DEVELOPMENT OF A NOVEL ULTRASOUND MONITORING SYSTEM FOR CONTAINER FILLING OPERATIONS

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ABSTRACT

Development of a novel ultrasound monitoring system for container filling operations

Current methods for measuring the liquid level in containers are often carried out downstream of the filling operation. While these methods meet the requirements of Trading Standards Legislation, they contribute very little to improving the real-time control of the filling process. Among the measurement techniques involving the use of non-invasive sensors, ultrasound has attracted an increasing level of interest in its application in the food industry because of its inherently safe characteristics. The aim of this research was to explore the utilisation of ultrasound measurement techniques in the development of real-time fluid level monitoring system.

Most of the previous research developing fluid level measurement techniques has focused on developing ultrasound monitoring systems with sensors positioned at the base of the container for ease of operation. The objectives of the current work was to explore the potential benefits of mounting the sensors on the side and top of containers and explore the possibilities of integration of ultrasound sensors with dispensing valves to maximise the efficient use of space, particularly where ease of access is restricted.

The present research programme has sought to develop an ultrasound monitoring system for container filling in both static and dynamic operations. For these studies, a static laboratory-scale container filling system was developed and utilised. The performance characteristics of the filling system were investigated in order to enhance the response time of an ultrasound monitoring system.

The key results of this work are the utilisation of an air transmission approach to ultrasound sensing as opposed to wall resonance and far wall echo approaches requiring contact transducers. This research has shown that the distances that can be measured using air transmission under ideal/experimental conditions are within expectable tolerances. To this end research involved construction of specific piezoelectric sensors and development of novel methods of data interpretation using a threshold approach to gain time-of-flight measurements.

It has been possible to characterise the effects of filling/environmental variables on ultrasound signal in a carbonating procedure (gas, gas mixtures, temperature, and pressure). Utilising known temperature/ultrasound signal characteristics temperature effects were obviated through the design and development of specific software. An increase in carbon dioxide content caused a reduction in signal amplitude (attenuation) and an increase in the time of flight measurement responding to a change in speed of sound. Pressure had little effect on the time of flight measurement but an increase in environmental pressure increased the ultrasound signal strength.

Surface plots were designed to build signatures of the relationship between pressure, carbon dioxide content, ultrasound signal amplitude and time of flight measurement, so that they may be incorporated into a control strategy.

The actual environment of a carbonated soft drink when filling was investigated, utilising carbon dioxide and nitrogen flushing in order to purge the system of oxygen. In addition, the research investigation has indicated that the custom built equipment for air transmission analysis could define minute quantities of gas and could therefore be applied to gas analysis.

The major conclusion from the research undertaken was that the novel application of ultrasound within the carbonating environment was capable of determining fluid level changes within expected levels of accuracy.

Acknowledgements

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Nomenclature and Abbreviations

ADC - analogue to digital converter

AGC - automatic gain control

AM – amplitude modulation

BP- band pass

C - capacitance

CW - continuous wave

D - time of flight received by transducer

d - transmitting constant

D/P – differential pressure

DSP - digital signal processing

E - modulus of elasticity

emf - electromotive force

EPA - environmental protection agency

f - frequency

FFT - fast Fourier transform

FM - frequency modulation

G - modulus of rigidity

g - receiving constant

h - height

HP – high pass

Ii - intensity of incident beam

Ir - intensity of reflected beam

It - intensity of transmitted beam

k - electromechanical coupling coefficient

Ka - adiabatic volume elasticity

LCD – liquid crystal display

LP – low pass

M – molecular mass

NDT - non - destructive testing

PE - piezoelectric

pi - acoustic pressure of incident beam

PID – proportional integral differential

PLD - point level detector

ppm – parts per million

pr - acoustic pressure of reflected beam

PRF - pulse repetition frequency

PSD - power spectral density

PVDF - polyvinylidene fluoride

PZT - lead zirconate titanate

Qm - mechanical quality factor

R – gas constant

R - resistance

$r(\tau)$ - correlation function of summed lagged products

R^2 – linear correlation

RF - radio frequency

RMS – root mean square

Rp - pressure reflection coefficient

Rx – receiver

SAWS - surface acoustic wave sensors

SME - small - medium enterprise

SNR - signal to noise ratio

T - temperature

TCG - time-corrected gain

TFT – thin film transistor

TI - intensity transmission coefficient

TOF - time of flight

Tp - pressure transmission coefficient

TVG - time varying gain

Tx – transmitter

Tx/Rx - transmitter/receiver

V – volume

Vc - velocity of a longitudinal compression wave

Vpp – voltage peak to peak

Vr - velocity of Raleigh wave

Vs - velocity of shear wave

W – watts

x - distance between transducers

Z - acoustic impedance

λ - wavelength

ν - Poisson's ratio

ρ - density

Chapter 1 - Introduction

1.1 Background

Food and drink production represents the largest manufacturing sector in the UK economy, and food and drink companies are among the largest UK exporters (£8.2bn in 1995). The industry makes essential contributions to UK wealth creation and to the quality of life within the UK, and is seen to add value at each of the major stages of the supply train. Around 45,000 companies are involved in food processing and production in the UK, and 90% of these are classed as small or medium enterprises (SMEs) with less than 250 employees. Most of the SMEs possess little, if any, research facilities or research expertise.

The Government funded Technology Fore*sight* Panel on Food and Drink has focused on scientific and technological priorities, and has stressed the need for increased investment in R & D to maintain the UK in the first division of food manufacture. Emphasis has been placed on collaborative research with Government departments, with industry and academia. There is significant interest in new and innovative research in raw materials, packaging, the supply chain, retailing, safety and processing. Food processing represents a field of rapid development and implementation of new approaches in process technology, in particular, automation systems, quality procedures, efficiency improvements and sensor systems for in process monitoring and control.

Until recently, food and drink processing companies have lagged behind in the use of high technology measurement instrumentation, and most of them employ inaccurate bulk measurement techniques in virtually all areas of process control. Advances in technology and increasing customer awareness have forced manufacturers to rethink their strategies. As a result, they have embarked on the task of streamlining the production process for improved efficiency as well as quality. Technological advancement in sensor design has had an impact on the available measurement techniques for food process engineering, and research has been carried out to develop sensors aimed at establishing systems that can cope with the rapid improvements in processing technology.

Ultrasound fulfils all the criteria required for a fully automated sensor system for process monitoring and control. This thesis explores the application of ultrasound to rapid on-line fluid level measurement.

1.2 Outline of Thesis

For the purpose of this thesis, different types of level measurement have been critically assessed and the reasons for choosing ultrasound as a possible accurate tool for rapid on-line fluid level measurement of containers, (such as the filling of carbonated soft drinks) has been explained. This is discussed in the context of existing uses in industry, the food industry and fluid level measurement. Techniques using ultrasound are discussed and common problems associated with level measurement are highlighted. The introductory chapters also describe three industrial processes currently in use for container filling and level control.

Having introduced the project and discussed the situation at present in industry, the following sections of the thesis describe variables associated with the filling process and their effect on ultrasound. Different ultrasound sensing techniques governed by mechanical design considerations are presented, as is the understanding of commercially available equipment. This thesis outlines preliminary experiments that verify the use of certain techniques. An explanation is presented on the development of custom-built equipment for air-transmission type ultrasound signal processing methods. The bottling apparatus for research and associated problems of size restriction is discussed resulting in the development of a transceiver module. More detailed work on processing and the modelling of the filling environment is presented prior to modelling the carbonating environment.

Finally, experiments have been carried out to establish the accuracy and signal strength trends, so that intelligent control strategies can be married with returning echo data to assist the operation of the filling valve. All results and conclusions of experiments are discussed and recommendations are made for future development.

1.3 Aims and objectives

The overall aim of this research was to design and develop a prototype system for rapid on-line measurement of fluid dispensing levels in food containers. The research was approached in three stages:

- Exploration of ultrasound fluid level measurement techniques.
- Design and development of a bottling rig.
- Use of ultrasonic technique for fluid level measurement.

The main objectives were as follows:

1. To carry out a critical review of available methods for fluid level measurement and assess their suitability for high-speed on-line level measurement of bottle and container filling.

2. To explore the characteristics of available industrial bottling and container filling processes to enable the design and manufacture of a filling rig for experimental monitoring purposes.

3. To investigate the operation of dispensing equipment with particular attention given to the filling process and associated variables.

4. To investigate various ultrasound techniques for fluid level measurement and assess the performance of such methods of measuring fluid levels.

In order to fulfil these objectives an appreciation and understanding of the nature and principles of ultrasound and bottling techniques found in industry was required. This was accomplished by reviewing the research literature and personal communications with food manufacturers. This information is given in Chapters 2-4.

Chapter 2 - Fluid Level Measurement Techniques

As outlined in chapter 1, a major objective of this research was to assess the use of ultrasound and compare the advantages and disadvantages/limitations with alternative fluid level measurement techniques. In order to successfully utilise ultrasound in this novel application the physical characteristics of fluids will be discussed. Summaries of a variety of fluid level measurement techniques will then be described (Section 2.2) followed by an explanation of the reasoning behind the choice of ultrasound (Section 2.3).

2.1 Fluid Characteristics

The condition and motion of a fluid or gas filling a certain volume of space may be characterised by a number of scalars and vectors such as density, temperature, and flow velocity. If correctly determined, such parameters could either singly or collectively be used as a lead to process control in industries. An area that has proved intriguing to the minds of the engineer is that of liquid level control in containers.

Normally, level measurement falls under two conditions. The first is static, involving the supervision of either raw material or end product for inventory and management purposes. The second is dynamic, where *ON-OFF* control is exercised as the product moves through various stages within the process. It is the latter case that poses difficulties in control, particularly, because of the transient nature of the parameter(s) (e.g. volume, weight) being monitored.

The technologies applied to level measurement may not follow clearly defined parameters since the conditions under which such technologies are applied can vary extensively. For example, a process may require equal volumes of two types of liquids at a different temperature from each other. However, of the systems currently on the market, any one technology may be used. The spectrum consists of low range, high range, point, continuous, dynamic or static measurement methods. The level of accuracy will greatly vary.

Despite there having been no major technological breakthrough in fluid level measurement, there is a growing acceptance of methods that have been developed over the years [Shortall 1990]. Fluid level measurement techniques have been studied and their scope of application remarkably expanded. The problem of accuracy has however persisted, demanding further research into potentially superior technologies.

2.2 Level measurement methods

There are many solutions to level-measurement problems ranging from the use of a simple dipstick to radiation devices, depending on the types of materials and the methodology employed for variable measurement.

Studies have been undertaken, [Bacon, 1996], [Brown, 1990] which investigate the developing application of level measurement devices based on changes in developing technology, environmental and safety regulations and economic changes associated with installation costs and expected life cycle.

The different level-sensing techniques can be grouped into five major categories according to the primary level sensing principle: force, pressure, electric, ultrasonic and others (i.e., infrared, microwave, nuclear and thermal). In addition, sight level detection utilising glass gauge, displacer, or tape float (similar to the dipstick) can be used for visual observation. Members of the level sensing family are shown in Table 2-1[From Cho 1982]

Table 2-1 Level-sensing family

(a) Dipstick	
(b) Sight	Glass gauge, Displacer, Tape float
(c) Force	Diaphragm, Weighing, Buoyancy
(d)Pressure	Hydrostatic head, Bubbler, Differential pressure
(e) Electric	Admittance probes, Capacitance probes, Conductance sensors, Resistance sensors
(f) Ultrasonic and Sonic Detectors	Contact and Non-Contact probes
(g) Others	Infrared detectors, Microwave detectors, Nuclear-Type detectors, Thermal Type detectors

Under certain circumstances, one technique may be preferred to another, but as yet no one system has proved sufficiently versatile for use under widely different or varying situations common in the process industries. However, ultrasonic and electronic sensors offer industrial users a quick response time, a high degree of reliability, easy installation and a long service life.

The following section provides a brief overview of different fluid level measurement techniques that were considered for the application of rapid on-line measurement, also the suitability of each method for the application is highlighted.

2.2.1 Sight Type.

The sight type level measurement technique is a direct descendant of the dipstick. The dipstick is the simplest of level measurement devices, requiring physical insertion and removal of the dipstick and utilising the contact of the fluid medium to observe the level at that particular moment There are three basic sight types of level measurement: glass gauge, displacer and tape float.

2.2.1.1 Glass gauges

Level gauges for visual tank level observations are very common in the process industry. Direct reading of liquid levels with glass gauges have been used widely for many years for pressure vessels, boiler drum levels and tanks. There are two different types of sight glass gauges for liquid level measurement these are tubular and flat glass gauges.

A tubular level gauge (Figure 2.1) can be considered as a manometer that provides local level reading as accurate as the calibration scale and visibility of liquid height in the tube.

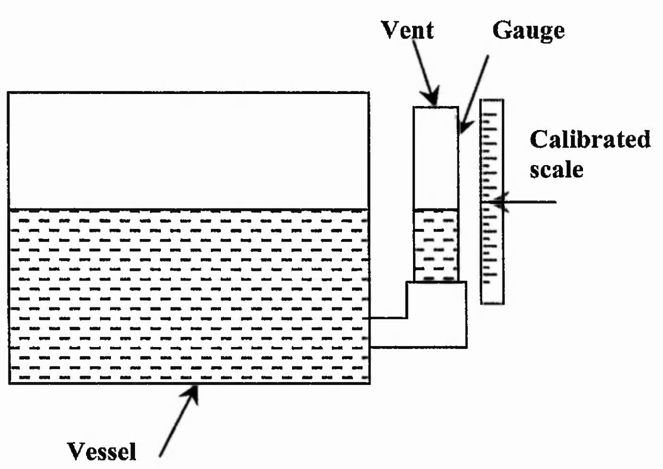


Figure 2.1 Tubular Glass Gauge

The flat glass gauges are the most widely used sight gauges in industry, providing a wide range of pressure and temperature liquid service. There are two basic designs of the flat-level gauge: reflex and transparent gauges. The reflex-type gauge is designed to produce a dark area for the liquid and a light area in which the vapour space is present. The reflex-type design is normally chosen for liquid that is colourless, clean and non-viscous. The transparent gauge is preferred for service where the liquid is coloured, viscous and corrosive.

Suitability

- Slow process (reaction time restricted to visual identification).
- Not suitable for real-time measurement to control filling operation as there is no output signal.

2.2.1.2 Displacer

Displacer actuated level gauges (Figure 2.2) operate on the Archimedes' principle by using the change in buoyant force acting on a partially submerged displacer. It uses an accurate spring scale that is calibrated for liquids of known specific gravity.

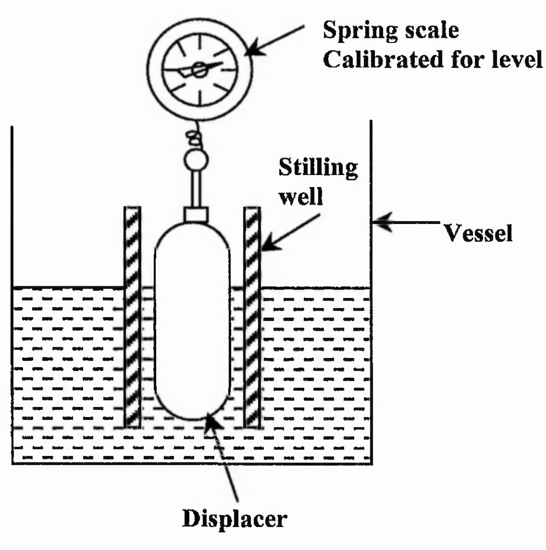


Figure 2.2 Displacer-Type Gauge

Suitability

- Invasive.

- Not suitable for real-time measurement because the output signal is a mechanical operation calibrated to show fluid level only.
- Inaccurate.
- Slow process.
- Not suitable for harsh conditions.

2.2.1.3 Tape Float

The use of tape floats in comparison to other level detection devices has been assessed more thoroughly [Elderfield 1990, Henry 1991, Wandzell 1989]. The tape-float gauge, Figure 2.3, is one of the simplest methods of float level measurement. The primary application of tape-float gauges is in open or vented vessels. The gauge assembly consists of a float resting on the surface of the liquid, a tape connected to the float and a counterweight over a pulley. The gauge has an indicated scale mounted on the external wall of the tank and the counterweight acts as a position or level indicator.

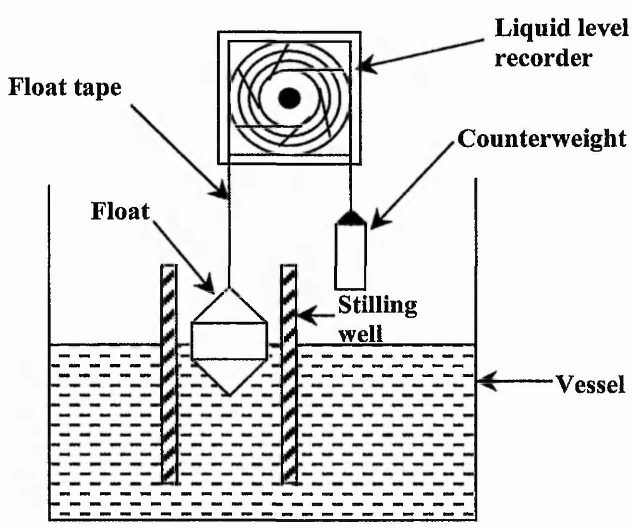


Figure 2.3 Tape-Float Gauge

The tape-float gauge is well suited to water and wastewater plants as well as to irrigation projects, to record levels of dams, rivers and lakes.

Suitability

- Inaccurate.
- Not suitable for real time measurement.
- Invasive.
- Not suitable for harsh conditions.
- Slow process.

2.2.2 Force Type

The force type level measuring technique is widely used in the process industry. This section introduces the diaphragm, weighing and buoyancy-type devices. In addition the weighing type is further subdivided into load cell and vibrating wire devices and the buoyancy type is subdivided into magnetic-float and displacer devices.

2.2.2.1 Diaphragm

Diaphragm level detectors can be classified as two types. There are diaphragm box systems (Figure 2.4) which consist of air filled diaphragm assemblies connected to pressure detectors via capillary tubing. As the level of fluid rises above the diaphragm, the liquid head pressure changes. The change in force compresses the diaphragm causing the displaced air to flow through the capillary tube to a pressure element as a level indication, moving either a pen or pointer.

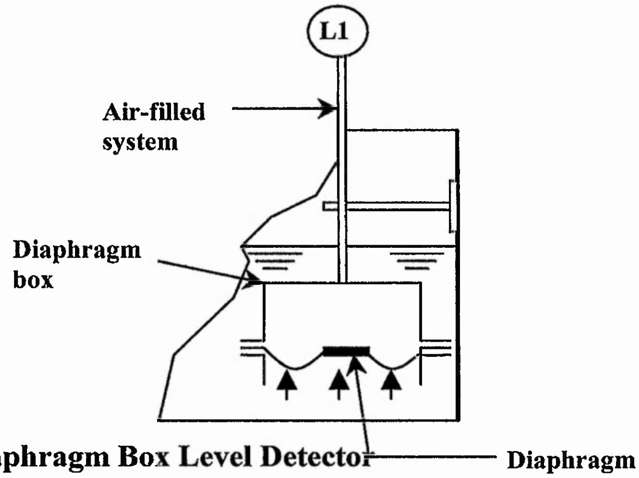


Figure 2.4 Diaphragm Box Level Detector

The continuous diaphragm level detector is a one-to-one pressure repeater. The unit is submerged, similar to the diaphragm box level sensor, and exerts an upward force on the diaphragm as the liquid level changes above the assembly. The diaphragm moves until the pressure inside the diaphragm increases to equalise the force; the level indicator senses the change in pressure. They are often used for recording levels at remote locations such as reservoirs and dams.

Suitability

- Invasive.
- Not suitable for harsh conditions.

2.2.2.2 Weighing

There are two types of weighing devices that can be used for level sensing and recording, namely the load cell and vibrating wire.

The load cell is usually placed on the leg of a vessel. As the level of liquid or material varies in the vessel, the load cell detects the change in weight and it outputs the signal that drives the chart and/or becomes a process variable signal for the controller.

The vibrating wire principle is used for measuring the change in frequency of vibrating wire as it is stressed. It is claimed that greater accuracy and stability are obtained by measuring mass instead of force, since scale is more easily isolated from surrounding vibration and shock.

2.2.2.3 Buoyancy

There are three major classes of level measuring devices that utilise the principle of buoyancy. These are float-actuated, magnetic-type float and displacer-type devices

Float-actuated level-measuring and control devices operate by float movement; that is, a float follows the liquid level changes. The float movement in conjunction with different lever designs positions the control valve that is installed at either inflow or outflow of the vessel, such as in a ball-float actuator in a cistern.

In a magnetic-type float device, a float senses the level change and positions a magnetic piston that is attached to the float rod. The piston moves up and down as the level changes within the container. Outside the enclosed tube of the piston is a permanent magnet that is attached to a pivot arm with a mercury switch. When the level is up, the magnetic piston is in the magnetic field and the magnet is drawn against the magnetic piston, thereby tilting the mercury switch to open position. When the level drops to a predetermined point, the piston will move down out of the magnetic field and the magnet will be pulled back by the tension spring, thereby tilting the mercury switch to its closed position.

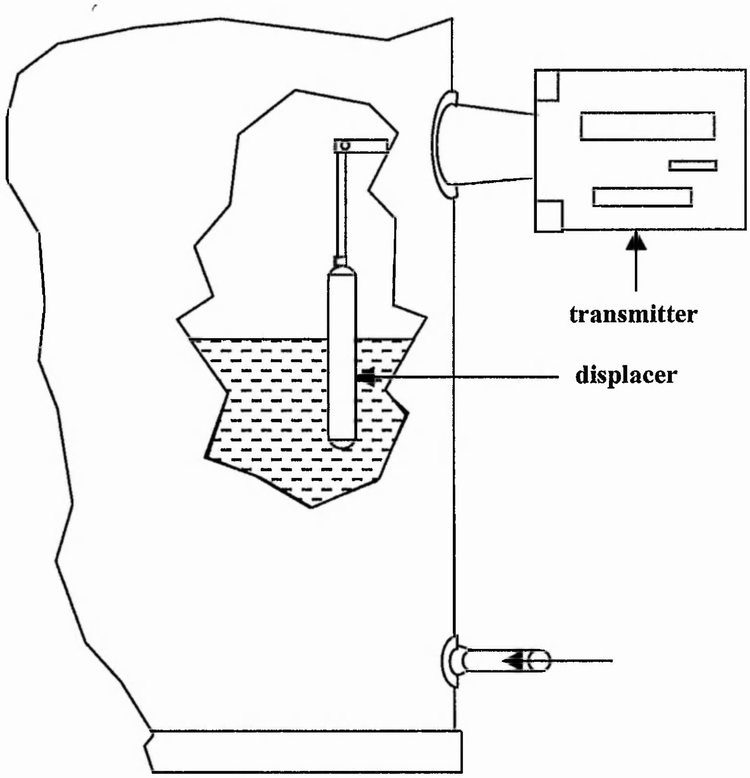


Figure 2.5 Typical Displacer-Level Transmitter

In a displacement-type level-sensing system, Figure 2.5, the displacer, a cylindrical tube, is used to measure the liquid level. Instead of the float floating on the liquid surface, the displacer is immersed in a cage or vessel and measures the level changes by the changes in the buoyant force. A small vertical movement of the displacer transduces the level measurement and/or control signal.

Since the introduction of displacer-type liquid level devices they have become the most widely used devices in process operations.

Suitability

- Invasive.
- Not suitable for harsh conditions.
- Slow process (Mechanical operation).

2.2.3 Pressure Type

There are a number of level-sensing techniques that are based on measuring the pressure or head change in a vessel containing liquid or material. Pressure-type devices can be grouped into three classes: hydrostatic head, bubbler and pressure differential. Among these, the pressure differential devices are most widely used in flow measurement as well as in liquid level sensing and transmitting applications. For example [Mandelkehr & Hausman 1989] demonstrated the use of the hydrostatic head principle for fluid level detection in an enclosed tank. Other applications of pressure-type devices have also been explored [Adams 1989, Brown 1990, Elderfield 1990, Henry 1991, Oglesby 1989].

2.2.3.1 Operating principle of the hydrostatic head

The operating principle of the hydrostatic head relies on understanding the relationships between pressure, specific gravity of liquid density, acceleration due to gravity and the height of the liquid level from a minimum level reference point. A pressure gauge is commonly used in measuring liquid levels in an open vessel.

$$P = (SG)(\rho)(g)(H) \qquad [2\text{-}1]$$

where,

P = Static head pressure,

SG = Specific gravity,

ρ = Density of water

g = Acceleration due to Gravity,

H = Level height.

Therefore, for level measurement, Eq(2-1) can be rearranged to obtain,

$$H = \frac{P}{(SG)(\rho)(g)} \qquad [2\text{-}2]$$

Local measurement using liquid head assumes the constant demand density of a liquid; therefore, any variation in the liquid density will introduce measurement errors.

The pressure tap is made at the lowest level of the vessel to be metered and the connection to the vessel transmits the sum of the liquid head and the atmospheric pressure to the high-pressure connection. The low-pressure connection is opened to the atmosphere. As a result, it will only measure the liquid head variations.

For example, the Delta Model 551 (See Appendix A) is used to measure and transmit the pressure of liquids and gases in pipelines, tanks, ducts and other containers. The pressure at the bottom of a vented tank is linearly proportional to the height of the liquid.

2.2.3.2 Bubblers

Air bubblers are the simplest level-measuring devices well suited for detecting corrosive liquids often found in slurries containing particulates. The bubbler-tube system (Figure 2.6) consists of a regulated air supply that provides a supply pressure through a bubbler tube and a pressure-sensing device such as a differential pressure transmitter, manometer or pressure switch.

When air bubbles escape from the opening of the bubble tube, approximately 760mm from the bottom or the sediment level, the back pressure from the bubble tube is in equilibrium with the hydrostatic head of the liquid in the vessel. The bubbler tube is connected to a high-pressure connection of a differential pressure transmitter and the low-pressure side is generally vented to atmosphere so that the transmitter output is proportional to the static head. The output signal can be calibrated in terms of the liquid level and can be displayed.

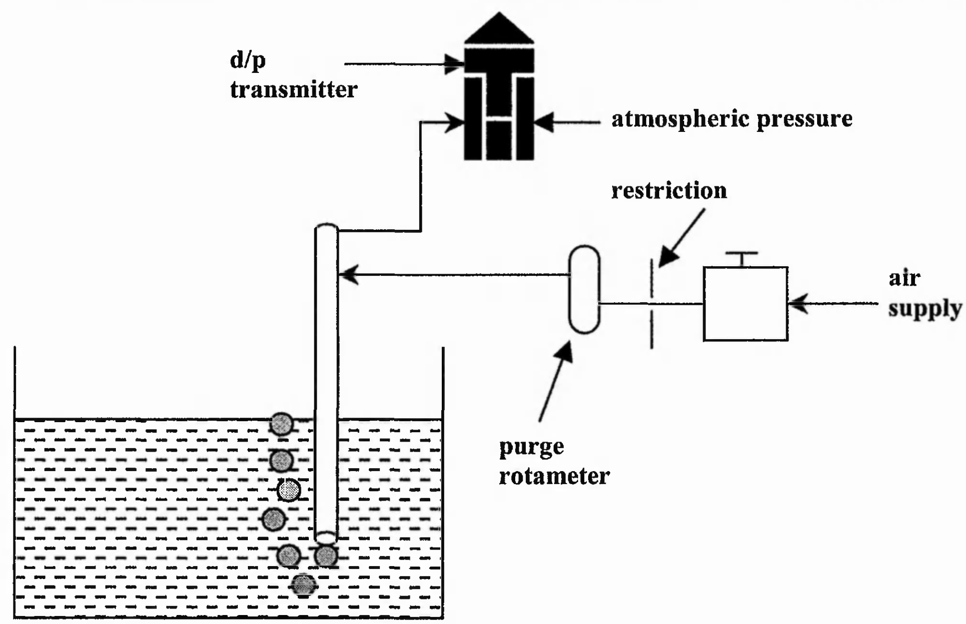


Figure 2.6 **Bubbler System with d/p Transmitter**

Suitability

- Prone to errors with constantly changing level.
- Not suitable for bottle filling.

2.2.3.3 Differential Pressure Sensors

When differential pressure (d/p) instruments measure liquid levels, the high-pressure connection is made to the bottom of the vessel and the low-pressure connection, generally a vapour space above the liquid level, is made to the low-pressure inlet part of the pressure differential sensor. Pressure differential detectors vary with respect to their designs and the methods by which they transduce the differential pressure to electronic or pneumatic signals for indicating, recording and control. A recent study examined the changing relationship between D/P and other technologies as viewed by the following three decision-making criteria, technology, regulations and economics. It was concluded that the D/P had reached its technical limits while other measuring devices such as radio frequency (R.F), ultrasonic, laser, microwave, optical and radar continue to expand their horizons [Bacon, 1995]. This type of level measurement instrument was considered unsuitable for the current research application because it is invasive.

