine a low base resistance (Rbb') of 17 ohms (for low noise operation) with a small physical size — giving a transition frequency, fT, in excess of 1 GHz.

The input transistor (TR1) is normally operated in common base, giving a well defined low input impedance. The full voltage gain is produced by this transistor and the output voltage produced at its collector is buffered by the two emitter followers (TR2 and TR3). To obtain maximum bandwidth the capacitance at the collector of TR1 must be minimised. Hence, to avoid bonding pad and can capacitances, this point is not brought out of the package. The collector load resistance of TR1 is split, the tapping being accessible via pin 5. If required, an external roll-off capacitor can be fixed to this point.

The large number of circuit nodes accessible from the outside of the package affords great flexibility, enabling the operating currents and circuit configuration to be optimised for any application. In particular, the input transistor (TR1) can be operated in common emitter mode by decoupling pin 7 and using 6 as the input. In this configuration, a 2 dB noise figure (Rs = 200 Ω) can be achieved. This configuration can give a gain of 35dB with a bandwidth of 75 MHz (see Figs. 8 and 9)or, using feedback, 14 dB witha bandwidth of 300 MHz (see Figs. 10 and 11).

Because the transistors used in the SL 560C exhibit a high value of fT, care must be taken to avoid high frequency instability. Capacitors of small physical size should be used, the leads of which must be as short as possible to avoid oscillation brought about by stray inductance. The use of a ground plane is recommended.

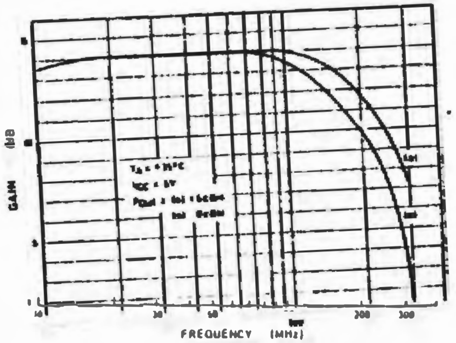


Fig. 4 Frequency response, small signal gain

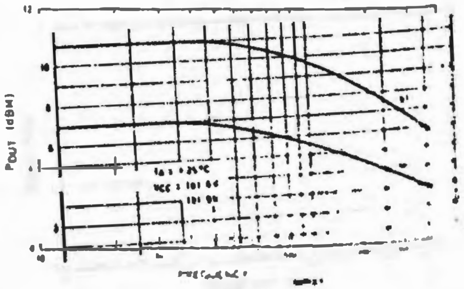
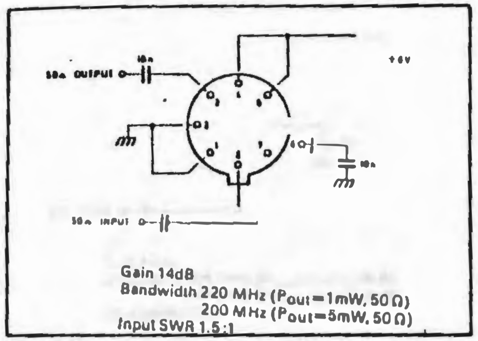


Fig 5 Frequency response, output [illegible]

TYPICAL APPLICATIONS



Gain 14dB
Bandwidth 220 MHz (Pout=1mW, 50 Ω)
200 MHz (Pout=5mW, 50 Ω)
Input SWR 1.5:1

Fig. 6 50 Ω line driver. The response of this configuration is shown in Fig. 4.

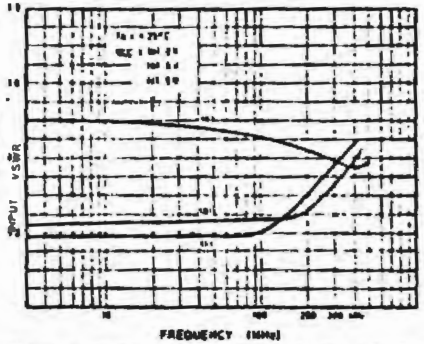
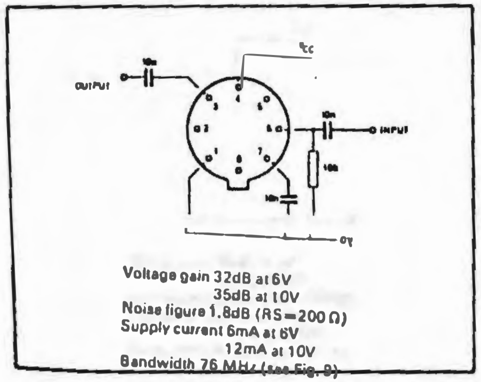


Fig. 7 Input standing wave ratio plot of circuit shown in Fig. 6



Voltage gain 32dB at 6V
35dB at 10V
Noise figure 1.8dB (RS=200 Ω)
Supply current 6mA at 6V
12mA at 10V
Bandwidth 76 MHz (see Fig. 9)

Fig. 8 Low noise preamplifier

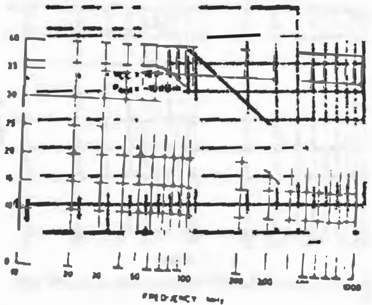
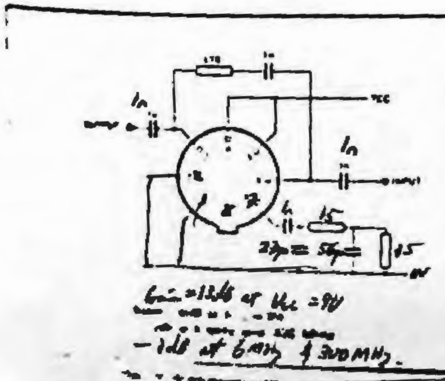


Fig. 9 Frequency response of circuit shown in Fig. 8



Gain = 13dB at Vcc = 9V
[illegible]
-1dB at 6MHz & 300MHz.