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LIQUID LEVEL MEASUREMENT USING A COPLANAR TRANSMISSION LINE

by

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ABSTRACT

The coplanar line has been used very successfully as an element in microwave circuits. Small size, high Q-factor, and accurate reproduction, are some of its many advantages. The coplanar transmission lines discussed in this report, are targeted at liquid level measurement, and are typically 30 cm. long. Their operating frequencies are consequently much lower than those of microwave coplanar waveguides, but they have common advantages.

The factor which separates the coplanar line from similar liquid level sensors, is that it makes use of the electrical component of the electromagnetic fringe field, setup between its inner conductor, and the surrounding ground plane. The line is effectively a sharply tuned resonator, incorporated as the frequency controlling element of an electronic oscillator. The output frequency falls as a dielectric material penetrates the fringe field. An impressive sensitivity is accomplished by using very thin conductors, thereby ensuring that the fringe field energy is maximised. The most important feature of this sensor is its ability to operate non-intrusively when used with non-conducting vessels, or if employed in a metal tank, the unit can be encased in a dielectric material where the line is non-contacting (the liquid does not penetrate the unit). This combined with its excellent mechanical and electrical stability, and an accuracy better than 1 percent, makes the coplanar line a strong competitor in the field of liquid level measurement.

The research began with a theoretical approach, and used lines machined from an Aluminium plate for characteristic impedance measurement. An empirical relation between the gap width, the line thickness, and the characteristic impedance of the line is presented. To assist with the design of the sensor, a lumped capacitance model of the line was developed. Various geometries were tested, and modified until a near linear response to water level was achieved. An advanced engineering model of the level sensor has been developed, which incorporates a stable digital output display, user calibration from the line's end points, and temperature compensation.

A T-shaped line, which concentrates the field around its open end, was used for other applications such as, evaporation monitoring, measurement of slurry settlement, and to observe the effect of acids, bases, and salts in water. Various applications of the different coplanar line designs are proposed.

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LIST OF SYMBOLS

v Velocity of an electromagnetic wave (m/s).

c_0 Free space velocity of an electromagnetic wave, equal to 2.998×10^8 (m/s).

ϵ Permittivity of a material = $\epsilon_r \epsilon_0$ (F/m).

ϵ_0 8.854×10^{-12} (F/m).

ϵ_r Relative permittivity of a material.

Z_0 Characteristic impedance. (Ω)

μ Permeability of a material = $\mu_r \mu_0$ (H/m)

μ_0 $4\pi \times 10^{-7}$ (H/m)

μ_r Relative permeability of a material.

L Inductance per metre of a transmission line.

C Capacitance per metre of a transmission line.

E The electric component of an electromagnetic field.

H The magnetic component of an electromagnetic field.

β Phase factor = 2π/wavelength.

f Frequency (Hz).

ω Angular frequency = $2\pi f$.

Q Quality factor.

CHAPTER 1

1. THE COPLANAR TRANSMISSION LINE

1.1. INTRODUCTION

The task of controlling and monitoring liquid levels is encountered in our homes and automobiles, in reservoirs and dams, as well as a broad spectrum of engineering applications. The sophistication of the sensing device is application specific, and ranges from a simple float to complex electro-optic devices.

In most applications liquid level is measured to determine the volume of liquid present, however this is not always the case. Whilst the primary requirement of this research was the accurate measurement of water level in various containers, the sensor also had to be suitable for use in industrial slurries. A problem encountered in a stirred slurry is the froth above the liquid, which causes erroneous results in electro-optic and ultrasonic surface measuring techniques. The height of froth is extremely important in the extraction of Gold by the flotation process, and the level of the froth-liquid interface must be controlled.

The principle behind the operation of most level sensors depends on a physical property of the liquid or its surface. For example floats or displacers rely on the buoyant forces of a liquid, differential pressure sensors require the density of the liquid to be known. Ultrasonic and electro-optic devices depend on reflection off the liquid surface, of an ultrasonic wave, and a light beam respectively[10 14].

One of the most common methods of monitoring liquid levels, is to measure the capacitance between two electrodes immersed into a liquid. As the level rises the capacitance increases, because the dielectric constant of the liquid is greater than that of air. Capacitive electrode sensors are therefore most suitable for use with polar liquids. ie. liquids with a high dielectric constant. The capacitance is most often measured in a bridge configuration, but some capacitive sensors have been incorporated in an oscillator to obtain a frequency output[9].

A transmission line sensor was developed by K. Lindström et al[2] in 1970, introducing a novel device in the form of a helix coil wound round a Perspex tube, surrounded by a concentric outer metal tube. J.B. Cole and J.K.L. Chin[1] refined this idea in 1982 by using concentric copper tubing to form a coaxial transmission line gauge. The principle of operation of both these gauges is that the liquid surface produces a step increase in the line's characteristic impedance, which reflects a pulse traveling down the line. The time for the pulse to travel from the transmitter to the impedance change and back, is a measure of the height of the transmitter above the liquid[1]. The major advantage of the Lindström and Cole-Chin gauges, is that the pulse travels along the length of the line above the surface, and therefore the measurement is insensitive to changes in the physical conditions of the liquid. Its disadvantages are that the tolerances of their mechanical design are critical for accurate operation, and because the gauges are intrusive they would be susceptible to clogging if used in a slurry.

The transmission line sensor described in this report, is a coplanar transmission line resonator, which is incorporated as the controlling element of an electronic oscillator. The principle of its operation is that as a dielectric material penetrates its electromagnetic fringe field, the capacitance per unit length is increased resulting in a reduction in the line's resonant frequency. Like the capacitive sensors the coplanar line is sensitive to the dielectric property of a liquid, and will therefore also be somewhat dependant on physical properties such as the temperature of the liquid.

The advantages of the coplanar line over conventional level detectors include:

* The unit can be used non-intrusively if the tank is not metallic eg. Glass or Fiber-Glass. Non-intrusive means that the unit would typically be attached to the outside of a Glass tank, and measure the level of liquid within it.

* When used in the role of a dipstick sensor in a metallic tank, it can be encapsulated in a dielectric material such as Perspex or Teflon, hence the line itself would not come into contact with the liquid. This is termed a non-contact application.

* As the line is coplanar it presents a flat surface to the liquid which reduces clogging, a problem that would be experienced by capacitive electrode sensors and concentric transmission line gauges, if used in slurries.

* Encapsulating the line in Teflon would make the unit suitable for use in corrosive liquids.

* It can be manufactured and reproduced simply, quickly, and accurately, by the standard photo-etch process used in the production of printed circuit boards.

* It has no moving parts and is therefore maintenance free.

1.2. THE BASIC COPLANAR TRANSMISSION LINE

Coplanar transmission lines are relatively unknown except in the microwave field, where they are called strip lines or coplanar waveguides. The name is derived from the fact that the conductors occupy the same plane. In microwave circuits coplanar lines are useful circuit elements because of their compactness, high Q-factor, and the ease and accuracy with which they can be manufactured[12]. In this application the coplanar lines are several orders of magnitude larger, being typically 30 to 50 cm. in length.

In its simplest form the coplanar line is a quarter wave transmission line resonator, open at one end and shorted at the other (fig. 1.1). The electric (E) field distribution has a maximum at the open circuit end, and a minimum at the short circuit end. The reverse applies to the magnetic (H) field. This field distribution is equivalent to the field distribution between two plates of a capacitor, however the coplanar line is sensitive to dielectric materials in the fringe field rather than the field between the capacitor plates. Fig. 1.1 illustrates the E and H field distributions associated with the coplanar line, from which it is evident that the fields protrude to the left and right of the line. The advantage of this fringe field is that a coplanar line can operate non-intrusively (positioned on the outside of a non-metallic tank), or it can be encapsulated in a dielectric material and therefore isolated from a liquid even when the unit is totally immersed.

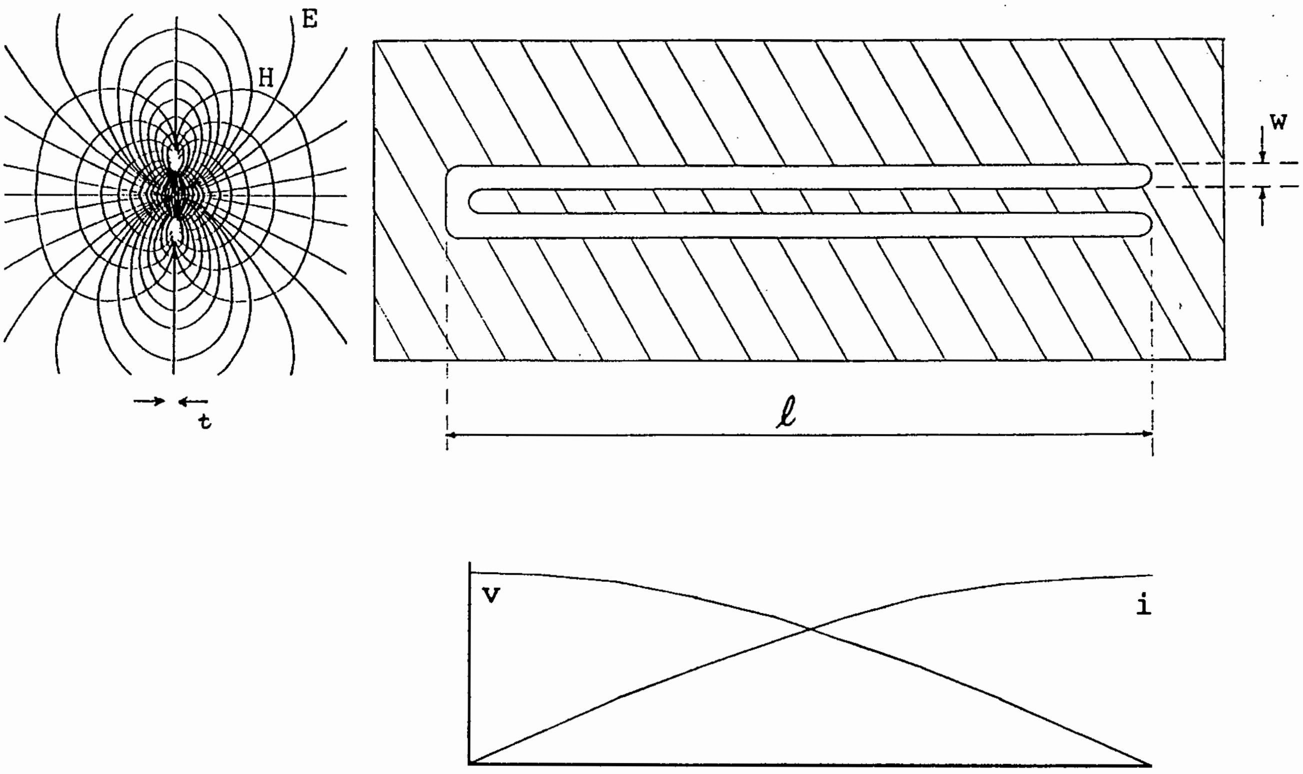


Fig. 1.1 A simple air-cored coplanar transmission line with a cross-section showing the electric (E), and magnetic (H) field distributions, which form curvilinear squares. The E field is orthogonal to the H field, and perpendicular to the direction of propagation of the wave. The length (l) is typically 30 cm, and gap width (w) 6 mm, corresponding to a resonant frequency of 250 MHz. Reducing the thickness increases the energy of the fringe field, and reducing the gap width increases its penetration. It is this fringe field that enables the coplanar line to be used as a sensing element. Also shown are the voltage (v) and current (i) amplitudes for the resonant line.

The coplanar lines investigated are of two basic types;

i. The air-cored line machined from Aluminium plate typically 3 to 9 mm. thick, and

ii. The line etched on a Copper clad printed circuit board, where the thickness of the Copper layer is almost negligible in comparison with that of the Fibre-Glass substrate.

The Q-factor of these lines is in the order of 500 for the Aluminium lines and 200 for the Copper lines, which makes the sensors inherently very stable. The relatively thick Aluminium lines were useful for initial investigation, because the absence of a dielectric substrate simplified calculations. However the field between the conductors of these Aluminium lines was not useful for detection of dielectric liquids as the liquid does not penetrate the line. To reduce this field and maximise the fringe field, the conductors were made very thin, which was achieved by manufacturing the line on Copper clad printed circuit board. This Copper line with its Fibre-Glass substrate provides high mechanical stability, combined with extremely stable electrical operation. Although the Fibre-Glass substrate introduced losses to the line, it is an ideal sensor to be included as the frequency controlling an electronic oscillator, and in isolated operation proved to be stable to below 1 ppm.

The coplanar line is not limited to water level monitoring, other applications of this type of sensor include:

i) Location of the slurry-froth interface in a flotation cell.

ii) Measurement of the reduction of water content in the settlement of slurry.

iii) Measurement of water content in agricultural products.

iv) Measurement of the evaporation of water from an open surface.

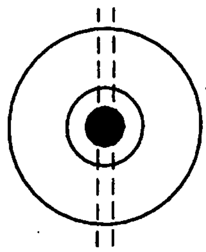
A full scale frequency change of 10 % was obtained from a prototype coplanar line water level sensor described in this report, and an accuracy of better than 1 % of the full scale reading was achieved. This accuracy is largely attributed to the electrical and mechanical stability of the sensor. The long term stability is governed by the temperature dependance of the liquid being measured. Tests conducted using water showed that temperature plays a significant part (1 mm per degree C), and that a form of temperature correction was necessary. This temperature dependance is largely attributed to the liquid, especially using water because its dielectric constant falls by one percent per degree K.

To counteract any temperature effects due to the liquid or the sensor itself, a temperature to frequency converter circuit was included as an integral part of the coplanar line, enabling a microprocessor to monitor both the level and temperature outputs from the sensor, and correct the level reading accordingly. The prototype instrument developed for this project includes such features as; a stable digital output in engineering units, automatic calibration, temperature compensation, and a computer interface to facilitate accumulation and subsequent processing of data.

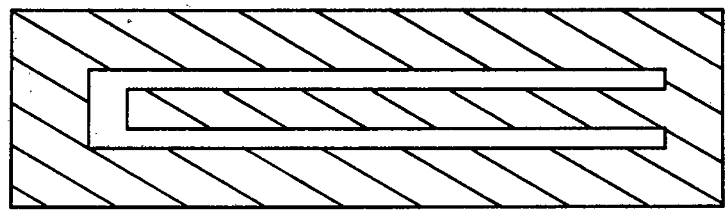
The most outstanding properties of this sensor are its non-contact nature (its active surface never comes into contact with the liquid being measured), and excellent mechanical and electrical stability, enabling it to monitor very small changes in water content.

1.3. FEATURES OF THE COPLANAR LINE

The coplanar line can be thought of as a section of the more familiar coaxial transmission line. Fig 1.2 shows this diagrammatically, and fig. 1.3 indicates the electromagnetic field distribution for each line.

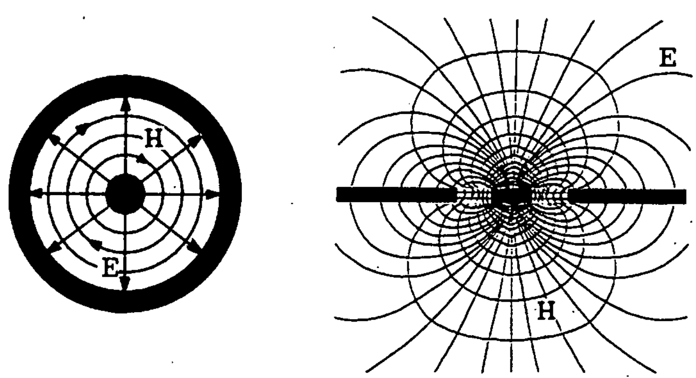


Coaxial Line



Coplanar Line

Fig. 1.2 The coplanar line can be represented by a thin section through a coaxial transmission line. The dielectric material in the coaxial line is air in the case of the coplanar line shown.



(a) (b)

Fig. 1.3 (a) The electromagnetic field distribution within a coaxial line, and (b) that surrounding a coplanar line, termed the 'fringe field'.

The coplanar line can be incorporated as the frequency controlling element of an electronic oscillator, as is illustrated in fig. 1.4. Here the line oscillates at its resonance, where it is a quarter wavelength long.

$$Z_0 = \sqrt{\frac{\epsilon}{\mu}} \qquad \text{....(1.2)}$$

where (ϵ) is the permittivity, and (μ) the permeability of the medium.

In terms of the line's inductance (L) and capacitance (C) per metre, equations (1.1) and (1.2) can be expressed as;

$$Z_0 = \frac{L}{C} \qquad \text{....(1.3)}$$

$$v = \frac{1}{\sqrt{LC}} \qquad \text{....(1.4)}$$

Equations (1.1) to (1.4) are valid for a coplanar line, but the field in this case is not confined to the dielectric material as in the case of a coaxial line. The velocity (v) can be obtained from the line's length (l) and resonant frequency (f_0), since at resonance the line is a quarter wavelength long. Knowing the velocity is the product of the frequency and wavelength, we deduce:

$$v = 4f_0l \qquad \text{....(1.5)}$$

The line's characteristic impedance Z_0 can not be simply determined, and its measurement requires some explanation.

1.3.1. Characteristic Impedance

The characteristic impedance Z_0 is obtained by first measuring the line's resonant frequency f_0 in air, then inserting a known value parallel capacitor (C_1) at the open end of the line, and again measuring the resonant frequency (f_1).

The equations for the input impedance of open circuit Z_{SC} and short circuit Z_{OC} coplanar lines, are identical to those of a coaxial line.

$$Z_{SC} = Z_0 \tanh (\alpha + j\beta)l \qquad ....(1.6)$$

$$Z_{OC} = Z_0 \coth (\alpha + j\beta)l \qquad ....(1.7)$$

Where α is the attenuation factor (Nepers/m), β the phase factor (rad/m), and l the length of the line[11]. If the coplanar line is assumed lossless ($\alpha = 0$), then equations (1.6) and 1.7) become:

$$Z_{SC} = j Z_0 \tan (\beta l) \qquad ....(1.8)$$

$$Z_{OC} = -j Z_0 \cot (\beta l) \qquad ....(1.9)$$

For coplanar lines less than a quarter wavelength long, the short circuit input impedance is inductive, and the open circuit input impedance capacitive.

$$Z_{SC} = j\omega L \qquad ....(1.10)$$

$$Z_{OC} = -j \frac{1}{\omega C} \qquad ....(1.11)$$

Where L and C are the inductance and capacitance per metre respectively. Equating the input impedance for lossless short circuit lines, see equations (1.8) and (1.10), we find:

$$\omega L = Z_0 \tan(\beta l) \qquad \ldots.(1.12)$$

Equation (1.12) suggests a method of determining the line's characteristic impedance Z_0, for at resonance:

$$\omega_0 L = \frac{1}{\omega_0 C}$$

When the known capacitance C_1 is introduced to the resonant circuit shown in fig. 1.4, the equations for resonance with and without C_1 would be;

$$\frac{1}{\omega_1 (C + C_1)} = Z_0 \tan(\beta_1 l) \qquad \ldots.(1.13)$$

and

$$\frac{1}{\omega_0 C} = Z_0 \tan(\beta_0 l) \qquad \ldots.(1.14)$$

From equations (1.13) and (1.14) an expression for Z_0 can be derived.

$$Z_0 = \frac{1}{\omega_1 \left[\frac{1}{Z_0\ \omega_0 \tan(\beta_0 l)} + C_1\right] \tan(\beta_1 l)}$$

which can be rewritten as;

$$Z_0 = \frac{\omega_0 \tan(\beta_0 l) - \omega_1 \tan(\beta_1 l)}{C_1\ \omega_0\ \omega_1 \tan(\beta_0 l) \tan(\beta_1 l)} \qquad \ldots.(1.15)$$

The phase factor (β) can be calculated, as it is the ratio of the angular frequency (ω) to the velocity (v) of electromagnetic waves on the coplanar line.

$$\beta_0 = \frac{\omega_0}{v} \quad \text{and} \quad \beta_1 = \frac{\omega_1}{v}$$

Equation (1.15) provides a method of measuring Z_0 for the

Copper line on a Fibre-Glass substrate. The velocity v can be calculated from equation (1.5).

1.3.2. Experiment To Characterise Coplanar Lines In Terms Of Their Geometry

To obtain a practical understanding of coplanar lines, twelve were machined from Aluminium sheets of four different thicknesses, each with three gap widths, and analysed using a network analyser. Fig. 1.5 shows three of the lines used. The lines were all shorted at one end and open at the other, forming simple quarter wavelength resonators.

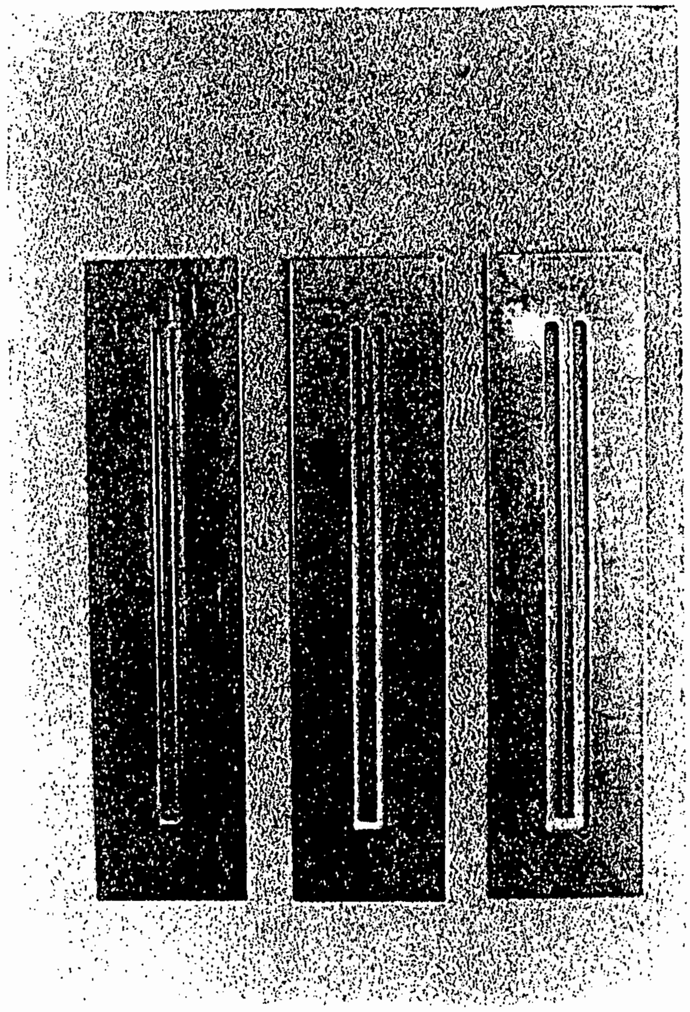


Fig. 1.5 Three of the Aluminium coplanar lines used to gain a practical understanding of the line's characteristics. All the lines used in this experiment were approximately 30 cm. long.

Each line's resonant frequency, and Q-factor, were measured from the amplitude response of the reflection coefficient obtained on a network analyser. The Q-factor is obtained from the 3dB bandwidth (Δf_0) since,

$$Q = \frac{f_0}{\Delta f_0} \qquad \text{....(1.16)}$$

The experiment was repeated for each line with a 1pF parallel capacitor inserted across the open end. The new resonant frequency (f) allowed Z_0 to be calculated from equation (1.15). Table 1.1 summarises the results.

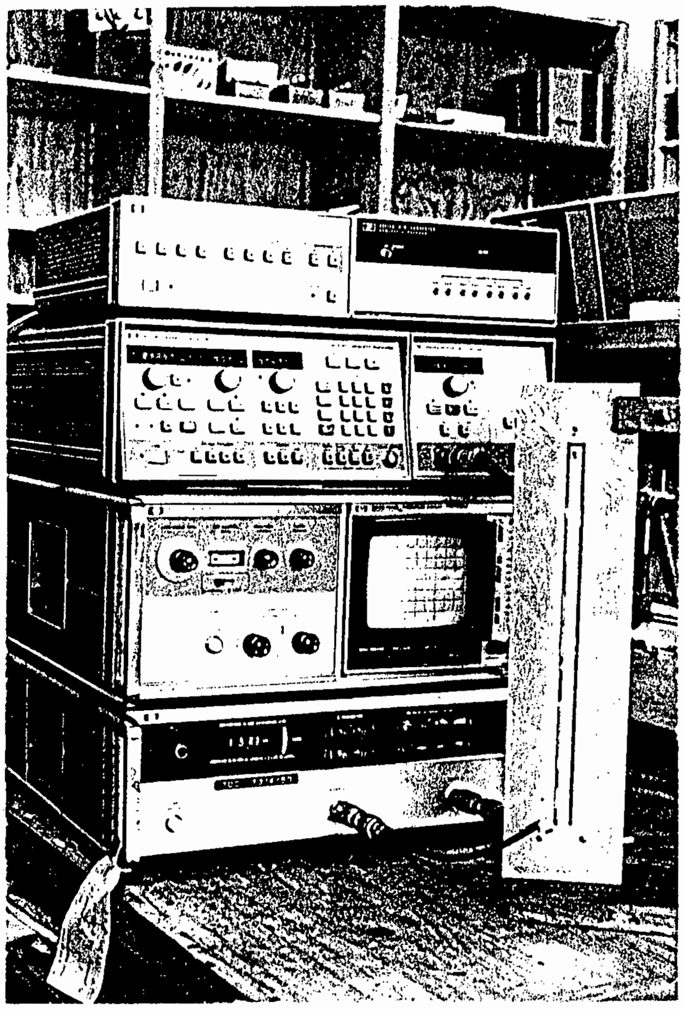


Fig. 1.6 The experimental setup showing the line under test inductively coupled, to the transmit and receive port of the network analyser by a 50 ohm loop. The two loops are on opposite sides of the line to reduce direct coupling, and positioned at the short circuit end where the H field is a maximum.