2.2.4 Electric Type

Electronic level-sensing methods include admittance, capacitance, conductance, resistance and electromechanical principles. Basic operational principles are utilised in the design in level-sensing instrumentation and control for liquid as well as solid materials. Almost all electronic-type devices consist of sensors, amplifiers and recorders and/or transmitters [Shortall 1990, Watnough 1989].

2.2.4.1 Admittance

Admittance probes monitor two electrical properties, the dielectric constant and the conductivity of the material. This is accomplished by generating a radio frequency pulse of energy which travels from the sensing probe to the ground reference (usually the vessel wall). The amount of liquid between the two determines how much energy is transferred. The amount of energy flowing is a measure of the liquid level and interface position. The amount is compared to an internal reference and produces a switching action at a selected material elevation [Delta controls corporation 1998]. For example, the Delta models 103 and 105 probe type level switches use RF Admittance technology to produce a switching action when a material level crosses the set-point of its sensing probe.

2.2.4.2 Capacitance

The second electronic level-sensing method is the capacitance probe, an application for which has been described by [Brown 1990]. Figure 2.7 illustrates the operating principles of the capacitance probe. The probe comprises of a variable capacitor. The area of the conductors, the distance between them and the dielectric constant of the insulator determines the capacitance of any capacitor.

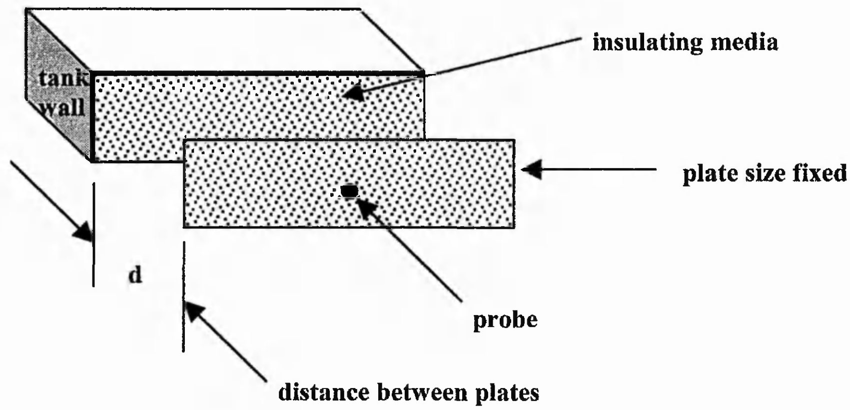


Figure 2.7 A Capacitor Formed by Two Plates

The operating principle of a capacitor probe suspended in a fluid container involves its response to the changes in the dielectric value between itself and the container walls. As all products, liquids or solids, have a dielectric constant higher than that of air, material covering or rising up the probe increases the capacitance effect.

An example of a tubular capacitor is found in the Trans-Sonics (see Appendix A) capacitor-type liquid-level transducer. The digital out-put is provided for tank gauging of booster fuels and oxidisers during spacecraft flight. A change in the liquid level causes an imbalance in a capacitance bridge. When the bridge is balanced the counter provides a digital output corresponding to the liquid level.

Another example of a capacitor is the liquid quantity probe. In this form, the capacitor is designed to yield an incremental capacitance that is a linear function of the corresponding incremental volume in the containment vessel. The signal can then be related to the density of the liquid to convert the measurement to a mass readout.

2.2.4.3 Conductance

Another form of electronic level sensing device is the conductance probe. A conductivity-level controller supplies a small voltage (i.e., about 12V ac). One pole is connected to the partially insulated probe and the other to the container wall and a

Wheatstone bridge measures the electrical resistance change. Resistance is high when the container is empty, but as soon as the conductive medium contacts the probe, a low resistance path is formed between the probe and the container wall. This change in resistance is amplified and used to operate a relay

Milltronics FE series (see Appendix A) of level sensors are examples of conductance probes. These sensors are designed for point indication of conductive liquids. A typical system consists of three major components; an electrode holder, the electrodes and a relay unit. The electrode holder serves as a mechanical support for the electrodes and electrically insulates them from the tank. The electrodes are vertically mounted to the holder, above the liquid, with their lower ends positioned at the required actuation levels. The relay unit provides the voltage and current required (8V, 5mA max.) for sensing as well as suitable relay outputs.

2.2.4.4 Resistance

The use of resistance sensors as methods of level monitoring has been described [Ehrenfried 1989]. Resistance sensors (Figure 2.8) detect material levels by monitoring the change in resistance of a partially submerged electrical element. The sensor responds to level changes in a vessel with changing loop resistance in the measuring tape.

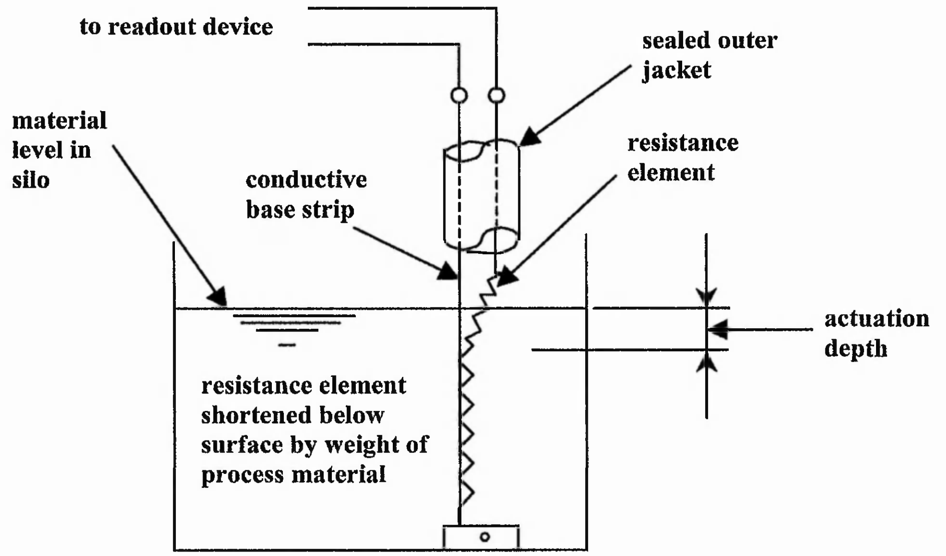


Figure 2.8 Resistance Level Sensor

The tape-type sensing element consists of a precision wound resistor helix. A flat resistance wire is wound to form a continuos helix along the full sensor length and is held away from the conducting base strip by a thin insulation layer. An outer jacket, comprising several thin plastic layers, encloses the wound resistance element and serves as the pressure receiving diaphragm.

Suitability

- Electrical properties of either container or fluid required which gives rise to health risks when dealing with consumable goods.
- Invasive.
- Radiation/material property change.

2.2.5 Ultrasonic Type

There have been several novel applications for the use of ultrasonics in level measurement in recent years. Groetsch [1989], Brown [1990] and Stuckman [1990] used ultrasonics to measure variables involved in large tank filling. Soltz [1989] explored the use of air borne ultrasound transmission for level measurement. More recently Evans [1996] and Duncan [1998] investigated the use of ultrasound level measurement in high temperatures and harsh chemicals involved in reactor vessels and dry/dusty environments. In all these examples ultrasound provided a non-invasive method of fluid level measurement

The operating principle of ultrasonic type level sensors is that a transducer emits a series of ultrasonic sound pressure waves that are reflected by a product surface. The system measures the 'time of flight' from transmission to reception of the echo and can thus calculate the distance travelled and derive a meaningful reading of level. The transducer can be positioned above the product or immersed in it.

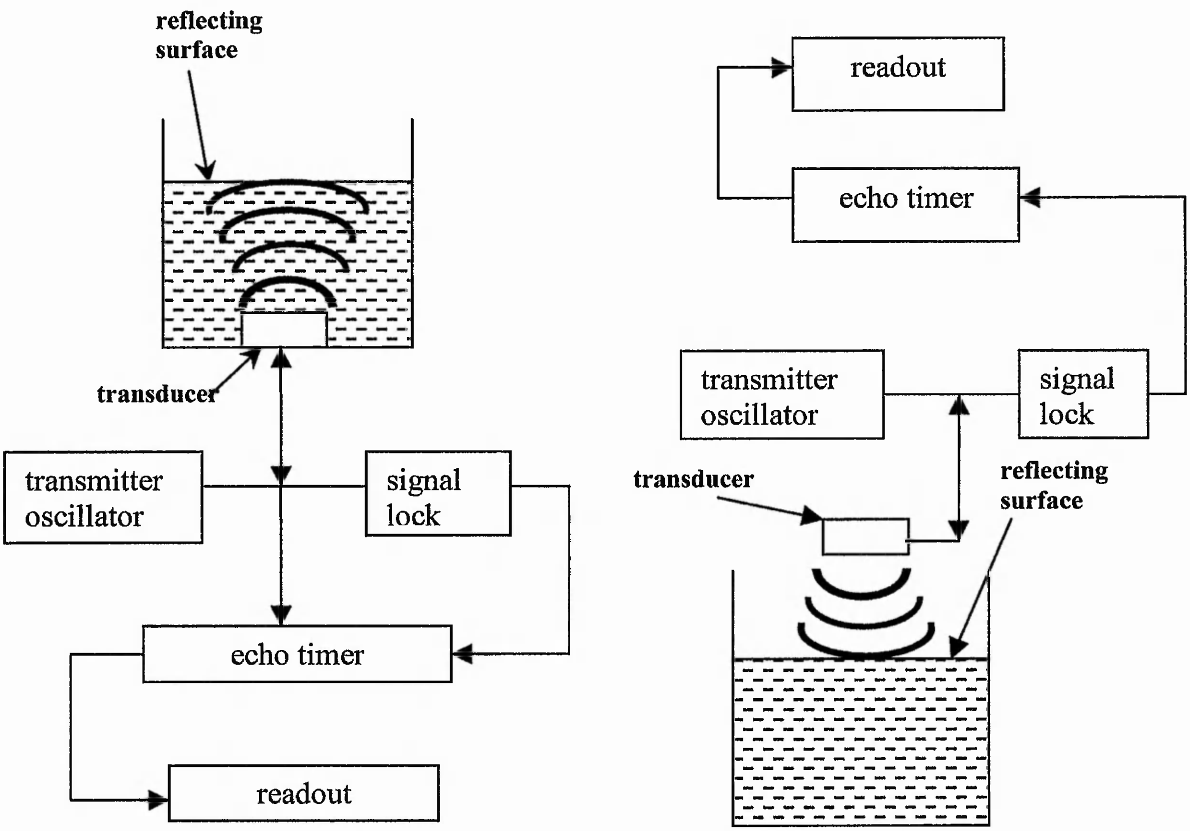


Figure 2.9 Ultrasonic Techniques (a) in Liquid and (b) in Air

Figure 2.9 illustrates a basic, echo-based system in which an ultrasonic sound-pulse transducer is located in the bottom of a vessel filled with liquid of which the level is to be determined. The transducer is connected to a transmitter where the sound pulse originates and to a receiver into which the echo is received. The transmitter and receiver are both connected with a time-interval counter that measures the elapsed time between the emission of the sound wave and the reception of the corresponding echo. The elapsed time can be converted into units of level of liquid that can be read from the recording devices.

Suitability

- Non-invasive.
- Non-mechanical operation. No moving parts.
- Rapid process, i.e., suitable for real-time measurement and control.
- Affected by interfering variables;

- Temperature
- Material properties
- Interfaces (reflecting boundaries)
- Turbulence
- Gas mixtures
- Pressure

2.2.6 Other Types

This section introduces the level-measurement technique of infrared, microwave, nuclear and thermal types. These techniques can be classified as more complex and sophisticated in that they can be costly in the initial purchase and installation. Alternative methods of level detection were explored as possible solutions to more complex environments [Oliver 1991].

Application of infrared detection techniques to liquid level measurement and control is a fairly recent development in the process industry. Figure 2.10 illustrates the operating principle of an infrared detection and control system.

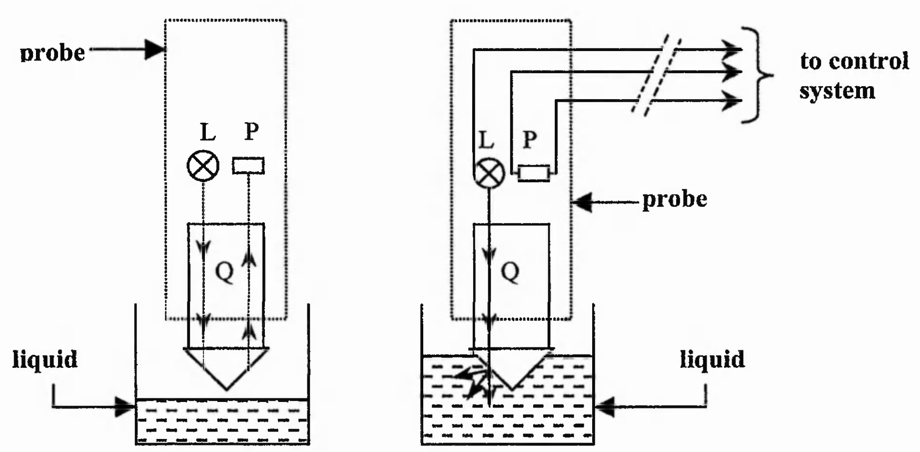


Figure 2.10 Infrared-Level Detection System

The level detection is based of the change in refraction when the conical tip of a quartz light conductor is immersed in the liquid. Infrared light from a light emitting diode (L)

passes through the light indicator (Q) and is reflected by its conical tip if surrounded by air, gas or vapour. The reflected light is detected by a phototransistor (P). When the light conductor is immersed in the liquid, the refraction at the tip changes and the light is dispersed in the liquid; thus the phototransistor does not receive reflected light. The control unit is designed to provide an output signal as a function of the liquid level changes that cause the phototransistor to conduct when the light is reflected.
Infrared level-detector systems can be used in a wide range of liquid-level applications such as storage tanks, processing vessels, pipelines, cargo tanks with crude oil, chemicals, liquified gases and fuel-oil tanks [Shortall 1990, Watnough 1989].

Microwave-based systems are non-contact devices that include transmitters, oscillators and directional antenna. The receiver consists of a directional antenna, a high gain, low noise amplifier, a pulse coding network, a voltage-comparator circuit and a relay driver circuit. Figure 2.11 illustrates a block diagram of a microwave level-detection system.

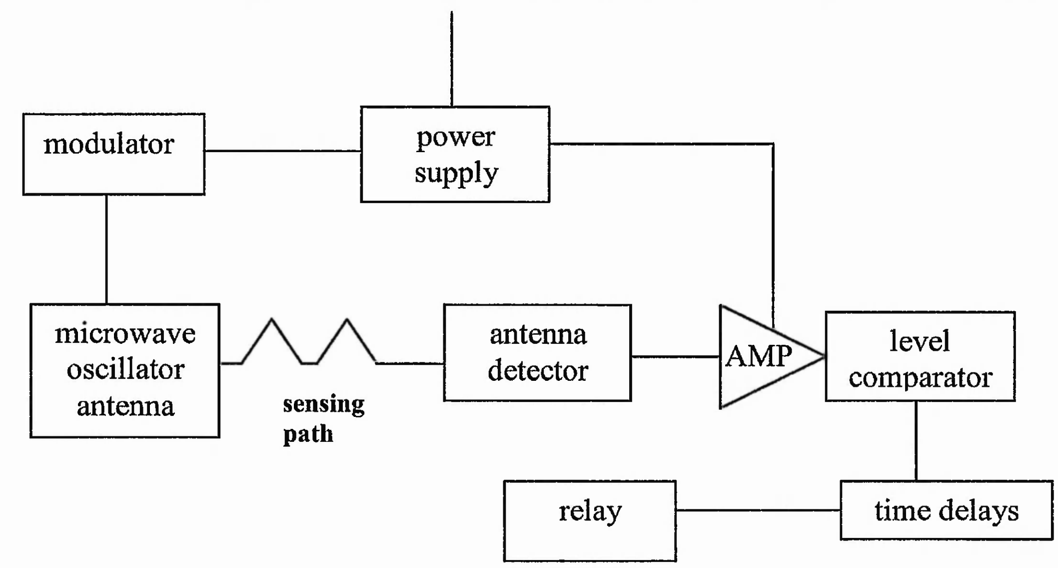


Figure 2.11 Block Diagram of Microwave Level-Sensing system

The operating principle is such that a low power microwave signal is established between a transmitting antenna and receiver. The interruption of the beam results in a reduction of the received signal strength due to attenuation of the beam into the product itself.

In the transmitter, line voltage is converted to a well regulated and filtered 12 Vdc supply. It is then pulsed randomly at about 1 KHz by a pulse modulator circuit. The pulsed dc is fed to an oscillator in the antenna assembly and converted to a pulsed microwave signal. The signal is radiated by a directional antenna.

In the receiver, the signal is received by a directional antenna and converted to a low-level DC. The level of the amplified received signal is compared with a present value in a voltage comparator circuit. When the signal level received exceeds the comparator setpoint, output signal is initiated which processes through a time-delay circuit to drive the output relay.

Nuclear level gauging systems use the principle of gamma radiation to measure the level or interface position of liquids, solids or slurries. In this category is the stockray-gauging system, Robertshaw nucleonic fixed level system, varied level detectors and radiation propellant gauge systems [Oliver 1991].

Isotope-source level controls are used to detect, indicate or control the level of almost any liquid, solid or slurry stored in a vessel. All elements of the system are external to the vessel so that pressure, vacuum, temperature or materials that a re highly viscous, corrosive abrasive or very heavy have no influence on the system. Figure 2.12 shows a radiation level-sensing system.

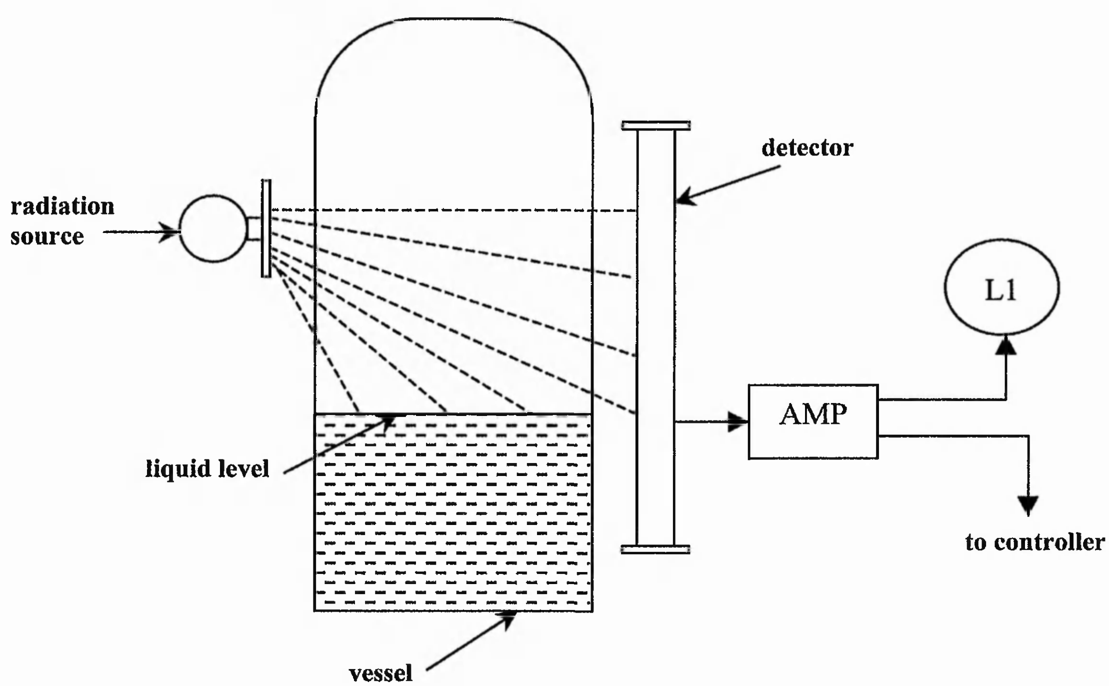


Figure 2.12 Radiation Level-Sensing System

The simplest system is a point-control application. The radioactive source in the holder emits a beam of gamma rays across the tank through the container walls to the detector. In the detector, a Geiger counter produces an electrical impulse in response to each gamma photon passing through the tube. Theses pulses are integrated and transformed into a DC signal proportional to the radiation received at the counter. If the level of the material is below the beam, the signal received is larger than when the material is in the path of the beam, because the material will absorb or scatter a certain amount of the gamma radiation. The difference in the two values measured is used to operate a relay.

For continuous indication, the system basically remains the same. The only difference is that the radiation leaves the source-holder over an angle large enough to cover the total height range to be measured. The signal received at the detector tube varies according to the actual level in the tank. The different path lengths are taken care of by a built-in gain compensator system.

Common gamma-ray-emitting materials that are used as sources include Radium 226 with a half-life of 1585 years, Cobalt 60 with a half-life of 5.2 years and Caesium 137 with a half-life of 33 years.

Another type of level measurement system is the thermal-type level sensor. A self-heated thermistor probe is used to detect the surface of a liquid. As the thermistor reacts to heat dispersion rather than electrical conductivity, it can be used with water or oil-based liquids. The sensor element is totally insulated from its environment.

The thermistor is a negative-temperature coefficient resistor in which the resistance reduction is proportional to the temperature rise. Internal temperature depends upon the heat dispersion of its surrounding environments. As heat dispersion is greater in a liquid than in a gas, there is a sharp voltage change whenever the probe enters or leaves a liquid. The thermistor operating temperature assures accurate operation in liquids as high as 212 °F. Figure 2.13 shows a typical thermistor used in level measurement.

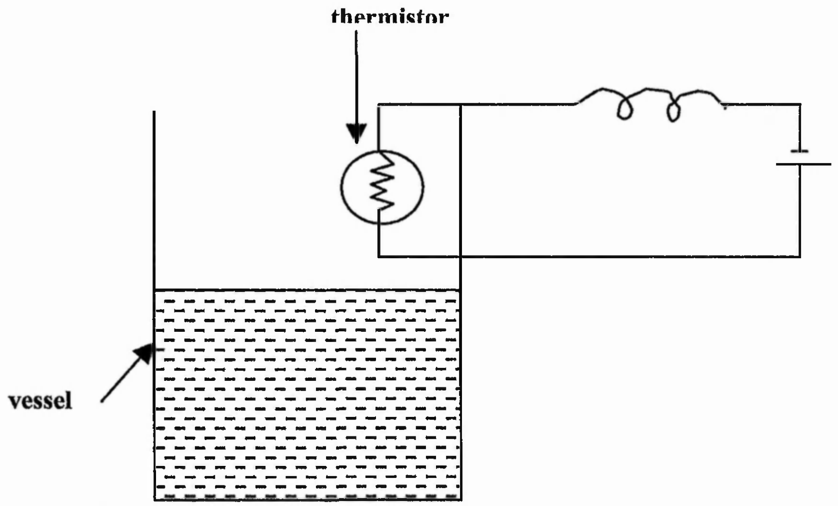


Figure 2.13 Thermal Level Sensor

The thermal sensor can be made quite accurate with electronic feedback circuits. These keep the thermistor at a constant temperature by varying the amount of power applied to it. It is commonly used for point measurements in liquid, at liquid/liquid and liquid/vapour interfaces and in slurries.

2.3 Summary of Analysis of Fluid Level Techniques

In the previous section, details have been presented on a variety of level measurement techniques. From this information a number of conclusions can be drawn as to the practical application for one or more of these techniques for use as an on line process control system for liquid level measurement. The requirements for such a system are:

- be non invasive to negate any hygiene problems.
- able to operate in real-time.
- be highly repeatable and accurate.
- be readily installed into existing filling equipment.

The following Table 2-2, illustrates various advantages, disadvantages and limitations of the level measurement techniques as applied to on-line fluid level measurement in containers.

Certain advantages and disadvantages have been grouped together in the key to the table. It is obvious that limitations of some techniques render their use for this type of application impossible. If this is the case the symbol depicting that type of limitation is coloured red. Green symbols represent a perfect example of a positive match to on-line fluid level measurement.

Key to Level Measurement Technique Analysis Table 2-2

Advantages

(A) Non-Invasive

(B) Non-Contact and Non-Invasive

(C) Accurate

(D) Inexpensive

(E) Maintenance free

(F) Impervious to Most Harsh Environments

(G) Mechanical/electronic operation

Disadvantages

(1) Expensive

(2) Unhygienic due to radiation/material property change

(3) Slow process

(4) Dark and transparent materials cannot be measured

(5) Not suitable for harsh conditions

(6) Accuracy affected by interfering variables; temperature, transducing medium, target surface and filling method.

Limitations

(i) Invasive

(ii) Not suitable for real-time measurement

(iii) Limited to Level detection not Level Measurement

(iv) Electrical Properties of either container or fluid required

(v) Inaccurate

Table 2-2 Level measurement technique analysis table

Techniques	Advantages							Disadvantages						Limitations				
	A	B	C	D	E	F	G	1	2	3	4	5	6	i	ii	iii	iv	v
Dipstick				X						X		X	X	X	X			X
Sight Type																		
Glass gage	X			X	X					X		X	X		X			X
Displacer										X		X	X	X	X			X
Tape float							X			X		X	X	X	X			X
Force Type																		
Diaphragm			X	X			X					X	X	X				
Weighing	X		X	X		X	X						X					
Bouyancy			X	X		X	X					X	X	X				
Pressure Type																		
Hydrostatic head										X		X	X		X			X
Bubbler				X	X		X		X				X	X	X			X
Differential Pressure			X			X	X						X	X				
Electric Type																		
Admittance probes			X	X	X				X				X	X			X	
Capacitance probes			X		X	X			X				X	X			X	
Conductance sensors				X	X				X	X		X	X	X	X	X	X	
Resistance sensors			X	X			X					X	X	X			X	
Ultrasonic Type																		
Contact	X		X	X	X		X						X					
Non-Contact	X	X	X	X	X		X						X					
Other Type																		
Infrared detectors	X	X	X		X		X	X			X	X	X					
Microwave detectors	X	X	X		X	X	X	X	X						X	X		
Nuclear-type detectors	X	X	X		X	X	X	X	X									
Thermal Type detectors			X		X		X	X				X	X	X	X			

It can be seen from Table 2-2, some of the simpler techniques are totally unsuitable to rapid on-line measurement. The weighing method does not suffer the limitations of the other simpler methods but was deemed unsuitable due to its physical design constraints in the incorporation of rapid real-time level measurement, which in many instances requires the container to be suspended as filling takes place. Optical systems can also be discounted as errors can be introduced by fluid splashing onto any lens. The electric range of conductive, capacative and admittance probes are unsuitable owing to their being invasive and mechanically difficult to install. In comparison ultrasound offers considerable benefits:

- non-contact and non-invasive
- mechanically simple
- robust and reliable
- accurate
- applicable to many different media
- mechanical/electronic operation
- fast response, i.e., suitable for on-line measurement and control

To conclude, ultrasound was the clear choice for a rapid on-line fluid level detection mechanism. Ultrasound can be used in several different ways to measure liquid levels, an analysis of these methods is included in the next section.

Chapter 3 - Ultrasonic Level Detection

In chapter 2 ultrasound was identified as a novel method that would be suitable for a rapid on-line fluid level detection system. In this chapter the main principles of ultrasound are reviewed and the applications of the use of ultrasound in industrial processes, and key learning from these are described.

Introduction

The beginnings of ultrasonic echo ranging in air and water are found in nature, examples of which include (a) echolocation and communication underwater by dolphins and (b) active and passive methods used in air by bats and moths. Here, the ultrasonic signal and returning echo are used to estimate the position of objects.

One of the earliest references to the research of acoustic principles was that by Pythagoras, who in the sixth century BC discovered that the shorter of two similar stretched strings emits a higher musical note [Lynnworth 1989].

The early mathematicians and physicists gained further understanding of acoustic principles. In 1638 Galileo observed that the pitch of a note was associated with the frequency of vibration. Mersenne, a contemporary of Galileo, was the first to measure the frequency of a vibrating string and calculate the frequency of shorter strings from it. Another breakthrough in the study of acoustics was the calculation of the speed of sound in air (1635) and water (1826), as recounted by Lindsay [1966].

In later years, Newton's Laws of Motion provided a basic understanding of wave equations in ultrasound, whilst more recently, Fourier's theorem was ideally suited to analysis of ultrasonic waves.

Turning to more recent events, in 1847 Joule discovered magnetostriction that was to become an important method of generating and detecting ultrasound. Magnetostriction involves a change in the dimensions of a magnetic material under the influence of a magnetic field. In 1877 Lord Rayleigh published the first edition of his classic work, The Theory of Sound. The next major discovery was that of piezoelectricity by the Curie brothers in 1880. Piezoelectricity describes the electric charges developed on the surfaces of certain types of crystal when subject to pressure or tension. Their discovery, which underlies the majority of ultrasonic sensors in use today in process control, occurred before Roentgen's discovery of X-rays in 1895.

At the time of the Second World War electronic aspects of ultrasonic measuring systems became of real research interest, due to developments in radar and sonar in the 1939-1945 period. More historic milestones in the use of ultrasonic non-destructive testing and flow-metering occurred in the late 1940's, perhaps due to developments in space and military projects. Since then, ultrasonic instrumentation has advanced considerably in terms of practical applications and technological developments [Lynnworth 1989].

3.1 Principles of ultrasound

The principles of ultrasound were previously discussed in detail [Hull & John 1988]. Sound waves are elastic waves that can be transmitted through both fluid and solid media. The audible range of frequency is from about 20 Hz to about 20 kHz but it is possible to produce elastic waves of the same nature of sound of frequencies up into the Giga hertz (GHz) range. Elastic waves with frequencies higher than the audio range are described as ultrasonic.

In fluids, sound waves are longitudinal compression type in which particle displacement is in the direction of wave propagation. In solids, they are both compression type and shear waves with particle displacement normal to the direction of wave travel, and with elastic surface waves also occurring. These are termed Rayleigh waves.

3.1.1 Wave velocity

The velocity of sound waves can be calculated using the following relationships. The velocity of longitudinal compression waves, V_c, in a fluid is given by

$$V_c = \left(\frac{K_a}{\rho}\right)^{1/2} \tag{3.1}$$

where K_a is the adiabatic volume elasticity and ρ is the density. In solids, the velocity of compression waves is given by the expression

$$V_c = \left(\frac{E(1-v)}{(1+v)(1-2v)\rho}\right)^{1/2} \tag{3.2}$$

where E is the modulus of elasticity and v is the Poisson's ratio. The velocities of longitudinal waves in several media are given in table 3-1

Table 3-1 Velocities of longitudinal sound waves

Medium	Velocity V_c (m/s)
Air*	330
Water	1430
Oil	1740
Aluminium	6190
Copper	4600
Magnesium	5770
Steel	5810
Perspex	2730
Polyethylene	2340

* At atmospheric pressure and 15°C.

The velocity of shear waves, V_S, within a solid is roughly half the longitudinal wave velocity and is given by the expression

$$V_S = \left(\frac{G}{\rho}\right)^{1/2} \tag{3.3}$$

where G is the modulus of rigidity of the material.

The velocity of Rayleigh waves, V_r, in a solid is about 90 per cent of that of shear waves, and is given by

$$\frac{V_r}{V_s} = \frac{0.87 + 1.12\nu}{(1+\nu)} \tag{3.4}$$

3.1.2 Wavelengths

The wavelength, λ, is related to the frequency and wave velocity as $V = \lambda f$ where f is the frequency. Table 3-2 gives the wavelengths of sound in various materials at several frequencies.

Sound waves can only be reflected effectively by objects that have dimensions equal to or greater than the wavelength of the radiation. As shown in Table 3-2, a frequency of 10 MHz will be capable of detecting defects in steel of sizes greater than 0.58 mm, but defects larger than 4.65 mm would only be observed if a frequency of 1.25 MHz were used.

Table 3-2 Wavelengths of sound (compression waves) in some materials

Material	*λ (mm) for frequency (MHz) of*			
	1.25	2.5	5.0	10.0
Air	0.26	0.13	0.066	0.033
Water	1.14	0.57	0.286	0.143
Oil	1.39	0.70	0.35	0.175
Aluminium	4.95	2.48	1.24	0.62
Copper	3.68	1.84	0.92	0.46
Magnesium	4.62	2.31	1.16	0.58
Steel	4.65	2.32	1.16	0.58
Perspex	2.18	1.09	0.55	-
Polyethylene	1.87	0.94	0.47	-

3.2 Ultrasound in industry

The use of ultrasound to measure fluid levels, the subject of the current research, is a novel application. However, ultrasound is widely used throughout industry for a wide variety of applications.

Low intensity ultrasound signals respond to the properties, state or quality of the medium in question by a change in the emission, transduction or proporgation of that signal. There are many important applications of ultrasound in research such as those in medical, dental and biological areas. For example, animal backfat thickness determination is often carried out using ultrasound instrumentation [Miles et al 1985]. In industry, there are many applications of 'high intensity' ultrasound including macrosonic and non-linear acoustic areas such as ultrasonic cleaning, machining, wire welding, atomising, cavitating, emulsifying, influencing of chemical reactions, shock-wave measurements and therapy. The proceeding list [from Lynnworth 1975] shows the diversity of measurements, tests and process-control that can be accomplished with the assistance of ultrasound;

- Flowmetery
- Thermometery
- Density, Porosity
- Pressure
- Dynamic force, vibration, acceleration
- Viscosity in fluids
- Level detection
- Location of low-reflectivity interfaces
- Phase, microstructure, nodularity
- Thickness
- Position
- Composition
- Anisotropy
- Non-destructive testing
- Grain size in metals
- Stress and Strain
- Acoustic emission
- Imaging, holography, microscopy
- Elastic properties
- Bubbles and particles
- Gas leaks

3.2.1 The Application of Ultrasound in the Food Industry

In a review of applications of ultrasound to food systems, Javanaud [1988] described research dating back to 1956. Table 3-3 from Javanaud's review, categorises ultrasonic methods according to their being based on velocity, attenuation, specular reflectance or scattering.

Table 3-3 Ultrasonic Methods Used to Evaluate Foods

System	Property
Velocity	
Cattle, pigs and sheep	% solid fat
Fruit juices	% fruit flesh or % sugar
Coffee (in water)	% grains
Wine	% alcohol and % solids
Milk	% fat and % solids
Emulsions	% oil
Oils	% solid fat
Yeast Slurry	% solids
Ice cream	Moisture content, structure
Ice/water mixture in meat	% ice
Fruit (various)	Ripeness
Eggs (white and yolk)	Age
Egg shells	Thickness
Cheese	Crack detection
Biscuits	Crispness
Attenuation	
Ice/water mixture in meat	% ice
Orange juice	Stability
Fruit (apples, cantaloupe)	Ripeness
Potatoes	Age
Eggs (white and yolk)	Age
Specular reflectance	
Orange skin	Smoothness
Tomato skin	Cracks
Husked sweetcorn	Defects
Scattering	
Fish	Lipid content
Beef	Quality grade through marbling

Many applications in food technology require techniques already developed to solve problems in biomedical and non-destructive testing areas. Interpretation ranges from relatively straightforward in a pure liquid or solid, to difficult or presently impossible in multiphase systems. But even in multiphase systems, velocity changes correlate well with concentration changes. Javanaud's review does not deal with industrial type process control measurements in food processing such as flow, temperature, liquid level, distance ranging or counting, for which ultrasound is sometimes the method of choice [Lynnworth 1989].

Technological advancement has had a tremendous impact on the available measurement techniques for process engineering. The variations of media to be measured has greatly expanded and now encompasses situations where physical properties of the media impose even greater demands on the monitoring components that come into contact with the measured medium [Shortall 1989]. The levels of hygiene that are required in the food processing and pharmaceutical industries have placed an even greater need for the use of non-invasive monitoring systems, of which ultrasound technology is a forerunner.

For example, there is considerable interest in the use of ultrasound for analysing foodstuffs that are emulsions (although in complex multicomponent systems) such as salad cream, milk and cream. [Javanaud 1988; McClements 1992; Povey 1997].

Many of the applications described within this section were the subjects of research papers, however, most of the applications have not actually been realised in practice in the food industry. The largest application area is probably level detection, to which ultrasound is well suited because of its relative insensitivity to layers of foam and other material which tends to congregate at air/liquid interfaces [Povey 1997]. Ultrasound speed measurement is a good way of monitoring solids in liquids, particularly crystallising solids [McClements & Povey 1988].

Most recently research has focused in on areas such as rapid determination of food material properties that may include food contamination [Povey 1997]. It is evident that the application of ultrasound has many benefits.

3.3 Methods of Measurements in Ultrasound

In most technical applications, the velocity of proporgation of an ultrasonic wave is utilised for the evaluation of the measured quantity [Kocis & Figura 1996]. Attenuation measurements are also considered as a primary method of analysis [Miles et al 1990]. As mentioned in section 3.3, scattering and specular reflectance are other methods utilised in fluid property measurements.

3.3.1 Velocity measurements

An ultrasonic pulse is emitted and the time taken for the pulse to return over a known distance is measured. This is described as the time of flight (TOF). Conversely, if the speed is known then the distance can be measured. Velocity measurements lend themselves to simple interpretation [Wood 1941], and near linear interpretation.

3.3.2 Attenuation Measurement

Attenuation measurements can reveal details of the viscosity of the medium or even the contents of the medium [Hull et al, 1996], especially when using spread spectrum techniques to observe the effects on a range of frequencies. (Different frequencies are attenuated at different rates.) For accurate attenuation measurements a variable path length is preferable but not always necessary [Hull et al, 1996]. Variable path lengths are not always easy to achieve, especially with foodstuffs. Another problem is that while it is straightforward to apply a linear relationship for velocity measurements, or the Wood's quadratic equation [1941] (also known as Urick's equation) for velocity measurements, there is no corresponding simple interpolation for attenuation [Javanaud & Robins, 1992].

3.3.3 Scattering Measurements

Scattering, like attenuation, is not easy to determine quantitatively.

One reason is the signals may be weak, especially if the concentration of the scatters is low. Another disadvantage to determining scattering measurements is the requirement for a small volume for inspection, since in larger volumes the scattering angle would be ill defined [Asher 1997].

A commercially available scattering measurement system is the Monitek system [see Appendix B]. It uses a focused beam and therefore interrogates only a small scattering volume. Scattering measurement systems are used for particle detection [Whitsel et al 1986].

3.3.4 Specular Reflectance

In light optics a 'speckle pattern' can be produced by, for example, the scattering of laser light from a surface which is rough in relation to the wavelength, or from a suspension of particles or droplets having similar small dimensions. A comparable phenomenon can be found with ultrasonic scattering from two-phase fluids. It is especially prominent when the two phases have a strong acoustic impedance mismatch, as in the case with bubbles of gas dispersed in a liquid. The mathematical analysis of the phenomenon is extremely complex but it is a potential method of determining the flow rate, velocity profile and the concentration of bubbles; fluid dynamics such as vortex shedding, oscillatory behaviour and instabilities in the flow [Blackledge 1992].

3.4 Accuracy of measurements

The use of ultrasonic waves has certain drawbacks, in particular, the large dependence of the velocity of the ultrasonic waves on the parameters of the medium and high attenuation and scattering especially in air.

In cases where a more precise measurement is required, ultrasonic techniques become more complicated due to the need to compensate for the effects of fluctuations of the parameters of the medium.

To improve the accuracy and resolution of the received ultrasound signal various techniques can be used. Canali et al [1992] describe a method of temperature compensation, and Jordan [1986] presents a thorough and comprehensive view of the theory, implementation and measurement applications of correlation functions. Included in this paper are examples of improved liquid level measurement and leak detection systems. Parrilla et al [1991] and Mariloli et al [1992] present discussions on digital signal processing techniques, including correlation, that can be used to improve the measurements on time of flight of ultrasound signals. In an attempt to obviate humidity and temperature, if detectors have a digital output, a correction to the measured value can be introduced by use of an algorithm [Kocis & Figura 1996]. With the development of computer technology, digital measuring and compensation has become widespread.

3.5 Ultrasonic Level Measurement

Groetsch [1989] has reviewed applications and solutions of ultrasonic level monitoring, and provides a practical insight into the likely problems of using ultrasound for level measurement. In his 1989 research paper Groetsch describes the problems of foam and turbulence on and in liquids. When foam is present on a liquid surface, it is not clear how good the echo will be, or indeed, whether the echo would come from the top of the foam or the liquid surface underneath. In general, several centimetres of light loose foam can be expected to give a weak echo from the *liquid* surface, and a thicker layer of loose foam will give no echo at all. Thick high-density foam will give a weak echo from the foam surface. A stilling tube may be used where possible to minimise the deleterious effects of disturbed surfaces [Asher 1997].

More recent research into ultrasonic sensing by Babb [1996] investigated the use of sensors acoustically coupled to the vessel wall by means of a special paste. This research used the resonance principle. A piezoelement generated a short ultrasonic pulse, which (with the correctly chosen frequency) generated a local resonance in the vessel wall. When the pulse ended the resonance died away. The crux of the measurement was how quickly it died away. After making its pulse, the sensor acted as a receiver, listening for the ringing following the resonance. The ringing time depended upon the presence or absence of the liquid on the other side of the wall from the sensor. The sensor analysed the signal and generated an empty or full indication, as appropriate.

In most forms of ultrasonic testing a couplant has to be used in order to transmit the ultrasound in and out of the test object (and the transducers). Water is the most frequently used couplant in immersion and squirter scanning techniques. However, these techniques are not compatible with some industrial processes and water may cause permanent damage and contamination to many materials.

Couplants are being used as a sound propagation medium between the transducers and the part under inspection. Although air is a reasonably good sound carrier in the frequency region of interest, it poses a major obstacle. The acoustic impedance of air differs so much from the acoustic impedance's of transmitter and test parts, that most acoustic energy is being reflected, and only a very small fraction of that energy penetrates in and out of the part and the transducers.

One solution to overcome this problem without introducing an additional sound transmitting medium consists of generating high enough sound levels and to use high-gain, low-noise amplification [Grandia & Fortunko 1995].

A Worcestershire company has made a breakthrough by using a non-contact ultrasound system to accurately measure the contents of cans. Developed by M&A Packaging Services Ltd (see Appendix C) during a two year TCS partnership with the Department of Physics at the University of Warwick, the system is being hailed as a major advance for the drinks industry world-wide. The device works by firing a pulsed carbon dioxide laser shot at a can to generate ultrasound inside its contents as shown in Figure 3.1. The ultrasound is detected electromagnetically and the results displayed on a computer screen, enabling the drinks manufacturer to determine whether the cans have been filled correctly [Dixon 1996].

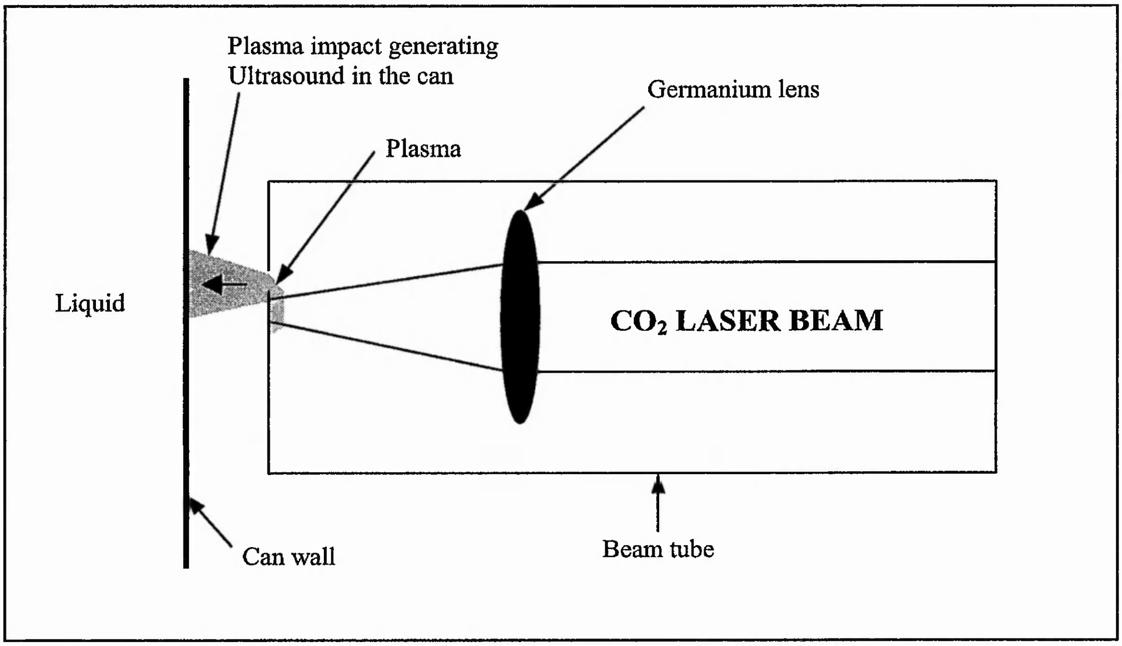


Figure 3.1 Principles of the laser generated ultrasound technique.

3.6 Problems Associated with Ultrasound

It can be seen that there are many diverse applications of ultrasound in the food industry, but it is clear that no ultrasound system is perfect. Several problems may be encountered such as those described by Fleischer[1993].

In his study Fleischer [1993] highlighted the typical problems in accurately gauging the volume in a tank. Although his paper is primarily aimed at underground storage tanks for fuel oils and the requirements of the American EPA, (Environmental Protection Agency), for this kind of tank, his findings and comments are just as valuable for above ground tanks and containers. To accurately monitor the volume in a tank it is necessary to know where the surface is and to know the profile of the tank itself. As Fleischer points out, build tolerances can be as much as 5% on large tanks. It is not unknown for tanks to distort when loaded, for floors to sink or tilt and for the sidewalls to bulge. This makes accurate volumetric measurements difficult. If the system is to be monitored for leakage it is particularly important to know the average liquid temperature and the coefficients of thermal expansion, (of both liquid and tank). If ultrasonic transducers are mounted so as not to be unduly disturbed by temperature fluctuations, then ultrasound can be used to measure both the temperature of the fluid and its height accurately.

In 1989, Oglesby compared various methods of deriving volume and mass from tank gauging systems and concluded that a combined system of hydrostatic and level gauging offered the best solution. If it is necessary to accurately assess volumetric content in very large tanks then this is an important conclusion. Mandelkehr & Hausman [1989] assess the applicability and uses of hydrostatic tank gauging and give useful practical advice to the correct use of hydrostatic systems.

There are other problems (that are the accepted), associated with the use of ultrasound, and these include:

- Ultrasonic sensors are not suitable for determining pressure, specific chemical analysis or for trace chemical analysis. One novel means of measuring pressure is the use of surface acoustic wave sensors (SAWSs), but these have not appeared commercially yet.

- Materials that are highly attenuative to ultrasound may cause loss of signal. These materials may be those under examination, constructional materials or deposits, corrosion or bubbles in the ultrasonic path.

- Transmission of ultrasound across an interface between two media is often inefficient, therefore the amount of usable ultrasound transmitted may be small, particularly if several interfaces are involved.

- Spurious signals and/or electromagnetic interference may cause confusion unless precautions are taken.

- Signal processing may have to be sophisticated and sometimes expensive.

To conclude, problems that may be encountered with ultrasonic techniques for fill level detection may include foaming, temperature and transmission environmental gas variables, such as gas mixture and pressure. It would be necessary to take these problems into consideration when developing ultrasound for fill level measurement as part of the current research project.

Chapter 4 - Bottling Techniques Found in Industry

Introduction

The main aim of this research was to develop a prototype system for rapid on-line measurement of fluid dispensing levels in a carbonated bottling unit. In order to carry out these objectives an understanding of the different methods for container filling currently used in industry was necessary.

Methods for container filling exist for fluids that are carbonated, non-carbonated and viscous. Much of the research to date has been carried out by the dairy industry. This has been driven by financial concerns arising from high levels of waste. The milk industry is a high volume, low margin industry where an average 'give away' of just 1 ml on each pint delivered costs the industry approximately £6.2 million in lost revenue every year in 1993. In this section the common bottling techniques found in industry are outlined.

4.1 Industrial Carbonating and Filling Machines

The filling and possible monitoring of carbonated liquids (which may include still soft drinks) involves a unique set of variables revolving around high-pressure gas. World wide manufacturers, Krones (see Appendix D), are suppliers of on-line machines for labelling, inspection, filling and sealing, mixing and carbonating, washing and pasteurising, and packaging for the food industry.

4.1.1 The Mecafill Range

Krones developed a "Mecafill" short tube filling system for carbonated beverages. The machines range from mechanically controlled fillers to electro-pneumatically and computer controlled filling valves. The machines include high-pressure filling systems (with and without pre-evacuation) and low-vacuum and gravity filling systems. The Krones Mecafill short tube filling system with mechanically controlled filling valve (illustrated in Figure 4.1) demonstrates the number of filling valves that can be incorporated into bottling machine, 144 in this case. The following section describes the operation of the mechanically controlled valves.

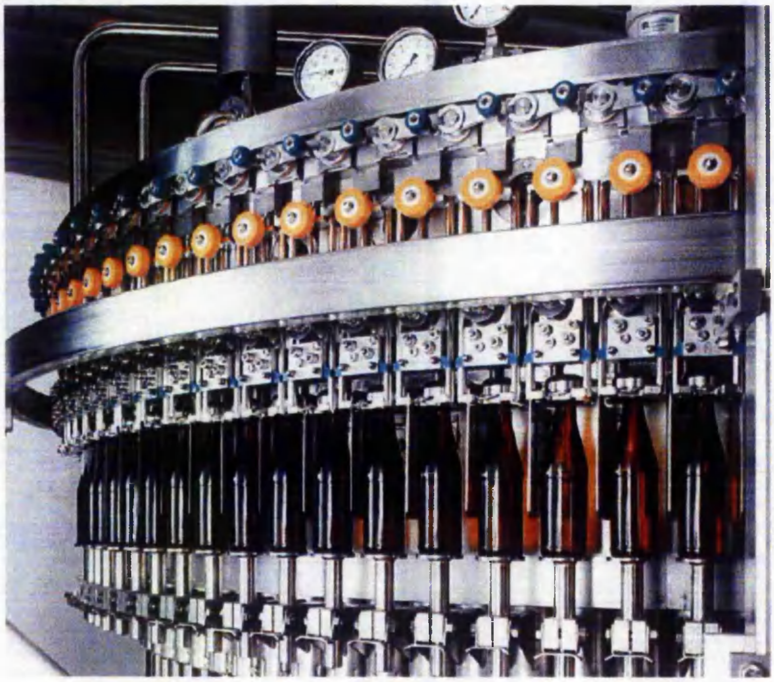


Figure 4.1 The Krones Mecafill Short Tube System

4.1.2 Filling operation

Figure 4.2 illustrates the carbonating and filling environment.

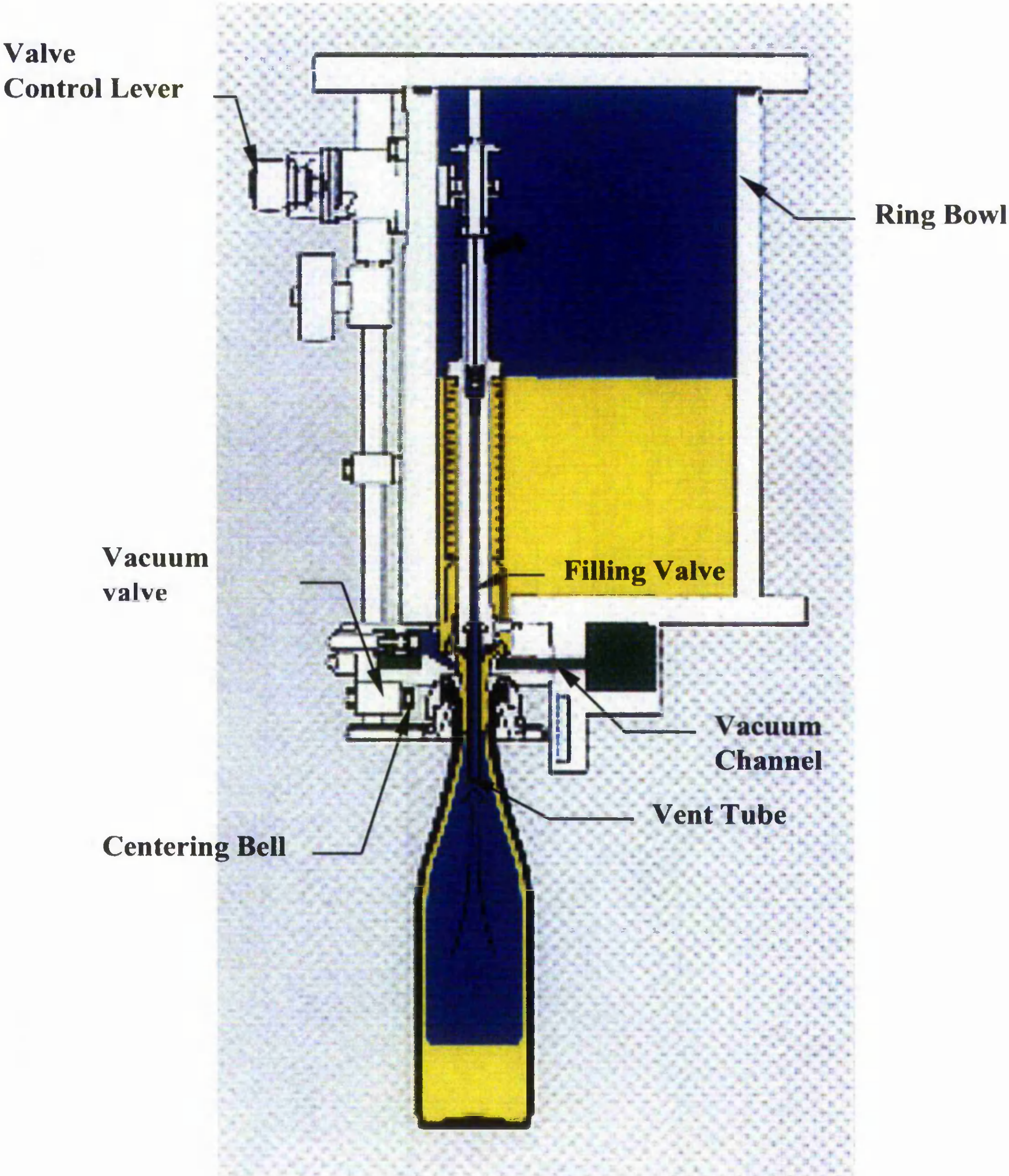


Figure 4.2 Short tube filling system with mechanically controlled filling valve

4.1.2.1 First evacuation

A pneumatic lifting cylinder elevates the bottle and presses it against the filling valve to give a gas tight seal. A fixed cam operates the vacuum valve and connects the bottle to the vacuum channel, drawing a vacuum of at least 90% in the bottle (Figure 4.3 (1)). The filling valve ensures that pre-evacuation can only be activated in the presence of a bottle. When the bottle is presented, the centring bell, making a connection between the vacuum channel and the bottle automatically opens a valve within the filling channel. Hence if no bottle is present, no vacuum is introduced.

4.1.2.2 CO_2-Flushing

Immediately following the first pre-evacuation, CO_2 is fed into the bottle from the ring bowl through the vent tube. A control lever operated gas valve that then opens for gas flow achieves this. The bottle is filled with CO_2 up to approximately atmospheric pressure, depending on bottle size, filler speed and position of the mechanical control unit (Figure 4.3 (2)).

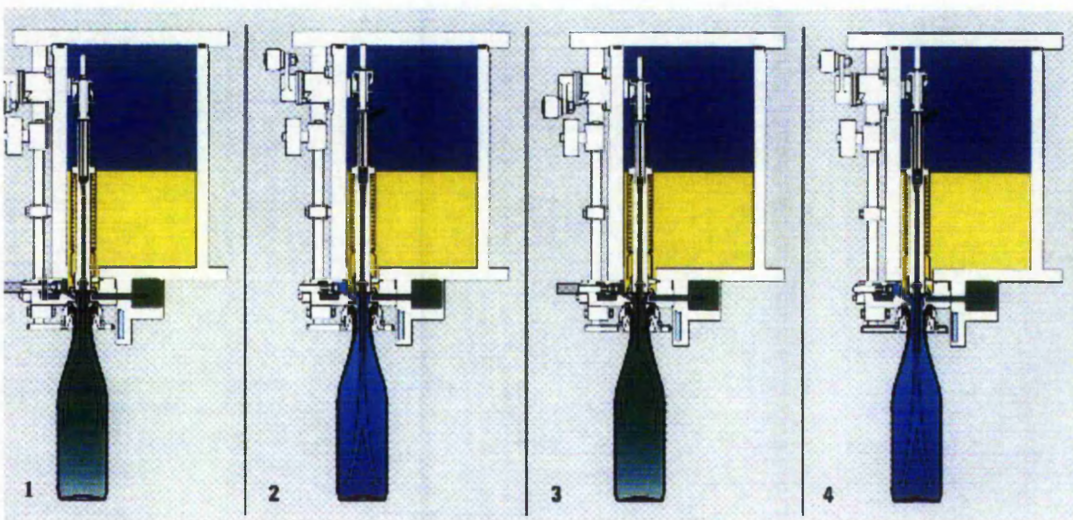


Figure 4.3 **Pre-evacuation and pressurisation process**

4.1.2.3 Second evacuation

A second fixed cam activates the vacuum valve to again produce a 90% vacuum in the same manner as the first evacuation (Figure 4.3 (3)). This guarantees a further reduction of the air content in the bottle. The feature of no bottle-no vacuum is particularly important in the phase, because otherwise a missing bottle would allow a large amount of air to enter the vacuum system. If this happened, the vacuum would break down and/ or be reduced to a rate below the required 90%. In particular, bottles adjacent to the missing one would have unacceptably high air content values.