As these lines have an air dielectric, the velocity will be the free space value (c_0). The resonant frequency (f_0) for each line obtained from the network analyser, therefore yields an effective length from equation (1.5)

$$l_{eff} = \frac{c_0}{4f_0} \quad \ldots\ldots(1.17)$$

The ratio of the effective length (l_{eff}) to actual length (l), [see fig. 1.1 for dimension l] represents a correction factor for both the air-cored and substrate based coplanar lines, which is useful when designing a line for a specific frequency.

Table 1.1

w (mm)	t (mm)	No Capacitor f_0 (MHz)	Q_0	1 pF Cap. f (MHz)	Q	Z_0 (Ω)	l_{eff}/l
9	1.54	234.1	544	206,3	368	147.1	1.049
	2.95	234.9	534	210.1	420	127.9	1.046
	4.11	236.2	525	213.1	444	116.4	1.043
	8.95	238.8	569	220.2	512	89.1	1.033
6	1.54	235.5	491	211.0	406	125.3	1.04
	2.95	236.4	503	215.0	457	106.6	1.039
	4.11	237.2	565	217.1	505	98.6	1.036
	8.95	240.4	572	225.0	536	71.5	1.030
3	1.54	236.5	415	217.6	389	92.8	1.039
	2.95	238.6	434	222.5	428	76.3	1.030
	4.11	239.3	435	225.1	417	66.2	1.026
	8.95	240.6	446	230.3	419	46.6	1.023

1.3.2.1. Analysis And Discussion Of Results

The distributed capacitance per unit length (C) has two components, the parallel plate capacitance (C_{plate}), and a fringe field capacitance (C_{fringe}).

$$C = C_{plate} + C_{fringe} \quad \ldots\ldots(1.18)$$

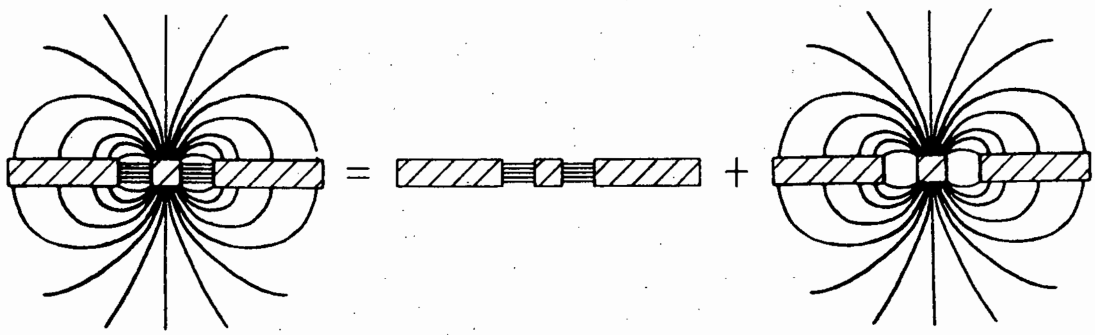


Fig. 1.7 The total E field distribution of the air-cored coplanar line is the sum of the field between the plates and the fringe field. Hence the capacitance is the sum of the parallel and fringe capacitance.

The fringe capacitance will be a function of the line's gap width (w), and will be relatively insensitive to the thickness (t). By definition the plate capacitance is,

$$C_{plate} = \frac{\epsilon_0 t}{w} \qquad \ldots.(1.19)$$

Equation (1.18) can be rewritten as;

$$C = \frac{\epsilon_0 t}{w} + C_{fringe}(w) \qquad \ldots.(1.20)$$

The distributed inductance (L) per unit length is proportional to the reluctance round the inner conductor, and increasing the thickness (t) will not appreciably increase its reluctance. The inductance was therefore assumed to be a function of the gap width (w) only.

Equations (1.3) and (1.20) can be rearranged to yield an expression equal to the reciprocal of the square of the characteristic impedance Z_0.

$$\frac{1}{[Z_0(w,t)]^2} = \frac{1}{L(w)} \left[\frac{t}{w} + C_{fringe}(w) \right] \qquad \ldots.(1.21)$$

Equation (1.21) predicts that $(1/Z_0)^2$ will be proportional to the line thickness. Fig. 2.5 shows $(1/Z_0)^2$ plotted against the thickness for three gap widths.

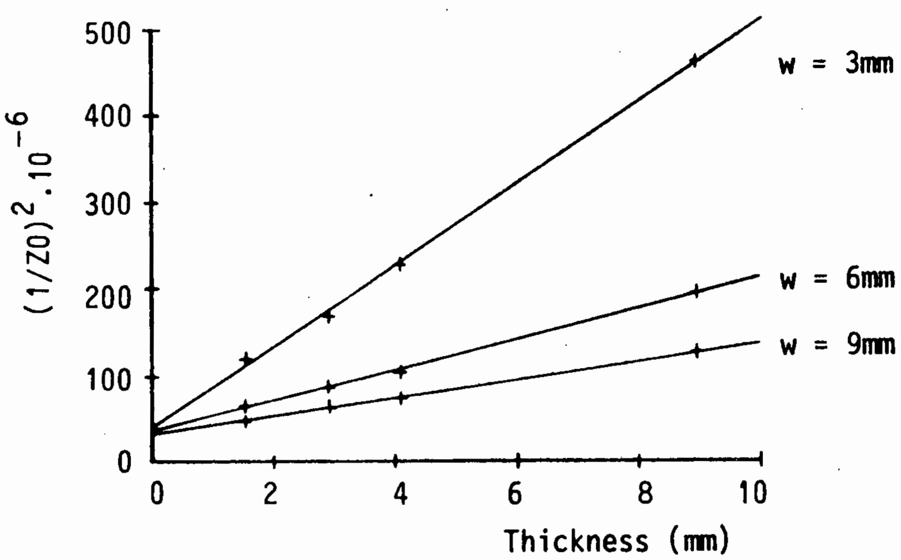


Fig. 1.8 A graph showing the dependance of $(1/Z_0)^2$ on the line thickness (t) for three different gap widths (w). Values originate from Table 1.1. Linear regression on the three straight lines yielded regression coefficients (r^2) better than 0.997.

The linear relationship between $(1/Z_0)^2$ and the thickness for constant gap width indicate that it is possible to derive a general equation relating Z_0, w and t. Each line in fig. 1.8 has the form,

$$\left[\frac{1}{Z_0} \right]^2 .10^{-6} = \text{Slope}(w).t + \text{Intercept}(w) \quad ....(1.22)$$

Using curve fitting routines, expressions for the slope and intercept as a function of w were found. The linear regression coefficients (r^2) are indicated in brackets.

Slope (w) = 203.74 w (r^2 = 0.999)

Intercept (w) = 42.72 - 1.46 w (r^2 = 0.999)

Substituting these functions into equation (1.22) and rearranging the terms an expression for Z_0 can be written;

$$Z_0 = (k_1 t w^p - k_2 w + k_3)^{-\frac{1}{2}} \cdot 10^3 \quad ....(1.23)$$

where k_1 = 203.74, k_2 = 1.46, k_3 = 42.72 and p = -1.345. The thickness (t) and gap width (w) are measured in millimetres, and Z_0 in Ohms. When compared with the Z_0 values measured for the twelve lines, the corresponding values calculated from equation (1.23) had an average error of less than 1 percent.

A graph of the length correction factor plotted against line thickness for the threes gap widths is shown in fig. 1.9, from which the designer of a coplanar line oscillator can estimate the length correction factor for any thickness and gap-width. It is expected that the correction for the thinner Copper lines on a Fibre-Glass substrate, will be in the order of 5 percent, since the thickness of the conductors is almost negligible.

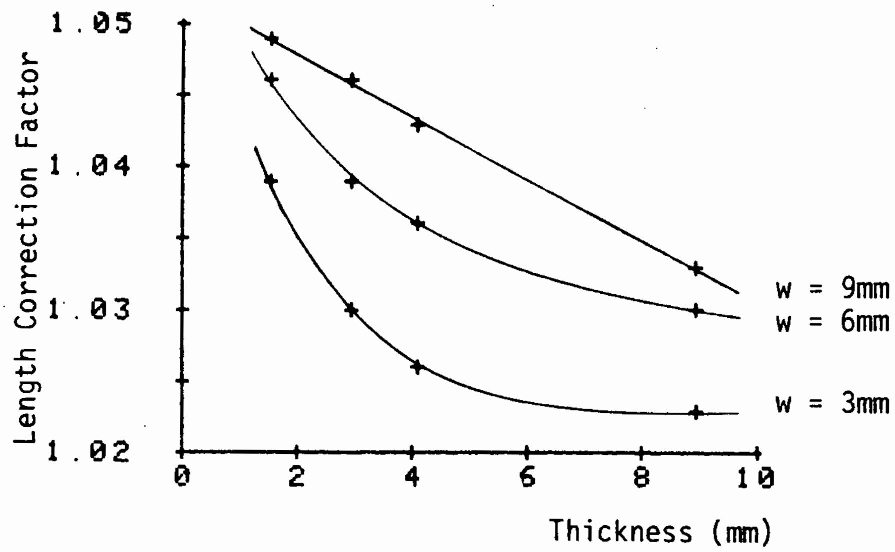


Fig. 1.9 The length correction factor (l_{eff}/l) plotted against the line thickness (t) for three gap widths (w). A notable feature is that the dependance of (l_{eff}/l) is linear for w = 9 mm. and becomes more nonlinear with reducing gap widths.

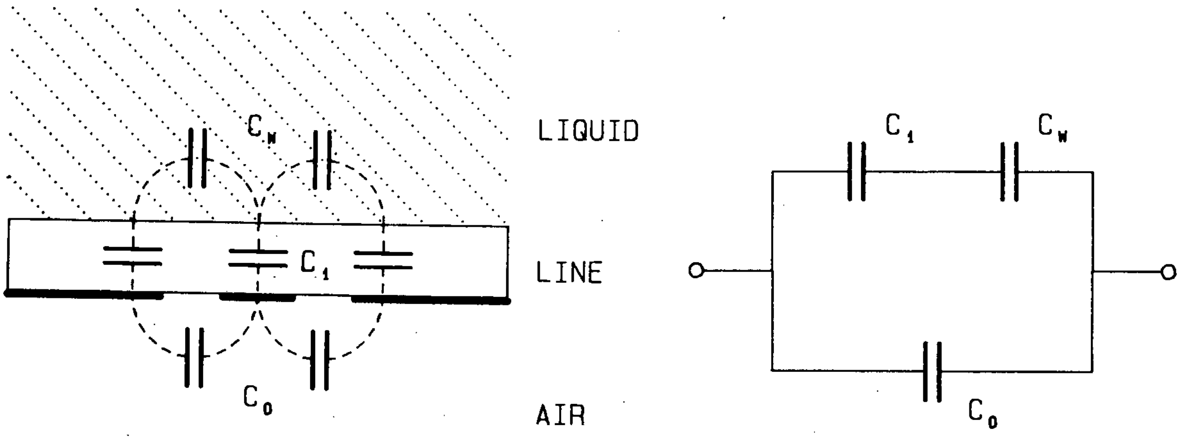
To the designer equation (1.23) and fig. 1.9 provide a method of accurately characterising air-cored coplanar lines, and proved useful in subsequent designs. The linearity of equation (1.23) with respect to t, confirms an assumption made deriving equation (1.21), that is that the fringe field capacitance, and distributed inductance are independent of the line thickness.

The analysis of the Copper lines is complicated by the presence of the dielectric substrate. This type of coplanar line has been analysed in detail due to its importance in microwave integrated circuits. Appendix A contains a discussion of various techniques used in the analysis a coplanar line with a dielectric substrate, including Wen's conformal mapping technique, and various numerical methods.

The Aluminium lines were used largely as an introduction to the coplanar line. They provided an understanding of the effects of the length, gap width, and thickness of the line, and a platform for the development of the oscillator circuit used with all lines in this report. To analyse the Copper line on a dielectric substrate, a model of it was developed for its operation in water.

1.4. LUMPED CAPACITANCE MODEL OF THE COPLANAR LINE

The coplanar line can be modeled by three lumped capacitors, to give an indication of its response to different dielectric materials. The total capacitance C_T consists of the capacitance between the conductors in air C_0, in the substrate C_1, and in the liquid C_W.



(a) (b)

Fig. 2.11 (a) A simple model of the Coplanar line, and (b) its equivalent electrical circuit.

The total capacitance C_T is given by:

$$C_T = C_0 + \frac{C_1C_w}{(C_1 + C_w)} = C_0 + \frac{rC_0}{(1 + C_1/C_w)}$$

where r is the ratio C_1/C_0.

$$C_T = C_0 \, [1 + r(1 - C_1/C_w)]$$

By substituting $C_w = \epsilon_r C_0$, where ϵ_r is the relative permittivity of the liquid, the total capacitance is given by;

$$C_{liquid} = C_0[1 + r(1 - C_1/(\epsilon_r C_0))] \qquad ....(1.24)$$

and for the line in air,

$$C_{air} = C_0[1 + r(1 - C_1/C_0)] \qquad ....(1.24)$$

As the square of the frequency is inversely proportional to the capacitance, the air-to-water ratio of the line's operating frequency can be derived.

$$\left[\frac{f_{air}}{f_{liquid}}\right]^2 = \frac{1 + r[1 - C_1/(\epsilon_r C_0)]}{1 + r(1 - C_1/C_0)}$$

$$\approx 1 + r\left[1 - \frac{C_1}{\epsilon_r C_0}\right] - r\left[1 - \frac{C_1}{C_0}\right]$$

$$= 1 + R\left[1 - \frac{1}{\epsilon_r}\right] \qquad \text{....(1.25)}$$

where $R = r^2$. The line constant R can be determined from equation (1.25) for a given coplanar line, using a liquid of known dielectric constant, and measuring f_{air} and f_{liquid}. Substituting R into equation (1.25) the frequency range of the selected line can be determined for any other liquid with a known dielectric constant.

With an understanding of the behaviour of the air-cored coplanar lines relative to their geometry, and the lumped capacitance model to give an indication of frequency ranges for the different lines line, the main object of the research was addressed. ie. the design a coplanar line suitable for vertical level measurement.

CHAPTER 2

2. LEVEL MEASUREMENT USING THE COPLANAR LINE

2.1. OBJECTIVE

The aim of this research was to develop a non-intrusive coplanar transmission line liquid level transducer, which could be used in a wide range of industrial and commercial applications, including the measurement of slurry in floatation cells.

2.2. PREVIOUS TRANSMISSION LINE SENSORS

Examples of existing transmission line sensors are those developed by Lindström et al[2] (1970), and the Cole-Chin gauge[1] (1982). Although both gauges are intrusive, the results provide a benchmark for comparison. The Lindström gauge consisted of Copper wire wound helically round a Perspex tube, contained within a metal tube. The principle of its operation was that a pulse applied to the input of the line, would be reflected at the liquid surface due to the impedance change there. A sing around loop enabled this sensor to achieve a frequency output with a claimed

0.3 percent non-linearity. Similarly the Cole-Chin gauge[1] depends on the liquid entering a concentric transmission line, and the impedance barrier set up at the surface. A tunnel diode was used to sustain a square wave oscillation, the period of which was linearly proportional to the height of the diode above the liquid. The disadvantages of these sensors are that their manufacture is both complex and critical to the quoted accuracy, and both rely on the liquid penetrating the unit, which makes them susceptible to clogging if used in a slurry.

The coplanar line exhibits none of these drawbacks, being accurately reproducible on printed circuit board, by the standard photo-etch process. In operation the line would be separated from the liquid by a dielectric material such as Perspex or Teflon, and thereby present a smooth, flat, surface to the liquid. This type of surface is likely to is minimise clogging in slurries. However the coplanar line's suitability as a vertical level sensor had to be investigated.

2.3. A PILOT EXPERIMENT ON WATER EVAPORATION

The aim of this experiment was to determine whether the fringe field could be used to detect changes in water level, and to gain some knowledge of its penetration above the surface of the line.

An Aluminium line 30 cm. long was machined from a 9 mm. thick plate in the shape of a 'T' at the open end. It was driven by the oscillator circuit described in section 2.5, and inductively coupled via a 50Ω loop, to a Digital Frequency Meter (DFM). Introducing a slab of Perspex into the fringe field reduced the operating frequency, and as expected, the maximum sensitivity was detected at the open 'T' end of the line where the voltage is a maximum. When a plastic box containing water was placed over the 'T' end, the operating frequency fell by 7 percent.

To increase the sensitivity the same shape line was etched on a Fibre-Glass printed circuit board, which increased the energy in the fringe field. The Copper layer on these boards is very thin, so the majority of the field is fringe field. Fig. 2.1 shows the geometry of the 'T' line.

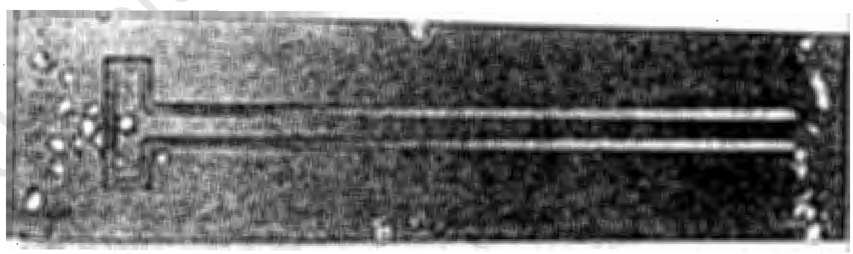


Fig. 2.1 The 30 cm. long 'T' line etched on a Copper printed circuit board. The gap width is 6 mm. and the thickness of the Copper and dielectric layers are 0.034 mm. and 1.5 mm. respectively. The short circuit line is the inductor, and the 'T' shaped open end, together with the capacitance of the driving transistor, the capacitor.

Using this Copper line calibrations of frequency as a function of liquid depth were carried out by running liquid from a burette, into a plastic box placed over the sensitive 'T' end. The depth was calculated from the ratio of the volume of liquid added, to the area of the box. Fig. 2.2 shows the calibration curves for water and Paraffin, the latter having a low dielectric constant (2.3), has far less effect on the line's operating frequency than water which has a dielectric constant of 80.

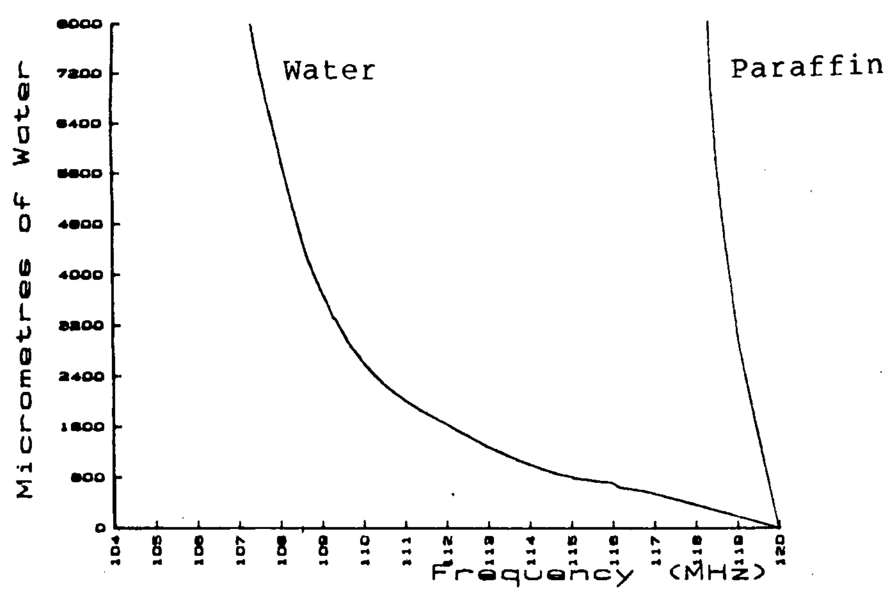


Fig. 2.2 The relative calibrations of depth of water and Paraffin, as a function of the 'T'-line's operating frequency. Water can be considered to be a good 'concentrator' of the dielectric field, and Paraffin a poor one.

The 10 percent full scale range of the line's response to water, and the stability of the readings, meant that the 'T' line was capable of measuring very small changes in water content. On the other hand, the response to the organic liquid was minimal, suggesting a possible application of the line in measuring the interface between water, and any organic liquid such as Petrol.

To test the sensitivity and stability of the line, an experiment was set-up to monitor the evaporation of water from a plastic box over a long period, during which the equipment was left in a locked room to ensure isolated operation. Measurements of operating frequency were recorded in groups of 10, every 10 minutes, by interfacing a DFM to a HP85 computer. The computer calculated the standard deviation of each set of readings, as well as the rate of change of successive groups of readings. Fig. 2.3 shows the gradual increase in the line's operating frequency, as the water evaporated over a 90 hour period. Fig. 2.4 (a) shows the rate of evaporation during the experiment, and fig. 2.4 (b) indicates that a more meaningful interpretation can be obtained, by averaging the rate of evaporation over 5 cycles.

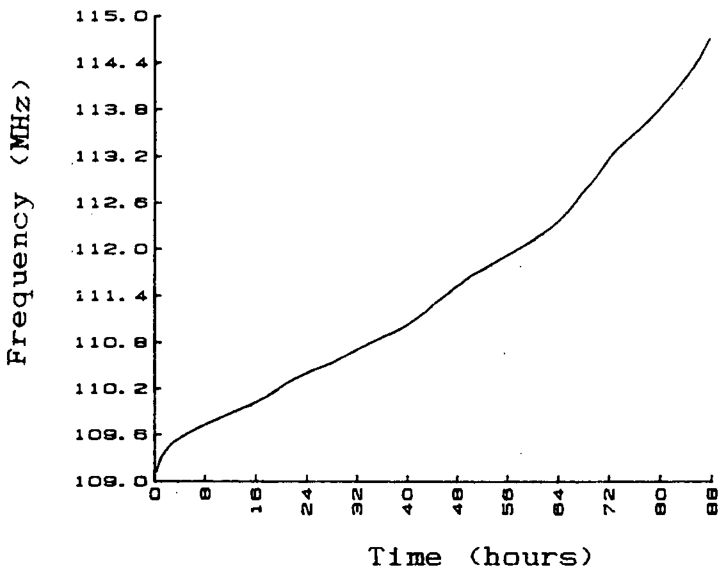
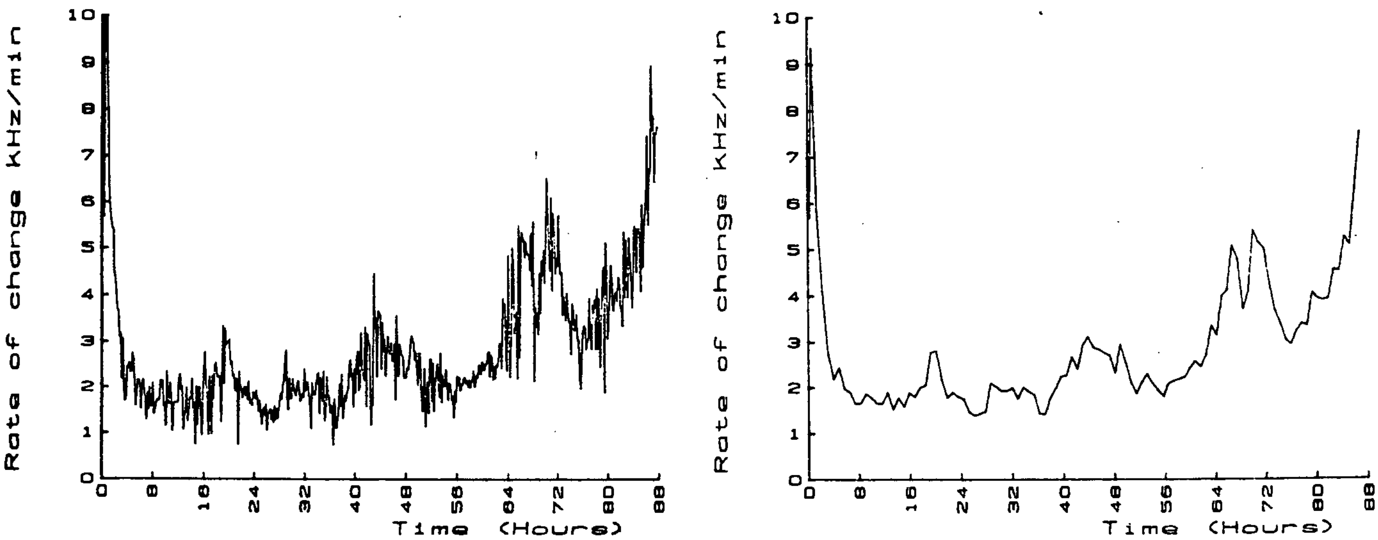


Fig. 2.3 The response of the 'T'-line to evaporation of water from a small plastic container, monitored over a 90 hour period. The depth of water started at 3 mm. and ended at 1 mm., to which the line responded with a 5 percent change in frequency.