4.1.2.4 Pressurisation

The valve control lever now opens the gas valve, similar to in the flushing phase. CO_2 gas passes from the ring bowl through the vent tube into the bottle (Figure 4.3 (4)). The pressure within the bottle increases until it equals the pressure within the ring bowl. Due to the preceding double evacuation with intermediate flushing a CO_2 concentration of 99% approximately is achieved. This high concentration in the bottle ensures low oxygen absorption during the filling process.

4.1.2.5 Filling

After the pressure equalisation between bottle and ring bowl, the liquid valve stem is lifted by the outer valve spring. A product deflected by the vent tube spreader flows down the inner surface of the bottle (Figure 4.4 (5)). The CO_2-air mixture displaced by the product is fed through the vent tube back into the ring bowl. With the valve control lever in its neutral position, the gas-valve needle that is held by a spring remains in the lifted position. In the case of bottle breakage the gas valve and the filling valve will automatically close.

4.1.2.6 Completion of Filling

As soon as the product reaches and covers the lower end of the gas return bore of the vent tube, the gas/product exchange is automatically interrupted (Figure 4.4 (6)). A siphon-type gas lock prevents the gas trapped in the bottle head from rising into the ring bowl.

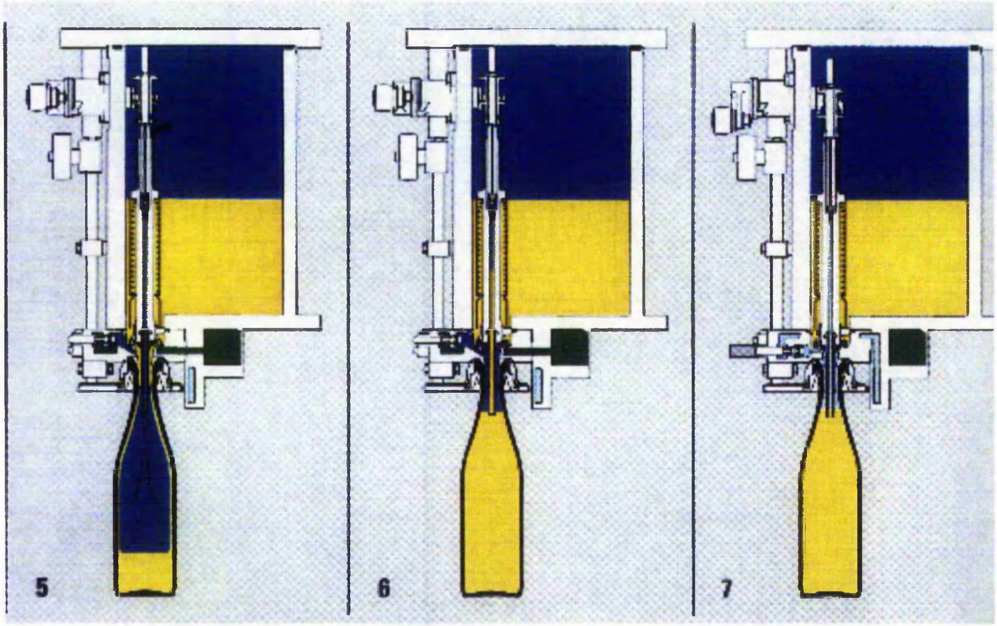


Figure 4.4 Filling and snifting process

4.1.2.7 Snifting

The final phase of the filling cycle begins with the closing of the gas valve. This is affected by moving the valve control lever towards its final position. Following this a stationary cam operates the snift valve, and through a small orifice, the gas pressure in the bottle is slowly reduced to the atmospheric pressure level (Figure 4.4 (7)). After the snifting phase, the lifting cylinders lower the bottles and transfer them to the closing turret.

4.2 The Dairy Industry: non-carbonated liquids.

Work by Peers[1993], identified the dairy industry as a possible market for an ultrasonic measuring device. A study was conducted covering types of milk, percentages of milk for sale, types of packaging and source of packaging. Peers concluded that Dawson Ltd manufactured approximately 98% of the UK market of milk bottling lines.

The manufacturer identified the need to improve the accuracy and repeatability of fill volume on their machines and for on-line process monitoring of fill volume. These measures were incorporated in a new line. These innovations led to the monitoring of the fluid dispensed but did not include any method of checking the amount put in on-line.

4.2.1 Description of a Milk Bottling Line.

In a study by [Zeng et al 1995] a description of a milk bottling line was presented to illustrate the integration of ultrasound monitoring techniques with an existing plant

4.2.2. The Filling Mechanism.

A schematic of the valve mechanism is given in Figures 4.5 & 4.6. The complete valve mechanism consists of two concentric tubes (2,5), held together by the plastic insert (1), a rubber diaphragm (3), a plastic spacer (4) and by the outer tube being welded to the header tank (6). The inner tube (5) connects to the vacuum above the milk in the header tank. The outer tube (2) carries the milk from the tank to the bottle.
When the bottle connects to the valve mechanism, the vacuum via the inner tube causes the bottle to be evacuated. As the bottle is pushed into the valve the pressure decreases in the bottle, so the rubber diaphragm deforms and milk is allowed to flow from the outer tube into the bottle.

Milk continues to flow into the bottle until the level of the milk reaches that of the inner tube. Depending upon the depth of vacuum within the inner tube an amount of milk is 'sucked' back up when the bottle pulls away from the valve mechanism.
The fill rate of the bottles is dependent upon the depth of vacuum in the header tank, the level of milk in the header tank (hydrostatic pressure will affect fill rate), speed of rotation of the tank and flexibility of the rubber diaphragm. Problems occur if there is a shortage of bottles coming onto the header tank because the vacuum is then sucking in more air reducing the depth of vacuum above the milk. (The inner tube is not closed off when there is no bottle attached to the valve mechanism.)

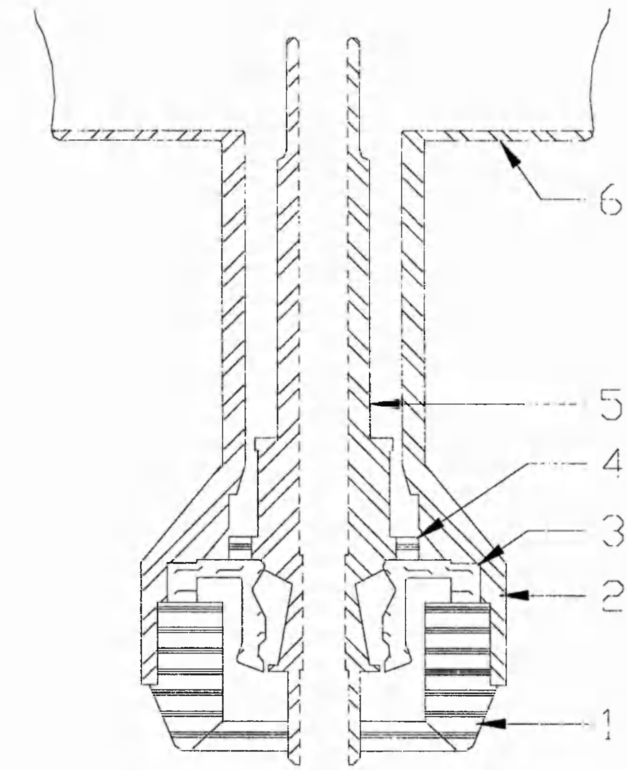


Figure 4.5 Valve Mechanism

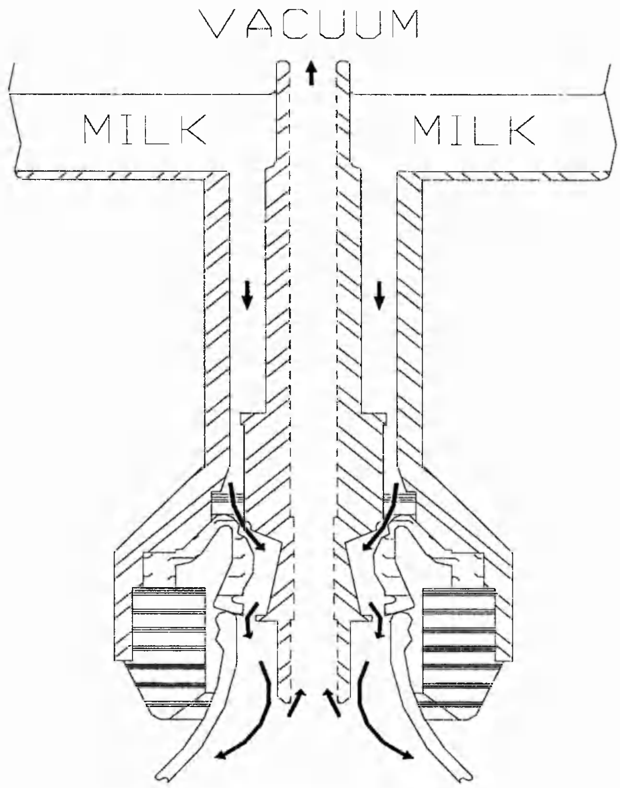


Figure 4.6 Valve Mechanism Filling

It can be seen from the complexity of the bottling line, that there is much scope for inaccurate fill level. The bottling line manufacturers have identified that accurate control of the header tank level is crucial to maintaining an accurate fill level in the bottles. Numerous experiments have been carried out to try and accurately measure this height [McMillan 1993]. If this could be achieved then the signal could be used to control the valve mechanism feeding the header tank.

The major problem in accurately measuring this level is due to foam build up on the surface on the milk. [Quirk, McMillan 1993] This foam has the unusual property of solidifying, i.e. turning into a cheese-like substance that causes havoc with instrumentation measuring the liquid level. At typical rates there are eighty gallons of milk passing through the header tank every minute. This would cause extreme turbulence exacerbating the problems caused by the foam.

4.3 British Sugar: Volumetric filling of viscous liquids.

Filling of viscous liquids requires a different process, for example that used by British Sugar. A typical bottling line fills 8 bottles at one time at a rate of 60 a minute. It uses a bottom fill operation, in so much that the filling nozzle is plunged to the base of the bottle and extracted upwards until the end of the filling stroke.

Figure 4.7 is a simplified sketch of the valve that delivers metered quantities of syrup by a combination of mechanical, pneumatic and hydraulic action.

The main piston is controlled via a camshaft that also controls the switching of an air line. As the piston draws outwards, (towards the left) air is allowed into the top air line so that the pre-metering valve at the top of the diagram is moved leftward closing the outlet and syrup is drawn into the metering chamber. At the end of the stroke the air switches to the lower inlet, moves the pre-metering valve rightwards closing the inlet. As the main piston moves rightwards, syrup is forced out to the inlet and fills the empty containers.

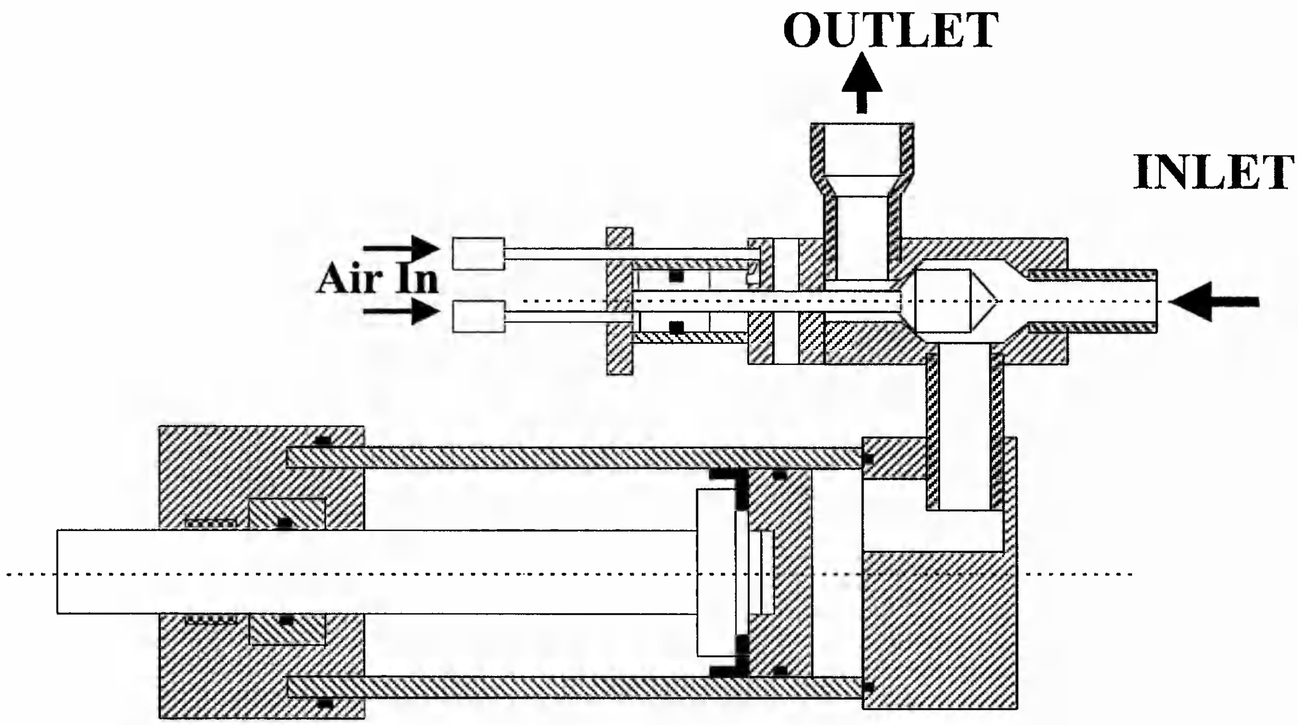


Figure 4.7. Dispensing Valve at British Sugar

The method is simple but highly inaccurate. Two locking nuts can be adjusted to alter the stroke of the main piston consequently altering the volume of fluid drawn into the chamber. The caustic nature of warm syrup, often involving the addition of cocoa powder, means that total overhaul of the valve is required every 3 months with the replacement of all O-rings and cup seals. Both the main piston and the pre-metering valve are back-washed every cycle with warm water in an attempt to reduce the corrosive effects of syrup.

Again, an ultrasonic level detection system would greatly improve the accuracy of filling, and minimises the damage resulting from the corrosive effects of the syrup.

4.4 Summary

To summarise, the carbonation filling process used by the food industry manufacturers currently is extremely complex and requires the bottles to be evacuated, flushed with CO_2 and evacuated again before filling. The use of ultrasonic sensors in this application would increase the accuracy of the fill levels, but would require careful understanding of the impact of gas and pressure on ultrasonic signals.

Different methods for container filling exists for beverages that are non-carbonated, viscous and carbonated. There are currently no high-speed on-line monitoring techniques to control the final level requirement as the filling process takes place.

The current thesis examines the application of ultrasound for measuring fluid levels in carbonated and non-carbonated liquids. The next section describes variables associated with the filling mechanism as applied to ultrasound monitoring.

Chapter 5 - Variables associated with filling and how they may affect ultrasound

Introduction

In light of the previous discussions (Chapters 1- 4) a research programme was initiated to develop a basic model for using ultrasound for fluid level detection. Research has identified certain variables involved in filling, and this section describes these variables and the effects they may have on ultrasound measurements. The variables associated with filling include transducer positioning, temperature fluctuations, and gas changes associated with carbonation, turbulence and foaming, viscosity of fluids, bubbles and others.

5.1 Basic Model

In order to understand the variables and develop a system for ultrasonic fluid level detection, a simplified experimental model set up was designed. The basic model illustrated in Figure 5.1 shows a simple set-up of the components that make up the container filling operation, illustrating the position of the ultrasound transducer on the side of the container [Griffin 1997].

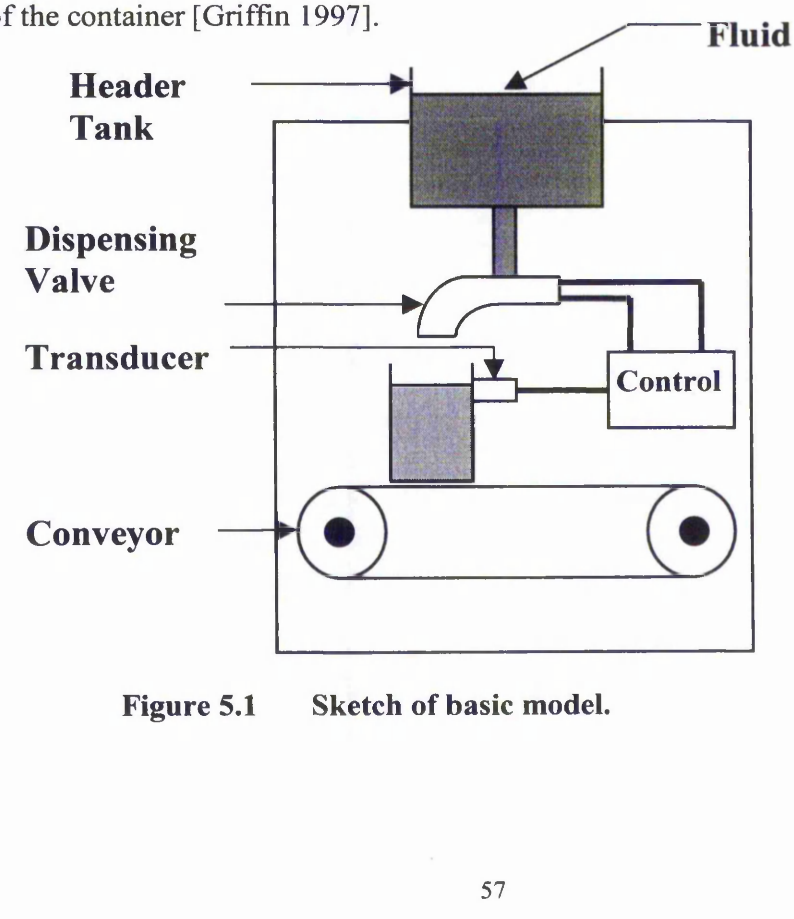


Figure 5.1 Sketch of basic model.

The basic model incorporates a fluid tank, dispensing valve, container and ultrasound transducer. Fluid substances are filled to the optimum level, as detected by the transducer, prior to transportation via the conveyor. The conveyor also illustrates the potential of feedback control, in order to regulate the filling as investigated by Ridgeway et al [1999].

A fundamental design consideration is the positioning of the sensors. Figure 5.2 illustrates the various methods of sensor positioning that are possible, namely on the side, bottom and top of the container. Part of the current objectives was to optimise sensor positioning, taking physical design constraints and response times into account. When considering the access for level measurement, the ultrasonic methods used to monitor the level can be categorised as contact, non-contact, non-invasive and non-intrusive or combinations of these.

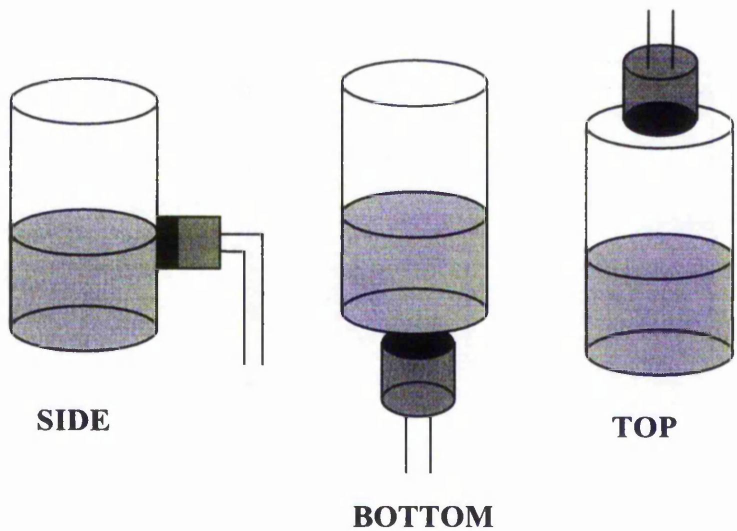


Figure 5.2 Sensor mounting positions

5.2 Transducer position and access

5.2.1 Bottom mounted sensors - Contact non-invasive techniques.

Example of contact, non-invasive techniques were described by Canongate and Peek in their trade literature. These systems use an upward-looking sonar sensor Transmitter/Receiver (Tx/Rx) to detect liquid levels. Figure 5.3 illustrates the non-intrusive model where the Tx/Rx was mounted outside the vessel. The sensor was well coupled to the vessel wall and a wedge was introduced to ensure that efficient coupling could be achieved if the vessel wall was not flat and/or horizontal at a convenient point.

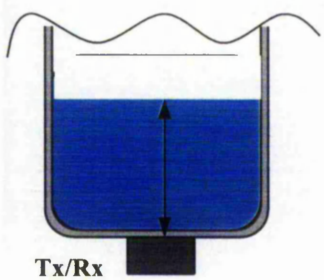


Figure 5.3 A non-invasive, non-intrusive configuration (upward Looking)

A sound emitter (transducer) is located at the bottom of a vessel filled with liquid of which the level is to be determined. The liquid surface acts as an acoustic reflector and the transducer receives the reflection of its sound pulse. The transducer is connected to a transmitter where the sound pulse originates and to a receiver into which the echo is received. The transmitter and receiver are both connected with a time interval counter that measures the elapsed time between the emission of the sound wave and the reception of the corresponding echo. The elapsed time can be converted into units of level of liquid that can be read from the reading or readout devices.

5.2.2 Side mounted sensors - Point Level Detectors

The ultrasonic methods using side-mounted transducers are referred to as point level detectors (PLD). Figure 5.4 illustrates side mounted sensors used for PLD; the role of a PLD is to detect whether the level of a liquid, sediment or a dry product is above or below a particular point.

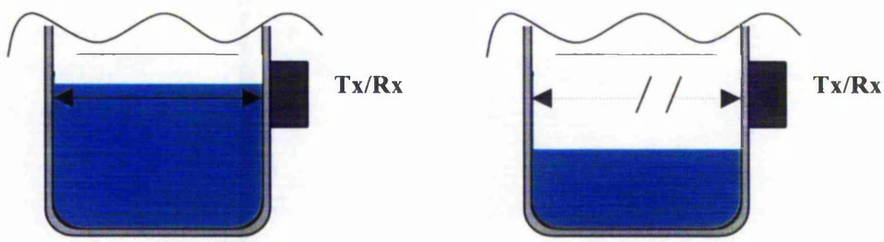


Figure 5.4 Side mounted transducers

Side mounted sensors generate ultrasonic signals that can be used as in the far wall echo approach. A typical ultrasonic signal is shown in Figure 5.5 [Griffin 1997]. The dead zone is significant as no returning echoes can be processed within this small distance in front of the sensor. The time gate indicates the band in which a returning echo, if returned, represents the presence of fluid.

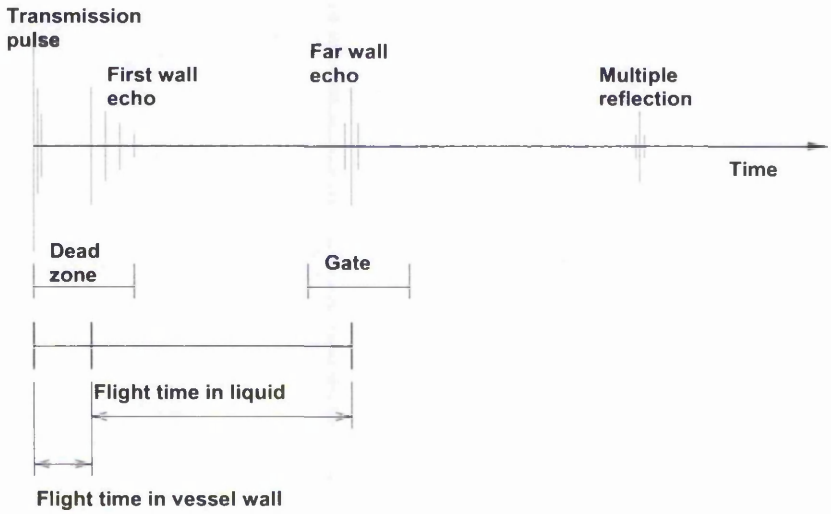
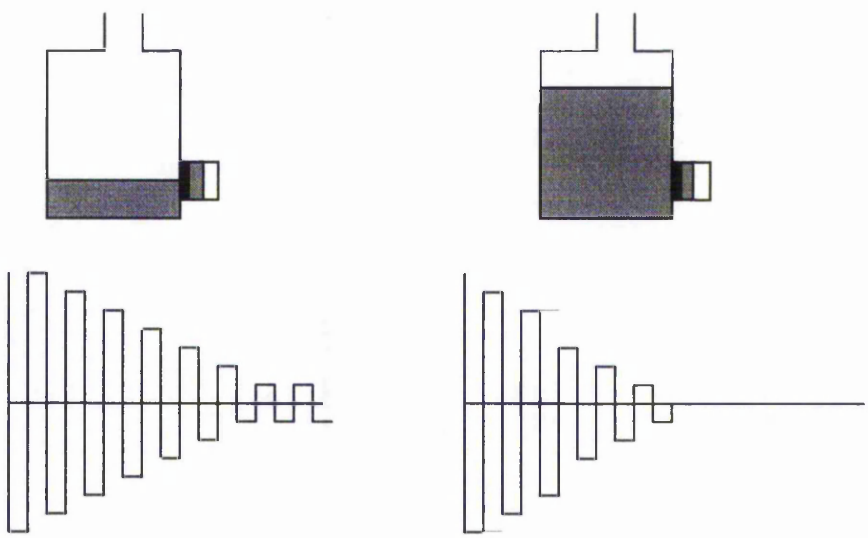


Figure 5.5 Far Wall Echo Principle

If a contact transducer is acoustically coupled to the side of a container and excited with a pulse, an echo will be detected a short time after denoting the first wall. If a liquid is present between the transducer and the far wall of the container a shorter dampened echo will be detected a period of time after, (dependent on the diameter or width of the container) detecting the presence of the far wall. This principle is advantageous since it gives a clear response. However there are problems due to the fact that good coupling is required for every repeated measurement, and accurate alignment is required between transmitter and receiver. Signal strength may be affected by attenuation caused by bubbles or turbulence (filling, mixing).

Fluid levels can also be detected using the wall resonance approach, where sensors are mounted on the side of the vessel (Figure 5.6).



Tank empty: long ringing time

Tank full: short ringing time

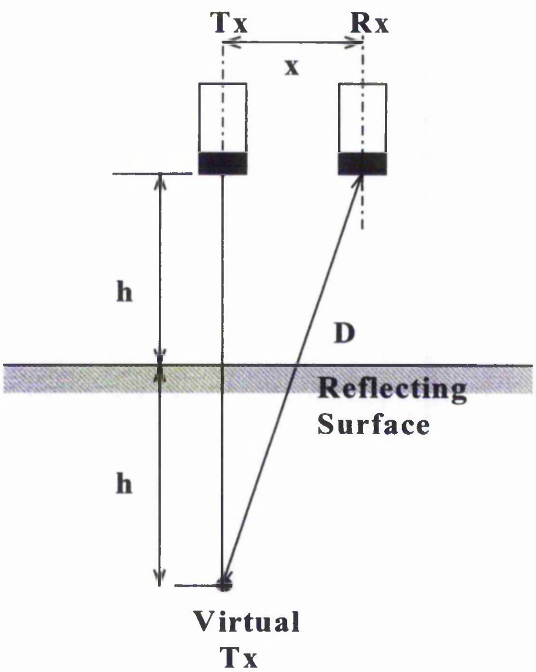
Figure 5.6 Wall Resonance Principle

The sensor is acoustically coupled to the vessel wall by means of a paste (couplant), and generates a short ultrasonic pulse, which causes a local resonance in the vessel wall. When the pulse ends, the resonance dies away, whereby the ringing time depends upon whether or not the liquid is to be found immediately behind the sensor.

The sensor, which now operates as a receiver, measures the ringing time and generates an empty or full signal as appropriate.

5.2.3 Top mounted sensors (non-contact)

The air transmission approach is a term that describes an ultrasound technique used when sensors are mounted at the top of a container or vessel. The following diagram (Figure 5.7) illustrates how the time of flight (TOF) can be used to calculate distances (the level) of a reflecting surface [Griffin 1997].



x = Distance between transducers.

h = Height above reflecting surface.

D = Calculated distance from TOF received.

$$x^2 + (2h)^2 = D^2$$

$$h^2 = \frac{D^2 - x^2}{4}$$

$$\therefore h = \frac{\sqrt{(D^2 - x^2)}}{2}$$

Figure 5.7 Air Transmission Principle

5.2.4 Summary of advantages and disadvantages of bottom mounted / side mounted (PLD/Resonance) and top mounted (Air Transmission) ultrasound sensors

In the previously discussed techniques where the transducers were side or bottom-mounted, a couplant was required as a sound propagation medium between the transducer and the reflecting surface. In addition, slight changes in the dimensions of the walls or base of vessels caused contact problems and therefore loss of ultrasound signal. The air transmission technique has the advantage that no couplant is required, but poses another obstacle. Air is a reasonably good sound carrier in the frequency region of interest. However the acoustic impedance of air differs from the acoustic impedance of transmitter and reflecting medium. This results in most of the acoustic energy being absorbed through scattering, and only a very small fraction of that energy being reflected to the receiver. One solution to overcome this problem without introducing an additional sound transmitting medium consists in generating high enough sound levels and to use high-gain, low-noise amplification.

The clear advantage of mounting the sensors at the top of the vessel is that no couplant was required and any irregularities present in the vessel walls or base had no intrinsic effect. Thus, this technique was employed for the current research project.

5.3 Effects of variables on ultrasonic transmission through air

5.3.1 Effects of temperature

Many variables will affect the ultrasound signal, many of which relate to the carbonation environment. There are two major problems that are likely to arise from using ultrasound. The velocity of the signal will vary due to temperature and/or density fluctuations of the propagating medium, and the attenuation of the signal may be so much as to render the system unusable. Canali et al [1992] explored the effect of temperature on ultrasound and demonstrated that as the temperature rises the echo amplitude decreases, and the speed of sound increases, e.g., temperature change from 25

– 90 °C altered the speed of sound from 337m/s to 378m/s (Table5-1/Figure 5.8). Thus, temperature would have to be controlled in the current experimental model.

Table 5-1 Effect of Temperature on Sonic Velocity

Temperature (C)	Echo Amplitude (mV)	Echo Delay (ms)	Speed (m/s)
25	40	0.83	337.35
30	40	0.80	350
40	39	0.79	354.43
50	38	0.78	358.97
60	37	0.77	363.64
70	30	0.76	368.42
80	25	0.75	373.33
90	22	0.74	378.38

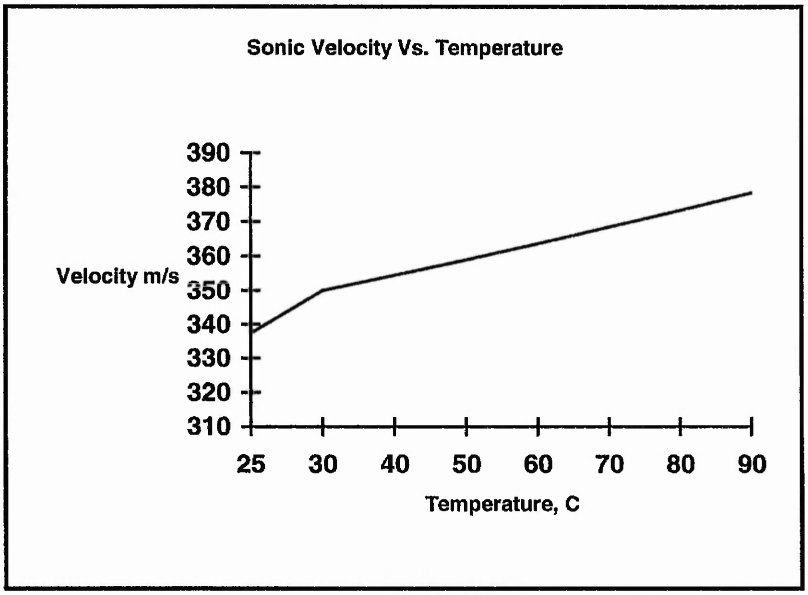


Figure 5.8 Effect of Temperature on Sonic Velocity [Canali 1992]

The table gives the results of an experiment of measuring the velocity of pulses reflected from a target 14 cm away. These experimental results confirm, to a first approximation, the theoretical temperature relationship of sound velocity in air (0.16%/C) [Soltz 1989].

This work confirms that for the use of ultrasound that temperature compensation of some form must take place. This can be done in two ways, either by discrete temperature measurement or by using a comparative technique. The simplest technique is to use a reflector at a known fixed distance from the transducer and a simple ratio calculation can then be used to establish the distance to the fluid surface [Soltz, 1989].

5.3.2 Gas mixtures and pressure

Gases are generally rather attenuating in the MHz range, typically above 5MHz. The attenuation usually elevates as the frequency is increased, and the presence of humidity and dust exacerbates the problem. Therefore sensors in gas generally operate at low frequencies. This problem is illustrated by the use of carbon dioxide in sonar sensors, since it attenuates ultrasound signals severely at the frequency used in sonar. This is also a problem in fermentation vessels if the concentration of carbon dioxide in the ullage exceeds 5% [Denbow 1988]. To compensate for this, if the frequency is lowered to 50 kHz, transmission can be achieved successfully through pure carbon dioxide at atmospheric pressure if the transmission path is approximately 10cm [Lynnworth 1995b].

In air, (in which case the sensors are often called 'airborne'), very low frequencies of approximately 8 kHz are required to achieve long transmission ranges of up to 60 m from which the pulses are often clearly audible. Many long-range sensors use frequencies below 40 kHz.

Higher frequencies of around 215 kHz have been used when long-range is not a requirement. At a higher frequency the wavelength is shorter and hence resolution greatly improved. The wavelengths in air are roughly 28 mm at 10 kHz, 7 mm at 40 kHz and 1.3 mm at 215 kHz.

Another advantage of using high frequency is that interference from plant and factory noise is more often avoided; this noise tends to be of lower frequency.

The practical range of any sensor is greatly affected by the presence of stratified temperature layers, dusty gases, ripples or waves on liquid target surfaces and the nature of solid target surfaces (i.e., their coarseness and hardness)

Gas pressure is another variable to be considered due to its effects on ultrasound. The pressure range for sensors used in air is generally 0.25 bar to 5 bar. At lower pressures the attenuation tends to be the restricting factor and at higher pressures the transducer may fail mechanically. In such instances transducers must be specially designed to operate at high pressure, for example transducers that operate at 100 bar for use in gas flow meters (Lynnworth 1995b).

Therefore, initial experiments would need to be undertaken to understand the impact of gas mixtures and pressures on ultrasound signals (at resonance frequency of specially designed transducers), prior to looking at fluid level monitoring.

5.3.3 Turbulence

Turbulence may have the effect of destroying an ultrasound signal. Correct focusing of the ultrasound sensor is required to direct the sensor away from the area of turbulence. Turbulence can cause ripples on the reflecting surface or the inclusion of bubbles within the liquid.

5.3.3.1 Ripples

Turbulence during filling may create ripples on the reflecting target surface, and intermittent signals could arise due to echoes not being received or spurious echoes being received. A stilling tube is an effective method of reducing destructive interference (Figure 5.9). The tube can also act as a wave guide to prevent spurious signals.

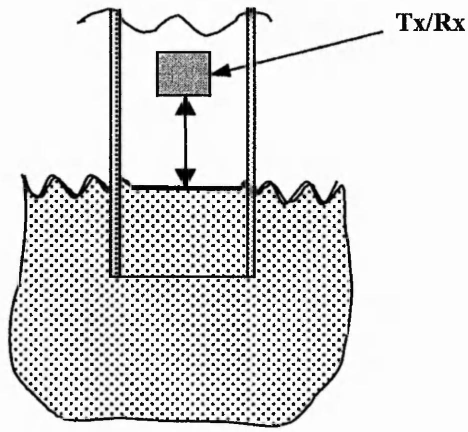


Figure 5.9 Example of the use of a stilling tube

5.3.3.2 Bubbles

Bubbly liquids are highly attenuative unless the concentration of bubbles is low. If a bubbly liquid needs to be studied, low frequency ultrasound or even audible sound is often used. Furthermore, it is important to avoid frequencies that cause the bubbles to resonate. When these conditions apply the salient points can be summarised schematically by Figure 5.10

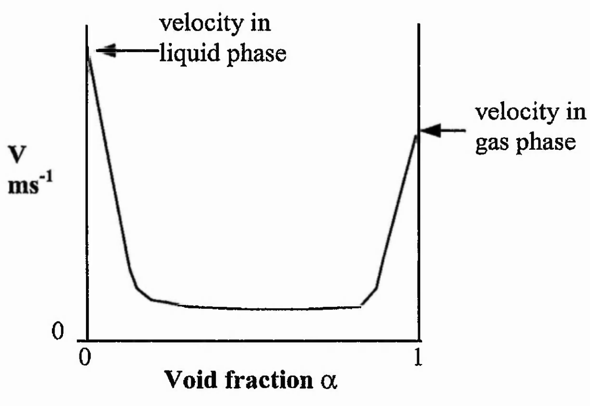


Figure 5.10 The behaviour of ultrasound in a bubbly liquid (void fraction is the volume fraction of the gas or vapour phase). (a) Velocity versus void fraction [Asher 1997].

From Figure 5.10, it is clear that the presence of a very small amount of gas dispersed in a liquid decreases the velocity enormously compared with that in the bubble free liquid. The velocity rapidly decreases to a low value, and this value can be lower than the velocity of sound in the gas itself. At high void fractions, when the medium begins to approach a froth or foam, the velocity rises again until ultimately, as expected, it attains the velocity of sound in the gas itself.

The effect of bubbles in reducing the velocity of ultrasound below that in the bubble-free liquid becomes less dramatic at higher frequencies. At the same time, the bubbly liquid becomes even more attenuating.

5.3.4 Other variables

There are additional variables associated with the filling process that cause similar symptoms to those already discussed. These variables are often a result of the process speed and bottle positioning during filling, where airtight fluidity of ultrasound transmission is required. Ultrasonic pastes or gels are required to minimise acoustic impedance mismatch between interrogated measurand. Hence, with a rapid process speed the required contact is a problem.

1) Residue and build up. Although residue on ultrasonic sensor surfaces can result in diminished signal strength the methods illustrated previously use non-invasive techniques therefore there is no direct contact between any fluid material and the probe.

2) Foam. Liquid-gas interfaces are usually relatively easy to detect. This is because of the high acoustic impedance mismatch that is almost invariably found between liquids and gases.

3) If floating material is present, then a returning echo may have greatly reduced amplitude. Also it will detect the underside of the floating material; this means that, for example, a thick layer of foam on the top of a liquid may be ignored.

5.3.5 Summary of affecting variables

- It is necessary to understand impacts of temperature on ultrasound signals and introduce the concept of temperature compensation in order to obviate its effect.

- It is necessary to understand the impact of gas mixtures and pressure on ultrasound signal strength and time of flight measurements, in order to determine the validity of the use of top mounted sensors.

- It is necessary to accommodate an appreciation of the effects of turbulence and compensatory methods to minimise/obviate its effect.

A study of ultrasonic methodology and equipment presented in the next section, describes the different facets of system requirements required to develop an ultrasound level measurement tool.

Chapter 6 - Development of an ultrasound detection system.

6.1 Familiarisation of Ultrasound Inspection Equipment

Introduction

From chapters 4 and 5 it was clear that the carbonating and bottling environment would pose many variables to affect the ultrasound signal. These variables included temperature, gas mixtures, gas pressure and turbulence. The development of an off-line ultrasound monitoring system would allow these variables to be determined experimentally. Ultrasonic equipment would have to be chosen for the specific needs of this research project. This section describes different ultrasound equipment available commercially ('off the shelf') and experimentally verifies its usefulness.

6.1.1 Basic Inspection Methods

The vast majority of ultrasound equipment available commercially was developed for non-destructive testing. For an introduction into the complexity of associated requirements for ultrasound equipment an appreciation and investigation of this type of equipment was necessary.

Ultrasound can be used to detect flaws in materials by measuring (a) intensity and time of flight of reflected sound waves having a single frequency, (b) intensity of either transmitted or reflected sound waves or (c) intensity and time of flight of reflected sound waves having varying frequencies. The first of these is a pulse-echo method that is the most widely used of all ultrasonic methods. However, echoes from flaws are not essential to their detection. Merely the fact that the intensity of the back reflection from a test piece is lower than that from an identical work-piece known to be free of flaws implies that the test piece contains one or more flaws.

This second method of detecting the presence of flaws - that is by sound attenuation - is used in transmission methods as well as in the pulse echo method. The main disadvantage of attenuation methods is that flaw depth cannot be measured.

The third, which was the precursor of the pulse-echo method, is known as the frequency modulation (FM) method. In this technique the ultrasonic pulses are transmitted in wave packets whose frequency varies linearly with time. The frequency variation is repeated in successive wave packets resulting in a plot of frequency versus time that has a saw-tooth pattern. There is a time delay between successive packets. Returning echoes are displayed on the readout device only if they have certain characteristics as determined by the electronic circuitry in the instrument. Although the FM method is less frequently used than the pulse-echo, the FM method has a lower signal-to-noise ratio and therefore has somewhat greater resolving power.

6.1.2 Principles of the Pulse-Echo Method

The most widely used of all ultrasonic methods to measure time of flight (TOF) is the pulse echo method and is the method explored and developed for the purpose of level measurement.

The pulse-echo method uses short bursts of ultrasonic energy, pulses or wave packets. If pulses encounter a reflecting surface, some or all energy is reflected back. The system comprises (a) an electronic clock; (b) an electronic signal generator; (c) a sending transducer; (d) a receiving transducer; (e) an echo signal amplifier and (f) a display device.

A pulse-echo system with a signal transducer operates as follows. At regular intervals, the electronic clock triggers the signal generator, which imposes a short burst of high frequency alternating voltage on the transducer. Simultaneously, the clock activates a time measuring circuit connected to the display device. The operator pre-selects a constant interval between pulses by means of a "pulse-repetition rate" control on the instrument; pulses are usually repeated 60 to 2000 times per second. The operator may also pre-select the output frequency of the signal generator. For best results, the frequency (and sometimes the pulse repetition rate) should be tuned to achieve the maximum response of the transducer (resonance in the vibrating element) and maximum signal-to-noise ratio (lowest amount of signal noise) in the electronic equipment. The transducer converts the pulse of alternating voltage into a pulse of mechanical vibration having essentially the same frequency as the imposed alternating voltage. The mechanical vibration (Ultrasound) is introduced into a test piece through a couplant, and travels by wave motion through the test piece at the speed of sound. When the pulse of ultrasound encounters a reflecting surface that is perpendicular to the direction of travel, ultrasonic energy is reflected and returns to the transducer. The returning pulse travels along the same path and at the same speed as the initial pulse, but in the opposite direction. Upon reaching the transducer through the couplant, the returning pulse causes the transducer element to vibrate, which induces an alternating electrical voltage across the transducer. The induced voltage is instantaneously amplified (and sometimes demodulated), then fed into the display device. This process of alternately sending and receiving pulses of ultrasonic energy is repeated for each successive pulse, the display device recording any echoes each time.

6.2 Data Presentation

Information from pulse-echo inspection can be displayed in one of three forms; (a) A-scan, which is a quantitative display of intensity and time-of-flight data obtained at single point on the surface of the test piece; (b) B-scan, which is a quantitative display of time-of-flight data obtained along a line on the surface of the test piece; or (c) C-scan, which is a semi-quantitative display of echo intensity obtained over an area of the surface of the test piece.

6.2.1 A-scan display

An A-scan display represents a plot of amplitude versus time, in which a horizontal base line on an oscilloscope screen indicates elapsed time while the heights of vertical deflections (called indications, pips or blips) represent intensities of echoes. An estimate of flaw size can be determined by comparing the height of a discontinuity blip with that of a blip from a discontinuity of known size and shape. Flaw location (depth) is determined by comparing the horizontal position of a flaw indication on the oscilloscope screen with the positions of two major indications that represent the front and back surfaces of the test piece.

A-scan data can be displayed in either of two modes - radio-frequency (RF) mode, in which the individual cycles comprising each pulse are visible in the trace; or video mode, in which only a rectified voltage corresponding to the envelope of the RF wave packet is displayed.

A typical A-Scan set-up that illustrates the essential elements in a basic system for a pulse-echo inspection is shown in Figure 6.1.

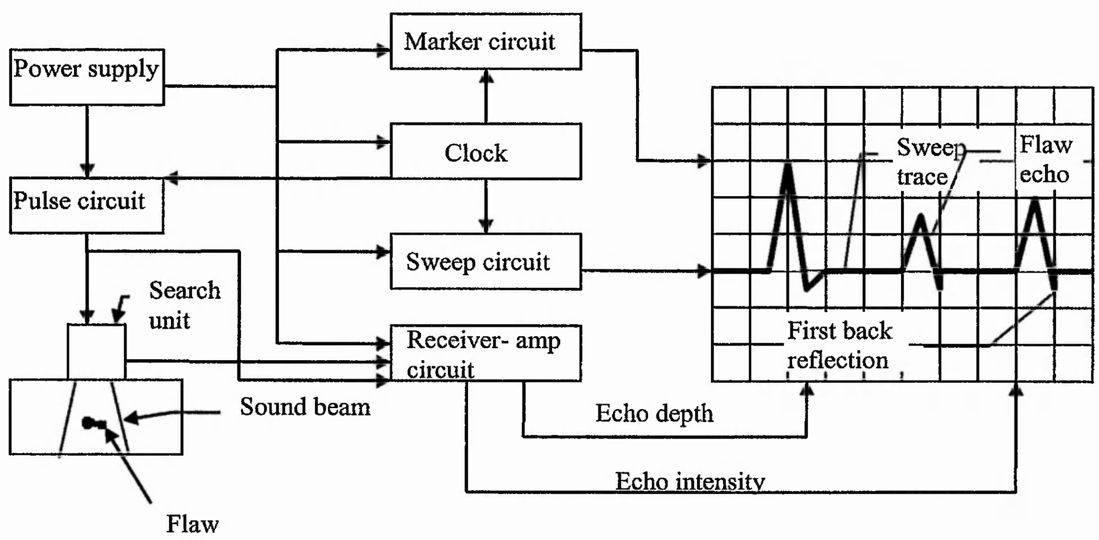


Figure 6.1 Typical A-scan set-up, including video mode display, for a basic pulse-echo ultrasonic inspection system

The elements of the above system include:

1 Power supply, which may run on 110 volt alternating current or on batteries.

2 Electronic clock, or timing circuit, to trigger pulser and display circuits.

3 Pulser circuit, or rate generator, to control frequency, amplitude and pulse repetition rate of the voltage pulses that excite the search unit.

4 Receiver-amplifier circuit to convert output signals from the search unit into a form suitable for oscilloscope display.

5 Sweep circuit, to control (a) time delay between search unit excitation and start of oscilloscope trace and (b) rate at which oscilloscope trace travels horizontally across the screen.

6 Marker circuit (optional) to produce a secondary trace, on or below the main trace, usually in the form of a square wave, which is used for precise depth measurements.

7 Oscilloscope screen, including separate controls for trace brightness, trace focus and illuminated measuring grid.

The oscilloscope screen in the above Figure 6.1 illustrates a typical video mode A-scan display. The trace exhibits a large blip corresponding to the initial pulse (or front reflection), shown at left on the screen, and a smaller blip corresponding to the first back reflection, at right on the screen. Between these two blips are indications of echoes from any interfaces within the test piece, one small blip corresponding to the flaw shown. The depth of the flaw can be quickly estimated by visual comparison of its position on the main trace relative to the positions of the initial pulse and back reflection.

The A-scan display is not limited to the detection and characterisation of flaws; it can also be used for measuring thickness, sound velocities in materials of known thickness, attenuation characteristics of specific materials, and beam spread of ultrasonic beams.

6.2.2 B-Scan display

A B-scan display consists of a plot of time versus distance. One orthogonal axis on the display corresponds to elapsed time, and the other axis represents the position of the transducer along a line on the surface of the test piece, relative to the position of the transducer at the start of the inspection. A B-scan display can be likened to an imaginary cross-section through the test piece, where both front and back surfaces are shown in profile.

The system functions of the B-scan display are identical to the A-scan system except for the following differences:

1. The display is generated on an oscilloscope screen that is composed of a long persistence phosphor. A phosphor continues to fluoresce a long time after the means of excitation ceases to fall on the fluorescing area of the screen. This characteristic allows the imaginary cross section to be viewed as a whole without having to resort to permanent imaging methods such as photographs.

2. The oscilloscope input for one axis of the display is provided by an electromechanical device. This generates an electrical voltage proportional to the position of the transducer relative to a reference point on the surface of the test piece. Most B-scans are generated by scanning the search unit in a straight line across the surface of the test piece at a uniform rate. One axis of the display, usually the horizontal axis, represents the distance travelled along this line.

3. Echoes are indicated by bright spots on the screen rather than by deflections of the time trace. The position of a bright spot along the axis orthogonal to the search-unit position axis, usually measured top to bottom on the screen, indicates the depth of the echo within the test piece.

4. To ensure that echoes are recorded as bright spots, the echo intensity signal from the receiver-amplifier is connected to the trace brightness control on the oscilloscope. In some systems, the brightness corresponding to different values of echo intensity may exhibit enough contrast to enable semi-quantitative appraisal of echo intensity, which is related to flaw size and shape.

The chief value of B-scan presentations is their ability to reveal the distribution of flaws in a part on a cross section of that part. B-scan techniques have been more widely used in medical applications than in industrial applications. They can be used for the rapid screening of parts, and for the selection of certain parts or portions of certain parts, providing a more thorough inspection than A-scan techniques. Optimum results from B-scan techniques are generally obtained with small transducers and high frequencies.

6.2.3 C-Scan display

A C-scan display records echoes from internal portions of test pieces as a function of the position of each reflecting interface within an area. Flaws are shown on a read out, superimposed on a plan view of the test piece, and both flaw size (flaw area) and position within the plan view is recorded. Flaw depth normally is not recorded, although it may be measured semi-quantitatively by restricting the range of depths within the test piece that is covered within a given scan.

In a basic C-scan system, the search unit is moved over the surface of the test piece in a search pattern. The search pattern may take many forms, for example a series of closely spaced parallel lines, a fine zigzag pattern or a spiral pattern (polar scan). Mechanical linkage connects the search unit to the X-axis and Y-axis position indicators, which in turn feed position data to the X-Y plotter or facsimile device. Echo-recording systems vary; some produce a shaded line scan with echo intensity recorded as a variation in line shading, while others indicate flaws by an absence of shading so that each flaw shows up as a blank space on the display.

An electronic depth gate is another essential element in C-scan systems. A depth gate is an electronic circuit that measures time of flight data and allows only those echo signals that are received within a limited range of delay times following the initial pulse to be admitted to the receiver-amplifier circuit. Usually, the depth gate is set so that front reflections and back reflections are just barely excluded from the display. Thus, only echoes from within the test piece are recorded, except for echoes from thin layers adjacent to both surfaces of the test piece. Depth gates are adjustable. By setting a depth gate for a narrow range of delay times, echo signals from a thin slice of the test piece parallel to the scan surface can be recorded, with signals from other portions being excluded from the display.

Some C-scan systems particularly automatic units, incorporate additional electronic gating circuits, for marking, alarming or charting. These gates can record or indicate information such as flaw depth or loss of back reflection, while the main display records an overall picture of flaw distribution.

6.3 Flaw detectors

There is a wide variety of flaw detectors which range from small portable instruments for field work to large mains operated assemblies used typically in laboratories and production lines. Figure 6.2 depicts the analogue display on the screen of an ultrasonic flaw detector containing an electrostatic type of cathode-ray tube.

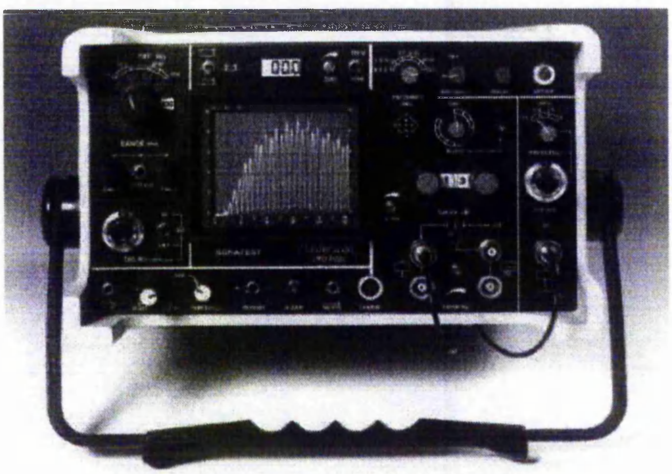


Figure 6.2 Sonatest Masterscan 310D Advanced Materials Flaw Detector (analogue)

Figure 6.3. depicts the more recently developed High Brightness, Colour TFT (thin film transistor) LCD display, Eight colour combinations with brightness variable.

Figure 6.3 Sonatest Masterscan 330 (digital)

The operation of digitised instruments is based on conversion of the continuously variable output of conventional analogue signals to digital form, by sampling them at regular intervals. If these signals are sufficiently short, the display bears a close resemblance to that obtained from the analogue signals. With this process, the original analogue signals are reduced to a series of digits that are then converted into binary numbers, or bits. Once the signals are in a digital form they are suitable for processing by means of a computer and then can be conveniently stored [Highmore and Short, 1988].

Digitised ultrasonic flaw detectors can achieve high degrees of resolution by using thousands of samples with sampling frequencies up to 200 Hz. The output is displayed on the screen in the form of hundreds of pixels, each one of which contains a group of perhaps 15 samples. The screen display changes at a rate of 50 kHz or more so as to provide steady indications. For tests over a short range of 10 mm, the pixel dimension is of the order of 0.05 mm and it is thus possible to obtain a greater accuracy in measurement than with an analogue display, especially as readings are displayed numerically on the screen and thus do not require judgement by the eye (Figure 6.4 Display).

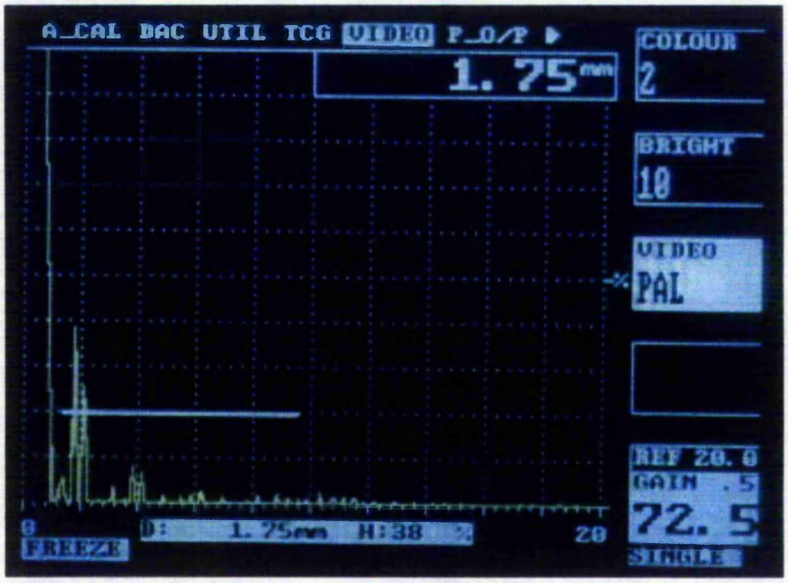


Figure 6.4 An example of the Sonatests masterscan 330 display

6.3.1 Advantages and disadvantages of the use of digitised displays

The advantages of converting analogue signals to digital ones are that all of the signals can be stored for future use and that images can be processed either to enhance or suppress certain features. This could be done with analogue signals but with more difficulty. Advantages of digital types of equipment include automated calibration techniques enabling the operator to achieve a correct calibration in one or two easy steps. Self-calibration takes place during operation; once the calibration is established, the instrument automatically corrects itself and, if unable to do this, a warning is signalled. In the digital system, the measured values are displayed in numerical form, which benefits the user because he is not required to read the position relative to that of the graticule by the eye. This would be difficult to achieve accurately. It is also possible to have these readings transferred to a 'head-up' display on a visor, which allows the operator to turn away from the set to concentrate on moving the probe and still see the indications.

Additional readings on the digital display include surface distance, beam path, and depth and thickness of the plate, when working with an angle probe, provided that the angle is known.

- Calibrations and details of the necessary parameters can be stored in a memory bank and recalled when required.
- The display on the screen can be 'frozen' at any time with the A-scan information remaining on the screen until the controls are operated again.
- The display can be 'peaked' (the positions of the peaks of the echoes located) so as to build up an envelope of the echoes as the probe is moved over the required range, after which the display is 'frozen'. This allows the operator to comply with British Standard BS 3923.
- Because the brightness of the screen is not affected by the pulse repetition frequency, as with analogue displays, it remains constant when the range is reduced.
- Readings can be taken at either the flank, the leading edge of the echo, or the peak. With analogue displays, the standard reading position is the leading edge which moves as the echo height rises and falls due to changes in signal amplitude. On the other hand, with digital displays, the peak height remains constant irrespective of any changes of the value of the signal amplitude and there is thus no need to maintain the height at fixed level; (e.g., 80% full screen height).
- The use of noise reduction can ensure that only genuine echoes appear on the screen.
- With the time-corrected gain (TCG), up to 20 reference echoes can be amplified to indicate constant heights over the required range.
- The instrument can be calibrated and then locked to prevent tampering.
- Digitised screen displays can be transferred to video recorders personal computers and television monitors.
- The use of digitisation enables printouts of test data in different languages.
- Interfacing to personal computers and modems, so as to record or analyse results, can be made.
- Circuit boards and extra chips can be easily added to accommodate future accessories.