(a) (b)

Fig. 2.4 The rate of change of operating frequency, equivalent to the rate of evaporation, is shown in (a). To extract a more meaningful result the graph in (a) was smoothed by a factor of five to give graph (b). Note that the maximum evaporation occurs approximately every 24 hours, as one would expect from room temperature variations.

Fig. 2.2 indicates that the sensitivity of the 'T' line falls off rapidly for depths greater than 2 mm., but the stability of the sensor enabled the evaporation at 3 mm. to be accurately monitored. Another experiment showed that readings of water depth could be obtained up to a maximum of 20 mm., which gives an indication of the penetration of the fringe field for this coplanar line. In air the penetration would increase because water condenses the field, and it is reasonable to conclude that any dielectric material within 40 mm. of line will reduce the operating frequency.

A notable feature of the evaporation experiment was the absence of any long term drift. This coupled with an average stability of 5 ppm. suggested that an ideal application of the 'T'-line, would be the monitoring of the long and short term evaporation from open reservoirs or dams. The ability of the sensor to accurately determine the rate of evaporation (see fig. 2.4), would facilitate the real time monitoring of the effects of temperature, humidity, and pressure, on the rate of evaporation.

Another application would be a system which uses water in a box as a constant displacement sensor. The box, which must be sealed, could be connected via a siphon or otherwise to a reservoir, and a control system used to adjust the pressure in the box to maintain a constant reference water level, which is then measured by the 'T'-line. The pressure in the box would then be a measure of the level in the reservoir. This is a version of the well known 'force balance' instrumentation technique.

2.4. INITIAL DESIGN CONSIDERATIONS

The evaporation experiment had shown that the fringe field could be used to detect the presence of water. There were however several unknowns which could only be answered by further experimentation. Would the full scale range of the transducer be sufficient to make it a viable liquid level sensor? And if so, would the coplanar line oscillate in the proximity of water over its entire length? What would be the best shape be for the line to obtain a maximum range with reasonable linearity, and no discontinuities? To ensure the sensor's viability a target accuracy of 1 percent was specified for a prototype unit 30 to 50 cm. long, with a full scale range of greater than 5 percent.

A single coplanar line open at one end and shorted at the other, has an E field distribution which is a maximum at the open end, and a minimum at the shorted end (see fig. 1.1. The E field maximum occurs where the voltage is a maximum on the line). This E field distribution is totally unsuited to vertical level measurement, and a more sophisticated design was required. It was felt that a line open at both ends would be more suitable. However the E field is not constant over the length of this line, and therefore the linearity of a sensor with this geometry, was not expected to be as high as that of conventional capacitive transducers.

It is worth noting that the linearity of a sensor is not as important today as it was in the past, because as long as the response of the transducer is reproducible, a microprocessor can be used to correct for any non-linearities.

2.5. THE TRANSISTOR OSCILLATOR CIRCUIT

At this stage a brief understanding of the oscillator circuit is required. A full description of the circuit is presented in the following chapter.

The oscillator circuit consists of an earth-based transistor, with the coplanar line in the collector. Positive feedback necessary to make the circuit oscillate, is provided by an external capacitor connected across the collector and emitter. Note that it is the coplanar line that is the frequency controlling element of this oscillator. The circuit employs a positive earth, which ensure that the line's ground plane is at a.c. and d.c. earth.

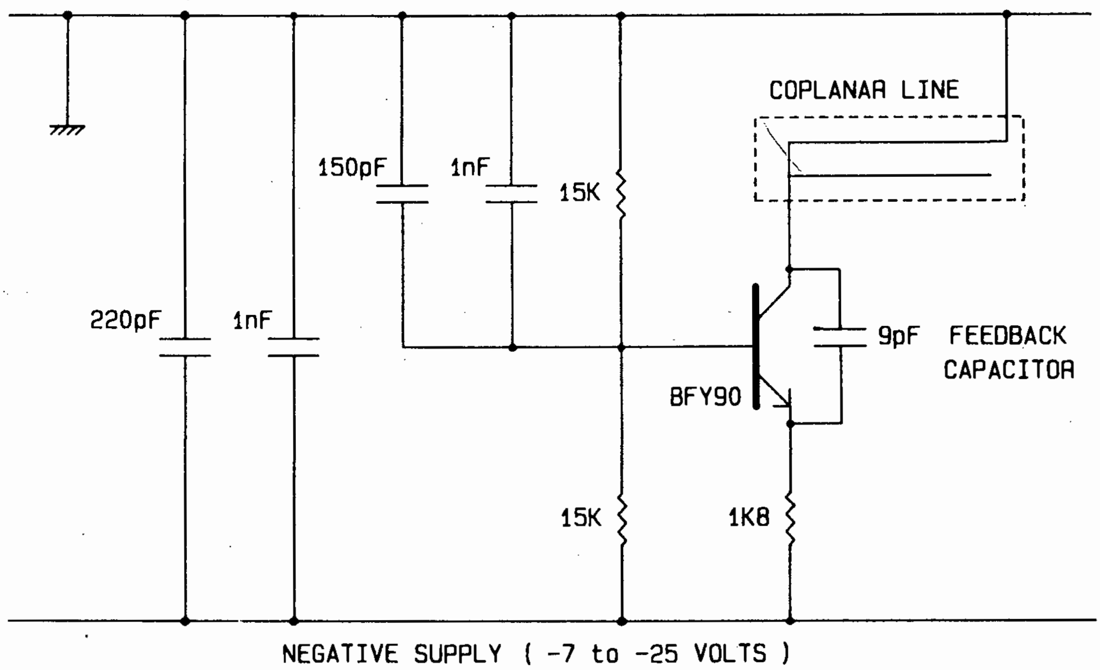


Fig. 2.5 The transistor oscillator circuit used with all the coplanar lines. The line is connected to the collector of an earth based transistor, with a low value collector-emitter capacitor providing the positive feedback necessary to make the circuit oscillate. The remaining capacitors are decoupling capacitors selected for the 40 to 160 MHz frequency range.

2.6. LEVEL-FREQUENCY RESPONSE EXPERIMENTS

2.6.1. Experimental Procedure

A means of determining the water level-frequency response of each coplanar line was required. Water was used for each experiment because it was readily available, and because its high dielectric constant would produce a maximum response. Thus any discontinuities and non-linearities would be easily detected.

A tank was made from 3 mm. thick Perspex and the coplanar line attached to the outside of one wall, with the length of the line orientated vertically to measure the height of water. Another wall was graduated in centimetre steps to enable the water level to be accurately read. The non-intrusive nature of the line meant that changes to the oscillator circuitry, or the line itself, was a quick and simple task. To fill the tank water was siphoned from a reservoir, and a stopper used to control the flow so that readings could be taken under static conditions. In the following experiment the water would be siphoned back into the reservoir, again in a controlled manner. This meant that the same water was used for a whole batch of tests, which increased the consistency of the results.

The output frequency of each sensor was extracted inductively, by coupling a 50Ω loop at the position where the H field was a maximum. A D.F.M. was interfaced to a HP85 computer via the HPIB bus, and used to record a set of ten frequency readings for each level reading keyed in. An indication of the stability of the sensor, was obtained by computing the standard deviation for each group of readings. By interfacing directly to a computer, the level-frequency response could be plotted immediately after the test. This instant graphical result contributed greatly to the success of these experiments.

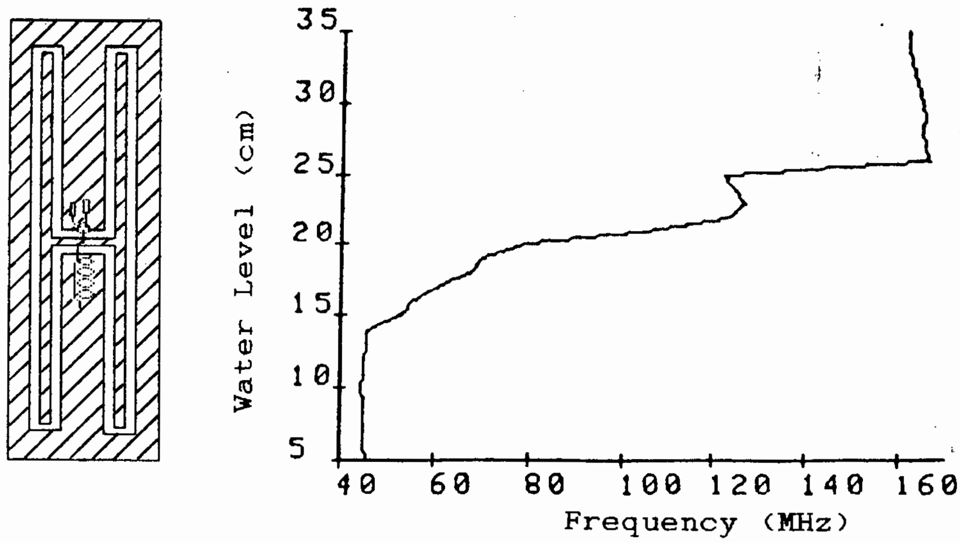
2.6.2. The 'H' Shaped Coplanar Transmission Line

The first variable that had to be determined was the length of the level sensor. An active length of 30 cm. was chosen to facilitate laboratory testing. Using a longer line would be no problem, because the line's resonant frequency falls with an increase in length. However shorter lines may require more work to achieve comparative results, because of their higher operating frequencies and therefore more involved interfacing techniques that are required.

In an attempt to find a suitable geometry for the coplanar line level sensor, a geometry which exploited a capacitive or open circuit line was sought. A single vertical line open at both ends would have been a reasonable choice, but it was felt that the capacitance of this line would be too low, and an extra line running parallel to the first one and open at both ends was added. Initially a central driving point for the lines seemed to offer the most symmetrical solution, so a geometry representing the shape of an 'H' was tried.

The 'H-line' is shown in fig. 2.6 (a). It was driven from the centre, and as such formed four open circuit capacitive stub lines. Initial experiments were carried out using a wire wound air-cored inductor in parallel with this line, which formed an oscillator with a free-air resonant frequency of 47 MHz.

Fig. 2.6 (b) shows the response of this line, which clearly exhibits an abrupt jump in frequency as the tank is filled with water. The frequency should have decreased as the water level rose, but a jump from about 47 to 166 MHz was recorded at the centre of the line. This phenomenon is termed a mode jump, and is attributed to the changing pattern of standing waves on the line, as the position of the impedance discontinuity associated with the water surface changes. Knor and Kuchler[3] discuss the even and odd modes of wave propagation, in their analysis of coplanar lines.

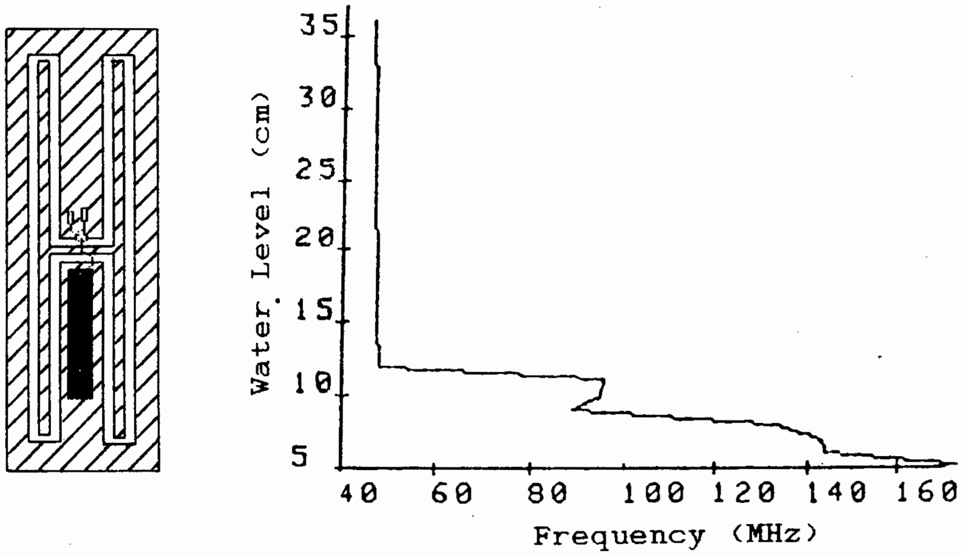


(a) (b)

Fig. 2.6 (a) The geometry of the 'H-line', showing the position of the driving oscillator and wire wound inductor. (b) The water level-frequency response of this line, indicating a mode jumping phenomenon.

The sensitivity of the line was reduced by moving it away from the side of the tank by 3 mm., but a mode jump still occurred when the tank was about one third full.

In an attempt to improve the stability of the inductor and pick-up, the wire coil was replaced by a 40nH strip line inductor, which was soldered onto the ground plane of the coplanar line as shown in fig. 2.7 (a). The response of this configuration (fig. 2.7 (b)), had an 11 % full scale range but became non-linear for levels below 15 cm.



(a) (b)

Fig. 2.7 (a) The 'H-line' with a 40nH strip line inductor and, (b) its water level-frequency response. The signal was extracted via a 50Ω loop positioned at the end of the strip inductor. With this geometry a mode jump occurred with the tank one third full. This jump could be attributed to the field distribution around the end of the inductor.

This experiment showed that the coplanar line had the sensitivity required for level measurement, and that the response exhibited promising linearity over 75 % of its range. However a suitable inductor was required to achieve linearity over the entire length of the line.

The experiment was repeated to ensure that the result was reproducible, and the two experiment's results found to be identical. During both experiments it was observed that the standard deviation of the readings increased when the level fell below 15 cm. Thus the stability was inversely proportional to the linearity, a feature that was used to instantly detect sensitive sections of subsequent designs. The non-linearity of the response below 15 cm. indicated that the inductor, or the pick-up loop, was affecting the field distribution.

Moving the oscillator circuit to one side of the 'H-line', and incorporating a longer strip line inductor on the opposite side, improved the response and no mode jump or reversal in frequency occurred. The resulting response exhibited a 7 percent full scale range, but was only linear over one third of this range.

To increase the stability of the inductor, one side of the 'H-line' was made inductive by shorting it at each end to the ground plane, the other strip remained capacitive (fig. 2.8). In this configuration the line resonated at 120 MHz in air, with a response that was almost linear. To eliminate discontinuities and mode jumping, a capacitor was connected in parallel with the line, thereby reducing the resonant frequency and effectively desensitising the response. In addition an Aluminium ground plane was positioned 2 cm. from the copper side of the line to reduce interference, and connected to its ground plane by supporting screws.

There were now four variables that could be altered to achieve an optimum response from a coplanar line sensor;

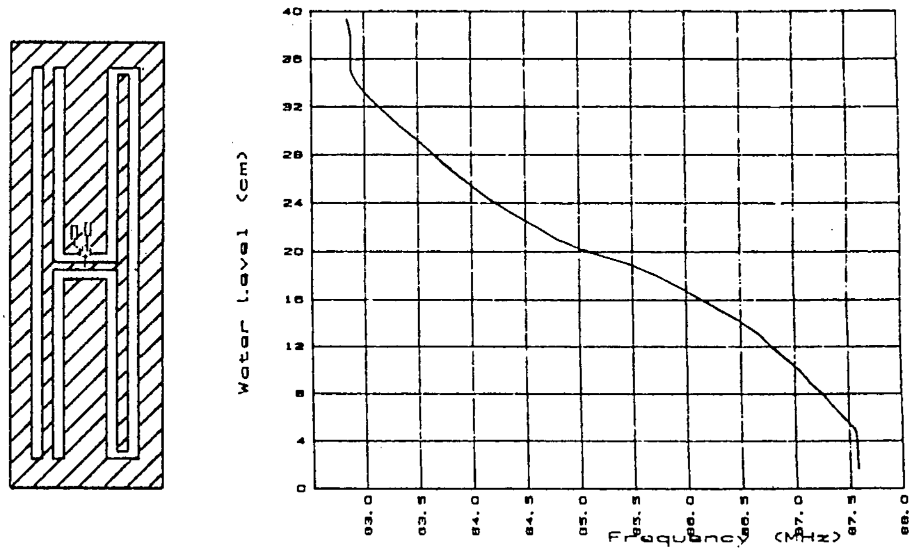
i. The feedback capacitor of the transistor oscillator circuit which ranged from 3 to 15pF, the larger being used for lower operating frequencies.

ii. The capacitor in parallel with the coplanar lines which reduced the line's sensitivity.

iii. The oscillator supply voltage which was varied from -5 to -20 volts, and had the effect of increasing the intensity of the field with increasing voltage.

iv. The distance of the ground plane from the line which was altered from 10 to 30 mm. This alters the actual field distribution around the coplanar lines.

A combination of a supply voltage of -15 volts, the ground plane positioned 12 mm. from the line, and a parallel capacitor of 50 pF, proved to be optimum for this 'H-line geometry (fig 2.8(a)). Fig. 2.8(b) shows the response obtained has a range of 5 percent, and clearly exhibits two linear sections above and below the centre of the line. A reassuring feature of this response, is that there is very little change in output frequency above and below the line's end-points, (at 35 cm and 5 cm on the graph).



(a) (b)

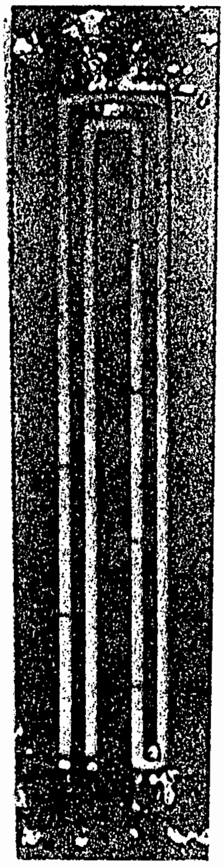
Fig. 2.8 (a) The 'H-line' with one side shorted to form the inductor, and (b) the water level-frequency response obtained from this line. The line had a 50 pF parallel capacitor to optimise the response, and a ground plane to reduce interference.

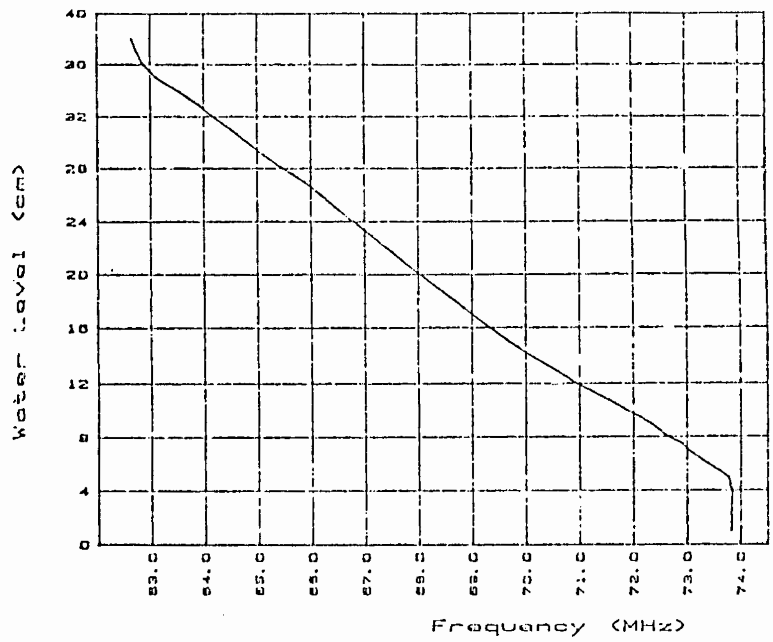
It is obvious that the non-linearity at the centre of the response (fig. 2.8(b)) was caused to a greater or lesser extent, by the central driving point of the 'H-line' geometry, and that a modification was necessary to achieve even better linearity. However the experiments conducted on the 'H-line' had demonstrated that the coplanar line was indeed viable as a vertical level sensor, and any non-linearities present were at least reproducible.

2.6.3. The 'U' Line Geometry

The resulting water level-frequency response shown in fig. 2.8 indicated that effect of a central driving point was undesirable. So the drive point of the 'H-line' was moved from to one end of the coplanar lines, thus forming a 'U' shape. The refined 'H-line' (fig. 2.8) consisted of four stub lines, two open and therefore capacitive, and two shorted lines which formed inductors in parallel, effectively halving their individual inductance.

The most obvious solution was to shift the drive position to the end of the lines, forming a single capacitive and inductive line, which increased the inductance and therefore reduced the overall resonant frequency. This reduction in operating frequency meant that the development of the associated electronics, required to interface the unit to the outside world, was made considerably easier. The 'U' geometry was also expected to increase the full scale range of the water level-frequency response, as the value of the capacitor used in parallel with the lines could be reduced, again because of the lower resonant frequency. Fig. 2.9 shows the 'U-line' and its response to water level, which exhibits a high degree of linearity and shows no sign of an increase in sensitivity at the centre of the line, as was the case with the 'H-line' geometry.





(a) (b)

Fig. 2.9 (a) The 'U-line' geometry and, (b) its water level-frequency response. The oscillator circuit had a 9 pF feedback capacitor to adjust for the lower operating frequency, and no parallel capacitor was used. The supply voltage was -5 volts.

With a 16 percent full scale range and near linear response, the 'U-line was considered to be a most suitable geometry for the sensor. In an attempt to increase the range of the output a three line geometry was tested, the centre line being shorted and the two outer lines open circuit. The addition of the second capacitive line reduced the operating frequency further, but the range of the response remained about 16 percent without a parallel capacitor. Fig. 2.10 shows the response of this line with a straight line fitted, which was obtained by performing a linear regression on the data. The graph gives an indication of the linearity of this line's response over its active range, which yields an accuracy of 2 percent. If two lines are fitted to the response the accuracy falls to below 1 percent for this line.

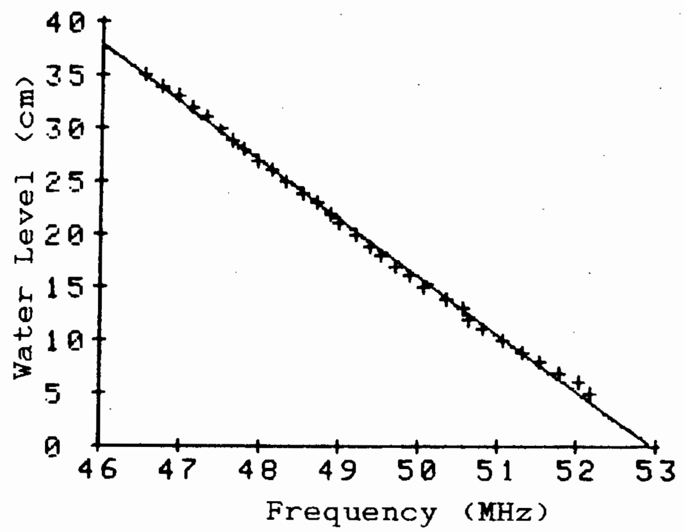


Fig. 2.10 The response of the three line sensor with a straight line fitted, indicating the high degree of linearity. The accuracy obtained from this straight line fit is 2 percent.

The three line geometry was chosen as the design to be used for vertical level measurement. The linearity and reproducibility of the response were considered to be quite acceptable, and fell within the specifications for the sensor.

Efforts were now directed at the foam-liquid interface encountered in stirred slurry solutions. To try and simulate a foam, soap was added to the tank and the solution stirred until the density of the foam was as high as possible. It was hoped that by making the foam dense any changes in the line's response would be detectable. The level response experiment was repeated several times employing varying heads of foam from about 1 to 5 cm. The results obtained were the same as the response shown in fig. 2.12 (b). It is reasonable to conclude that the foam has an effectively low dielectric constant relative to water, and therefore will have little if any effect on the coplanar line when operated in industrial slurries.

Now a method of extracting the line's operating frequency, other than by inductive coupling was required. This would ensure the energy extracted from the line was constant, and a minimum. An interface circuit was designed which coupled the oscillator (fig. 2.5) to a TTL divider, enabling a frequency of about 2 MHz to be transmitted to the DFM, and adding to the mechanical stability of the sensor, by discarding the inductive loop pick-up. This interface circuit is described in the following chapter.

2.7. THE 50 CENTIMETRE LONG COPLANAR LINE

With an active length of 30 cm., the coplanar lines described so far were considered too short for certain applications. Increasing the length of the lines has the advantage of decreasing their operating frequency, as this effectively increases the inductance and capacitance of the oscillator. Practical limitations during the etching process meant that the coplanar line could not exceed 60 cm. in overall length. However longer lines could be fabricated as long as required for a specific application, by manufacturing lengths of the line in sections.

To demonstrate that increasing the length of the line was feasible, and to make a more general purpose transducer, the active length of the line was increased to 50 cm., keeping the same geometry as the three line sensor discussed in the previous section. Fig. 2.11 shows the response of this longer line to water level. The interface circuit has divided the operating frequency by a factor of 16.