Disadvantages of the use of digital equipment are few. One disadvantage arises from the complexity of the equipment and the necessity for operator training. Another is the longer response time compared with that of analogue equipment which can be considered a drawback with the use of automated systems. It should also be mentioned that the industry has invested heavily in the more conventional analogue flaw detectors and they are unlikely to be discarded in favour of digital instruments until it is economically feasible to do so.

6.3.2 Commercially available flaw detection equipment

As part of the current research it was necessary to become familiar with commercially available equipment. This was made possible making use of a Krautkramer USD10 and an analogue control IIB Sonatest pulse echo display unit (see Appendix B). A variety of transducers, 2-5 MHz dual and single acting and standard reference blocks gave an insight for the correct interpretation of returning echo displays.

Krautkramer and Sonatest are two of the world's largest designers, manufacturers, and marketers of high technology ultrasonic instruments and transducers. These instruments utilise ultrasound to examine the internal integrity of metals, plastics, and composite materials. The Krautkramer instrument product line includes flaw detectors, thickness gauges, hardness testers, and inspection systems. Sonatest provide a range of equipment and accessories, specialising in Analogue Flaw Detectors which are often preferred since the equipment provides a faster response and better performance for specialised applications.

The products are used mainly to test materials such as steel or plastic for cracks and defects, and to measure material thickness either as part of a manufacturing cycle or during the life of a product or component.

Each of the flaw detectors and thickness gauges requires a piezoelectric transducer to convert electrical impulses to acoustic energy. The resultant sound wave propagates through the material under test until reflected by a crack, inclusion, disbond or the boundary of the part under test. The reflected acoustic wave is reconverted to electrical energy by the transducer. The lapsed time and amplitude of the reflection yields information about the thickness and/or integrity of the part.

Ultrasonic flaw detection and thickness measurement has applications in most industries.

For example:

- In-line inspection in the manufacture of primary metals to detect defects and wall thickness of tubes, pipes, bars and billets.
- Flaw detection is used during welding, in nuclear, construction and automotive industries. Both new welds and welds re-tested after service are inspected for defects.
- Flaws are detected using ultrasound in the aerospace industry (Airframe and Engines, Military and Civilian). Critical components are inspected during manufacture, and as an in-service inspection to check for fatigue or corrosion defects.
- In the chemical and petroleum industry the thickness in pipe work is monitored to insure that corrosion or erosion does not lead to a dangerous situation.

6.4 Development of an ultrasound monitoring system using flaw detection equipment.

As part of the current project, experiments were undertaken to verify the use of ultrasound to detect fluid level and to determine possible accuracy. For this purpose the Krautkramer USD 10 equipped with a standard serial interface RS232C was employed (Figure 6.5).

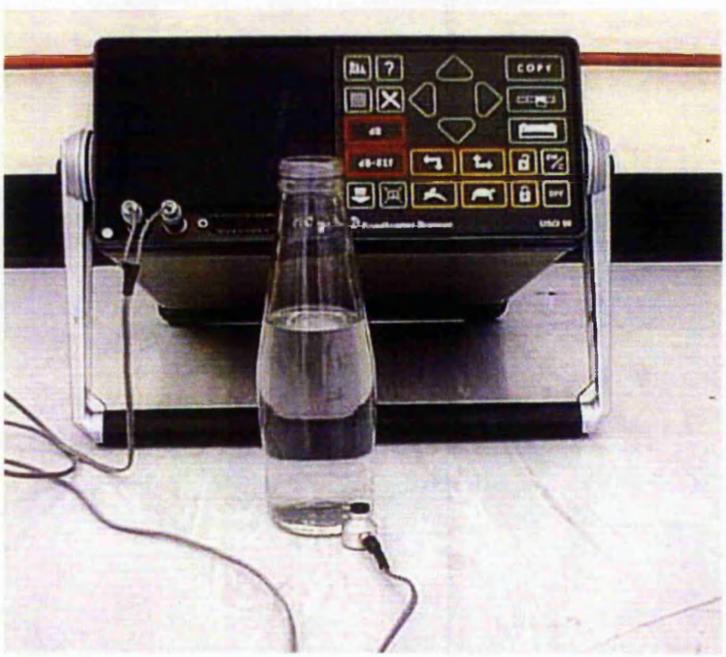


Figure 6.5 The Krautkramer USD10 digital flaw detector

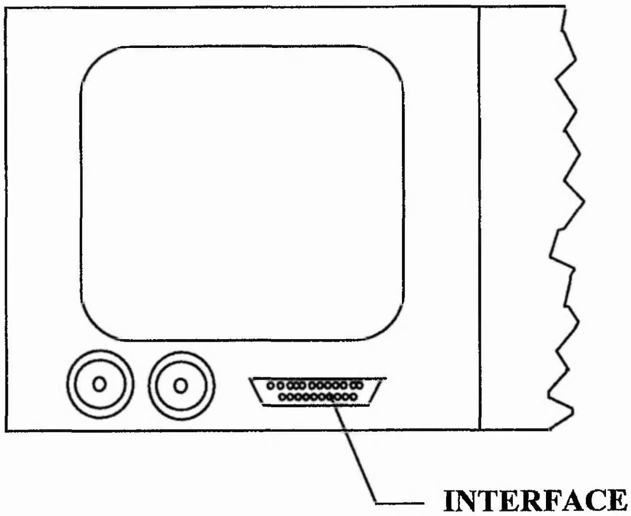


Figure 6.6 USD10 Interface

The RS232 port interface enabled remote operation to be carried out and the connection of a printer (Epson FX or compatible), The interface could allow data exchange with a computer or terminal, as long as there was a corresponding interface within the computer (Figure 6.6).

The data traffic with the computer was carried out using codes allocated to individual USD10 functions. These instructions were given via the computer keyboard or by using a special computer program (Appendix D). In doing this one differentiated between the recalling of the value or state of the USD 10 function and the keying-in of a new value and state for the corresponding function.

A communication program was necessary for the computer or the entry of a short utility program, which enabled the computer to be used as a terminal, (Appendix D).

Having prepared the computer for data traffic with a basic program and successfully communicated with the USD 10, a program in 'C' was compiled to do the job more effectively.

It was now possible to interpret data using Matlab® software, building a database for level measurement. However, it was soon realised that the number of data points that the USD 10 was capable of sending to the computer for analysing were few by comparison with the distances attempting to be differentiated.

Verification of level detection

6.4.1 Side and Bottom of Container Monitoring

Experiments were carried out to verify the accuracy of using ultrasound in level detection. A water level control rig, developed by staff at the Nottingham Trent University for teaching purposes, was employed. The set-up of the rig is illustrated in Figure 6.7.

A dual 5 MHz transducer was side mounted to a tall clear plastic tube and connected to a USD 10 as shown (Side mounting was utilised here for ease of operation). The filling rig filled the tall tubes with water via a compressed air controlled dispensing valve. A pressure transducer, connected to an ECA40 single-loop sampling proportional integral differential (PID) controller updated the control function every 200 ms.

The set point was adjusted to within 0.1mm of a chosen level and at this particular level a consistent rise and fall of signal intensity on the pulse echo display was clearly visible (Figure 6.8).

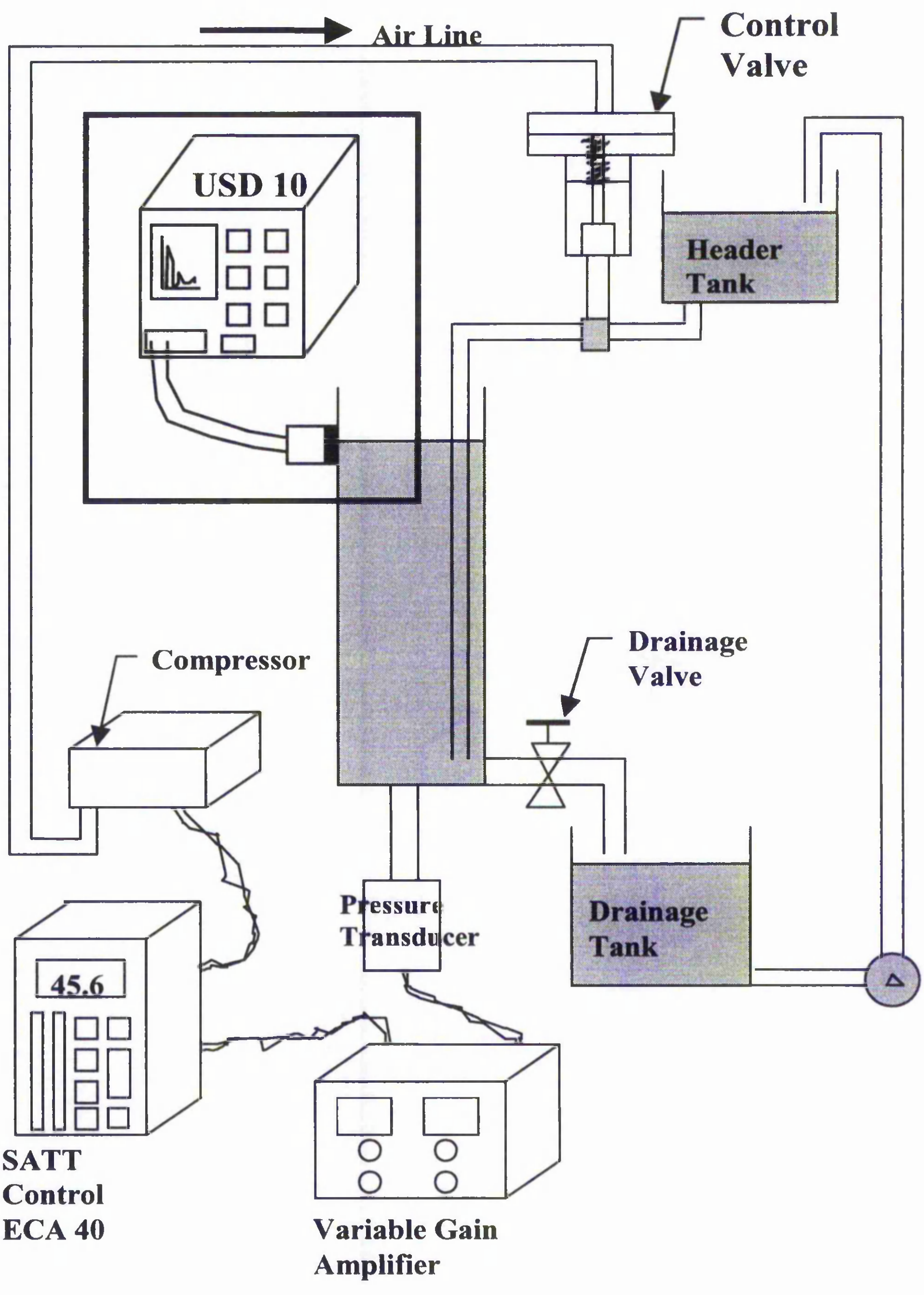


Figure 6.7 Level Detection Rig.

A gate was set on the USD10 that would sound a buzzer at a pre-determined intensity level of ultrasound returning echo signal and as the set point on the ECA40 was statically set, the buzzer sounded at equal intervals as the level rose and fell within the 0.1mm range.

6.4.2 Results

Figure 6.8 represents the pulse echo displays of the USD10 with the signal intensity growing and decaying as the level of fluid was detected within the beam of the transducer. A gate (horizontal line) was pre-set and as the echo pulse intercepted the gate a buzzer sounded. The buzzer sounded at equal intervals.

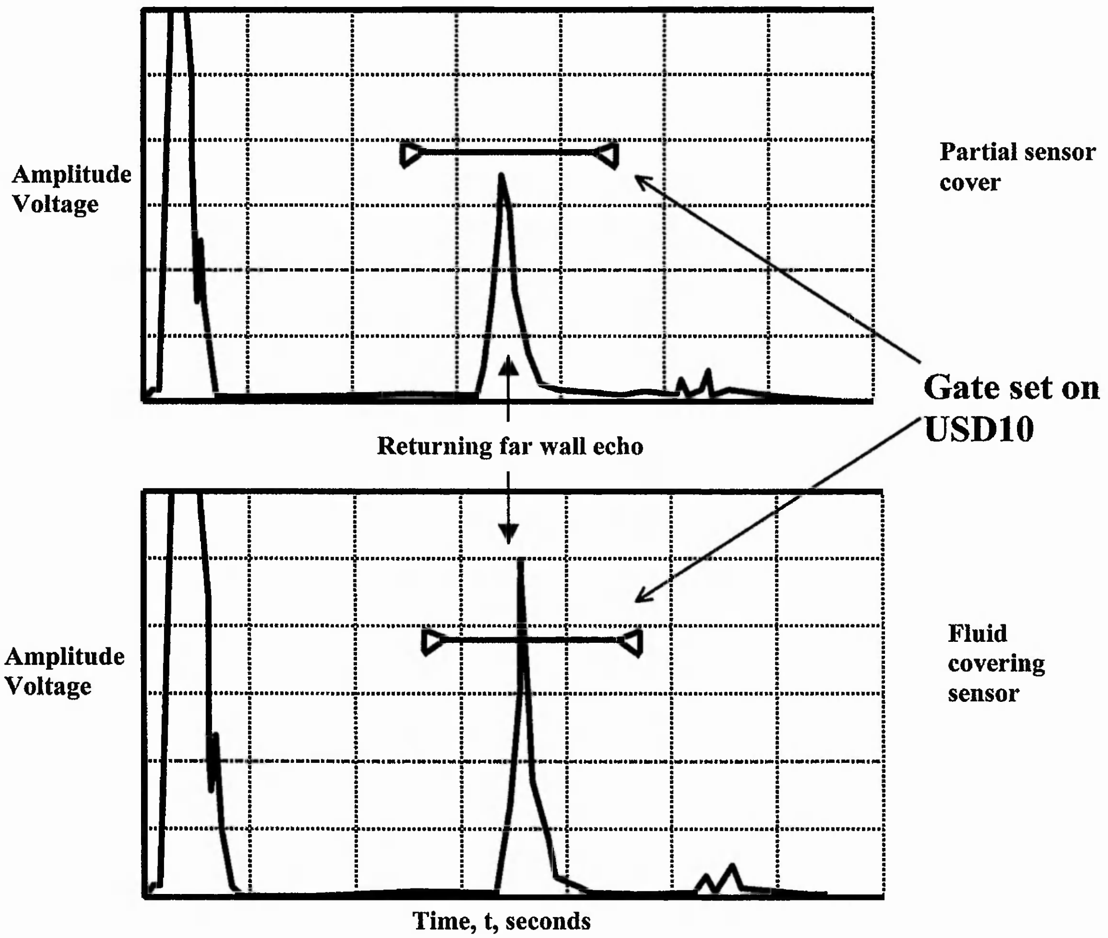


Figure 6.8 USD10 Pulse-echo display

6.4.3 Conclusions

This work has illustrated that ultrasound is capable of determining the presence of a fluid level set by the PID controlled electronic/pneumatic system employed by the filling rig (Figure 6.7),

However, the drawbacks with using a contact method of measurement remain. These drawbacks, as concluded in § 5.2.4 include, airtight contact is required for every level measurement obtained and an acoustic couplant is necessary.

- The results show that ultrasound can be used to detect changes in fluid level precisely, as indicated by the USD10 pulse-echo display.
- It was clear that the USD10 was limited by the number of data points it was able to communicate to a PC for digital processing resulting in a lack of accuracy and suggesting that it would not be fast/sensitive enough to respond to a rapidly changing fluid level.

In summary, it was deemed necessary to explore an alternative system not only based on the non-contact ultrasound approach but to incorporate a more rapid system for acquiring data points. The following section describes the considerations in the building of custom equipment to successfully transmit/receive and analyse air transmission ultrasound.

Chapter 7 - Method development:
Building the Air Transmission Analysis Equipment

This chapter describes the design and building of equipment for ultrasonic transmission through air and analysis of returning echo data. It was concluded in § 5.2.4, the non-contact (top positioned) ultrasound level measurement approach was the method to be investigated further within this project. It was described in chapter 6 that alternatives to the available Krautkrammer USD10 ultrasound testing equipment would be required to attain an accurate ultrasound air transmission system. This chapter discusses the choice of transducers, electronic considerations and different signal processing techniques. The section on electronics provides information on energising transmitters, amplifiers and filters. The section describing the processing techniques also incorporates the allied analogue-digital converter.

7.1 Ultrasonic Transducers

7.1.1 Transducers for use in air and other gases

General points

Transducers for use in air and other gases generally operate at quite low ultrasonic frequencies, typically below 200 kHz. These low frequencies are generally preferred because of the rapid increase in attenuation often found as the frequency is increased.

The majority of these transducers are piezoelectric but capacitive transducers are quite common. Spark transmitters are another possibility.

The problem of transmitting ultrasound from the transducer face into a gaseous load can be tackled in several ways. The difficulty is that the movement of the transducer face is generally relatively small and if it were transmitted to the gas in an unamplified way then the ultrasonic intensity in the gas would be vanishingly small. This is because of the enormous difference in acoustic impedances of the transducer face and the gas. One way of reducing the problem is the use of acoustic impedance matching layers as described in § 7.1.4; the use of a horn can have the same effect.

Another approach is to design the transducer so that it has a high compliance. This means that the amplitude of the movement of the front face of the transducer is high (compared with that for the reference design of PE transducers). The result is that more energy is transferred to the gas. Flexural transducers are a good example of this approach.

A Helmholtz resonator has the same effect because it is arranged that a mass of gas in front of the transducer face oscillates in resonance with the face. Thus, the particle displacement is greatly increased and, with it, the intensity of the transmitted ultrasound.

7.1.2 Type of transducer used in the air transmission equipment.

As part of the current research in the application of fluid level measurement, a flat air coupled transducer was used, Figure 7.1. The transducer comprised a piezoelectric element of resonant frequency 156 kHz, manufactured from lead zirconate titanate, (often shortened to PZT). It is the best known of the ferroelectric ceramics used in piezoelectric transducers.

Figure 7.1 A photograph of two air transmission transducers manufactured by Stresswave Technology (Matlock, Derbyshire).

The transducers were custom manufactured to give suitable characteristics, such as high-resolution measurements through gaseous mixtures. This required the piezoelectric disc to be constructed of certain thickness and diameter to determine the frequency and beam profile respectively. A simple piezoelectric transducer for generating longitudinal ultrasound is illustrated diagrammatically in Figure 7.2.

7.1.3 The Piezoelectric effect

A piezoelectric material is one in which the application of mechanical stress results in the production of an emf. When such material is subjected to a pressure between opposite faces, it will generate equal and opposite charges on the two faces. Such materials also show the inverse piezoelectric effect; i.e., when an emf is applied between opposite faces it causes a change in thickness. The inverse piezoelectric effect is employed in generating ultrasound and the direct piezoelectric effect is the basis of many ultrasonic receivers. At this point it is necessary to explain the behaviour of ultrasound at interfaces.

The criteria used for assessing piezoelectric materials include the mechanical quality factor (Qm), the Curie Point and acoustic impedance. Details of these criteria and criteria for the transducers used for this research are found in Appendix C (section 1).

7.1.3.1 The reference design piezoelectric transducer

The reference design piezoelectric transducer (Figure 7.2) is a simple unfocused (planar) transducer intended to emit compressional ultrasound. When designing a piezoelectric transducer, many advantages and disadvantages have to be taken into consideration.

Such critical decisions include the choice of optimum frequency, factors such as spatial resolution and the likely attenuative nature of the system being interrogated. These decisions often lead to a compromise, since good resolution implies a short wavelength, whereas low attenuation is associated with low frequency.

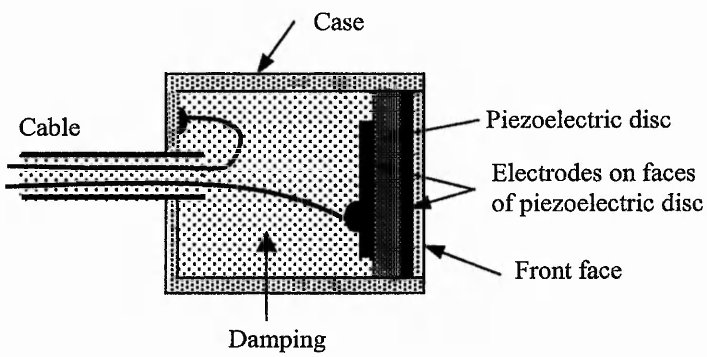


Figure 7.2 A piezoelectric transducer

When the transducer is operating as a transmitter, a suitably varying voltage causes a piezoelectric disc or 'element' to behave as a piston radiator. This generates a sound wave in the 'load', i.e., the front face of the transducer. The amplitude of the oscillation in the element is generally very small and movements as little as 10^{-9} m are not uncommon.

When it is operating as a receiver, the sound waves impinging on the front face of the transducer generate strains in the piezoelectric slice; the consequential emf's are picked up by the electronic system. The simple transducer illustrated in Figure 7.2 incorporates important refinements such as ultrasonic damping behind the element and a protective front face, which assists in acoustic impedance matching.

In order to reduce sensitivity to environmental noise the transducer designed for this project was effectively back-damped with epoxy resin loaded with tungsten powder. Appendix C (section 2) describes more fully back damping requirements of a transducer depending on its intending application.

7.1.4 Acoustic impedance matching

The transmission of ultrasound from any PE material into a gas load is exceedingly inefficient; for example the efficiency from PZT to air is only 6×10^{-3}%. The efficiency of transmission was improved by using one or more matching layers on the front face (Figure 7.3), as discussed in more detail by [Silk 1983] and [Khuri-Yakhub et al 1988]. The improvement can be as much as several tens of dB.

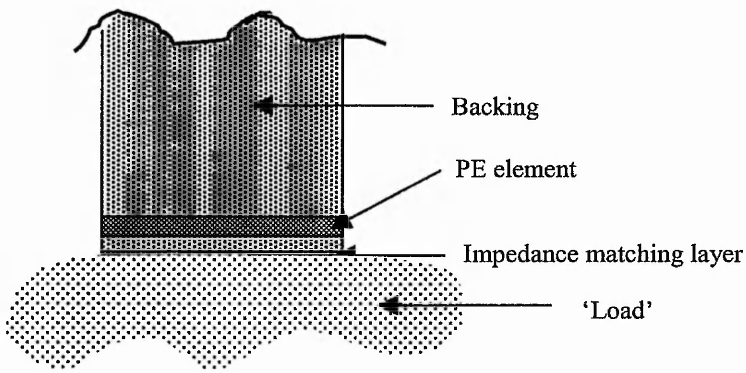


Figure 7.3 An acoustic impedance matching layer

The effectiveness of these matching layers is determined by calculations as described in Appendix C (section 3). The transducers designed for this project utilised matching layers for ultrasound transmission into air.

7.1.5 Electrodes and connections

The electrodes on either side of the PE element are usually thin films of metal, very often silver that is applied by evaporation or sputtering. Electrical connections are usually made by soldering or by using conductive epoxy resins. Transducers that have to be installed and removed easily for maintenance or replacement are normally protected by a metal or plastic case. This is often sealed against the ingress of water and other aggressive environments. There will usually be a length of electrical cable or a suitable electrical connector; co-axial cables or connectors are frequently used. The PE transducers used for the current application were inserted into short aluminium tubes with an interference fit, the front face of the element was earthed to its case, as shown in Figure 7.2.

7.1.6 Bonding

The bond between the transducer components in the ultrasonic path must be very sound. Gas gaps are particularly problematic, and even if only a few μm thick can significantly impair the transfer of ultrasound. As a result, bad bonding can seriously alter or distort the beam profile.

Faulty bonding (non-parallelism, thickness variation or inhomogeneity) is one of the commonest sources of poor transducer performance. For the transducers developed for the current project, correct bonding was tested and achieved by electromicroscopic examination at Stresswave Technology Ltd.

7.1.7 Examples of Air-coupled Transducers

Transducers for the generation and reception of sound are the most critical components of an air-coupled ultrasonic NDE system. In current commercial applications, thickness-mode type piezoelectric elements are widely used. Such transducers are constructed using a circular disk of an efficient piezoelectric material.

To take advantage of the high mechanical-quality factor Q of the piezoelectric disk, no backing layers are applied. A thin front-layer of porous material with low specific impedance to improve generation and reception efficiencies is also employed. As a consequence, such transducers can be operated in the resonant-mode, resulting in much higher sensitivities. The construction of a typical flat air-coupled transducer is shown in Figure 7.4a.

Transducers with high mechanical quality factors Q are best suited for operation in the tone-burst mode. In this case, the centre frequency of the driving electrical signal is chosen to correspond exactly to the thickness-mode resonance of the transducer. As a result, the mechanical amplitude of the piezoelectric material is significantly increased and the transmission and receiving sensitivities can be increased by as much as 20 dB. Such transducers are necessarily narrow-band and can be operated at one frequency only.

Further increase of the sound pressure and sensitivity can be achieved by using focused transducers. Several methods of constructing such transducers are depicted in figure 7.4 b-e. The simplest method, shown in figure 7.4 b, uses a spherical shaped piezoelectric ceramic disk, while the same can be achieved by using composite piezoelectric materials (figure 7.4 c). Such disks are also used for water immersion transducers. Figure 7.4 d shows a transducer that uses a flat piezoelectric disk and a refractive lens made of a light material. In figure 1e, the same goal is achieved by using reflective optics.

Figure 7.4a. Flat air-coupled transducer, backed by air and with a thin front layer with low impedance.
Figure 7.4b. Focusing air-coupled transducer with spherical shaped ceramic disk.
Figure 7.4c. Focusing air-coupled transducer with composite ceramic element.
Figure 7.4d. Focusing air-coupled transducer. Flat disk with refractive lens added.
Figure 7.4e. Focusing air-coupled transducer. Flat disk with reflecting optics added.

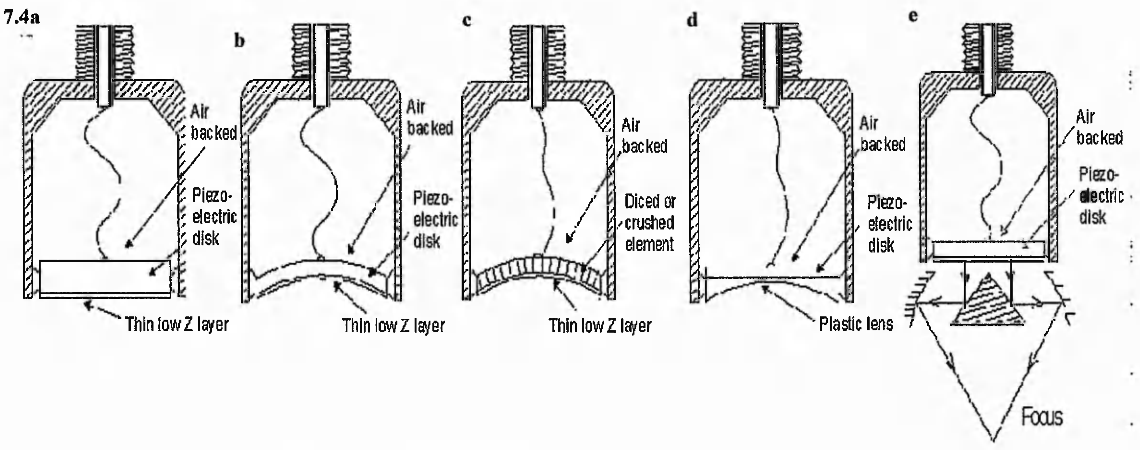


Figure 7.4 Examples of Air-coupled Transducers

To summarise, Stresswave Technology Ltd assisted in the development of two flat air-coupled transducers, comprising of a piezoelement of PZT of operating frequency 156Khz. The design incorporated back damping, impedance matching layer, waterproofed silver electrodes and connections and air tight bonding.

7.2 Electronic design

The next step in the development of an ultrasonic level detection system was the incorporation of the correct electronic equipment in order to energise, receive and process ultrasound signals.

7.2.1 Energising transmitters

General points

Virtually all types of ultrasonic transducers are energised in the same way, namely by means of a suitable varying emf. This section concentrates on the tone burst energising of air transmission ultrasound transducers.

7.2.2 Tone bursts (gated continuous waves)

Tone bursts (also called gated CW) are generated by using a sine wave oscillator and interposing an electronic time switch (often known as a 'time gate' or simply 'gate') between the oscillator and the Tx (Figure 7.5). The timing gates are triggered by another oscillator either directly (if its frequency is suitable) or through a 'divider' to give the required frequency.

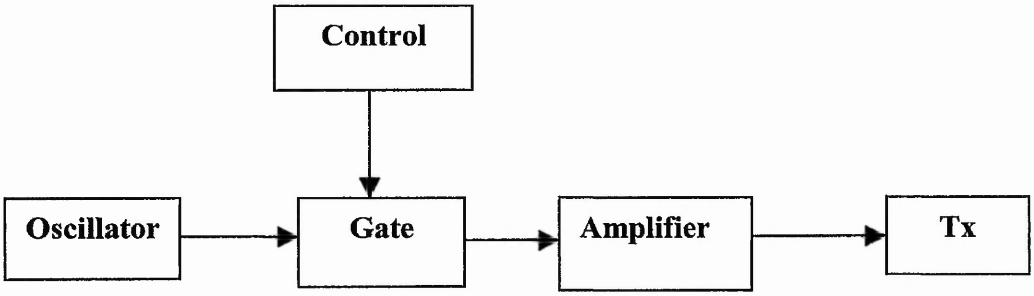


Figure 7.5 A block diagram showing the production of tone bursts (gated CW).