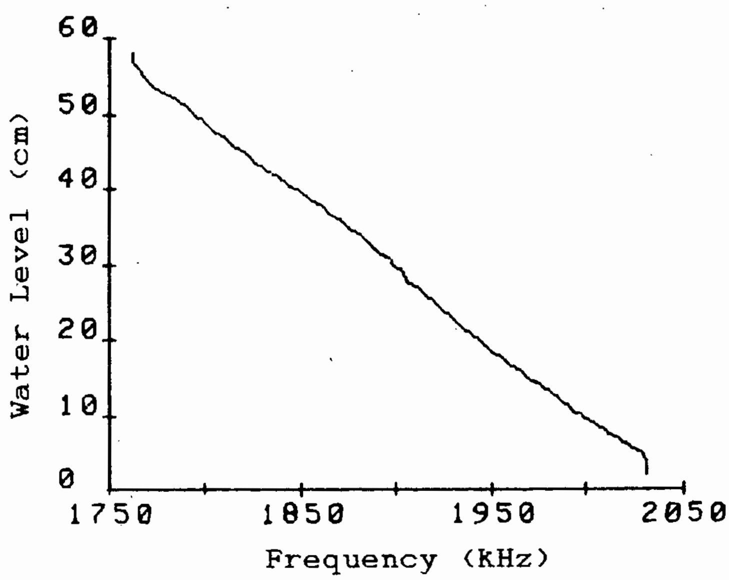
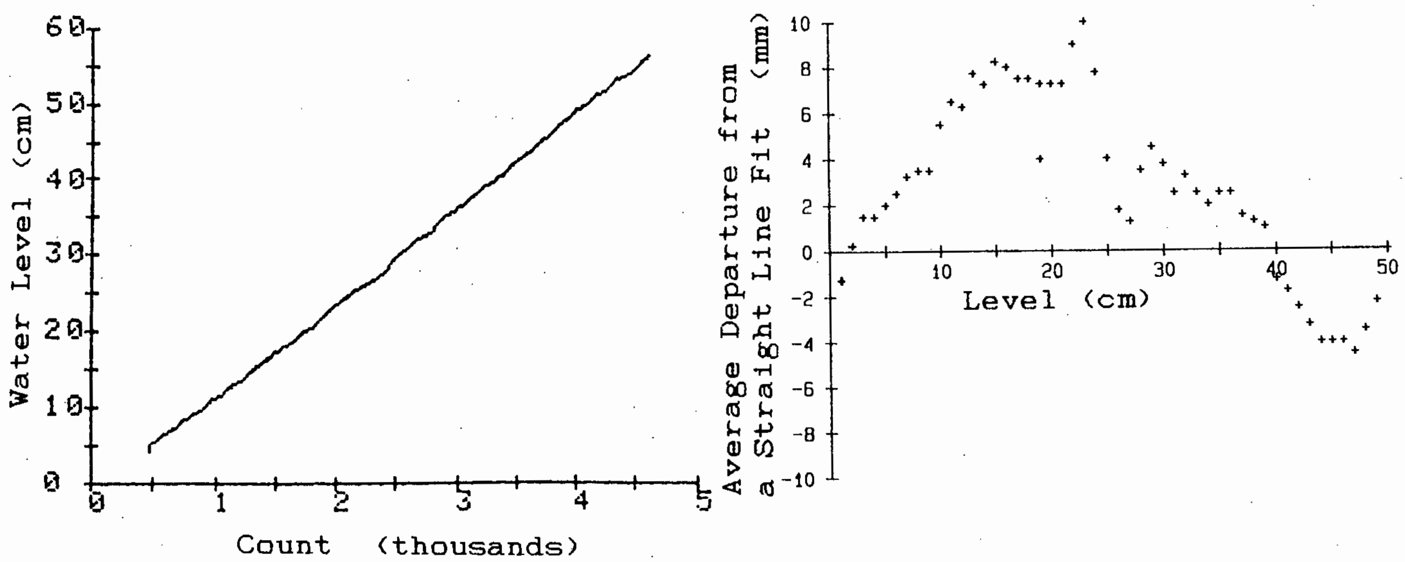


Fig. 2.11 The water level-frequency response of the 50 cm. coplanar line, indicating that there is no degradation in performance of the longer sensor. The operating frequency of the line has been divided by a factor of 16. It will be noted that the total change is over 15 %, while the resolution is better than 0.05 percent. Substituting the frequency range shown above into equation (1.25), the constant R is found to be 0.32. By using this value for R, the frequency range of the 50 cm. line can be calculated for liquids other than water.

In the form of a non-intrusive sensor attached to the outside of a tank, the coplanar line is only suitable for tanks and containers which are non-conductive, ie. Glass or Fiber-Glass tanks. There are of course many metallic tanks for which this configuration would be unsuitable. To make the coplanar line as general and as practicle as possible, it was enclosed with its Aluminium ground plane in a Perspex container. In this configuration it could be used in the role of a 'dip-stick' type sensor. The container walls were made 3 mm. thick, the same thickness as the tank on which the experiments were conducted, so that the response of the sensor when immersed into the tank, would be the same as that of fig. 2.11.

Fig. 2.12 shows the response of the encapsulated line, with an error graph showing the average departure from the straight line joining the end points. This information could be used with a microprocessor to correct the level reading, thereby greatly increasing the accuracy of the sensor. Fig. 2.13 shows the encapsulated unit.



(a) (b)

Fig. 2.12 (a) The response of the encapsulated line, and (b) the average departure of the response from a straight line joining the line's end points at 5 and 55 cm. Obviously for high accuracy applications, a correction can be implemented in software to largely eliminate this departure.

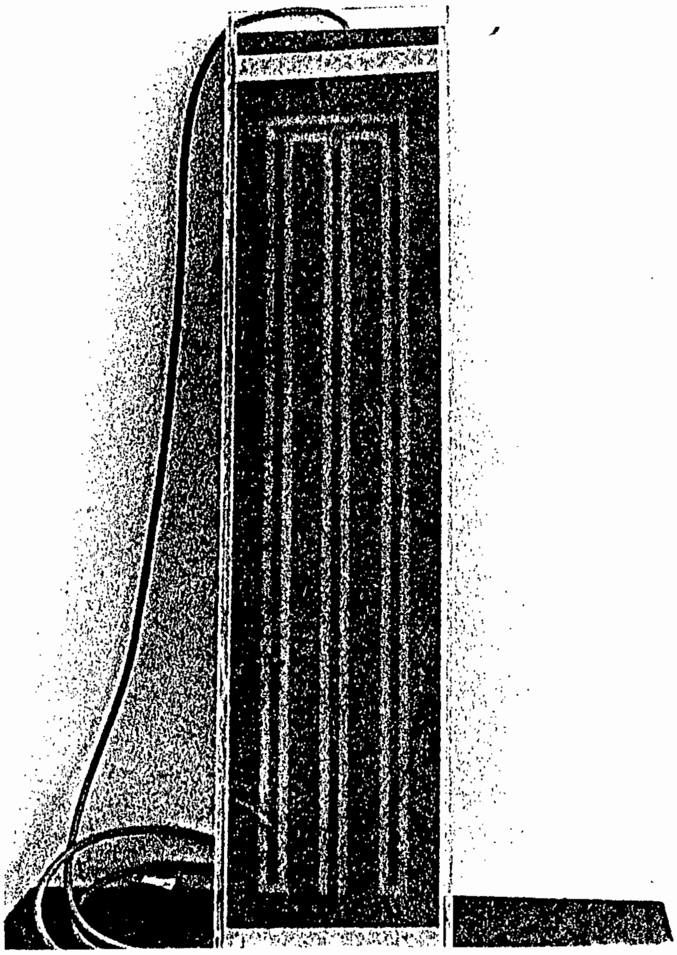


Fig. 2.13 The three line sensor with its Perspex container which enables it to be used in the role of a 'dip-stick' type sensor.

2.7.1. The Level Sensor's Temperature Dependance

An important consideration for the development of any sensor, is its response to changes in physical conditions, such as temperature and pressure. In a typical application pressure variations are likely to be small and have little effect, however the temperature could change by several degrees over a 24 hour period, and have a considerable effect on the output. It was felt that the coplanar line would be most sensitive to the temperature of the liquid, as opposed to the temperature dependance of the line itself, since the dielectric constant of a liquid is highly dependant on temperature. This property is explained by an increase in temperature, causing a reduction in the polarisation of the liquid, and hence decreasing its ability to neutralise an applied electromagnetic field. The dielectric constant of water is a prime example, as it falls by approximately 1 percent per degree K. rise in temperature.

What was required was a method of extracting the temperature of the liquid in a convenient form, so that the level and temperature readings could be monitored simultaneously. This was achieved by interfacing the current output from the AD590 temperature sensor, to a current-to-frequency converter circuit. This meant that both level and temperature outputs were TTL compatible frequencies, and could therefore be received by the same device. The converter circuit is described in the following chapter, with calibration and performance evaluation experiments.

To determine the coplanar line's temperature coefficient when used with water, an experiment was conducted with the sensor fully immersed in warm water. Results of the output frequency as the water cooled, are shown in fig. 2.14. An important feature of the temperature dependance is its linear nature. From this experiment the slope df/dT was found to be -0.43 kHz/°C, and from fig. 2.11 dl/df is -2.12 mm./kHz, which yields the sensor's temperature coefficient dl/dT of 0.9 mm./°C. The experiment was repeated under the same conditions and this result confirmed.

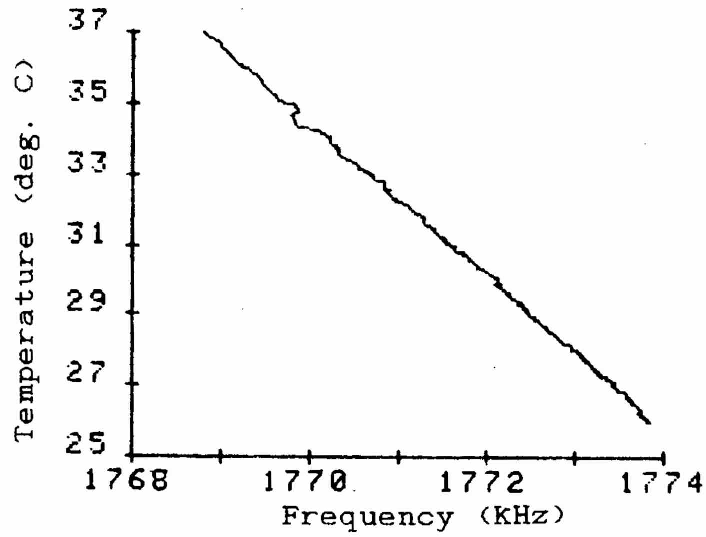


Fig. 2.14 The temperature of the line plotted against the output frequency for a constant water level. This result represents a temperature coefficient (dl/dt) of 0.9 mm./°C.

The significance of this temperature coefficient, is that it is too large to ignore, and therefore a form of temperature correction is necessary for applications using water. The correction applying to other liquids will be smaller, but this correction could be used with any application where the liquid is predominantly water.

CHAPTER 3

3. ELECTRONIC DETAILS

The electronics developed in this project can be split into two sections; the electronics integrated onto the coplanar line, and the circuits used to monitor and display the outputs.

The main oscillator, a temperature sensing circuit, and their respective TTL interfaces, were incorporated on the line. An initial readout circuit was developed which measured the line's operating frequency, and output the information in the form of a BCD 3-digit display, and an analog signal suitable for driving a pen recorder or an oscilloscope. Later a microprocessor controlled readout interface was developed for the prototype instrument, which corrected for temperature variations of the liquid, and provided digital level and temperature outputs, in addition to a 4 to 20 mA. analog level output.

3.1. THE TRANSISTOR OSCILLATOR CIRCUIT AND TTL INTERFACE

Coplanar lines are sharply tuned resonant circuits, which in this application are used as the controlling element of an electronic oscillator. This oscillator consists of an earth-based transistor with the coplanar line in the collector. The positive feedback necessary to make the circuit oscillate is provided by an external capacitor connected across the collector and emitter. The value of this capacitor ranged from 3 to 15 pF, and was dependant on the line's operating frequency, a low value being used for high frequencies. The emitter resistor determines the collector current and hence the intensity of the field. The 1K8 value of this resistor was chosen to optimise the high frequency performance of the BFY90 transistor.

Fig. 3.1 shows this circuit with a TTL interface developed to extract the line's operating frequency electronically, rather than by inductive coupling to one of the coplanar lines.

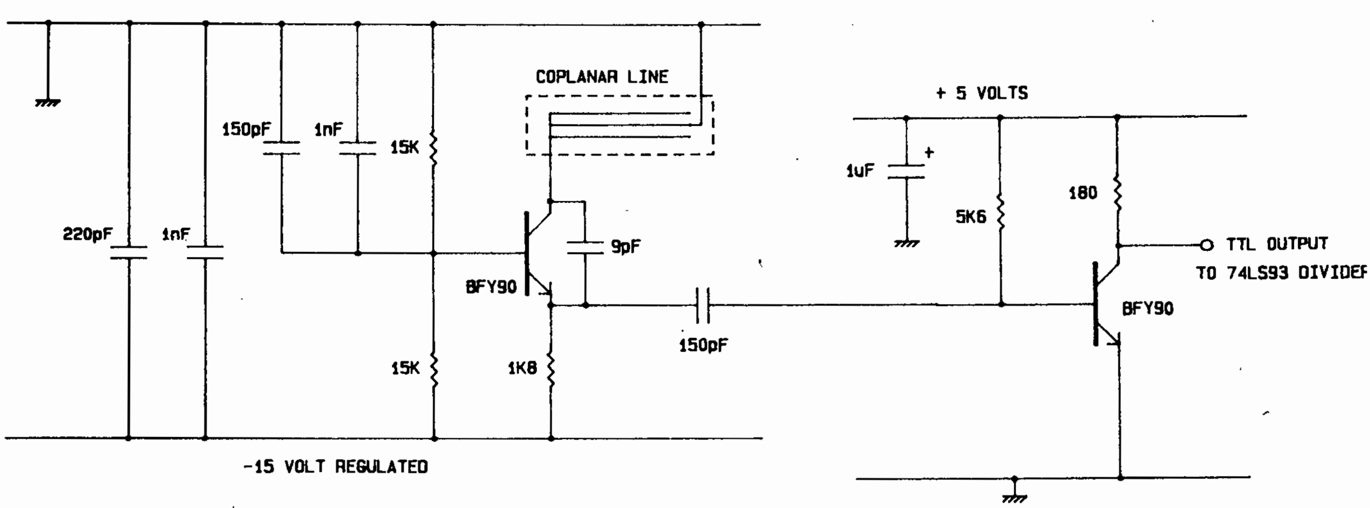


Fig. 3.1 The transistor circuit used to form an oscillator with the coplanar line, and the TTL interface which directly drives an LS-TTL divider. The collector of the drive transistor is coupled to the inner strip lines, and the line's ground plane is at a.c. and d.c. earth.

The circuit employs a positive earth, an important practical feature which ensures the ground plane of the line is at both a.c. and d.c. earth. This earth plane was extended via the Aluminium back cover, which reduced interference and confined the radiation to the front of the line. The ground plane enabled the oscillator and TTL interface connections to be etched directly onto the line, improving the stability of the circuit.

The TTL interface consists of an common-emitter transistor supplied from +5 volts, which ensures TTL voltage levels. The base is coupled to the emitter of the oscillator transistor via a 150 pF capacitor, chosen to minimise the energy extracted from the oscillator. The collector is coupled directly to an LS-TTL divider which divides the operating frequency by a factor of 16.

The operating range of the TTL interface was restricted to about 60 MHz by the LS-TTL divider. However the use of an 'Advanced Schottky' TTL divider would improve the performance of the circuit and increase the range to around 85 MHz.

At frequencies above 50 MHz the division factor should be greater than 16, ie. 32 or even 64. The success of this circuit at such high frequencies was in part due to the surface mounting of components onto the coplanar line's ground plane, which enabled the leads to be cut as short as possible, thereby reducing inductive pick-up and optimising high frequency performance.

3.2. AN IMMEDIATE READOUT INTERFACE

Tests conducted on the first coplanar line sensors used a DFM to measure the line's operating frequency, and transferred the results to a computer via the HPIB interface bus. What was required for stand-alone operation was a unit which could replace the DFM, and provide an analog output capable of driving a chart recorder or an oscilloscope. In this way the performance of the sensors could be recorded and evaluated on site. The unit described was specifically designed for use in flotation cell tests conducted at Mintek (The Council for Mineral Technology), and provided the basic design criteria for the final microprocessor controlled instrument.

A readout interface was designed and built which in addition to an analog output, displayed a three digit decimal count proportional to the input frequency. Fig. 3.2 shows the circuit schematic.

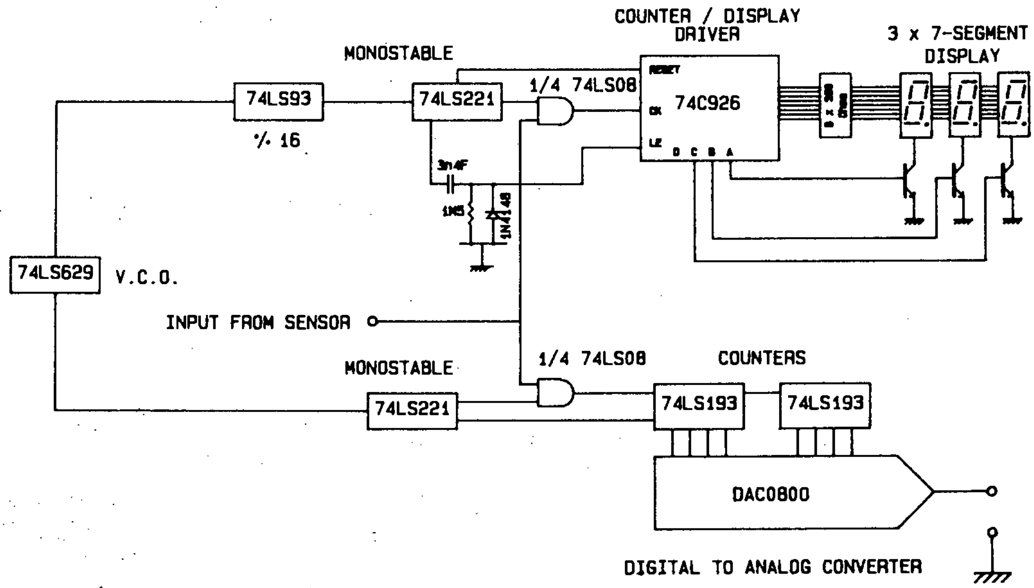


Fig. 3.2 The design of the immediate readout interface, comprising both analog and digital outputs.

The input signal was gated by two different length pulses, derived from a dual voltage controlled oscillator (VCO). One gated signal was fed to a counter/display-driver, and the other to a digital-to-analog converter (DAC). Variable potentiometers enabled a 10 % control of the gating pulse lengths, so that the unit could be adjusted for different sensors and liquids.

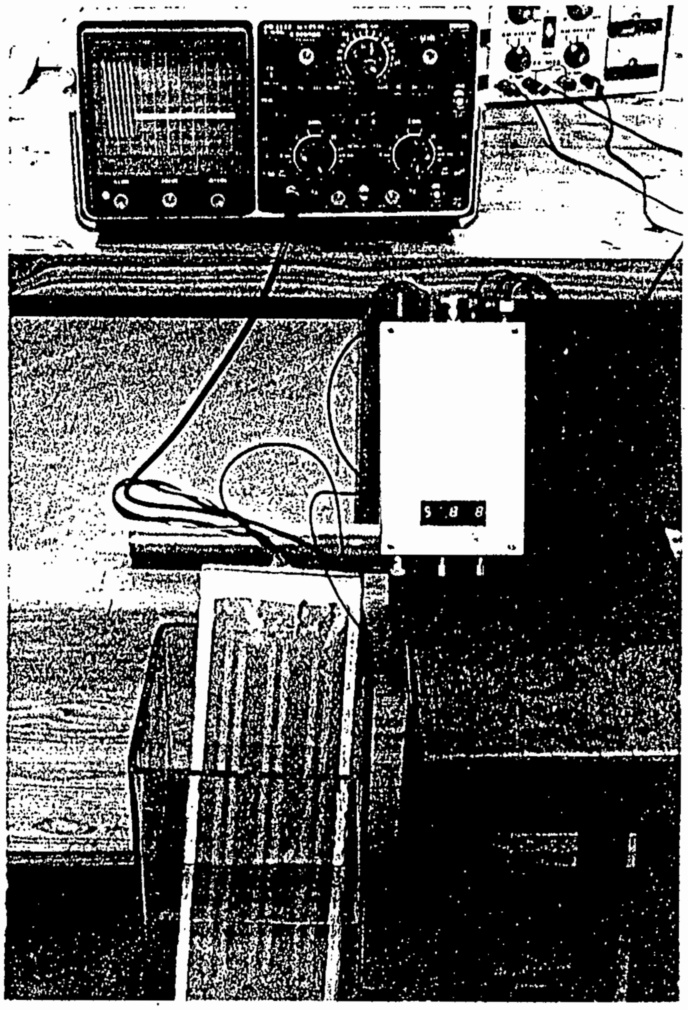


Fig. 3.3 The readout interface used with the three lined coplanar line sensor. The analog output is shown on an oscilloscope, and clearly shows the counter which drives the DAC, clocking through its range several times before latching the correct count.

3.2.1. Digital And Analog Readout Design Considerations

The TTL input signal would typically fall from 3 to 2.5 MHz as the sensor was immersed in water, for which the analog and digital readouts had to output full scale readings. In the case of the analog output this meant a minimum and maximum input to the 8-bit DAC, of 20 and 245 respectively.

A concept which can be regarded as a vernier counter was used. The counter was made to cycle through its range (0 to 255) over and over, until after n cycles, the count was latched in the required range. In this way the full range of the counter was utilised. The number of cycles n, depends on the minimum and maximum input frequencies (f_{min} and f_{max}).

$$n = INT\left[\frac{f_{min}}{f_{max} - f_{min}}\right] \qquad ....(3.1)$$

The gate time (t_{gate}) required to achieve a maximum range is given by;

$$t_{gate} = \frac{(n + 1) .\ C_{max}}{f_{max}} \qquad ....(3.2)$$

where C_{max} is the maximum count of the counter being used (eg. 255 for an 8-bit counter). For the input signal range 2.5 to 3 MHz, equations (3.1) and (3.2) give n equal to five and a gate time of 0.512 ms. The value of n was reduced to four and t gate to 0.420 ms., to provide a safety margin at the extremes of the count range. For the input frequency range 3.0 to 2.5 MHz, the corresponding count range was 26 to 236.

At the heart of the digital readout is the 74C926 counter/display-driver, which is a four decade incremental counter with an initial count of zero. To obtain a stable display the least significant digit was discarded. However the maximum count remained 9999 as far as the calculations line is a frequency, it was decided to convert the current output from the AD590 to a frequency as well. This would facilitate measurements by enabling both the line's output and the temperature output, to be measured by the same device. The conversion from current to frequency was not trivial, because such a low current range (70 μA) had to be converted to a reasonably large frequency range.

The first design tested employed a VCO to convert the AD590 output from a voltage dropped across a resistor, to a frequency. This configuration was found to have a long term drift, that was partially corrected by operating the other half of the dual VCO at a fixed frequency, and measuring the resulting difference frequency. However its short term stability proved inadequate, and another means of converting the AD590 output to frequency was sought. In the second design the VCO was replaced by a dedicated voltage to frequency converter, which proved to have a better short and long term stability than the previous circuit.

3.3.1. The Temperature To Frequency Converter Circuit

The voltage-to-frequency converter chip operates from a single 15 volt supply, as well as from split supplies. As a regulated -15 volts supply was already available on the sensor, the single supply option was favoured. The circuit was first designed and tested with a +15 volt supply, and later transformed to a positive ground configuration which used the existing -15 volt supply. The circuit was mounted directly onto the surface of the coplanar line, next to the transistor oscillator. The common ground plane provided good electrical and thermal stability, and ensured a minimum R.F. interference from the oscillator. The AD590 sensor itself was positioned at the bottom of the line, enabling it to respond to the temperature of the liquid irrespective of its level.

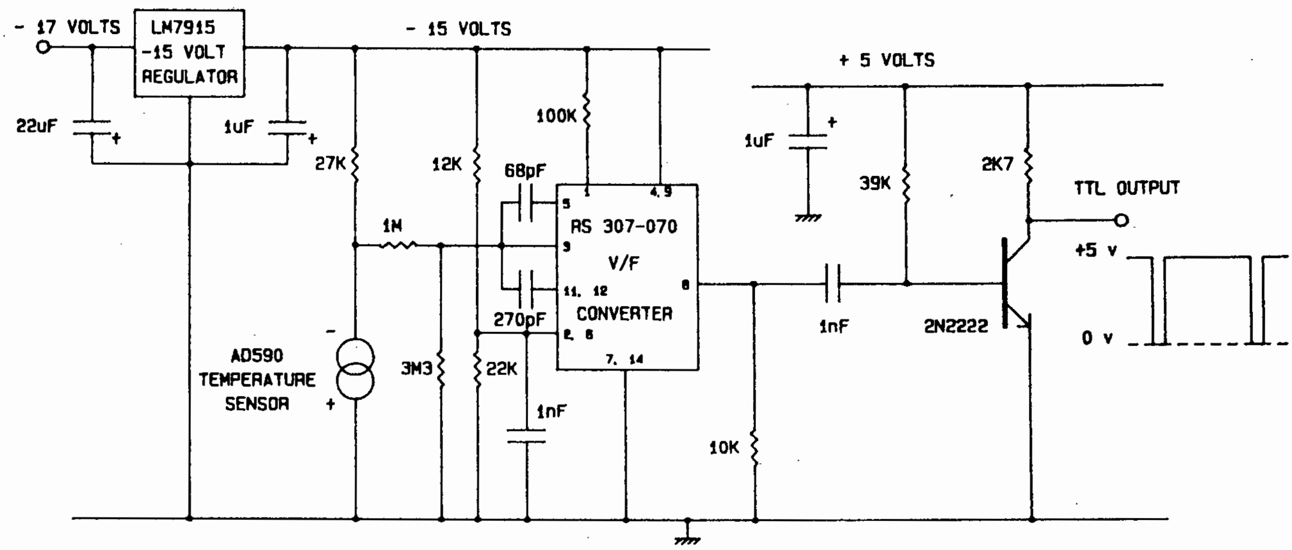


Fig. 3.4 The temperature to frequency converter circuit used with all the coplanar lines. The current output of the AD590 temperature sensor is converted from a voltage dropped across a resistor, to a frequency by a voltage-to-frequency converter chip (RS 307 070). Because the circuit was supplied from -15 volts, the pulse train output from the chip had to be converted to TTL levels by using a common-emitter buffer transistor supplied from +5 volts.

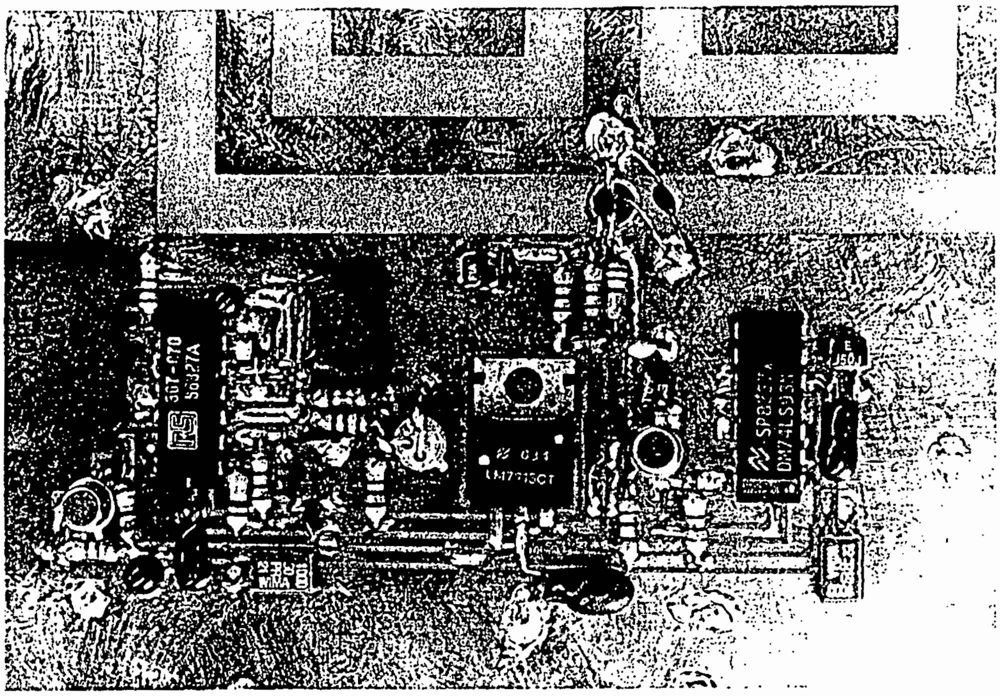


Fig. 3.5 The temperature-to-frequency converter (left), and the transistor oscillator and TTL interface (right). Surface mounting of components on a common ground plane ensures maximum stability with minimum R.F. interference.

The timing components of the voltage-to-frequency converter were chosen so that the output frequency was 11 KHz at 20 °C, at which frequency the non-linearity of the temperature sensor was a minimum (0.01 percent).

To calibrate the converter holes were drilled in an Aluminium block, so that the temperature sensor and a standard thermocouple could respond to the same temperature. Readings of temperature from the thermocouple, and the converter's output frequency were recorded as the block cooled from 40 °C. to room temperature, and then cooled further by a metal bar cooled in a fridge. Fig. 3.6 shows the results of the calibration experiment.

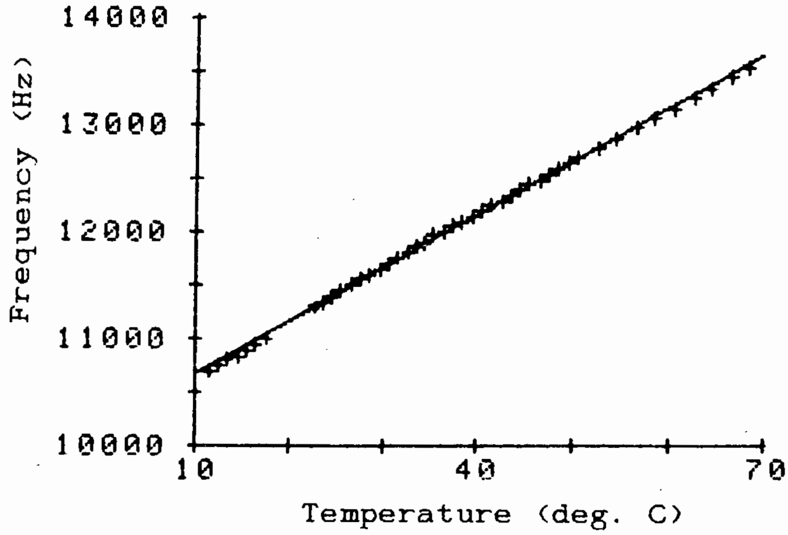


Fig. 3.6 The frequency output of the temperature converter circuit of fig. 3.4, plotted against the temperature measured by a standard thermocouple. This graph shows the excellent linearity of the converter.

Having calibrated the sensor it was necessary to test its stability. This was done by simply monitoring room temperature over a long period, taking sets of readings at fifteen minute intervals. The results of this experiment are shown in fig. 3.7.

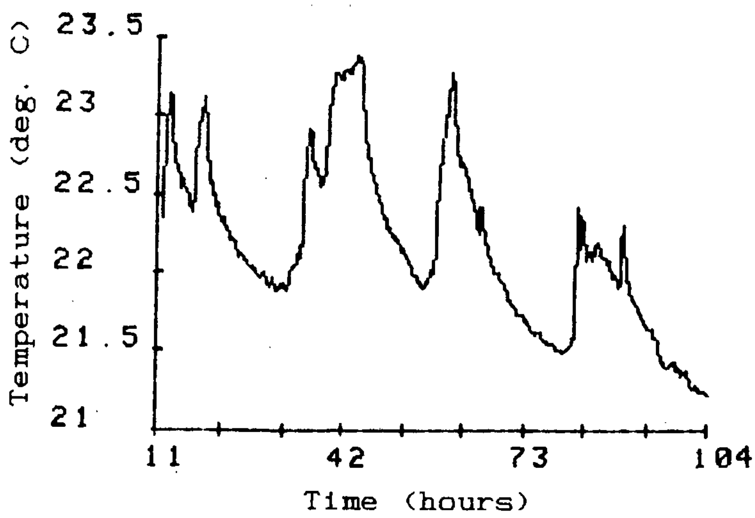


Fig. 3.7 Room temperature variations over a four day period, as measured by the converter circuit of fig. 3.4. The output frequency of this circuit is converted to °C from the calibration graph of fig. 3.6. The day-night temperature cycle is very prominent.

The sensor output shows no long term drift and clearly indicates the cyclic temperature variations of each 24 hour period, the coldest time of the day being indicated at 5 a.m. The short term stability can be assessed by the standard deviation of each set of ten readings, which was found to be approximately 30 ppm., an improvement on the 600 ppm. measured during a similar test on the earlier VCO converter circuit.

Having developed a suitable temperature sensor with the required stability, it was used to measure the temperature dependance of the coplanar line immersed in water. It was found that a correction for temperature was indeed necessary, making the temperature converter a permanent fixture of the coplanar line level sensor. The impressive electrical and thermal stability of the sensor and its converter, meant that a temperature correction could be made accurately, and having an output frequency ensured that the level and temperature could be measured by the same device.

3.4. THE PROTOTYPE READOUT INTERFACE

The requirements for the final prototype readout interface were an extension of the readout interface described in section 3.2. It had to be capable of operating in a stand-alone mode, and correcting the output according to the line's temperature dependance. In addition it was specified that a 4 to 20 mA. analog current output be provided for interfacing to existing equipment at Mintek. The unit also required an interface to a computer, for data logging during the experiment and development phases.

The ability to easily calibrate the instrument for different liquids, was a feature that would broaden the coplanar line's application to any dielectric liquid, and therefore was a desirable feature for the readout interface. For this application a display refresh time of one second was considered to be sufficient, as liquid levels tend to change relatively slowly. The one second cycle dictated that the software which would perform the averaging and temperature corrections, should be written in assembly level language, to speed up the BCD division and other necessary routines. These routines are relatively slow in a high-level language like PLM. A flow chart and a description of the software is given in chapter 5.

The 8085 microprocessor was chosen because of the availability of a suitable development system. Fig. 3.8 shows a block diagram of the microprocessor, and the peripherals of the readout interface.

The two input frequencies are counted by the 8254 timer/counter, which is software controlled. The 8085 CPU uses a 8279 keyboard-display controller to interface to a keyboard, and a display module containing eight seven-segment LED displays. The DAC0800 digital-to-analog converter was used to drive a 4 to 20 mA. analog output. An 8255 Parallel Peripheral Interface chip enabled the CPU to transmit data to the GPIO bus, via buffered outputs.

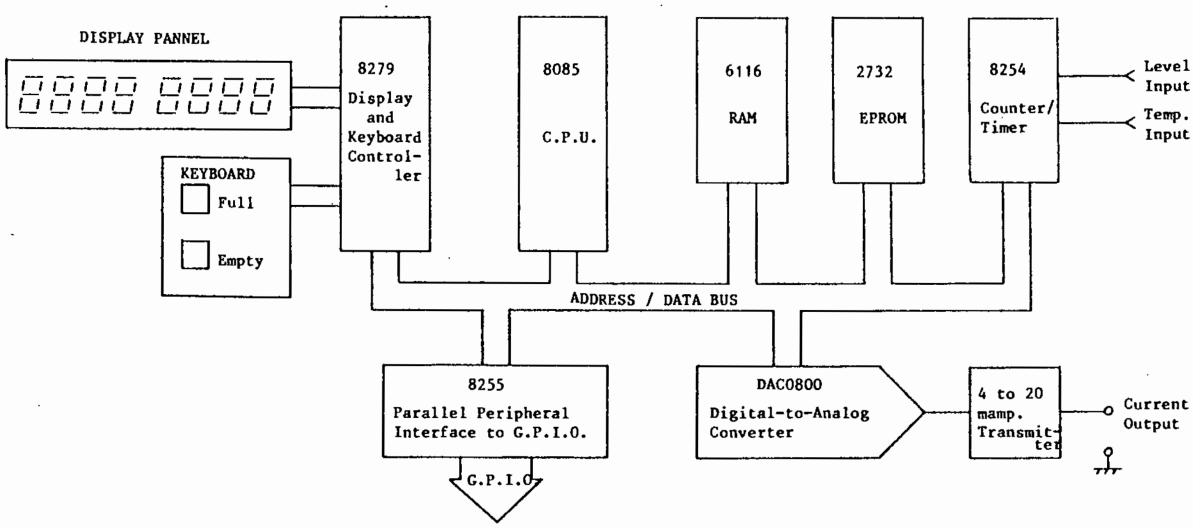


Fig. 3.8 A block diagram of the readout interface of the final prototype instrument. The frequency inputs are gated by a timer/counter, and read by the 8085 CPU. Peripherals enable the readings to be output on a digital display, and an analog current output. Data logging by computer is made possible by a general purpose parallel interface. In addition to a reset there are two calibration keys, used for end-point calibration of the sensor. This feature enables on site calibration of the sensor for different liquids.

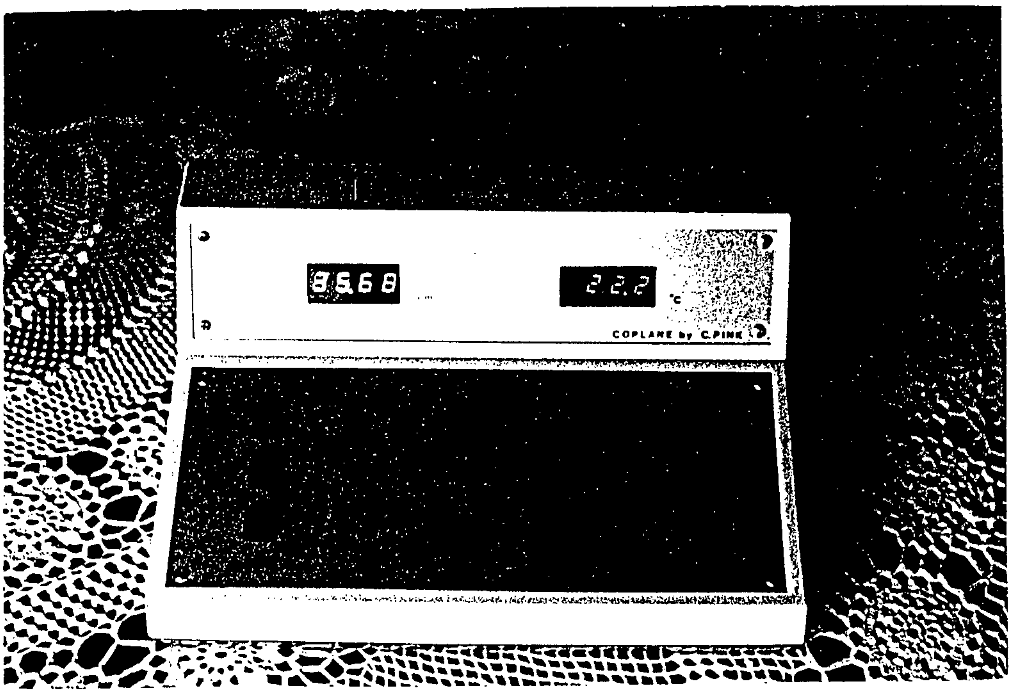


Fig. 3.9 The readout unit shows digital outputs of level and temperature, and the reset and calibration buttons on the front panel. The box contains the electronics described in the block diagram of fig. 3.8.

Water level measurement is only one of the many possible applications of the coplanar line, and in the next chapter various other applications are discussed.

CHAPTER 4

4. USER APPLICATIONS OF THE COPLANAR LINE

The primary advantage of the coplanar transmission line is its non-contact nature. This means that it can be used to measure dielectric materials and liquids, which do not penetrate or come into contact with the sensor. Initial development efforts were concentrated on a vertical liquid level indicator, however the coplanar line has many other possible applications:

i. Liquid level measurement in industrial tanks and slurries, including applications in hostile and corrosive environments. An ideal application would be the measurement of the water which collects at the bottom of Petrol storage tanks. This would be possible because Petrol, being an organic liquid, has a low dielectric constant (2.1), whereas that of water is extremely high (80). The coplanar line is suitable for detecting the boundary between any two liquids which have appreciably different dielectric constants.

ii. The measurement of evaporation from an open surface, which is very important in dams and reservoirs.

iii. Settlement and density measurement in slurries and other industrial mixtures. A typical application would be the monitoring of deposit build-up inside P.V.C. water pipes.

iv. Slurry foam density measurement, which is a requirement in the flotation process used in the extraction of Gold and other metals from ore. The foam density is very important, because the extracted metal is suspended in the foam.

v. Any application where the quantity of water present is critical, for example in the drying process of agricultural products.

vi. Certain industrial requirements involve the mixing of two liquids in a specific ratio. A version of the coplanar line could be an ideal sensor in this application.

The applications of the coplanar line described above have been focused on the mining industry, however tests were also conducted on the T-line, to investigate its suitability as a non-intrusive charge detector for a standard lead-acid cell. This work was carried out under the author's guidance by T. Christians[13], a final year B.Sc. student at the University of Cape Town.

4.1. SLURRY MEASUREMENTS USING THE T-LINE

In a slurry, which is a mixture of approximately 40 % mud and 60 % water, the presence of mud particles is in fact an absence of water, to which the coplanar line is very sensitive. It was therefore anticipated that it could be used to measure varying slurry density. The T-line was chosen as the most suitable sensor because it concentrates the electric field around the open 'T' end, which combined with its high stability, enables it to respond to very small changes in water content.

Two different experiments were conducted with slurries;

i. A stirring experiment in which the response of the T-line was compared for various stirrer velocities.

ii. A settlement experiment where a well stirred mixture was allowed to settle.

4.1.1. Stirred Slurry Experiment

The aim of this experiment was to observe the turbulence set-up by a stirrer immersed in a slurry. The density variations which may occur around a revolving stirrer in a dense slurry, would certainly be small and therefore difficult to measure using existing sensors.

In an effort to observe these variations, the T-line was attached to one side of a Perspex container with its length orientated horizontally. The slurry was stirred continuously and a D.F.M. used to measure the sensor's output frequency, and then transfer the readings to a computer via the HPIB bus. This was however a slow method of logging readings, and consequently it did not utilise the very fast response of the coplanar line. As a result the expected oscillatory nature of the response, due to the turbulence around the stirrer, was only evident at very slow stirrer speeds.

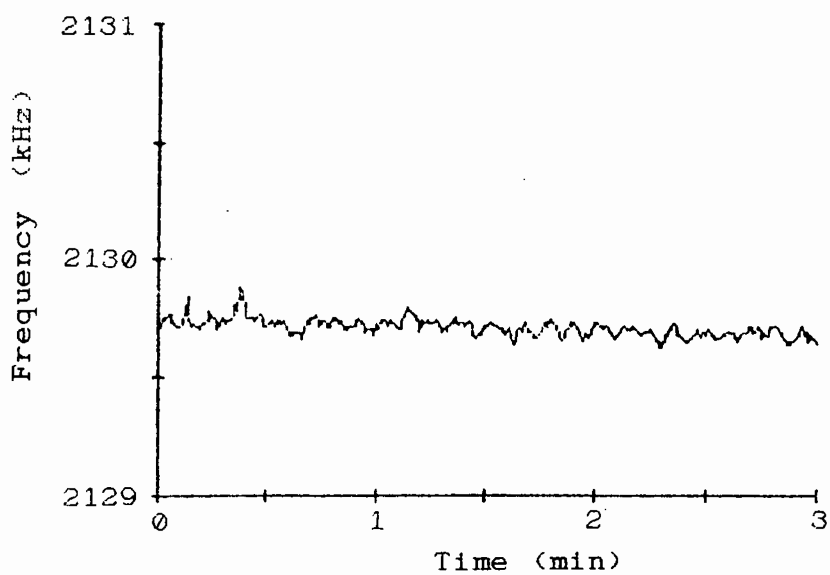


Fig. 4.1 The response of the T-line to slurry under low speed stirring.

An important feature of the experiment was that the fluctuations due to slurry being stirred were evident. By using a microprocessor based interface, the readings could be logged much faster and a more meaningful result obtained. Increasing the sensitivity of the line could also improve the results. This could be achieved by allowing the slurry to come into contact with the Fibre-Glass substrate of the coplanar line, instead of having a 3mm. thick Perspex wall separating the slurry from the line.

4.1.2. Slurry Settlement Experiment

Whilst the density of slurry changes under stirring, the fluctuations are small, and it was decided that a much larger response would be obtained if the stirred solution was allowed to settle. To monitor this settlement, the T-line was mounted under a Perspex tank supported on a wooden frame, so that the electric field distribution would be unaffected.

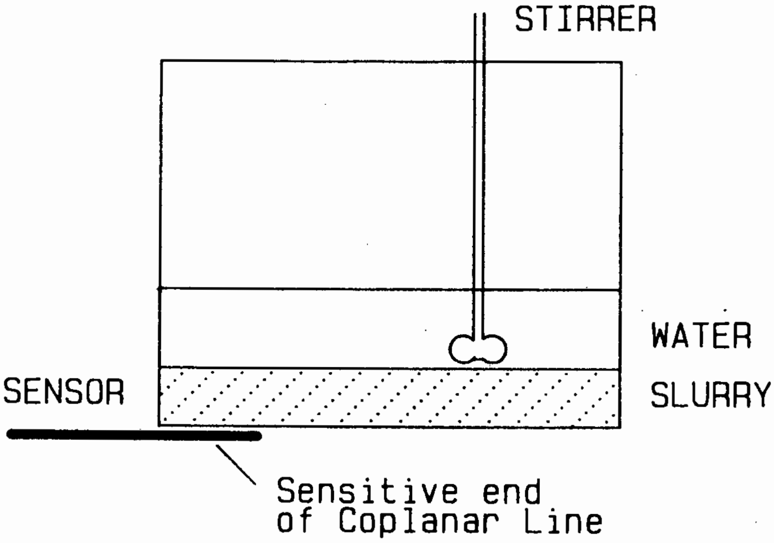
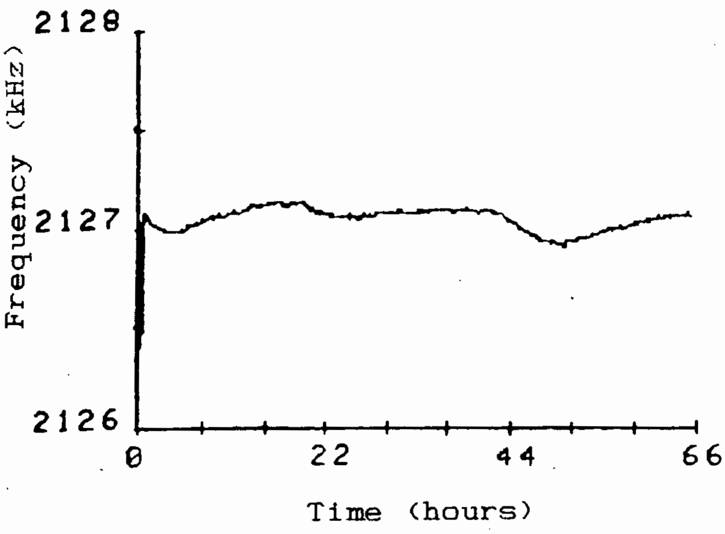


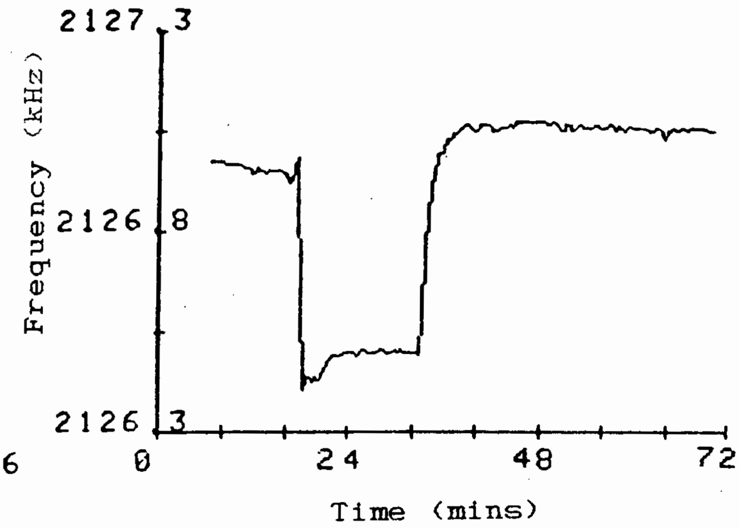
Fig 4.2 The experiment setup showing the position of the T-line sensor beneath the Perspex tank. The slurry is depicted in its settled state.

It was anticipated that the settlement would have two stages. An initial stage where the larger slurry particles settle quickly, and in so doing trap water molecules between them. Then a secondary long term stage, where the weight of the slurry that has settled on top of the larger particles, forces out the trapped water molecules. To observe the expected short term response, a computer was programmed to record the mean of ten readings once every twenty seconds. After the first hour the period between each set of readings was extended to ten minutes, so that the any long term effect would be captured.