With tone bursts the duty cycle, i.e., the ratio of time on to time off, is generally low; so the peak power density can be higher than for CW. Hence an amplifier is often needed.

Sometimes asynchronous tone bursts are used. They are distinguished by the fact the carrier wave and the gated signal are independent rather than being derived from one master oscillator. This can have the advantage of improving resolution when time intervals are being determined by averaging a number of measurements.

An important variation on the tone burst is the chirp. It is a tone burst in which the frequency is swept between fixed limits during the transmission period; the frequency can change either upwards or downwards. The chirp is generated by linearly increasing or decreasing the voltage applied to a VCO during the duration of the burst so that the required change of frequency is obtained. The Tx must be capable of operating over the required band of frequencies.

7.2.3 Pulsed signals

Pulsed signals are generated by applying a voltage 'spike' (pulse) to the transducer and ensuring the transducer does not ring excessively. Pulsed excitation of a transducer will rarely give a signal having exactly the same form as the excitation. Mechanical damping in the transducer is an important factor (seeAppendix C section 2).

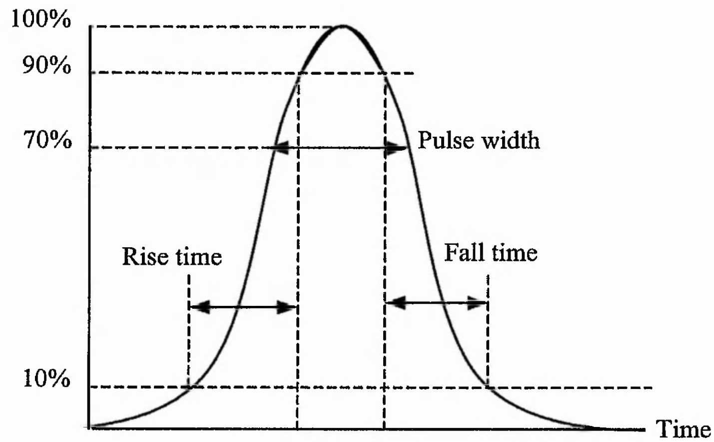


Figure 7.6 Pulse characteristics

The characteristics of the excitation pulse are important. These include the pulse width, pulse repetition frequency (PRF), amplitude, polarity, rise time and fall time. These characteristics can all be adjusted. Pulse width, rise time and fall time are illustrated in figure 7.6.

The pulse width is measured at 70% (actually $1/\sqrt{2}$) of the peak amplitude; the definition is analogous to that for bandwidth.

The rise time is the time required for the pulse signal to rise from 10% to 90% of the maximum amplitude; fall time has a similar definition. The characteristics of the pulse produced by the transducer can be expressed in the same terms.

The required voltage spike pulse is produced by the discharge of a capacitor. The voltage involved generally ranges from less than ten to several hundreds. A simple circuit for doing this is shown in Figure 7.7 and includes a switch to cause the discharge.

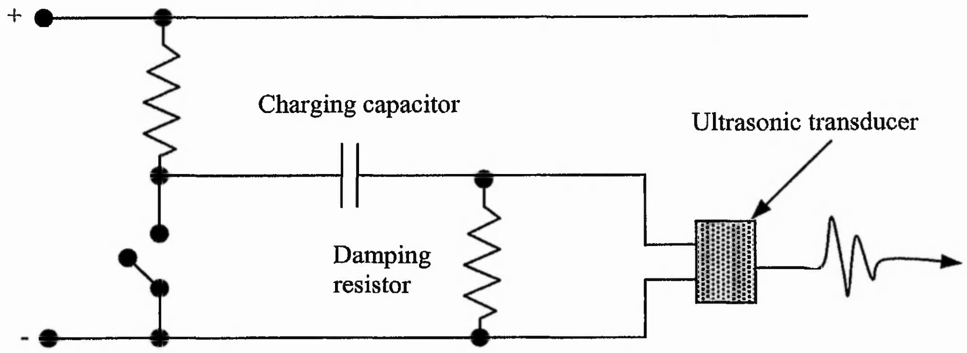


Figure 7.7 The production of spike pulses.

The switch can take several forms. It can, for example, be an avalanche transistor and these can give rise times as short as a nanosecond (10^{-9} s). Alternatively for longer pulses, a thyristor may be used. A trigger signal activates the switch and can be provided by an oscillator where the frequency of this oscillator controls the PRF.

The characteristics of the pulse depends on the components in the circuit given in figure 7.8 and can be, within limits, controlled by adjusting them.

Thus;

- The rise time is generally dictated by the speed of the switch.
- The fall time characteristics an exponential decay and is determined by *RC* where *R* is the resistance of the load (including the damping resistor) and *C* is the charging capacitor.
- The effective pulse width varies with both *R* and *C*.

7.2.4 Modulated function/pulse generators

For the current research, the Wavetek model 81 pulse/function generator, as depicted in figure 7.8, was employed.

Figure 7.8 The Wavetek model 81 pulse/function generator.

The model 81 can generate sine, triangle, square, positive pulse and negative pulse waveforms from 10 mHz to 50 MHz. With numerous continuous and non-continuous operating modes, including triggered, gated and triggered burst, as well as externally controlled AM, VCO and phaselock offset, the unit is ideal for ultrasonic sensor excitation for 'air-bourne' proporgation over short distances.

With programmable pulse period, width and transition times combined with the function generator features the model 81 provides a necessary set of capabilities for both analogue and digital applications. See appendix D for detailed specifications applicable to ultrasound excitation

7.3 Detecting the received signal

7.3.1 General points

The signals produced by most ultrasonic receivers are very weak, particularly when receiving echoes through air. These signals have to be amplified before they can be considered useful. Other processing such as demodulation may also be necessary.

Figure 7.9 shows a block diagram of a typical receiving circuit. The sequence of the components may be varied, in particular, noise elimination may be done after the amplification stage.

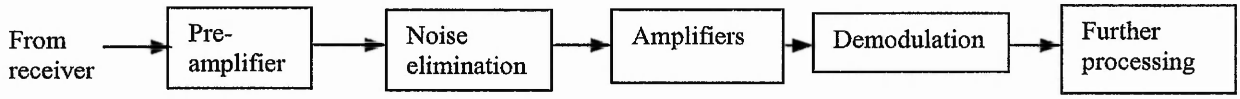


Figure 7.9 A block diagram of a receiving circuit

In the current research it was necessary to amplify ultrasonic signals and eliminate noise. The next section describes these stages in more detail.

7.3.1.1 Pre-amplifiers

Pre-amplifiers were used to gain a useful amount of amplification before too much noise was able to have a detrimental influence. They can also be used for impedance matching to allow long cables of low impedance to be used.

7.3.1.2 Methods of removing noise

In this context, noise is any undesired electrical disturbance superimposed on a useful signal. Three sources are relevant to all electronic circuits:

- Intrinsic noise (this includes Johnson-Nyquist, or thermal, noise and 'shot' noise). It results from the fundamental laws of nature; it is inherent in the circuit and nothing can be done about it (except cooling the electronics to cryogenic temperatures!).
- Flicker noise. This is due to the deficiencies in the components used and can be minimised by careful selection of the components.
- Interference. There are lots of external sources of interference: power lines, signal lines, cross-talk between adjacent circuits, car ignition systems, electrical equipment, radios and TVs, motors, electric welding sets etc. Correct shielding, avoidance of ground loops and the use of twisted pair cable are some of the techniques employed to minimise this interference.

In addition, ultrasonic systems can easily suffer from spurious ultrasonic signals picked up by the receiver. These may be termed a 'rival' route or there may be extraneous sources of ultrasound.

The amount of noise is quantified by the signal-to noise ratio (SNR). This is the ratio of the power (intensity rather than amplitude) of the signal to that of the noise and is usually expressed in dB.

The undesired effects of residual noise can be reduced in four ways.

- The use of filters. Usually, interference noise is at a lower frequency than the ultrasonic signal. Thus machinery and plant noise of the sort likely to be found in chemical and process plants tend to be most intense below approximately 150 kHz. Therefore 'high-pass' or 'band-pass' filtering is the first technique to consider. A high-pass filter passes frequencies above a defined minimum; a band pass filter passes frequencies above a defined band.

  The stratagem of filtering out low frequency components is of no help if the ultrasound itself being used is a low frequency.

- The use of time gates and amplitude discriminators. Unwanted signals can also be discarded by making use of time gates and amplitude discriminators (Figure 7.10)

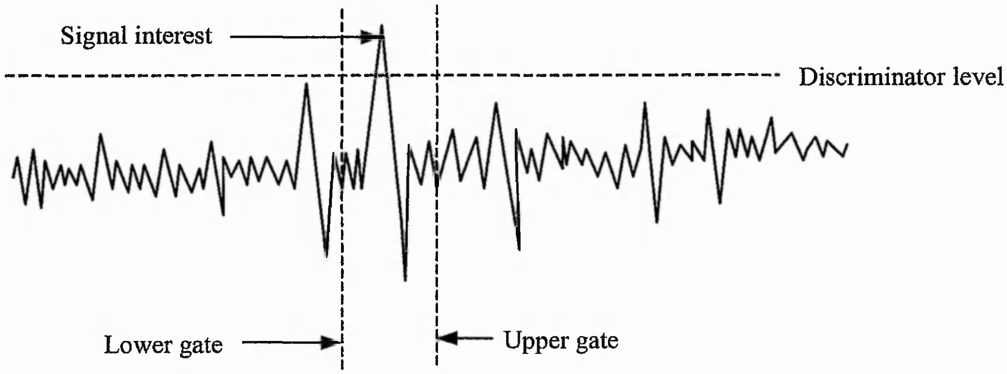


Figure 7.10 The use of time gates and amplitude discriminators to remove noise.

Time gates select only those portions of signals that occur between pre-set time intervals. The positions and widths of the gates are selected to eliminate noise signals. Amplitude discriminators have similar function in terms of amplitude rather than time; i.e., they select only those portions of the signal having amplitudes greater than a pre-set level.

Complicated 'envelopes' can be constructed from time gates and amplitude discriminators so that a predetermined pattern of spurious signal can be ignored.

- Averaging. Genuine signal components will generally consistently recur as many measurements are made over a period of time, t; they will therefore persist after averaging many signals. In contrast, random noise will be reduced by random cancellation during averaging; the improvement in the SNR will be proportional to $\sqrt{t}$.

A typical analogue averaging technique is the 'box-car' sampling technique. In this, the signal averaging occurs in a narrow time slice that is slowly swept across the time range of interest. The averaged signals are stored and then used to construct a 'clean' version of the input signal. Averaging can also be carried out digitally.

- Cross-correlation methods. Cross-correlation of the shape of the received signal with the known shape of the original signal can be a great help in identifying an echo signal when it is surrounded by noise. The technique is used in tag cross correlation flowmeters. Cross-correlation will be considered in more detail in section 8.1.

7.3.2 Amplification

Ultrasonic signals are often very faint and powerful amplifiers of consistent performance are needed. Amplifiers can be tuned to operate over a selected band of frequencies; e.g., broad band or narrow band.

Amplifiers unavoidably generate unwanted noise, the power of which is proportional to the bandwidth of the amplifier. Hence the bandwidth should be arranged to be no more than is necessary to accomplish an undistorted amplification of the input signal.

Amplifiers come with a variety of amplification characteristics. Four major versions include linear, logarithmic, swept gain (time varying gain) and automatic gain control. The characteristics of the first three are illustrated in figure 7.11.

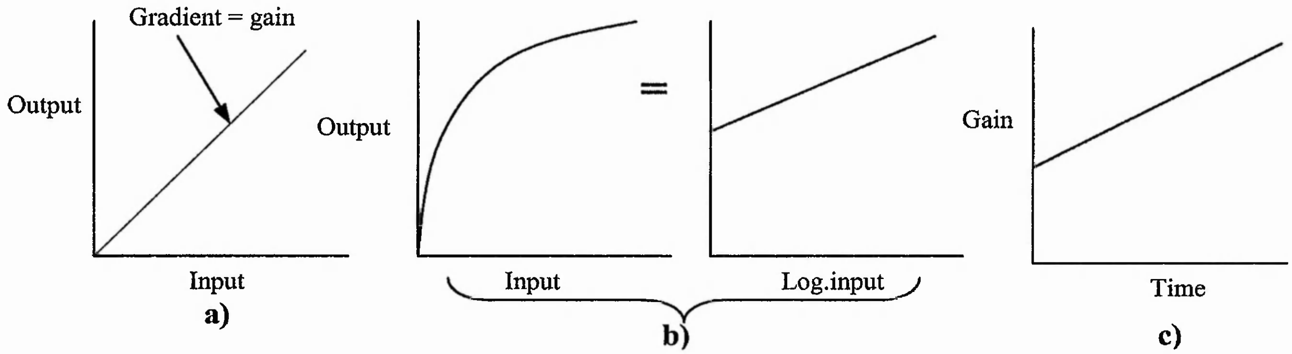


Figure 7.11 Some amplifier characteristics. (a) Linear. (b) Logarithmic. (c) Swept gain (time varying gain).

With all amplifiers, there is a maximum input signal above which there is no further increase in the output because the circuit is overloaded; hence larger input signals suffer from 'clipping'

7.3.2.1 Linear amplifiers

The output of a liner amplifier is directly proportional to the input (figure 7.11a); i.e., the gain is constant.

7.3.2.2 Logarithmic amplifiers

The output of a logarithmic amplifier is proportional to the log of the input voltage (figure 7.11b). They are often used because they can cope with a wider range of input signal amplitudes than can linear amplifiers.

7.3.2.3 Swept gain amplifiers (time varying gain TVG).

In a swept gain amplifier the gain is arranged to increase with time (Figure 7.11c) during the period of interest. This period is typically that between successive ultrasonic pulses in a pulsed system. This type of amplifier is particularly useful in situations when, for example, large echoes are received from nearby objects and are followed by weak signals from distant objects. The swept gain amplifier can compensate for this and give amplified signals which are more equal.

7.3.2.4 Automatic gain control (AGC).

The application of automatic gain control is different in CW systems and to that of pulse systems. For CW operation, the amplifier does its best automatically to adjust its gain so that the average output is constant irrespective of the input.

For pulsed systems, the aim is that the amplitude, after a predetermined time interval, should be automatically maintained constant. The time interval may be, for example, a pre-set number of milliseconds after energising the transducer.

7.3.3 Amplifier used in the air transmission analysis equipment

For the development of the model ultrasound system, an amplifier/filter from the Physical Acoustic Corporation (PAC) was purchased. (Figure 7.12).

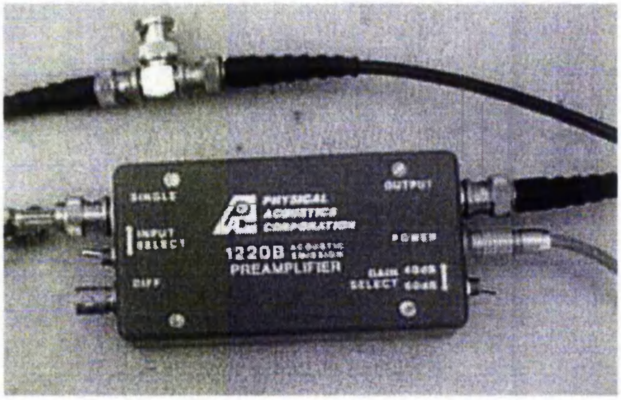


Figure 7.12 The 1220A preamplifier and filter

The 1220A preamplifier was provided with an interchangeable filter set for matching different sensors and dealing with diverse noise environments. The 1220A preamplifier featured single and differential input; it incorporated a switchable 40/60 dB gain and replaceable band pass filters with values from 10 kHz to 1.5 MHz. The preamplifier was powered by +28v, and used single BNC connections for both power and signal (See Appendix D for detailed specifications).

7.3.3.1 Display screens used in air transmission analysis equipment

In chapter 6 the three different ways of displaying ultrasound signals, A-Scan, B-Scan and C-Scan were discussed. For liquid level measurement techniques developed as part of this project, the A-Scan display representing a plot of amplitude versus time, in which a horizontal base line on an oscilloscope screen illustrates elapsed time, while the heights of vertical deflections represent intensities of echoes was used. The oscilloscope used was a Gould model 465 100MHz.

7.4 Signal Processing

7.4.1 Detection of time intervals

The time interval of interest is that between the pulse excitation of a transmitter and the detection of the pulse of the receiver. This is called the time of flight (TOF) or transit time.

One of the major problems was deciding what point on the pulse to use for a reference. The difficulty is that all pulses changes shape during their life. There are two reasons for this. Firstly, if velocity dispersion occurs, it will delay some frequency components of the pulse compared with others. Secondly, the higher frequency components will usually suffer the greater attenuation.

Often, the pragmatic approach is to detect the 'leading edge' of the pulse, namely, the region where the first significant increase in amplitude occurs. There are two ways of doing this, and both are compromises.

One is to choose the time when the signal first exceeds a defined discriminator level; this gives errors if the pulse shape varies or if the amplification varies. The second is to use the 'zero cross-over' time; ie, the time at which the signal level becomes zero after a peak which is greater than a set discriminator level.

Methods of determining the time intervals include:

-analogue. Here a capacitor is arranged to be charged from a constant current source during the time interval and at the end of the period, the voltage is determined.

-digital. A counter is started at 'zero time' and stopped at the end of the time interval.
-the 'vernier' digital technique. This uses two oscillators running at slightly different frequencies. One is started at 'zero time' and the other is started in synchrony, at the end of the time interval. Both are then left running and the number of cycles of the oscillators is counted. The electronic system detects when the two oscillators come into synchrony again. The number of cycles at this point is proportional to the time interval.

-cross correlation. Cross correlation is useful in applications where delays must be measured. With cross correlation the best match between a transmitted and received signal is found. The best match causes a maximum in the cross correlation function, and the distance from the maximum to the 'lag zero point' gives the delay between the two signals (see § 8.1 for more details).

Many of the methods outlined above require ultrasonic signals to be analysed in the digital form. By using a fast analogue to digital converter (ADC) to convert the signal, a customised computer can then be programmed to carry out Fourier analysis and other signal processing techniques. The use of digital signal processing (DSP) is by far the most powerful technique and is particularly useful for real-time analysis of transient signals. The current research project would use these approaches.

7.4.2 Analogue to digital converter (ADC). Used in the air transmission analysis equipment.

In the current equipment design, a Sonix STR*825 A/D converter board was used in order to capture and process returning ultrasound echo data within a personal computer (PC) system. The Sonix's STR*825 analogue to digital converter board is an IBM PC /XT/AT compatible instrument featuring a true 25 MHz transient sampling rate. The 16K on board high speed memory buffer provides data acquisition flexibility. All board functions are under software control. These include sampling rate, trigger selection, clock selection, threshold phase and level, channel designation, board select and interrupt enable. Industry standard BNC connectors are used for convenient set up while maintaining maximum signal integrity.

Plugging the STR*825 into a PC transforms the computer into a powerful wave form digitiser, a real time digital signal processor or a spectrum analyser. The ADC boards high speed data acquisition memory is mapped directly into PC memory space. Once the wave form has been captured, the PC can transfer data off the board at approximately 1 byte per microsecond. It is designed with 25 nanosecond static ram and fast bus interface logic.

Using the STR*825 means that processing is no longer locked into the static architecture of a stand alone digital oscilloscope or the unusable slow data transfer rates between a stand alone instrument and the computer. The ability to install additional boards for multi-channel applications increases the options and flexibility of the instrument. More detailed specifications can be found in appendix D.

7.5 Summary

In summary, the components for the air transmission analysis equipment were chosen based on the following criteria:

- Transmission medium: Air/Gas
- Transmission distance for measurement: $\leq$ 100mm
- Preferred accuracy: $\pm$ 1mm
- Transmission energy levels: $\leq$ 50 Vpp
- Required signal to noise ratio (SNR)
- Digital signal processing speed: As fast as possible
- Flexibility: Development of customised programming for signal processing

Chapter 8 describes further investigations that were carried out to test the validity of the equipment.

Chapter 8 – Method Validation: Investigations and results

In chapter 7, details of the components and processes for the air transmission ultrasound equipment were outlined. This chapter describes the investigations undertaken to validate the system. Two fundamental questions needed to be answered;

1) Which two different signal-processing timing methods, namely, cross-correlation and threshold timing, gave the better accuracy in measurement?
2) What were the levels of accuracy that could be obtained?

Air transmission equipment connections

The air transmission equipment, as alluded to in chapter 7, was connected to form an operational system (Figure 8.1). For these investigations an aluminium flat surfaced block was used as a reflecting surface.

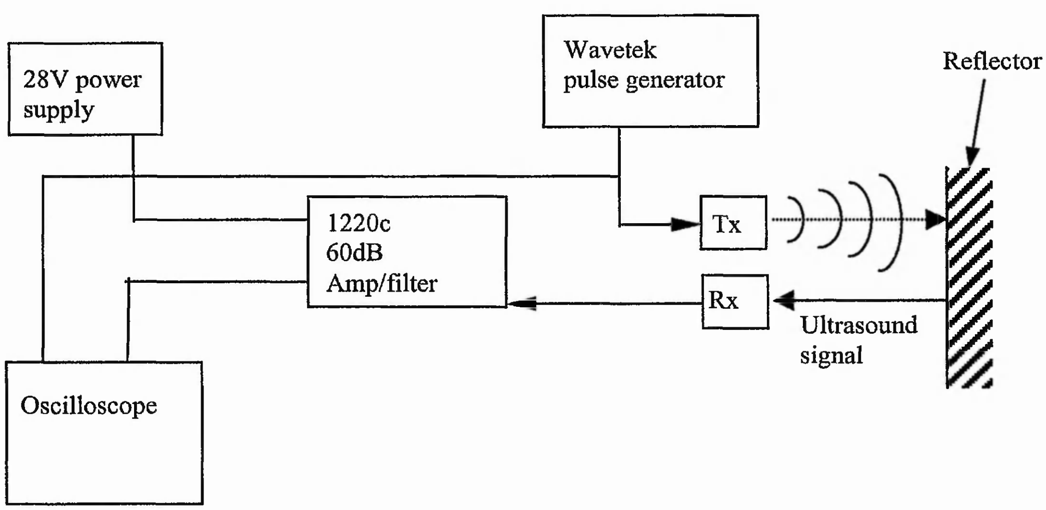


Figure 8.1 Air Transmission Equipment Connections

The air transmission transducer (Tx) was excited by a 156 kHz sine wave with 30Vpp amplitude of 24 cycle pulse duration from the Wavetek pulse generator. Ultrasonic compression waves were transmitted from the piezoelectric element into the air/gas load. The ultrasound was reflected back to the receiving transducer (Rx) off the metal surface. The signal was converted into a corresponding voltage that was filtered and amplified. The returning echo signal was displayed on an appropriate oscilloscope.

Initially Transition II (Data capture for Oscilloscopes) software was used to record the returning echo data into files on a PC.

8.1 Initial trials utilising Cross-correlation processing as a timing method

Experiments were devised to explore the validity of using air transmission ultrasound and to successfully analyse the returning echo data. A control experiment was devised that used a fixed reflector distance. Five returning echoes were imported into Transition 2 (data capture software for oscilloscopes). The data was saved as plane ASCII data files and opened in Matlab. The objective was to carry out a Fast Fourier Transform (FFT) and cross-correlation on data sets in order to determine the obtainable accuracy of measurement on a fixed distance and to compare these against a simple threshold approach to processing. The following section describes the cross-correlation process using FFT analysis and the threshold approach to time-of-flight measurement.

8.1.1 Correlation

Correlation is often equated with terms such as *association, cause and effect* and *similarity.* To a large degree, these are good, intuitive definitions for the mathematical operation of correlation.

The mathematical definition of correlation is:

$$\mathbf{r(\tau) = \lim_{T \to \infty} \frac{1}{2T} \int_{-T}^{T} x(t)y(t+\tau)dt} \qquad (8.1)$$

where **r(τ)** = the correlation function formed by summing the lagged products of the two wave forms,

x(t) and y(t),

(τ) = the time lag between, x(t) and y(t).

Functionally, correlation can be thought of as matching up of the wave form components or a similarity test between waveforms. The equivalent hardware definition in Figure 8.2 makes this operation easier to visualise.

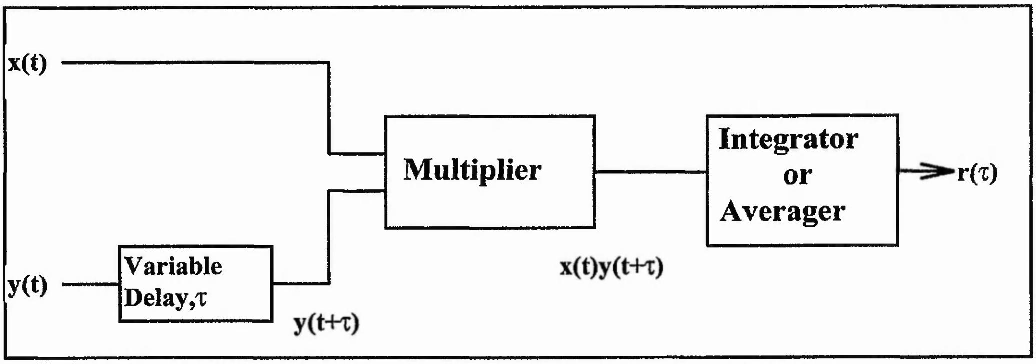


Figure 8.2 Hardware Implementation of Correlation

In terms of digital signal processing, correlation is greatly simplified by using the **FFT.** The two wave forms to be correlated, x(t) and y(t), are transformed to the frequency domain. Following this, one term is conjugated and then the complex product is formed to give:

$$\mathbf{R(f) = X(f)Y^*(f) = [X^*(f)Y(f)]^*}$$

In this equation the asterisk (*) is used to denote the conjugation. The final step necessitates an inverse transformation R(f) in order to return to the time domain to get r(τ).

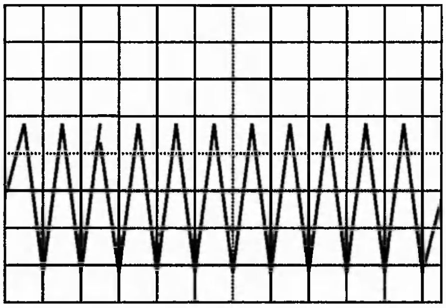
Depending on the waveforms used, two types of correlation can be carried out. If the waveforms are the same, x(t) = y(t), their correlation is referred to as *autocorrelation.* If the two waveforms are different, x(t) ≠ y(t), their correlation is referred to as *cross-correlation.*

8.1.2 Cross-Correlation.

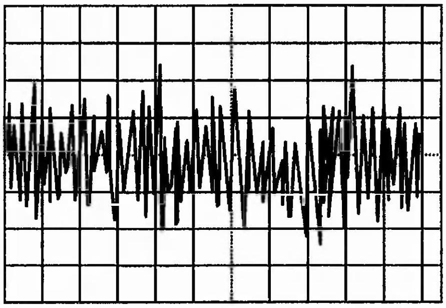
In autocorrelation, a signal is multiplied by delayed versions of itself. The process of cross-correlation differs only in that two signals are used; one is multiplied by delayed versions of the other. The resulting cross-correlation function contains only those frequency components common to both waveforms.

To demonstrate the usefulness of cross-correlation, the following figures illustrate the detection of a signal buried in noise. For example, a signal is received that is obscured by noise, but the type of signal being detected is not known. This often occurs in radar, sonar, and tone control, where the transmitted signal is well defined but the received signal is buried in noise.

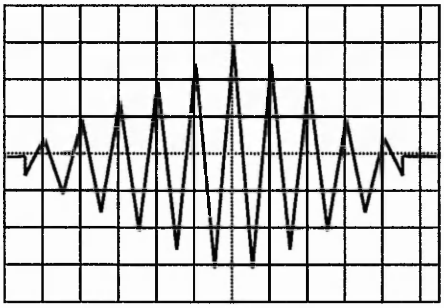
The situation is demonstrated in Figure 8.3 , where a sine wave buried in noise is illustrated. In the figure there are no noise components in the cross-correlation function. This is because noise is not common to the signals being correlated.



a. The reference signal



b. Is the reference part of the noise signal?



C. Cross correlation proves that it is

Figure 8.3 If you know the waveforms you are looking for, cross-correlation can help you find it.

Cross-correlation is useful in applications where delays must be measured. Time delay is an important parameter in studying path diversity problems, or characterising transmission systems. With cross-correlation, the best match between a transmitted and received signal is found. The best match causes a maximum in the cross-correlation function, and the distance from the maximum to the lag zero point gives the delay between the two signals. The basics of this concept are illustrated further in Figure 8.4.