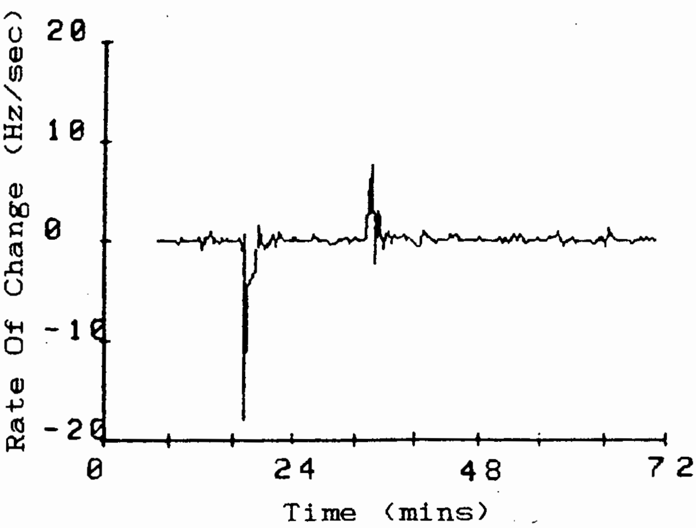
Fig. 4.3 (a) shows the response of the T-line to slurry that has been standing, then stirred until all the slurry particles are in suspension, and finally left to settle. The experiment was run over a 66 hour period, during which the equipment was totally isolated. From this response it



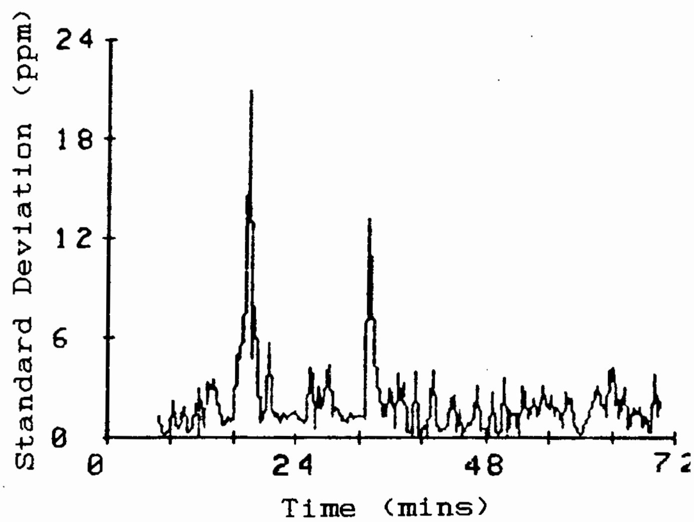
(a)



(b)



(c)



(d)

Fig. 4.3 shows the result of a typical settlement using the T-line to monitor slurry density. In (a) settled slurry was stirred briefly then allowed to settle. The experiment was continued over a 66 hour period to observe the any long term effects. Clearly the dominant effect is t e temperature of the slurry. Graph (b) shows stirred section of the experiment in detail. The rate of change of successive groups of readings (c), and the standard deviation (d), both indicate the turn on and turn off times. Interestingly the response when the stirrer was turned on, is greater than at turn off, indicating that during stirring a layer of denser slurry particles remained at the bottom of the tank. The step increase in frequency in graph (b) indicates that this layer was stirrer up initially, but the particles were too heavy to remain in suspension, and settled shortly afterwards.

The excellent stability of the sensor is again evident from the full scale response in fig. 4.3 (b), which is 0.03 percent of the output frequency. The T-line proved an effective method of measuring slurry settlement, with a repetitive response even though the range of the output was limited.

The T-line's concentrated electric field distribution would be most useful in the typical mining application, of assessing the build-up of slurry at different positions at the bottom of a flotation cell. Multiple sensors could be used to monitor various positions in the tank, and correlated data used to vary the speed and duration of stirring.

4.2. ELECTROLYTE EXPERIMENTS WITH THE COPLANAR LINE

As part of a project for the remote sensing of the specific gravity of Sulphuric Acid in a Lead-acid cell, T. Christians studied the influence of solutes on the coplanar line[14]. An understanding of the effect of ionic and other solutes on the coplanar line is important in most applications, because in general liquids encountered in industry contain many different solutes which contribute to the conductivity, and permittivity of the liquid.

4.2.1. Experimental Procedure

Due to the corrosive nature of the solutes, a thick walled glass tank was used for all the experiments, with the T-line mounted vertically on a side wall, allowing only the most responsive open end of the T-line to monitor the solution. To standardise the experiment 4.8 litres of distilled water was used as a basis for each solution, which ensured that the output frequency would not fall as a result of increasing the liquid level.

4.2.2. Results of Experiment

Fig. 4.4 (a) shows the output frequency of the T-line, plotted against volume of 33 % concentrated Sulphuric acid added to the water. Fig. 4.4 (b) shows the response to the first 30 ml. of acid.

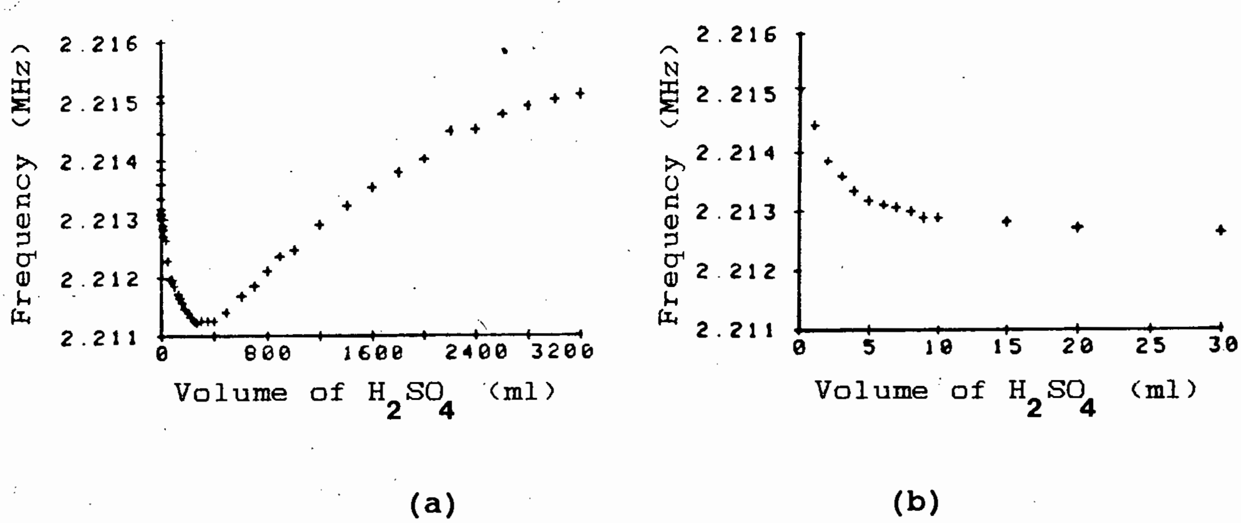
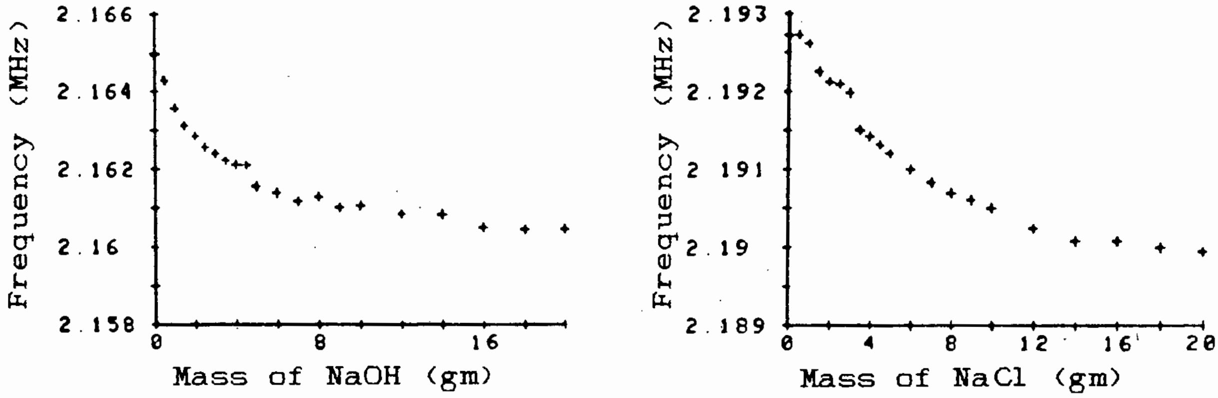


Fig. 4.4 (a) The T-line response to volume of 33 % concentrated Sulphuric acid, added to 4.8 litres of pure water. (3200 ml. corresponds to an acid concentration of 13.6 %). (b) A detailed graph of the

first 30 ml. of acid added, which corresponds to a concentration of 0.2 percent.

Although Sulphuric acid was the major consideration in this work, tests were also conducted on Sodium Hydroxide, and Sodium Chloride solutions. Fig. 4.5 shows the T-line's response to concentration of the alkali and salt respectively.



(a) (b)

Fig. 4.5 The T-line response to concentration of (a) NaOH, and (b) NaCl. Here 20 mg. corresponds to a concentration by weight of 0.4 percent. Note that 20 gm. of Sodium Hydroxide results in a greater drop in frequency than the equivalent mass of salt.

In addition to his concentration experiments, Christians ran a discharge test on a standard 100 ampere-hour cell using the T-line to monitor the acid density. Fig. 4.6 shows the results of discharging a fully charged cell at a rate of 2.5 amperes over a 65 hour period.

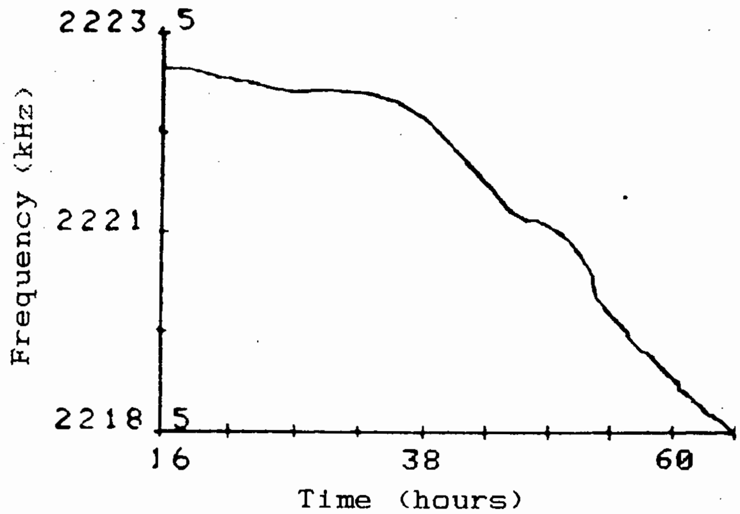


Fig. 4.6 The response of the T-line to the constant discharge of a standard 100 ampere-hour cell at a rate of 2.5 amperes. The forty hour mark indicates the useful period of the cell.

The 4.62 KHz full scale reading corresponds to a 0.2 percent range, from the cell being fully charged to totally discharged, and a corresponding specific gravity range from 1.245 to 1.080. This range was considered to be unsuitable for the T-line to be used as a remote charge detector. Certainly a means of increasing the sensitivity of the T-line would be required to make it a viable charge indicator. However its ability to detect a fall in specific gravity of 0.165 units, again indicates the impressive stability and sensitivity of the sensor.

An immediate method of increasing the sensitivity is to reduce the parallel capacitor of the T-line's oscillator circuit, from 150 pF to about 40 pF, which would increase the operating frequency, and thus the line's response to acid density. Originally the 150 pF capacitor was connected in parallel with the line to reduce its operating frequency to about 35 MHz, but a low operating frequency is not a prerequisite in this application.

4.2.3. Discussion And Analysis Of The Results

The similarities in the shape of graphs 1 (b), 2 (a), and 2 (b) indicate a common response by the coplanar line to the acid, base, and salt in solution. In each case the frequency fell with the addition of a few ppm. of the solute.

If this fall in frequency could be attributed to permittivity, it would represent a few hundred ppm., which is implausible. The loss in the line caused by the introduction of the solutes, was not sufficient to stop oscillations. The drop in frequency phenomenon must be attributed to conductivity, and in terms of the model presented in fig. 2.11, the conductivity will tend to short out C_W the liquid capacitance. The graph of fig. 4.4 (a) confirms this, as the fall and subsequent rise in frequency follows the variation in conductivity with acid concentration.

The general response of the line to the acid, base, and salt, are similar because the solutes all dissociate into ions in a solution. The equations for the dissociation of the acid, base, and salt, into ions are[5]:

Sulphuric Acid : $H_2SO_4 \rightleftharpoons H^+ + HSO_4^-$

Sodium Hydroxide : $NaOH \rightleftharpoons Na^+ + OH^-$

Sodium Chloride : $NaCl \rightleftharpoons Na^+ + Cl^-$

The fact that the conductivity of a solution is a measure of the concentration and mobility of the ions[13], is further evidence that the response to solutes is related to conductivity.

To summarise the results of Christian's experiments with electrolytes;

i. The increase in concentration caused by the dissociation of the solutes into ions, reduced the Q-factor of the line, but oscillations are maintained. This is important because the coplanar line is targeted at many industrial applications, where the pH of the solutions will vary widely.

ii. The frequency response to the introduction of solutes is attributed to the conductivity of the solution, rather than its permittivity.

CHAPTER 5

5. SOFTWARE FOR THE PROTOTYPE READOUT INTERFACE

5.1. OVERVIEW OF INSTRUMENT FUNCTION

The primary function of the instrument readout, is to gate the input frequencies from the level and temperature sensors, and to output the information on a digital display. The level and temperature frequencies are about 2 MHz and 11 kHz respectively, the latter therefore dictates the maximum gating period. In addition to the digital display, there was a requirement for an analog 4-20 mA. current output. To enable the device to be used in the laboratory, there was also a need to interface it to a host computer which would enable data logging. The parallel GPIO bus was chosen for this interface, as it has a high data transfer rate.

To extend the range of applications for this sensor, the facility for autocalibration was considered an important feature for the readout interface. This would enable on site calibration of the sensor for different liquids, and calibration could be performed at regular intervals without the need for removing the unit.

5.1.1. Description Of Software

The level frequency is read 10 times and the sum processed, which is a form of averaging that results in a more stable digital display. The temperature reading is only read once for every ten level readings, which is sufficient as the temperature will not change rapidly. To obtain an output level range which reads from zero, the minimum reading at calibration is subtracted from each reading during normal operation. The range calculated at calibration is then used to correct the maximum reading to 50 cm, the active length of the line. Thus the level output is:

$$\text{level output (cm)} = \frac{50 \times \text{count}}{\text{range}}$$

$$= \frac{100 \times \text{count}}{\text{range}} \qquad \ldots.(5.1)$$

Equation (5.1) indicates the implementation of the multiplication and division required, which is reduced to doubling the range measured at calibration, and a shift left by two BCD digits to effect a multiply by one hundred of the present count. The processing is thus reduced t a five by five-digit BCD division.

The conversion on the temperature reading which enables the output to be displayed in °C, is performed using a table lookup operation. Finally the level corrected relative to the difference between the temperature at calibration, and that at the time of taking the reading.

The software is written in five sections:

i. The main loop which handles data capture and calls the processing routines, before displaying the results.

ii. The data processing section.

iii. The calibration section.

iv. General purpose processing routines which the above sections utilise.

v. The table lookup section.

A full listing of the software is included in Appendix B for a more detailed description of the individual sections. The temperature lookup table has been shortened to the first and last few lines. Flow charts are presented in fig. 5.1 and fig. 5.2 which depict the main process, and calibration section respectively.

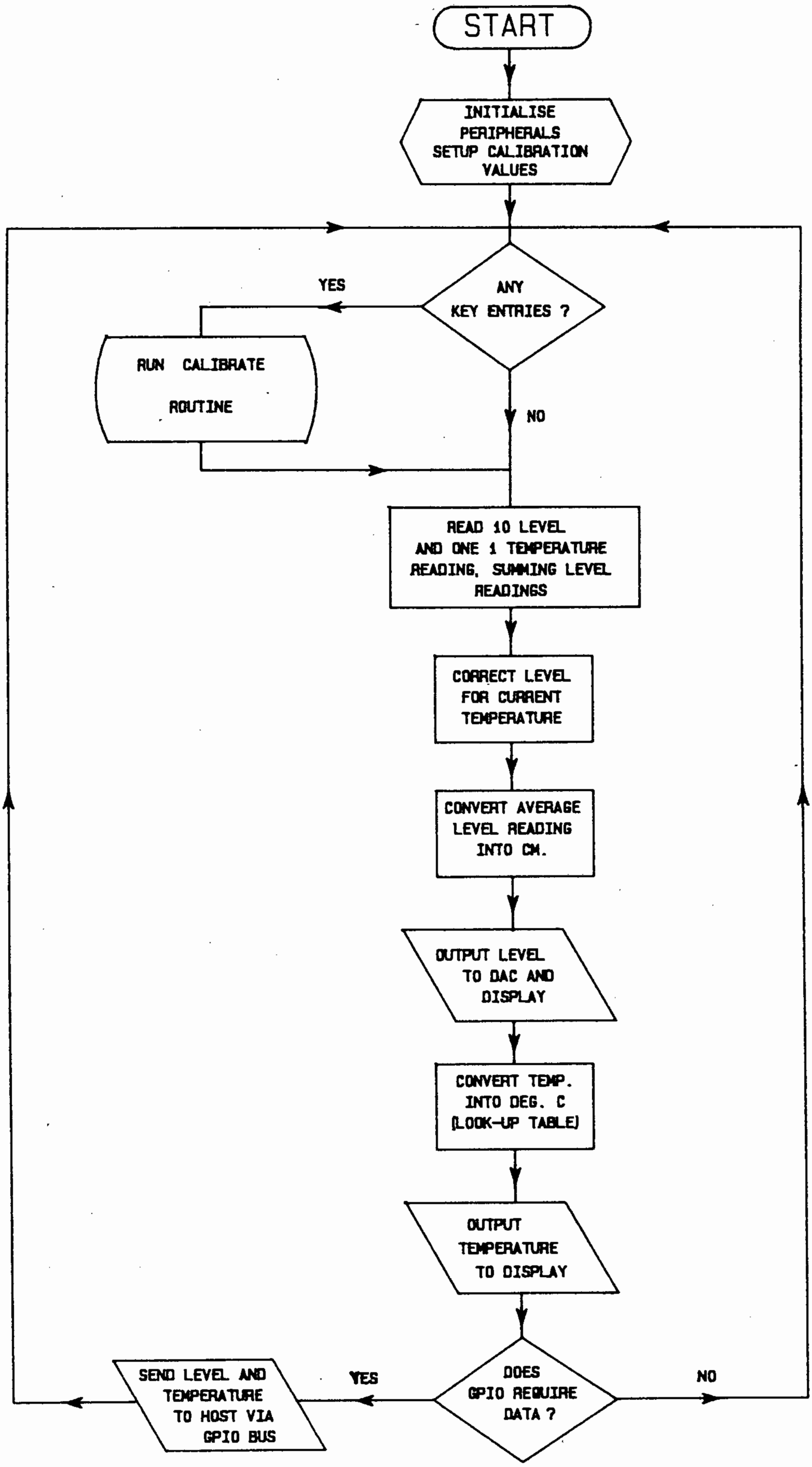


Fig. 5.1 A flow chart of the main process.

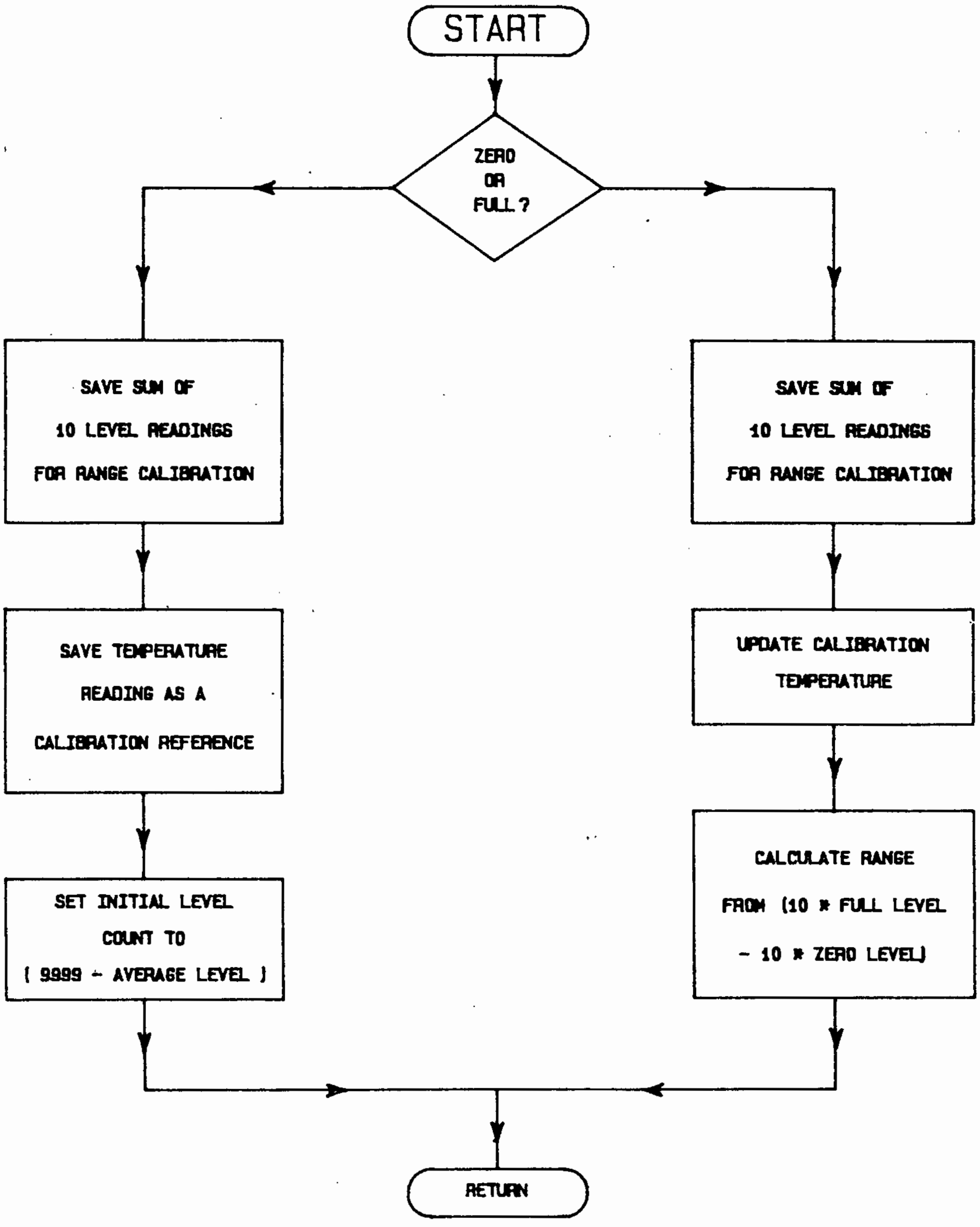


Fig. 5.2 A flow chart of the calibration routines.

CHAPTER 6

6. CONCLUSION AND RECOMMENDATIONS

6.1. CONCLUSION

The coplanar line sensor has been developed from a transmission line shorted at one end and open at the other, to a geometry with two capacitive and one inductive line. Each design tested exhibited a high mechanical and electrical stability, with Q-factors in the order of 100, and proved particularly sensitive to small changes in water content. The T-line which concentrates the electric field at its open end, was especially useful for point measurement applications.

These attractive features of coplanar line sensors, can be exploited in numerous industrial applications where the solution is predominantly water, or the liquid to be measured has a high dielectric constant. Possibly the most important feature of this type of sensor, is its non-intrusive nature. In applications where the container is conductive, the sensor is encased in a dielectric box and inserted into the liquid. Even in this form, there is no contact between the liquid and the actual coplanar line itself. ie. the liquid never penetrates this type of sensor the way it does the Cole-Chin[1] concentric transmission line gauge.

The most fundamental application of the line, is the monitoring of water level in tanks and reservoirs. The unit was also required to measure slurry levels in industrial flotation cells. To fulfil these requirements a laboratory prototype instrument has been developed, in the form of a sealed dipstick sensor. The prototype unit incorporates such features as temperature correction for water level measurement, where high precision measurement requires this feature, and automatic calibration from the line's end points, making it liquid independent. A parallel interface and a 4 to 20 mA. analog output, are provided to enable readings to be recorded on a computer and a chart recorder respectively. A minimum effort would be required to develop the unit further, into an industrial instrument with a sensor varying in length from 25 cm. to several metres. The accuracy obtained by the prototype sensor was better than 1 percent of full scale range, which can be improved by incorporating the error characteristic as a correction to the output.

Other applications of the coplanar line include; slurry foam density measurement, slurry settlement measurement, and the monitoring of evaporation. In addition the line is capable of being used in corrosive liquids when it is encased in Teflon. It is also well suited to monitoring the boundary between two liquids of extreme permittivities, such as water and Petrol.

6.2. RECOMMENDATIONS

I think that future work should follow two paths; improving the prototype sensor, and experimenting with different applications, which would undoubtedly result in new geometries for the coplanar line.

The improvements which could be made to the prototype unit include:

i. Integrating a microcontroller (such as the Intel 80C31) and its associated circuitry, onto the coplanar line. This would require careful shielding techniques such as those employed in the design of RF communications equipment, to ensure reliable operation. However the advantage gained is that no high frequency would need to be transmitted to the controlling device. An RS232 serial port or a high speed parallel port, could be used to interface directly to a computer.

ii. A digital readout could be incorporated on top of the sensor, which would alleviate the need for a readout interface unit.

iii. A redesign of the ground plane cover for the coplanar line, which would minimise the radiation behind the sensor.

New experiments for different applications should preferably be triggered by a requirement, such as Christian's remote charge detector. The coplanar line's potential for non-intrusive measurement, will favour its use in many industrial processes. Its sensitivity and the ease of its production, also offer a definite price-performance advantage over other level sensors.

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APPENDIX A

A. ANALYSIS OF A COPLANAR LINE ON A DIELECTRIC SUBSTRATE

Two different approaches to the analysis of coplanar lines on a substrate are discussed, Wen's conformal mapping technique and various numerical methods.

A.1 WEN'S CONFORMAL MAPPING TECHNIQUE

Wen's approximation for a coplanar transmission line was to assume that the dielectric substrate is infinitely thick[7]. This assumption allows the coplanar line in the Z-plane to be mapped onto a rectangle in the W-plane.

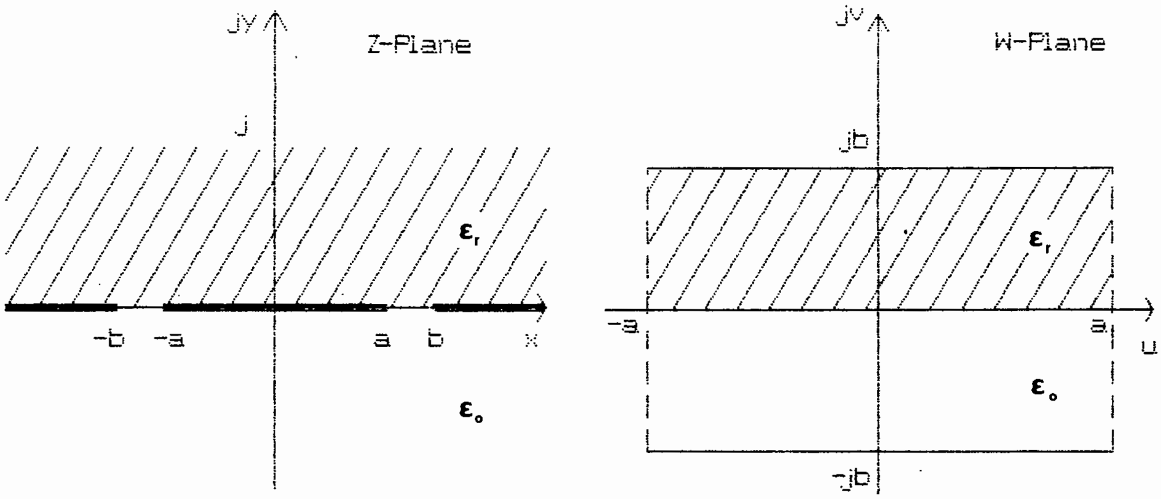

Fig. A.1 Wen's conformal mapping of a coplanar line with an infinitely thick substrate, in the Z-plane to a rectangle in the W-plane.

Wen's equation describing this conformal map is[7]:

$$\frac{dW}{dZ} = \frac{A}{\sqrt{(Z^2 - a^2).(Z^2 - b^2)}} \qquad \text{....(A.1)}$$

where A is a constant. From the rectangles in the W-plane, Wen produced an expression for the capacitance per unit length.

$$C = (\epsilon_r + 1)\epsilon_0 \cdot \frac{2a}{b} \qquad \text{....(A.2)}$$

He also employed a zeroth-order quasi-static approximation to estimate the velocity and characteristic impedance of a coplanar line. This approximation assumes the line to be totally immersed in a dielectric, with an effective dielectric constant of $\frac{1}{2}(\epsilon_r+1)$. From equation (1.1) the velocity is given by;

$$v = \frac{c_0}{\sqrt{\frac{1}{2}(\epsilon_r + 1)}} \qquad ....(A.3)$$

where c_0 is the free space velocity of electromagnetic waves. The characteristic impedance is given by;

$$Z_0 = \frac{1}{C.v} \qquad ....(A.4)$$

In 1973 M.E.Davis et al[8] modified Wen's approach by including the dielectric substrate boundary into the conformal map.

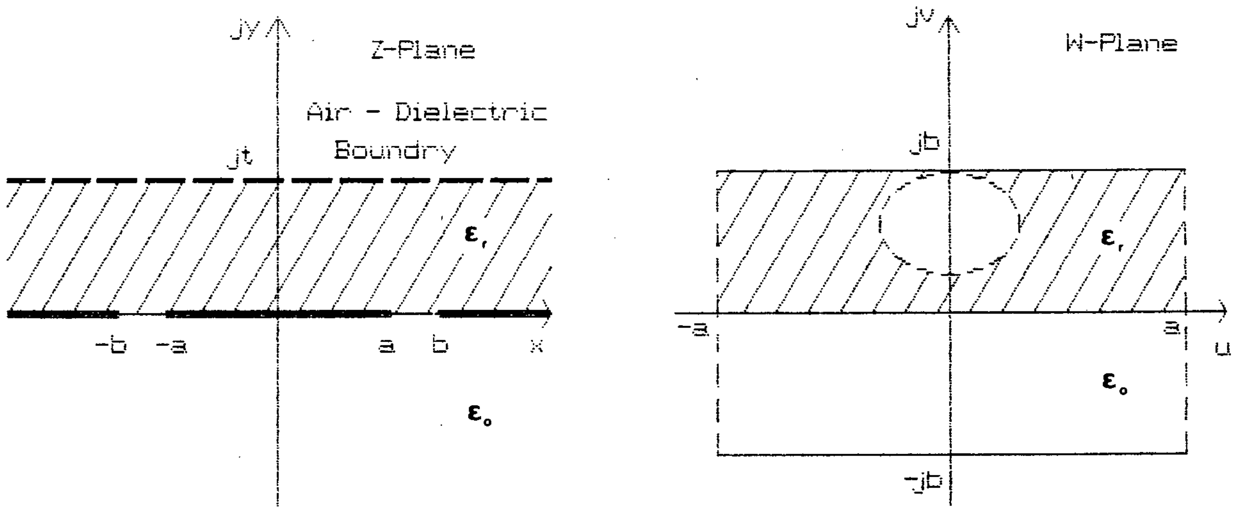

Fig. A.2 Conformal mapping of a finite thickness substrate coplanar line in the Z-plane into the W-plane.

The air/dielectric boundary in the Z-plane is mapped into an ellipse in the W-plane, the size of which is a function of the dielectric thickness, and shape ratio (a^2/b^2).

A.2 METHODS OF NUMERICAL ANALYSIS FOR THE COPLANAR LINE

The finite difference method of numerical analysis is widely used to calculate the field components, and wave impedance of coplanar lines. A nodal mesh of points is used to represent the line and its surrounding region, and a differential equation solved at each node in terms of its adjacent nodes. Repeated iteration over each point in the region converges to a stable solution. This method is accurate but requires considerable computer time.

J.B. Knorr et al[3] obtained the characteristic impedance and dispersion characteristics of coplanar lines, by applying a Fourier transform technique, and evaluating the resulting expressions numerically using the method of moments. His analysis was carried out for gap widths both larger and smaller than the thickness of the dielectric substrate.

T. Hatsuda[6] used the coplanar line's boundary conditions, to solve Laplace's equation using the relaxation method. For the line shown in fig. A.4, he found that the velocity ratio (v/c_0) and the characteristic impedance asymptotically approach constant values, when the ratio $b/(\frac{1}{2}w+a)$ is greater than one.

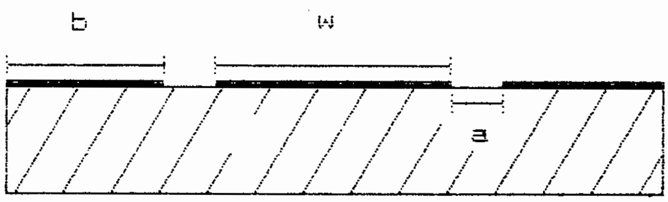

Fig. A.4 T. Hatsuda[6] found the ratio $b/(\frac{1}{2}w+a)$ to be significant when analysing a coplanar line.

A finite element approach was used by A.C. Celestini[4] in an attempt to achieve the same accuracy as the finite difference method, but with reduced computational time. He divided the line and surrounding region into triangular elements, and performed a polynomial approximation of the function in each triangle. The overall solution was the composite of the solutions of each triangular element, found by solving their individual boundary conditions. From this a field map of equipotential and flux lines was constructed. The resulting curvilinear squares represent a number of parallel (n_p) and series (n_s) field cells of depth (t). Celestini produced the following equation for the characteristic impedance of a coplanar line[4].

$$Z_0 = \frac{n_s}{n_p} \cdot \sqrt{\frac{\mu}{\epsilon}} \qquad \text{....(A.5)}$$

where (ϵ) is the permittivity, and (μ) the permeability of the medium. Celestini's results from the finite element field map approach, agree favourably with the modified Wen's approach for dielectric thicknesses greater than or equal to the gap width. They also confirm that Wen's approximation of an infinitely thick dielectric, is valid for dielectric thicknesses more than three times the gap width. This method is however not as accurate as the modified Wen's method.

APPENDIX B

```
;*************************************************************************
;    PROGRAM  COPLANE
;
;    This program handles all the data capture for the Coplanar Level
;    Instrument. It consists of a Calibration section, a Data Capture
;    section and a Data Processing section which incorporates the output.
;
;*************************************************************************

;    The Equates:
;    ------------

STACKS    EQU  27FFH          ;Stack pinter address in memory
BEGIN     EQU  ØØØØH

;    DAC address
;    -----------

DAC  EQU  ØAØH       ;DAC address

;    Equates for 8254 Counter Timer
;    ------------------------------

TIMER     EQU  Ø4ØH       ;The 8254 address
CTRL1     EQU  Ø79H       ;Control word for temp counter (1)
CTRL2     EQU  ØB9H       ;Control word for level counter (2)
CLOCK     EQU  Ø3FH       ;Control word for program clock
CLSB1     EQU  Ø61H       ;Set-up count for LSB of temp counter
CMSB1     EQU  Ø43H       ;Set-up count for MSB of temp counter
LATCH1    EQU  Ø4ØH       ;Mode Reg. control to latch temp count
LATCH2    EQU  Ø8ØH       ;Mode Reg. control to latch level count

;    Equates for the 8279 Programable Keyboard/Display Interface
;    -----------------------------------------------------------

PKDI EQU  Ø8ØH       ;The 8279 address
KEYBRD    EQU  ØØØH       ;Keyboard display mode select
WRITE     EQU  Ø9ØH       ;Write display RAM select
CLEAR     EQU  ØDFH       ;Clears the display
FIFO EQU  Ø4ØH       ;Sets up FIFO RAM for a read
ENTRY     EQU  ØØ7H       ;Mask for No. of characters in FIFO
READD     EQU  Ø5ØH       ;Control wd. to set-up PKDI for a read-keyboard

;    Equates for the 8255 Programable Peripheral Interface
;    -----------------------------------------------------

PPI  EQU  Ø6ØH       ;The 8279 address
PORTA1    EQU  ØA8H       ;Mode 1,port A output,port C input select
PC4  EQU  Ø1ØH       ;Mask for port C control input from GPIO
PC5  EQU  Ø2ØH       ;Mask for GPIO request data control line
ACK  EQU  Ø4ØH       ;Mask for Acknowledge from GPIO

;    Time equates for the Delay routine
;    ----------------------------------

T1   EQU  Ø8ØØH           ;Delay period for level counter
T2   EQU  88ØØH           ;Additional delay period for temp counter
```

```
T3    EQU   Ø8ØØH

;     General equates of Masks and Numbers
;     ------------------------------------

LSN   EQU   ØØFH
MSN   EQU   ØFØH
MSBIT       EQU   Ø8ØH
MAXH  EQU   ØFFH
MAXD  EQU   Ø99H
LMAX  EQU   Ø7ØH
BLNK  EQU   ØFFH
DPOINT      EQU   ØF7H

ZERO  EQU   Ø
ONE   EQU   1
TWO   EQU   2
THREE       EQU   3
FOUR  EQU   4
FIVE  EQU   5
SIX   EQU   6
SEVEN       EQU   7
EIGHT       EQU   8
NINE  EQU   9
TEN   EQU   1Ø
FIFTY       EQU   Ø5ØH
TWENTY      EQU   Ø2ØH
ZROLEV      EQU   ØØØØH
FSLEV       EQU   5ØØØH

;     Reserved space for variables in RAM.

      ORG   2ØØØH
RANGE:      DS    4
TCAL:       DS    4
TCALIM: DS        4
TCNTIM:     DS    4
TMINUS:     DS    4
TCOUNT: DS        4
FSCAL:      DS    4
ZCOUNT:     DS    4
ZROCAL:     DS    4
COUNT:      DS    4
ANS: DS     4
LSTCNT:     DS    4
DACMEM:     DS    4
```

```
;*************************************************************************
;
;                         **************************************
;                         *                                    *
;                         *  THE DATA CAPTURE & DISPLAY SECTION *
;                         *                                    *
;                         **************************************
;
;
;*************************************************************************
;
;       NAME:  MAIN
;
;       DESCRIPTION:  This is the routine which controlls the operation
;                     of the instrument readout interface. It tests for
;                     inputs from the calibration buttons, and handles
;                     the data capture and subsequent processing through
;                     to final output.
;
;
;*************************************************************************

        ORG     BEGIN

MAIN:   LXI     SP,STACKS               ;Set stack pointer
        DI                              ;Dissable Interrupts
        CALL    MINIT                   ;Set up default values of variables
        CALL    SETUP                   ;Initialise peripherals

LOOP:   IN      PKDI+1                  ;Test for key entry
        ANI     ENTRY
        CNZ     CALIB                   ;If key entry detected execute
                                        ;calibrate routine, otherwise continue.
        LXI     H,COUNT
        LXI     D,TCOUNT
        CALL    CLM                     ;Clear [COUNT], [TCOUNT]

;       Take ten readings of level count & one of temp count.

        MVI     C,TEN                   ;Set inner loop counter to ten

ILOOP:  PUSH    B
        IN      PKDI+1
        ANI     ENTRY                   ;Test for keyboard entry
        CNZ     CALIB                   ;and service Calibrate routine
        POP     B                       ;if necessary

        MVI     A,ONE
        CMP     C
        PUSH    PSW
        CZ      READLT                  ;Gate counters to obtain level & temp
        POP     PSW                     ;counts
        CNZ     READL                   ;Gate level counter only

        IN      TIMER+2                 ;Read LSB of level counter
        MOV     E,A
        IN      TIMER+2                 ;Read MSB of level counter
        MOV     D,A
        CALL    CTEST                   ;Check if count > 7000 dec
        LXI     H,COUNT
        CALL    ADDCNT                  ;Sum readings of level count
```

```
        MVI     A,ONE
        CMP     C                       ;Read temp count once
        LXI     H,TCOUNT
        CZ      RDTEMP

        DCR     C
        JNZ     ILOOP                   ;Done when inner loop counter is zero

;       Readings are complete, now processing is done.

        CALL    LTCORR                  ;Correct level count according to
                                        ;temp count
        CALL    BCDDIV                  ;Convert level count to cm

;       Output result to DAC.

        CALL    ANALOG
        OUT     DAC

;       Now read level result from ANS and output to the display

        LXI     H,ANS
        MOV     D,M
        INX     H
        MOV     E,M
        MOV     H,D
        MOV     L,E
        CALL    DISPLY

;       Now the temp count is converted to deg. C and output to the display

        PUSH    H                       ;Save level reading
        CALL    TMPCON                  ;Convert temp count to deg. C
        MOV     D,M
        INX     H
        MOV     E,M
        CALL    TDISP
        POP     H                       ;[HL] = level reading and
                                        ;[DE] = temp reading

;       Send data to GPIO on request

        IN      PPI+2                   ;Read port C of PPI to detect GPIO req.
        ANI     PC4                     ;Mask data request control line
        CNZ     OUTPT                   ;Transmit data if required

        JMP     LOOP

;***************************************************************************
;
;       NAME:  SETUP
;
;       DESCRIPTION:  This routine initialises all peripherals on the 'THING'.
;
;       INPUT:  None
;
;       OUTPUT:  None
;
;***************************************************************************
```

```
SETUP:  MVI     A,PORTA1
        OUT     PPI+3                   ;Select Mode 1, Port A as output
        MVI     A,CTRL1
        OUT     TIMER+3                 ;Initialise counters
        MVI     A,CTRL2
        OUT     TIMER+3
        MVI     A,KEYBRD
        OUT     PKDI+1                  ;Keyboard display mode set
        MVI     A,CLOCK
        OUT     PKDI+1                  ;Initialise internal clock of PKDI
        MVI     A,WRITE
        OUT     PKDI+1                  ;Write Display RAM initialise
BLANK:  MVI     A,CLEAR
        OUT     PKDI+1                  ;Clear display
CL:     IN      PKDI+1                  ;Read FIFO status word
        ANI     MSBIT                   ;Mask the most-sig.-bit
        JNZ     CL                      ;Wait for signal from GPIB
        RET

;*****************************************************************************
;
;       NAME:  MINIT
;
;       DESCRIPTION:  Initialises default values to variables storred in
;                     memory.
;
;       INPUT:  None
;
;       OUTPUT:  None
;
;*****************************************************************************

MINIT:  LXI     H,RANGE                 ;Set [RANGE] to 81460
        MVI     M,60H
        INX     H
        MVI     M,14H
        INX     H
        MVI     M,08H

        LXI     H,TCAL                  ;Set [TCAL] to 4954 -- 22 deg C
        MVI     M,54H
        INX     H
        MVI     M,49H

        LXI     H,ZCOUNT                ;Set [ZCOUNT] to 1605
        MVI     M,05H
        INX     H
        MVI     H,16H

        RET
```

```
;*******************************************************************************
;
;       NAME:  READLT & READL
;
;       DESCRIPTION:  These routines control the level & temp counts from the
;                     8254 timer/counter. They leave the calling routine to
;                     read the counts from the counter.
;
;       INPUT:  The content of ZCOUNT must be valid.
;
;       OUTPUT:  There is no output but the counter/timer is latched ready to
;                be read.
;
;*******************************************************************************

READLT: LXI     H,ZCOUNT                ;Load DE regs with zero level count
        MOV     E,M
        INX     H
        MOV     D,M

        MVI     A,CLSB1
        OUT     TIMER+1                 ;Set LSB of temp counter
        MVI     A,CMSB1
        OUT     TIMER+1                 ;Set MSB of temp counter
        MOV     A,E
        NOP
        OUT     TIMER+2                 ;Set LSB of level counter
        MOV     A,D
        NOP
        OUT     TIMER+2                 ;Set MSB of level counter

        LXI     D,T1
        CALL    DELAY                   ;Gate duration for level counter

        MVI     A,LATCH2
        OUT     TIMER+3                 ;Latch level counter

        LXI     D,T2
        CALL    DELAY                   ;Additional gate time for temp count
        MVI     A,LATCH1
        OUT     TIMER+3                 ;Latch temp counter
        RET


READL:  LXI     H,ZCOUNT                ;Load DE regs with zero level count
        MOV     E,M
        INX     H
        MOV     D,M

        MOV     A,E
        OUT     TIMER+2                 ;Set LSB of level counter
        MOV     A,D
        OUT     TIMER+2                 ;Set MSB of level counter

        LXI     D,T1
        CALL    DELAY                   ;Gate duration for level counter

        MVI     A,LATCH2
        OUT     TIMER+3                 ;Latch level counter
```

```
        RET

;***************************************************************************
;
;       NAME:  RDTEMP
;
;       DESCRIPTION:  Reads temp count and multiplies it by five.
;
;       INPUT:  The HL regs must contain the correct address.
;
;       OUTPUT:  The result is contained in memory
;
;***************************************************************************

RDTEMP: IN      TIMER+1                 ;Read LSB temp count
        MOV     E,A
        IN      TIMER+1                 ;Read MSB temp count
        MOV     D,A
        PUSH    H
        CALL    ADDCNT                  ;Save 5 * temp count
        POP     H
        PUSH    H
        CALL    ADDCNT
        POP     H
        PUSH    H
        CALL    ADDCNT
        POP     H
        PUSH    H
        CALL    ADDCNT
        POP     H
        PUSH    H
        CALL    ADDCNT
        POP     H
        RET

;***************************************************************************
;
;       NAME:  DISPLY
;
;       DESCRIPTION:  This routine outputs the BCD converted readings to the
;                     temp and level displays. DISPLY is called to output
;                     readings to the temp display digits, and DISP outputs
;                     to the level display digits.
;
;       INPUT:  DE regs contain the reading to be output.
;
;       OUTPUT:  The contents of the DE regs are output to the display
;
;***************************************************************************

DISPLY: MVI     A,WRITE
        OUT     PKDI+1                  ;Set up display RAM
LDISP:  MOV     A,D
        CALL    MSNIBB
        ANI     LSN
        JNZ     LD1
        MVI     A,BLNK
        JMP     LD2
LD1:    CALL    CONVRT                  ;Convert MSN to 7-segment display digit
LD2:    OUT     PKDI                    ;Output converted MSB to display
```

```
        MOV     A,D
        ANI     LSN
        CALL    CONVRT                  ;Convert next nibble to 7-segment
        ANI     DPOINT                  ;display digit with decimal point
        OUT     PKDI                    ;and output it to display
        MOV     A,E
        CALL    MSNIBB
        CALL    CONVRT                  ;Convert third nibble
        OUT     PKDI                    ;and output it to the display
        MOV     A,E
        ANI     LSN
        CALL    CONVRT                  ;Convert LSN
        OUT     PKDI                    ;and output it to the display
        RET

TDISP:  MOV     A,D
        MVI     A,BLNK
        OUT     PKDI                    ;Output converted MSB to display
        MOV     A,D
        ANI     LSN
        JNZ     TD1
        MVI     A,BLNK
        JMP     TD2
TD1:    CALL    CONVRT                  ;Convert next nibble to 7-segment
                                        ;display digit
TD2:    OUT     PKDI                    ;and output it to display
        MOV     A,E
        CALL    MSNIBB
        CALL    CONVRT                  ;Convert third nibble
        ANI     DPOINT
        OUT     PKDI                    ;and output it to the display
        MOV     A,E
        ANI     LSN
        CALL    CONVRT                  ;Convert LSN
        OUT     PKDI                    ;and output it to the display
        RET

;       Convert the BCD digits to seven-segment display format.

CONVRT: PUSH    D                       ;Save the DE & HL reg pairs
        PUSH    H
        LXI     H,TABLE1
        MOV     E,A
        MVI     D,ZERO
        DAD     D
        MOV     A,M                     ;Use lookup table to convert the BCD
        CMA                             ;digit to seven segment display format.
        POP     H                       ;Restore the DE & HL reg pairs
        POP     D
        RET
```

```
BCDDIV: LXI     H,ANS                   ;Initialise [ANS],[ANS+1] to Ø
        MVI     M,ZERO
        INX     H
        MVI     M,ZERO
        LXI     H,COUNT
        CALL    TIMS1Ø                  ;Multiply [COUNT] by 1Ø

        MVI     C,FIVE                  ;Set digit counter (M) to five
DDIV:   MVI     B,ZERO                  ;Set loop counter (N) to zero
DFLAG1: INR     B                       ;N = N+1
        PUSH    B
        CALL    DATSTO                  ;Save count(N-1) * 1Ø at LSTCNT
        LXI     H,RANGE
        LXI     D,COUNT
        CALL    SUBBCD                  ;Count(N) = Count(N-1)-[RANGE]
        POP     B
        JC      DFLAG1                  ;If Count(N) > or = Ø, goto DFLAG1
        CALL    ANSSTO                  ;Result(M) = N-1
        DCR     C                       ;M = M-1
        RZ
        LXI     H,LSTCNT
        LXI     D,COUNT                 ;Count(Ø) = Count(N-1) * 1Ø
        CALL    COPY
        JMP     DDIV

;       Stores Count(N-1) * 1Ø at location LSTCNT in memory. The result is only
;       valid when Count(N-1) < [RANGE]

DATSTO: LXI     D,LSTCNT
        LXI     H,COUNT
        CALL    COPY                    ;Copy [COUNT] to [LSTCNT]
        LXI     H,LSTCNT                ;Then [LSTCNT]*1Ø

TIMS1Ø: MOV     A,M
        CALL    LSNIBB                  ;(C2C1) --- (C1 Ø)
        MOV     C,M
        MOV     M,A                     ;Store (C1 Ø) in memory
        MOV     A,C
        CALL    MSNIBB                  ;(C2C1) --- (Ø C2)
        MOV     C,A
        INX     H
        MOV     A,M
        CALL    LSNIBB                  ;(C4C3) --- (C3 Ø)
        ADD     C                       ;(C3 Ø) + (Ø C2)
        MOV     C,A
        MOV     A,M
        MOV     M,C                     ;Store (C3C2) in memory
        CALL    MSNIBB                  ;(C4C3) --- (Ø C4)
        MOV     C,A
        INX     H
        MOV     A,M
        CALL    LSNIBB                  ;(Ø C5) --- (C5 Ø)
        ADD     C                       ;(C5 Ø) + (Ø C4)
        MOV     M,A                     ;Store (C5C4) in memory
        RET
```

```
;**************************************************************************
;
;       NAME:  OUTPT
;
;       DESCRIPTION:  This routine tests for a data request from the GPIO
;                     intreface device. Data is transmitted via the PPI when
;                     requested.
;
;       INPUT:  [HL] = level reading, & [DE] = temp reading
;
;       OUTPUT:  The output is to the GPIO interface via the PPI.
;
;**************************************************************************

OUTPT:  IN      PPI+2                   ;Read Port C of PPI
        ANI     PC5                     ;and mask Req. Data input
        JZ      OUT1                    ;If Req. Data is Low then output
        MOV     E,L                     ;temp reading, otherwise store level
        MOV     D,H                     ;reading in DE regs
OUT1:   PUSH    D
        LXI     D,T3
        CALL    DELAY                   ;Wait for host
        POP     D
        MOV     A,E
        CALL    SEND                    ;Output LSB of reading to host
        MOV     A,D
        CALL    SEND                    ;Output MSB of reading to host
        RET

SEND:   OUT     PPI                     ;Send byte to Port A of PPI
        PUSH    D
        LXI     D,T3
        CALL    DELAY                   ;Wait for transmission time
        POP     D
FLG1:   IN      PPI+2                   ;Raed Port C input acknowledge
        ANI     ACK                     ;Mask the ACK bit
        JNZ     FLG1                    ;Wait for the acknowledge
        RET

;**************************************************************************
;
;                       *********************************
;                       *                               *
;                       *  THE DATA PROCESSING SECTION  *
;                       *                               *
;                       *********************************
;
;**************************************************************************
;
;       NAME:  BCDDIV
;
;       DESCRIPTION:  This routine reads a 5 digit count which it divides by
;                     twice the range measured by the calibration routine.
;
;       INPUT:  5 digit BCD count located at COUNT (C2C1 C4C3 Ø C5) in memory.
;               2 * the calibration range is storred at RANGE in memory.
;
;       OUTPUT:  The location ANS contains the output.
;**************************************************************************
```

```
;***********************************************************************
;
;       NAME:  ANSSTO
;
;       DESCRIPTION:  This routine stores the result (N) of each stage
;                     of the long division routine BCDDIV, at location
;                     ANS in memory.
;
;       INPUT:  The result of the long division stage (N) in the B reg.
;               The digit counter (M) in the C reg.
;
;       OUTPUT:  The result of the long division routine at address ANS
;                ANS contains (A5A4 A3A2) + 1 if A1 > 4.
;
;***********************************************************************

ANSSTO: DCR     B                       ;N = N-1
        MOV     A,C                     ;Recall M
        CPI     FIVE
        JZ      A5                      ;If M=5 goto A5
        CPI     FOUR
        JZ      A4                      ;If M=4 goto A4
        CPI     THREE
        JZ      A3                      ;If M=3 goto A3
        CPI     TWO
        JZ      A2                      ;If M=2 goto A2

A1:     MOV     A,B
        SUI     FIVE
        RM                              ;Done if (N-1) < Ø
        LXI     H,ANS+1                 ;If N > or = 5 then
        MOV     A,M
        ADI     ONE                     ;[ANS+1] = [ANS+1] + 1
        DAA
        MOV     M,A
        RNC                             ;Done if no overflow
        DCX     H                       ;Address ANS
        MVI     A,ZERO
        ADC     M                       ;[ANS] = [ANS] + 1
        DAA
        MOV     M,A
        RET

A2:     LXI     H,ANS+1                 ;Address ANS + 1
        MOV     A,B                     ;Recall N
        ADD     M
        MOV     M,A                     ;[ANS+1] = [ANS+1]+N
        RET

A3:     LXI     H,ANS+1                 ;Address ANS+1
        MOV     A,B
        CALL    LSNIBB                  ;(Ø N) --- (N Ø)
        MOV     M,A                     ;Save in memmory (N Ø)
        RET

A4:     LXI     H,ANS                   ;Address ANS
        MOV     A,B
        ADD     M
        MOV     M,A                     ;[ANS] = [ANS] + N
        RET
```

```
A5:     LXI     H,ANS                       ;Address ANS
        MOV     A,B
        CALL    LSNIBB                      ;(Ø N) --- (N Ø)
        MOV     M,A                         ;Save in memmory (N Ø)
        RET


;*****************************************************************************
;
;       NAME:  LTCORR
;
;       DESCRIPTION:  The difference between TCOUNT & TCAL is determined and
;                     a table look-up used to correct the level count.
;
;       INPUT:  Routine uses info. storred at addresses TCOUNT & TCAL
;
;       OUTPUT:  The level count is adjusted at address COUNT
;
;*****************************************************************************

LTCORR: LXI     H,TCOUNT
        LXI     D,TCNTIM
        CALL    COPY                        ;Copy [TCOUNT] to [TCNTIM]
        LXI     D,TCNTIM
        LXI     H,TCAL
        CALL    SUBBCD                      ;[TCOUNT] - [TCAL]
        JNC     NEGAT                       ;If negative goto NEGAT
        LXI     H,TCNTIM
        CALL    TLOOK                       ;Look up level count correction

ADDTL:  LXI     H,COUNT
        MOV     A,E
        ADD     M                           ;(L2L1) + [TCORR]
        DAA
        MOV     M,A
        INX     H
        MOV     A,D
        ADC     M                           ;(L4L3) = (L4L3) + CY
        DAA
        MOV     M,A
        RNC                                 ;Done if no overflow
        INX     H
        MVI     A,ZERO
        ADC     M                           ;(Ø L5) = (Ø L5) + CY
        DAA
        MOV     M,A
        RET

NEGAT:  LXI     H,TCAL
        LXI     D,TCALIM
        CALL    COPY                        ;Copy [TCAL] TO [TCALIM]
        LXI     H,TCOUNT
        LXI     D,TCNTIM
        CALL    COPY
        LXI     D,TCALIM
        LXI     H,TCNTIM
        CALL    SUBBCD                      ;[TCAL] - [TCOUNT]
        LXI     H,TCALIM
        CALL    TLOOK                       ;Look up level count correction
```

```
SUBT:   LXI     H,COUNT+1
        MVI     A,TWENTY
        CMP     M
        RNC
        LXI     H,TMINUS                ;The correction is storred at
        MOV     M,E                     ;location TMINUS,
        INX     H
        MOV     M,D
        INX     H
        MVI     M,ZERO
        DCX     H
        DCX     H
        LXI     D,COUNT
        CALL    SUBBCD                  ;then subtracted from [COUNT]
        RET

TLOOK:  MOV     E,M
        INX     H
        MOV     D,M                     ;[DE regs] = (T4T3 T2T1)
        MVI     A,FIFTY
        ADD     E
        DAA
        MVI     A,ZERO
        ADC     D
        DAA
        MOV     E,A
        CALL    MSNIBB                  ;(T4T3) --- (Ø T4)
        MVI     B,ZERO
        MOV     C,A
        LXI     H,DHEX1
        DAD     B                       ;Position pointer at DHEX1+T4
        MOV     C,M                     ;Recall hex for T4 Ø decimal
        MOV     A,E
        ANI     LSN
        ADD     C                       ;Form hex for T4T3 decimal
        MOV     E,A                     ;and store in E reg.
        MVI     D,ZERO
        LXI     H,TCORR
        DAD     D                       ;Add 2*(T4T3) to address TCORR
        DAD     D
        MOV     D,M                     ;Read level correction into DE regs
        INX     H
        MOV     E,M
        RET
;***************************************************************************
;
;       NAME:  TMPCON
;
;       DESCRIPTION:  Reads in temp count which is 5*count(t) and performs
;                     the operation NINT(T4T3T2T1/1Ø). As TCOUNT contains
;                     5*count(t), & this routine divides by 1Ø, it is
;                     equivalent to count(t)/2.
;
;       INPUT:  TCOUNT address in memory must contain 5*count(t).
;
;       OUTPUT:  The routine retrns to the calling routine with the
;                pointer at the correct place in the temp look-up table.
;
;***************************************************************************
```

```
TMPCON: LXI     H,TCOUNT                  ;TCOUNT contains (T2T1 T4T3)
        CALL    DIVTEN                    ;(T2T1 T4T3) --- (T3T2 Ø T4)

;       The contents of DE are now converted to hex and then added to the
;       Temp lookup conversion table.


        MOV     A,E
        CALL    MSNIBB                    ;(T3T2) --- (Ø T3)
        MVI     B,ZERO
        MOV     C,A
        LXI     H,DHEX1
        DAD     B                         ;Position pointer at DHEX1+T3
        MOV     C,M                       ;Recall hex for T3 Ø decimal
        MOV     A,E
        ANI     LSN
        ADD     C                         ;Form hex for T3T2 decimal
        MOV     E,A                       ;and store in E reg.
        MVI     B,ZERO
        MOV     C,D                       ;(Ø T4) into C reg.
        LXI     H,DHEX2
        DAD     B
        DAD     B                         ;Look-up hex for Ø T4 decimal
        MOV     D,M                       ;MSB into the Dreg.
        INX     H
        MOV     A,M
        ADD     E                         ;Add LSB to hex for T3T2 dec.
        MOV     E,A
        JNC     LOOKUP
        INR     D                         ;If overflow from LSB then MSB+1

LOOKUP: LXI     H,TABLET
        DAD     D                         ;TABLET+HEX(ØT4 T3T2)
        DAD     D
        RET
```

```
;***********************************************************************
;
;                          *******************************
;                          *                             *
;                          *    THE CALIBRATION SECTION  *
;                          *                             *
;                          *******************************
;
;***********************************************************************
;
;       NAME:  CALIB
;
;       DESCRIPTION:  Execution is passed to this routine if either (i) ZERO
;                     CALIBRATE or (ii) FULL SCALE CALIBRATE buttons are
;                     pressed. CAL is displayed while the routine is running.
;                     The routine stores the calibration values and uses RNGCAL
;                     to calculate the full scale range of the readings.
;                     CAL is displayed whilst the calibrate routine is in use.
;
;       INPUT:  There is no input to the calibrate routine.
;
;       OUTPUT:  On (i) 10 level and 1 successive temp readings are summed at
;                ZROCAL & TCAL resp., and the mean level reading storred at
;                ZCOUNT. On (ii) 10 level & 1 temp readings are summed at
;                FSCAL & TCAL respectivly. RNGCAL stores twice the difference
;                between FSCAL & ZROCAL at the address RANGE.
;
;***********************************************************************

CALIB:  CALL    BLANK                   ;Blank the display
        MVI     A,WRITE
        OUT     PKDI+1                  ;Set up display for a write
        LXI     H,CAL
        MOV     A,M
        CMA
        OUT     PKDI                    ;Write C to 1st digit
        INX     H
        MOV     A,M
        CMA
        OUT     PKDI                    ;Write A to 2nd digit
        INX     H
        MOV     A,M
        CMA
        OUT     PKDI                    ;Write L to 3rd digit

        MVI     A,READD
        OUT     PKDI+1                  ;Set PDKI up for a read
        IN      PKDI                    ;Read key entry
        ANI     ENTRY
        CPI     ONE
        JNZ     FCAL                    ;Service appropriate routine


ZCAL:   MVI     A,WRITE+4
        OUT     PKDI+1
        LXI     D,ZROLEV
        CALL    LDISP
        LXI     H,ZCOUNT                ;Set [ZCOUNT] to 9999
        MVI     M,MAXD
        INX     H
```

```
        MVI     M,MAXD

        LXI     H,ZROCAL
        LXI     D,TCAL
        CALL    CLM             ;Clear [ZROCAL] & [TCAL]
        MVI     C,TEN           ;Set loop counter to ten
ZCAL1:
        MVI     A,ONE           ;Take the readings
        CMP     C
        PUSH    PSW
        CZ      READLT
        POP     PSW
        CNZ     READL

        IN      TIMER+2         ;Read LSB of level count
        MOV     E,A
        IN      TIMER+2         ;Read MSB of level count
        MOV     D,A

        LXI     H,ZROCAL
        CALL    ADDCNT          ;Add the level count to [ZROCAL]

        MVI     A,ONE
        CMP     C
        LXI     H,TCAL
        CZ      RDTEMP          ;Read temp if loop counter < one

        DCR     C
        JNZ     ZCAL1           ;Repeat loop for ten level readings

        LXI     H,ZROCAL
        CALL    DIVTEN          ;Determine Mean level reading and
        LXI     H,ZCOUNT        ;subtract it from 9999, then store
        MVI     A,MAXD          ;it at ZCOUNT
        SUB     E
        MOV     M,A
        INX     H
        MVI     A,MAXD
        SUB     D
        MOV     M,A
        RET

FCAL:   MVI     A,WRITE+4
        OUT     PKDI+1
        LXI     D,FSLEV
        CALL    LDISP
        LXI     H,RANGE
        LXI     D,TCAL
        CALL    CLM             ;Clear [RANGE] & [TCAL]
        MVI     C,TEN           ;Set loop counter to ten
FCAL1:
        MVI     A,ONE           ;Take the readings
        CMP     C
        PUSH    PSW
        CZ      READLT
        POP     PSW
        CNZ     READL

        IN      TIMER+2         ;Read LSB of level count
        MOV     E,A
```

```
        IN      TIMER+2                 ;Read MSB of level count
        MOV     D,A

        LXI     H,RANGE
        CALL    ADDCNT                  ;Add the level count to [RANGE]

        MVI     A,ONE
        CMP     C
        LXI     H,TCAL
        CZ      RDTEMP                  ;Read temp if loop counter < one

        DCR     C
        JNZ     FCAL1                   ;Repeat loop for ten level readings

RNGCAL: LXI     H,RANGE
DOUBLE: MOV     A,M                     ;Double the range and store it
        ADD     M
        DAA
        MOV     M,A
        INX     H
        MOV     A,M
        ADC     M
        DAA
        MOV     M,A
        INX     H
        MOV     A,M
        ADC     M
        DAA
        MOV     M,A
        RET

ANALOG: LXI     H,DACMEM        ;Clear DACMEM
        XRA     A
        MOV     M,A
        INX     H
        MOV     M,A
        INX     H
        MOV     M,A

        LXI     H,ANS
        MOV     E,M
        INX     H
        MOV     D,M             ;DE = level in cms.
        LXI     H,DACMEM
        CALL    ADDCNT
        LXI     H,DACMEM
        CALL    ADDCNT
        LXI     H,DACMEM
        CALL    ADDCNT
        LXI     H,DACMEM
        CALL    ADDCNT
        LXI     H,DACMEM
        CALL    ADDCNT          ;level in cm. * 5

        LXI     H,DACMEM+1
        MOV     E,M
        INX     H
        MOV     D,M             ;DE = [DACMEM] = D4D3 D2D1
        MOV     A,E
        CALL    MSNIBB
```

```
        MOV     C,A             ;C = (Ø D2)
        MVI     B,ZERO
        LXI     H,DHEX1
        DAD     B               ;look-up hex for (D2 Ø)
        MOV     C,M
        MOV     A,E
        ANI     LSN             ;(Ø D1)
        ADD     C
        MOV     E,A             ;E = (Ø D1) + HEX(D2 Ø)
        MOV     A,D
        ANI     LSN
        MOV     C,A             ;C = (O D3)
        MVI     B,ZERO
        LXI     H,DHEX2
        DAD     B
        DAD     B               ;Look-up HEX(Ø D3)
        INX     H
        MOV     A,M
        ADD     E               ;A = Hex(D3D2D1)
        RET

;*****************************************************************************
;
;                  ****************************************
;                  *                                      *
;                  *  GENERAL PURPOSE PROCESSING ROUTINES *
;                  *                                      *
;                  ****************************************
;
;*****************************************************************************
;
;       NAME:  DIVTEN
;
;       DESCRIPTION:  This routine reads the count (C2C1 C4C3 ØC5) from memory,
;                     and divides it by ten rounding the least significant
;                     digit before the division.
;
;       INPUT:  COUNT address in memory must be correct
;
;       OUTPUT:  The DE regs contain the count (C5C4 C3C2)
;
;*****************************************************************************

DIVTEN: MOV     A,M
        ANI     LSN                     ;(C2C1) --- (Ø C1)
        SUI     FIVE
        JM      DIV1Ø
        MOV     A,M
        ADI     FIVE                    ;(C2C1) = (C2C1)+5
        DAA
        MOV     M,A                     ;(C2C1) --- memory
        JNC     DIV1Ø
        INX     H
        MVI     A,ZERO
        ADC     M                       ;(C4C3) = (C4C3) + CY flag
        DAA
        MOV     M,A
        INX     H
        MVI     A,ZERO
```

```
        ADC     M                       ;(Ø C5) = (Ø C5) + CY flag
        DAA
        MOV     M,A
        DCX     H
        DCX     H

DIV1Ø:  MOV     A,M
        CALL    MSNIBB                  ;(C2C1) --- (Ø C2)
        MOV     E,A
        INX     H
        MOV     A,M
        CALL    LSNIBB                  ;(C4C3) --- (C3 Ø)
        ADD     E                       ;(C3 Ø)+(Ø C2) = (C3C2)
        MOV     E,A
        MOV     A,M
        CALL    MSNIBB                  ;(C4C3) --- (Ø C4)
        MOV     D,A
        INX     H
        MOV     A,M
        CALL    LSNIBB                  ;(Ø C5) --- (C5 Ø)
        ADD     D                       ;(C5 Ø)+(Ø C4) = (C5C4)
        MOV     D,A                     ;DE regs contain (C5C4 C3C2)
        RET

;*****************************************************************************
;
;       NAME:  SUBBCD
;
;       DESCRIPTION:  Subtracts two 5 digit BCD numbers at the addresses
;                     contained in the DE & HL regs.
;
;       INPUT:  The addresses of the minuend and subtrahend must be correct.
;
;       OUTPUT:  The result is restored at the DE regs address.
;
;*****************************************************************************

SUBBCD: MVI     C,THREE                 ;Set loop counter to 3
        STC                             ;Set the carry flag
SUB1:   MVI     A,MAXD
        ACI     ZERO                    ;Nine or Ten's comp. (depending on CY)
        SUB     M                       ;of byte in memory(addressed by HL)
        XCHG
        ADD     M                       ;Add byte addressed by DE regs
        DAA
        MOV     M,A                     ;Store the result in memory (DE)
        XCHG
        DCR     C                       ;Decrement loop counter
        RZ
        INX     D                       ;Increment both address pointers
        INX     H
        JMP     SUB1
```

```
;*************************************************************************
;
;       NAME:  ADDCNT
;
;       DESCRIPTION:  Adds four digit count (C1C2 C3C4) to memory
;
;       INPUT:  Count in DE regs , the memory pointer must point to the
;               correct place in memory.
;
;       OUTPUT:  The sum of the contents of the DE regs + the contents of
;                memory are storred back in memory.
;
;*************************************************************************

ADDCNT: MOV     A,E
        ADD     M                       ;(C1C2)+[memory]
        DAA                             ;Adjust result to BCD
        MOV     M,A                     ;Save result in memory
        INX     H
        MOV     A,D
        ADC     M                       ;(C4C3)+[memory]+CY
        DAA
        MOV     M,A
        INX     H
        MVI     A,ZERO                  ;(Ø Ø)+[memory]+CY
        ADC     M
        DAA
        MOV     M,A
        RET

;*************************************************************************
;
;       NAME:  CLM
;
;       DESCRIPTION:  This routine clears the contents of memory at the
;                     locations of the DE & HL regs.
;
;       INPUT:  The DE & HL regs must be correct
;
;       OUTPUT:  None
;
;*************************************************************************

CLM:    XRA     A                       ;Clear present memory locations
        MOV     M,A                             ;addressed by HL & DE regs
        STAX    D
        INX     H
        INX     D
        MOV     M,A
        STAX    D
        INX     H
        INX     D
        MOV     M,A
        STAX    D
        RET
```

```
;***************************************************************************
;
;       NAME:  COPY
;
;       DESCRIPTION:  Copies the contents of the three bytes of memory at
;                     the HL address to memory at the DE address.
;
;       INPUT:  The DE and HL addresses must be correct.
;
;       OUTPUT:  There is no output as this is a memory copy routine.
;
;***************************************************************************

COPY:   MOV     A,M                     ;Copy the contents of memory addressed
        STAX    D                       ;by HL, to that addressed by DE regs
        INX     H                       ;Increment both memory pointers
        INX     D
        MOV     A,M                     ;Copy the contents of memory addressed
        STAX    D                       ;by HL, to that addressed by DE regs
        INX     H                       ;Increment both memory pointers
        INX     D
        MOV     A,M                     ;Copy the contents of memory addressed
        STAX    D                       ;by HL, to that addressed by DE regs
        INX     H                       ;Increment both memory pointers
        INX     D
        RET

;***************************************************************************
;
;       NAME:  DELAY
;
;       DESCRIPTION:  A wait is effected by this routine by presetting the
;                     D reg.
;
;       INPUT:  D reg contains the no. of wait cycles.
;
;       OUTPUT:  None
;
;***************************************************************************

DELAY:  DCX     D
        MOV     A,D
        ORA     E
        JNZ     DELAY
        RET
;***************************************************************************
;
;       NAME:  CTEST
;
;       DESCRPITION:  CTEST checks the DE reg. pair to see if it exceeds the
;                     maximum level count 7000. This is equivalent to checking
;                     for a 0000 to 9999 transition. If the count exceeds 7000
;                     the DE reg. pair is reset to zero.
;
;       INPUT:  The count is in the DE reg. pair.
;
;       OUTPUT:  The DE reg. pair is zeroed if the contants exceed 7000,
;                otherwise unaltered.
;
;***************************************************************************
```

```
CTEST:  MOV     A,D
        CPI     LMAX                    ;Check if [D] > 7Ø
        JC      MAXTST                  ;Test for 5Ø<[D]<7Ø if [D] not > 7Ø
        LXI     D,ZROLEV                ;else zero contents of DE
        RET

MAXTST: CPI     FIFTY                   ;Check if [D] > 5Ø
        RC
        LXI     D,FSLEV
        RET

;*****************************************************************************
;
;       NAME:  MSNIBB, LSNIBB
;
;       DESCRPITION:  These routines perform right (MSNIBB) and left (LSNIBB)
;                     shifts on the MSN and LSN respectivly, after macking out
;                     the unwanted nibble.
;
;       INPUT: The A reg containes the word to be operated on.
;
;       OUTPUT:  MSN --- LSN with MSN=Ø, and LSN --- MSN with LSN=Ø respectivly
;
;*****************************************************************************

MSNIBB: ANI     MSN                     ;Byte(X1 X2) --- byte(Ø X1)
        RRC
        RRC
        RRC
        RRC
        RET

LSNIBB: ANI     LSN                     ;Byte(X1 X2) --- byte(X2 Ø)
        RLC
        RLC
        RLC
        RLC
        RET

;*****************************************************************************
;
;       This section contains the look-up tables for the temperature
;       conversion, the BCD-to-seven-segment conversion, and the
;       correction factor.
;
;*****************************************************************************

;       The bcd-to-seven segment conversion table.
;
;       The segments are labled (a) through (g)           a
;       with (.) the decimal point.                      ____
;                                                    f /_g/ b
;                                                   e /__/.c
;               dcba.gfe                                d

TABLE1: DB      111100Ø11B                      ;Seven segment Ø
        DB      Ø11ØØØØØB                       ;Seven segment 1
        DB      1Ø11Ø1Ø1B                       ;Seven segment 2
        DB      1111Ø1ØØB                       ;Seven segment 3
```

```
        DB      01100110B                       ;Seven segment 4
        DB      11010110B                       ;Seven segment 5
        DB      11010111B                       ;Seven segment 6
        DB      01110000B                       ;Seven segment 7
        DB      11110111B                       ;Seven segment 8
        DB      01110110B                       ;Seven segment 9
        DB      11000101B                       ;Seven segment a
        DB      11000111B                       ;Seven segment b
        DB      10000101B                       ;Seven segment c
        DB      11100101B                       ;Seven segment d
        DB      10010111B                       ;Seven segment E
        DB      00010111B                       ;Seven segment F

CAL:    DB      10010011B                       ;Seven segment C
        DB      01110111B                       ;Seven segment A
        DB      10000011B                       ;Seven segment L

;       The look up tables for decimal to hex conversion.

DHEX1:  DB      000H                            ;  00
        DB      00AH                            ;  10
        DB      014H                            ;  20
        DB      01EH                            ;  30
        DB      028H                            ;  40
        DB      032H                            ;  50
        DB      03CH                            ;  60
        DB      046H                            ;  70
        DB      050H                            ;  80
        DB      05AH                            ;  90


DHEX2:  DB      000H,000H                       ; 000
        DB      000H,064H                       ; 100
        DB      000H,0C8H                       ; 200
        DB      001H,02CH                       ; 300
        DB      001H,090H                       ; 400
        DB      001H,0F4H                       ; 500
        DB      002H,058H                       ; 600
        DB      002H,0BCH                       ; 700
        DB      003H,020H                       ; 800
        DB      003H,084H                       ; 900

;       The table look-up for the correction to the level readings.

TCORR:  DB      00H,00H,  00H,70H,  01H,40H,  02H,09H
        DB      02H,79H,  03H,49H,  04H,19H,  04H,88H
        DB      05H,58H,  06H,28H,  06H,98H,  07H,67H
        DB      08H,37H,  09H,07H,  09H,77H,  10H,47H
        DB      11H,16H,  11H,86H,  12H,56H,  13H,26H
        DB      13H,95H,  14H,65H,  15H,35H,  16H,05H
        DB      16H,74H,  17H,44H,  18H,14H,  18H,84H
        DB      19H,54H,  20H,23H,  20H,93H,  21H,63H
        DB      22H,33H,  23H,02H,  23H,72H,  24H,42H
        DB      25H,12H,  25H,81H,  26H,51H,  27H,21H
        DB      27H,91H,  28H,61H,  29H,30H,  30H,00H
        DB      30H,70H,  31H,40H,  32H,09H,  32H,79H
        DB      33H,49H,  34H,19H,  34H,88H,  35H,58H
        DB      36H,28H,  36H,98H,  37H,68H,  38H,37H
        DB      39H,07H,  39H,77H,  40H,47H,  41H,16H
        DB      41H,86H,  42H,56H,  43H,26H,  43H,96H
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