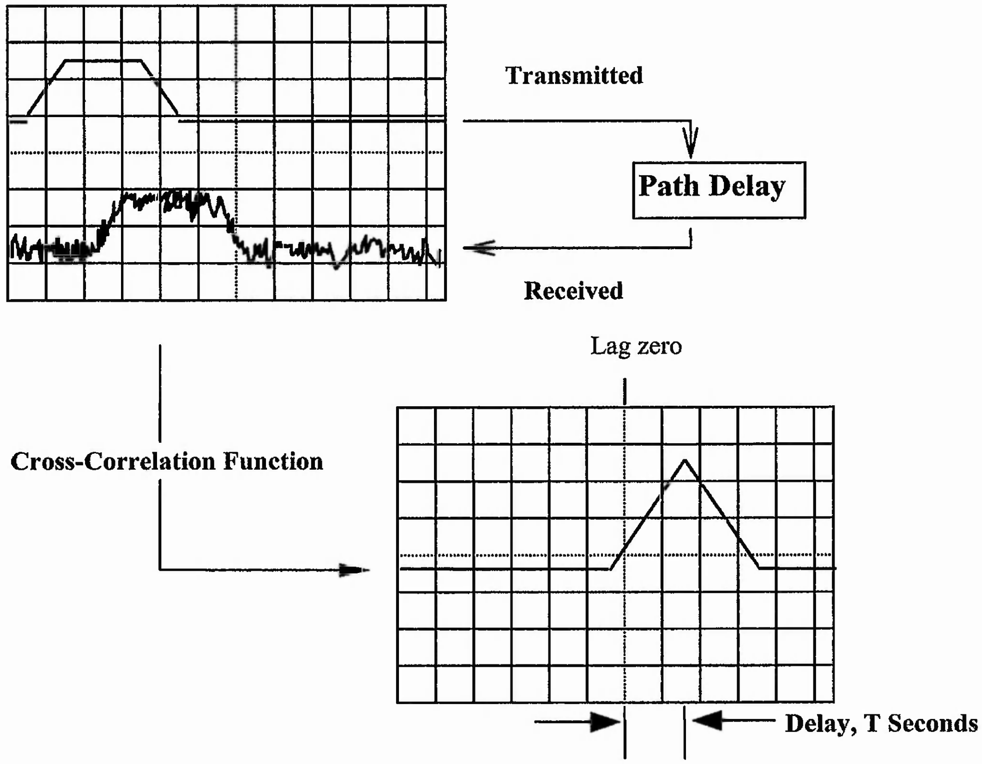


Figure 8.4 The location of maximum cross-correlation indicates the time delay between wave forms.

Power Spectra

A power spectrum is a result of the FFT of a correlation function. The FFT of an autocorrelation function is generally referred to as the auto spectrum. Also referred to as power spectral density (PSD), auto spectra are widely used for vibrational analysis. When a cross-correlation function is transformed by Fourier analysis to the frequency domain, the result is referred to as a Cross-spectrum. Cross-spectra contain the magnitude products and phase differences of the frequency components common to the signals involved in the cross-correlation. Like auto spectra, cross-spectra are frequently used in vibration analysis.

8.1.3 Fast Fourier Transform

The FFT algorithm for computing the discrete Fourier Transform of a sequence is the workhorse of digital signal processing. Its uses range from filtering, convolution, computation of frequency response and group delay, to applications in power spectrum estimation.

In Matlab, fft(x) is the discrete Fourier transform of vector x, computed with a radix-2 fast Fourier transform if the length of x is a power of two, and with a mixed radix algorithm if the length is not a power of two. **If x is a matrix, fft(x) is the fast Fourier transform of each column of x.**

fft(x, n) is the *n*-point FFT. If the length of x is less than n, x is padded with trailing zeros to length n. If the length of x is greater than n, the sequence x is truncated. When x is a matrix, the length of the columns are adjusted in the same way.

X = fft(x) and x = ifft(X) implement the transform and inverse transform pair given for vectors of length (N) by

$$\mathbf{X(k) = \sum_{j=1}^{N} x(j)\omega_N^{(j-1)(k-1)}}$$

$$\mathbf{x(j) = (1/N) \sum_{k=1}^{N} X(k)\omega_N^{-(j-1)(K-1)}}$$

where

$$\omega_N = e^{-2\pi i/N}$$

is an N^{th} root of unity.

The fast Fourier transform of a column vector x

x = [4 3 7 -9 1 0 0 0];

is found with

y = fft(x)

which results in

```
y =
      6.0000
     11.4853    -2.7574i
     -2.0000   -12.0000i
     -5.4853   +11.2426i
     18.0000
     -5.4853   -11.2426i
     -2.0000   +12.0000i
     11.4853    +2.7574i
```

8.2 Threshold Processing

The second processing method utilises a threshold approach. The principles of threshold processing are to determine at which point in time there is an increase in signal strength above a pre-set discriminator. Figure 8.5 illustrates noise and then the increase in signal strength at the start of a returning echo.

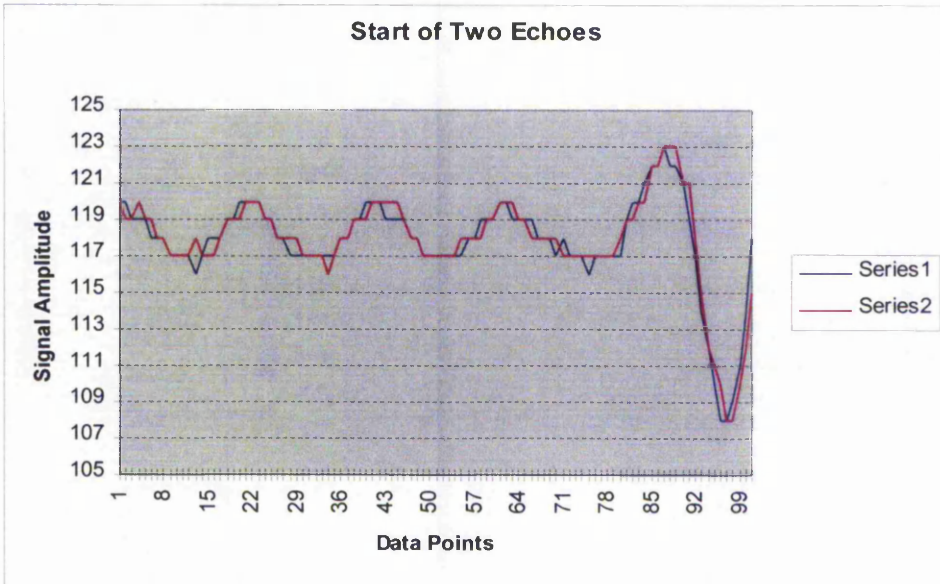


Figure 8.5 Application of the threshold principle

Start of first echo

- Series1 echo at time, t
- Series 2 echo at time, t +10seconds
- Noise at +/- 2

Threshold for signal trigger set at +/- 5

All data points captured in a string are assigned a number representing their signal intensity. In the above case, this value is between 116 and 120 until the first detection of the echo. If the reference signal is valued at 118 and a threshold set at +/- 5 (from 113 or 123), as soon as this value is detected within the string, the address is used to calculate the time taken to detect the first returning echo.

8.3 Software Development

In order to compare the different methods of signal processing involving cross-correlation and the threshold techniques, it was necessary to install the *Signal Processing Toolbox*, an add- on for Matlab® software.

Programmes have been written in the Matlab control window to manipulate the 'Ringing' and 'Echo' signal data sets, all the relevant software is presented in Appendix E.

8.3.1 Explanation of Data Capturing/outline of typical experiment

In preliminary experiments the signal data was captured in 500 data points, which represented the display window of a Gould 200Ms/sec 100MHz Oscilloscope, Model 465. A realistic time per data point was 1μs.

8.3.2 The Matlab Interface

1. Storing the Data

Five sets of transmission and echo signals were captured and stored, typically as shown in Figures 8.6 and 8.7,with the distance between the transducers and the reflecting surface remaining constant. The data sets were processed utilising Matlab software.

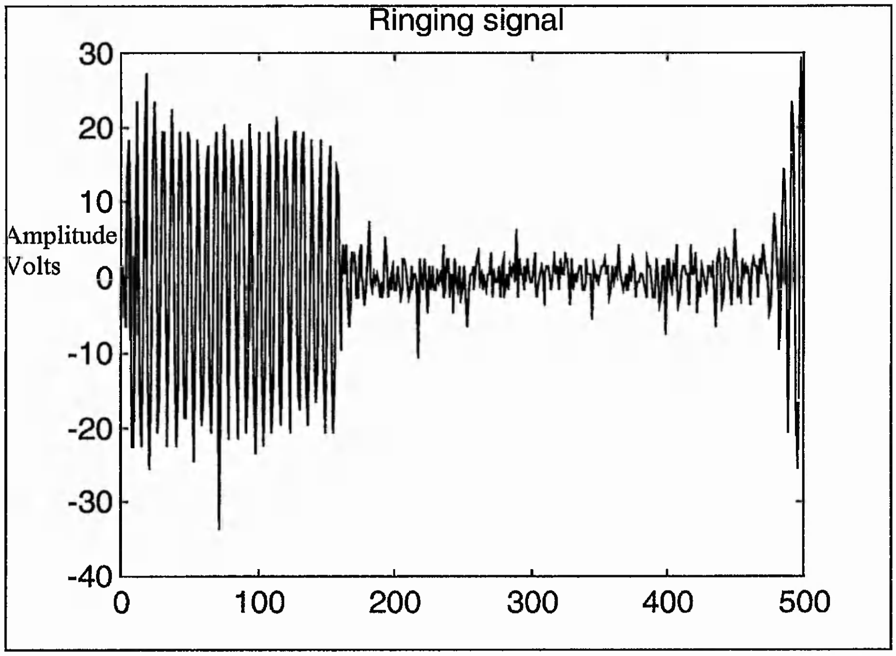


Figure 8.6 Transmission Signal

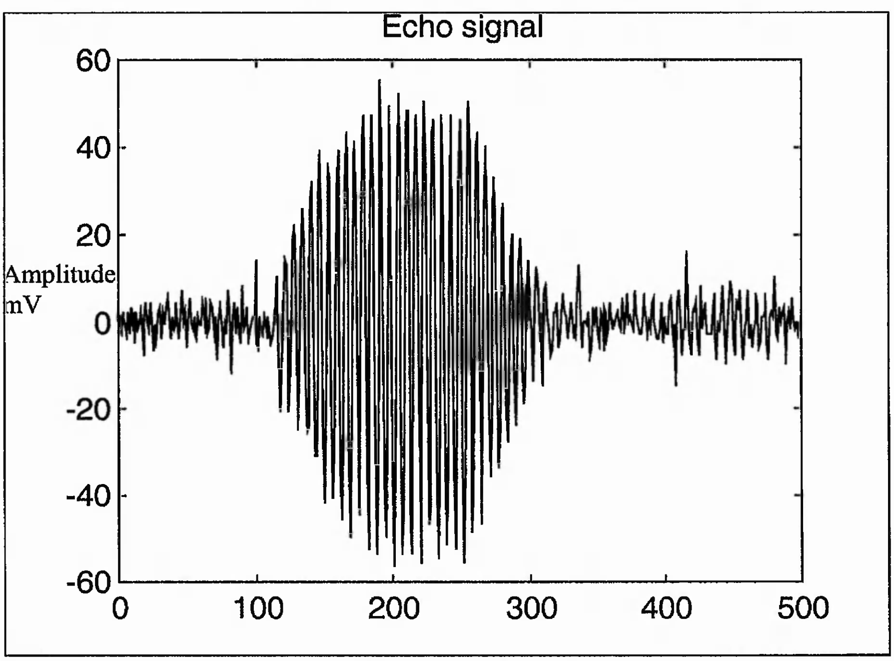


Figure 8.7 Echo Signal

A programme outlined below was designed to manipulate the 'transmission' and 'echo' signal data sets. This programme converted the signals to the frequency domain to illustrate power spectral density, cross correlation processing and to finally produce a time of flight between transmission and returned echo.

Programme written in Matlab to measure TOF using Cross-correlation

Programme	**Explanation**
clf reset	
echo on	
clc	
%	**This programme illustrates the FFT function for spectral**
%	**analysis. A common use of FFT's is to find the frequency**
%	**components of a signal buried in a noisy time domain signal.**
%	**The FFT is then used for Cross-correlation**
clc	
clear all; %	**Clear all variables**
%	**Next we can form a signal containing unknown frequency waves.**
load 030297\level3.dat;	**Loads experimental data.**
load 030297\level4.dat;	
test1 = level3;	
test2 = level4;	
me= mean(test1)%	**Removes mirroring of Square wave and shifts base line**
test1 = test1-me%	**to centre of signal**
me= mean(test2)	
test2 = test2-me	
figure(1)	**% Assigns the Figure to display plots**
plot(test1(1:500)), title('Ringing signal'), pause	**% See Figure 8.6**

```
plot(test2(1:500)), title('Echo signal'), pause          % See Figure 8.7
clc

%           Finding the discrete Fourier transform of the noisy signal y
%           is easy; we just take the fast-Fourier transform (FFT) :

R = fft(test1,512);
R(1)=[ ]          % Deletes DC offset

E = fft(test2,512);
E(1)=[ ]          % Deletes DC offset

%           The power spectral density, a measurement of the energy at
%           various frequencies, is found with:

PRyy = R.*conj(R)/512;
PEyy = E.*conj(E)/512;
clc
%           To plot the power spectral density, we must first form a
%           frequency axis:

f= 1000000*(0:255)/512;

%           which we do for the first 255 points. (The remainder of the 256
%           points are symmetric.)  We can now plot the power spectral
%           density:

stem(f,PRyy(1:256)), title('Ringing Power spectral density'),   See Figure 8.8
xlabel('Frequency (Hz)'), pause
stem(f,PEyy(1:256)), title('Echo Power spectral density'),          See Figure 8.9
xlabel('Frequency (Hz)'), pause
```

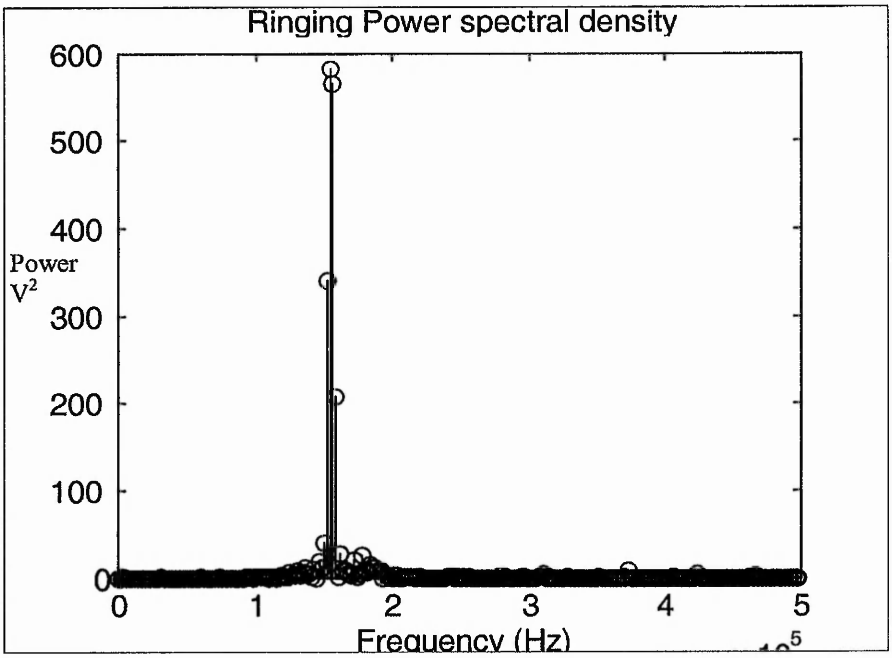


Figure 8.8 Ringing Signal Power Spectral Density

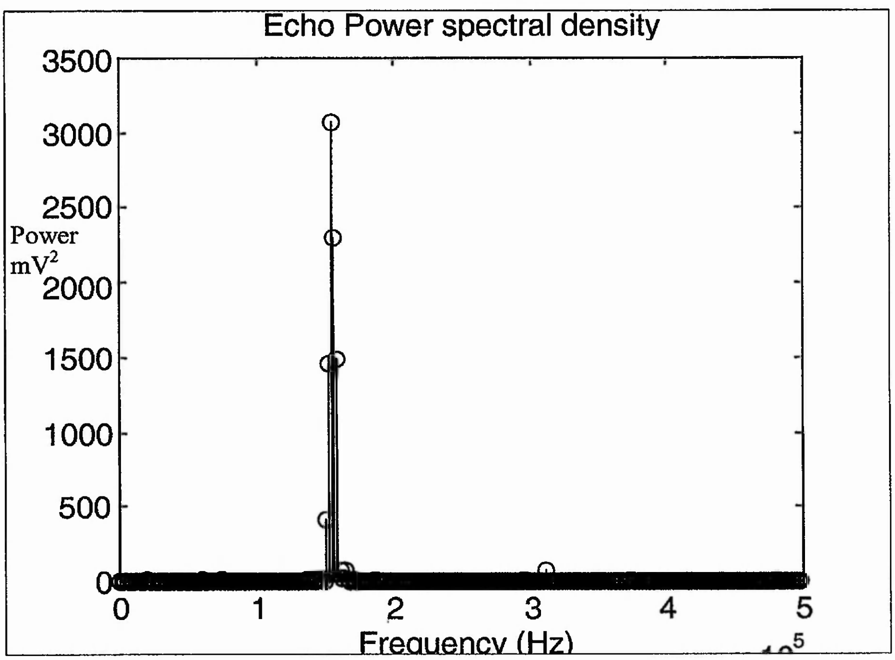


Figure 8.9 Echo Signal Power Spectral Density

Cross = xcorr(test1,test2), **% Performs Cross-correlation on the original data sets**

plot(Cross) **% Plots the Cross-correlation result, See Fig. 8.10**

pause

ACross = abs(Cross);**% Determines just absolute values of Cross-correlation**

plot(ACross) **% Plots the absolute cross-correlation results, see Fig. 8.11**

[m,i]=max(abs(Cross))**% Determines the maximum value and position within the**

pause **% Cross-correlation data set, See Fig. 8.12**

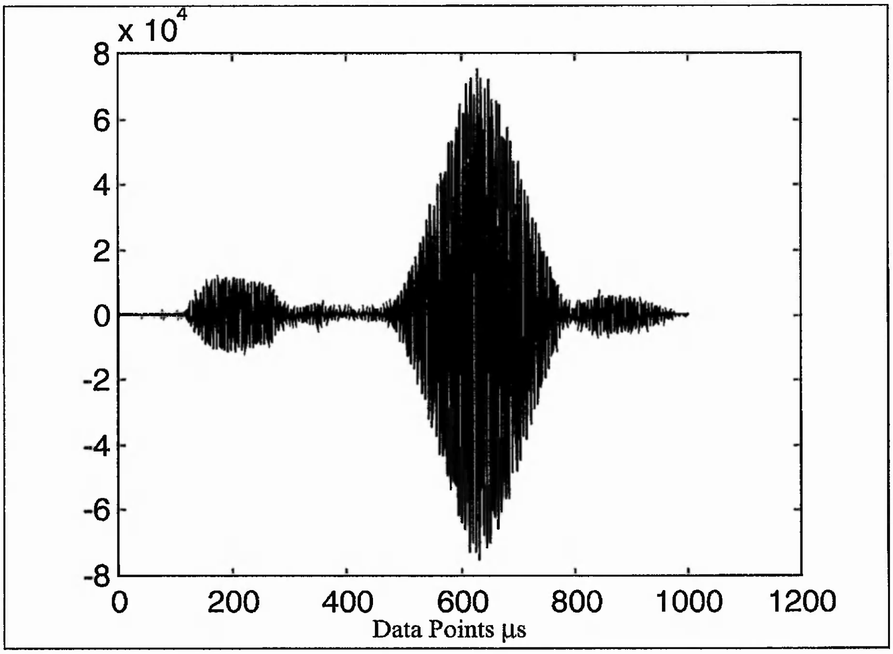


Figure 8.10 Cross-Correlation Result

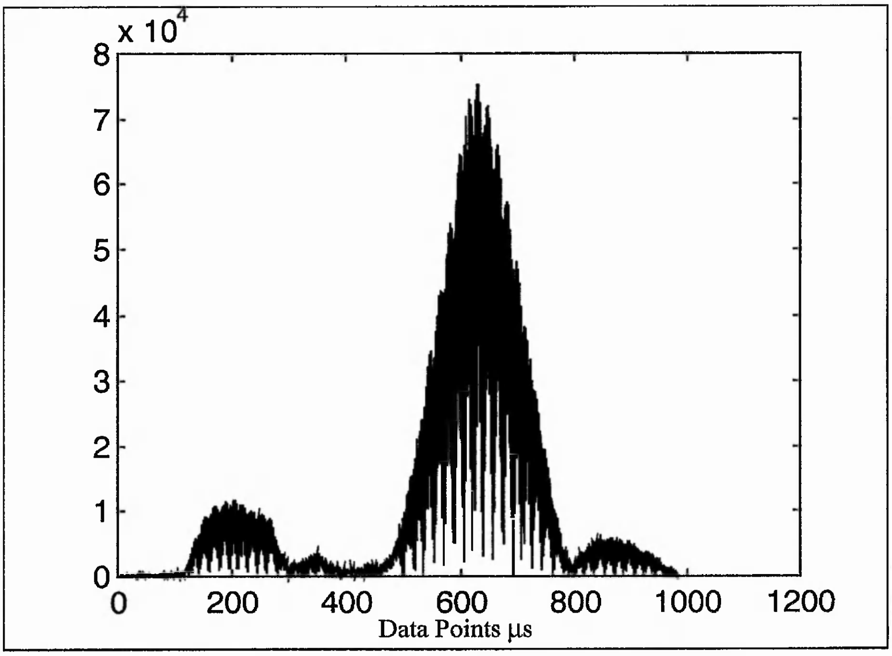


Figure 8.11 Absolute Cross-Correlation Result

```
m =

 7.5271e+004


i =

 633
```

Figure 8.12 Cross-Correlation Data Set (m =maximum value and i =position within the data set)

```
clc
echo off
disp('End')        % End of Programme.
```

8.3.3 Using the data to calculate time of flight

In the above example, the captured windows of the signals displayed on the oscilloscope were **364μS** ($364 * 10^{-6}$ seconds) apart. The sampling time chosen to display the signals was **1μs** per division. After Cross-correlation there were 1001 points and zero lag happens at point 501. Therefore the cross-correlation plot can be interpreted as shown in Figure 8.13.

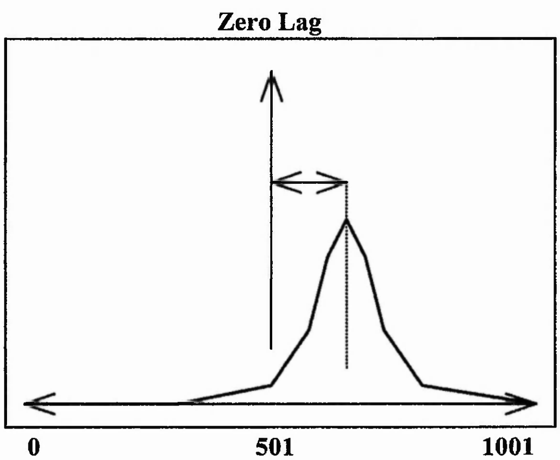


Figure 8.13 An interpretation of Cross-correlation plot and determination of time lag.

The calculation to find the time of flight of the signal is;

$$\mathbf{663 - 501 + 364 = 526\mu s}$$

and taking the speed of sound in air at approximately 340 m/s, the distance travelled by the ultrasound is;

$$\mathbf{340 \times (526 \times 10^{-6}) = 0.17884 \text{ metres}}$$

8.3.4 Results

Having captured five echoes without changing the reflector distance, it was possible to determine the stability of the cross-correlation method of processing the data. If similar signals were cross-correlated they should map onto each other exactly and exhibit zero delay, however this was not the case as can be seen in Table 8-1.

Table 8-1 Cross-correlation results table illustrating the Delay Differences in Similar Signals

Echo data files *.DAT	Echo	Signal	Samples	One to	Five.
	1	**2**	**3**	**4**	**5**
1	0	6	6	10	-4
2	-6	0	0	4	3
3	-6	0	0	4	3
4	-10	-4	-4	0	-1
5	4	-3	-3	1	0

Each data position number within the above table represents where the peak of the cross-correlation matrix occurred (0 to 10 +/-).

For a sampling rate of 50 µs each data point has a value of 1µs, therefore, taking the speed of sound in air to be 346 m/s at 25 °C, errors in terms of distance can be as much as 10e-6 x 346 = **3.46mm.**

In summary, the Transition II software and oscilloscope did not provide the most accurate way of digitising the data due to its slow sampling frequency. In addition, as the table illustrates, there is a jitter in the system possibly caused by the cross-correlation method of processing, details of which are given in § 8.5.2.1.

In order to rectify these problems, the use of a faster data transfer unit was explored as well as alternative methods of data processing.

8.4 Improvement of system

It was recognised that the use of a digitiser board would possibly provide a more rapid means of data transfer and sampling frequency. Through a collaborative venture with Stresswave Technology, an analogue to digital converter (ADC) and digitiser board were designed and installed in the PC, the principles of which were outlined (Chapter 7). The sampling rate of the card was set to 3.125 MHz and the number of data points capture to 4096. Time per data point was now 0.32μs with a total time of capture 1.31072 milliseconds, in contrast to the Transition II software value of 1μs per data point.

In order to integrate the ADC card into the system, the Wavetek Pulse Generator was set up in pulse mode and directly triggered the card. After further examination it was discovered that a constant 3V signal emitted from the trigger input of the ADC card. This interfered with the trigger input from the Wavetek Pulse Generator, and therefore no data could be captured. In order to rectify the situation, capacitors were introduced into the trigger connection to eradicate the impedance mismatch detected.

Returning signals could now be successfully captured and written to files, and viewed in Microsoft Excel. An example of a typical time-course trace is shown in Figure 8.14.

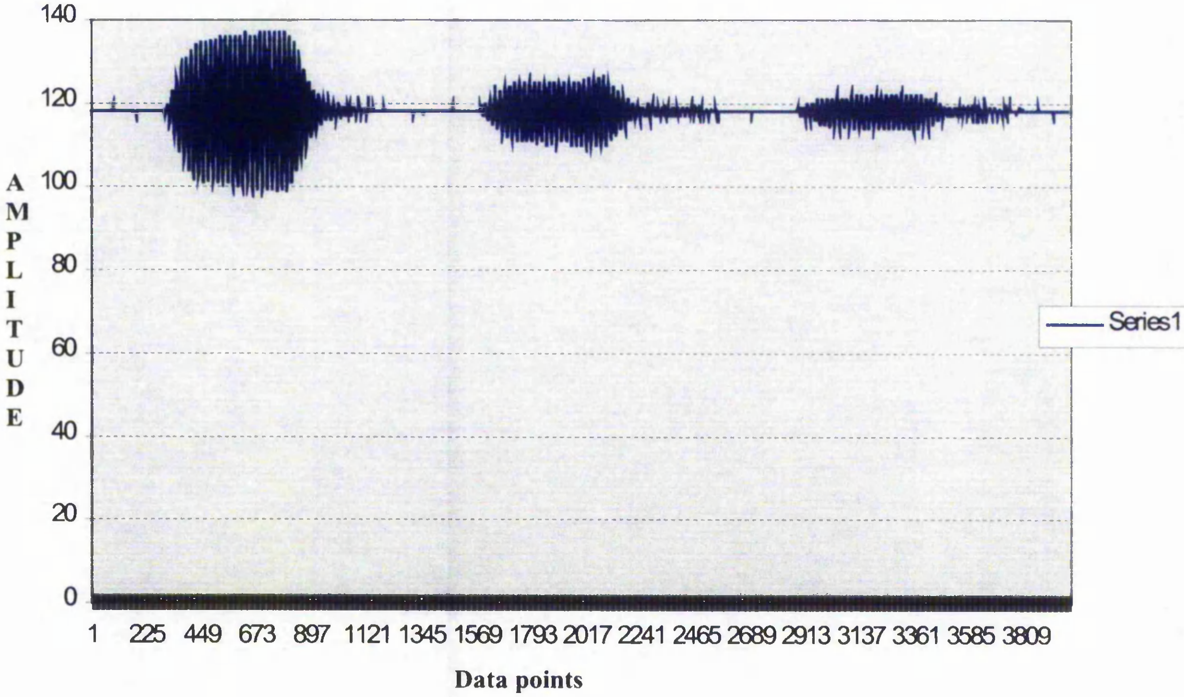


Figure 8.14 Representation of Signal using Sonix Digitiser

Figure 8.14 shows a returning echo pulse of ultrasound and two consequential reverberations of improved resolution. These improvements will be further discussed.

8.5 Air Transmission Connections and Development

Once that data was captured via the ADC board into the computer for storage and analysis, using equipment connected as shown in Figure 8.15, experiments could be conducted more accurately (from 1Mhz to 3.125Mhz sampling frequency) as described in the proceeding sections.

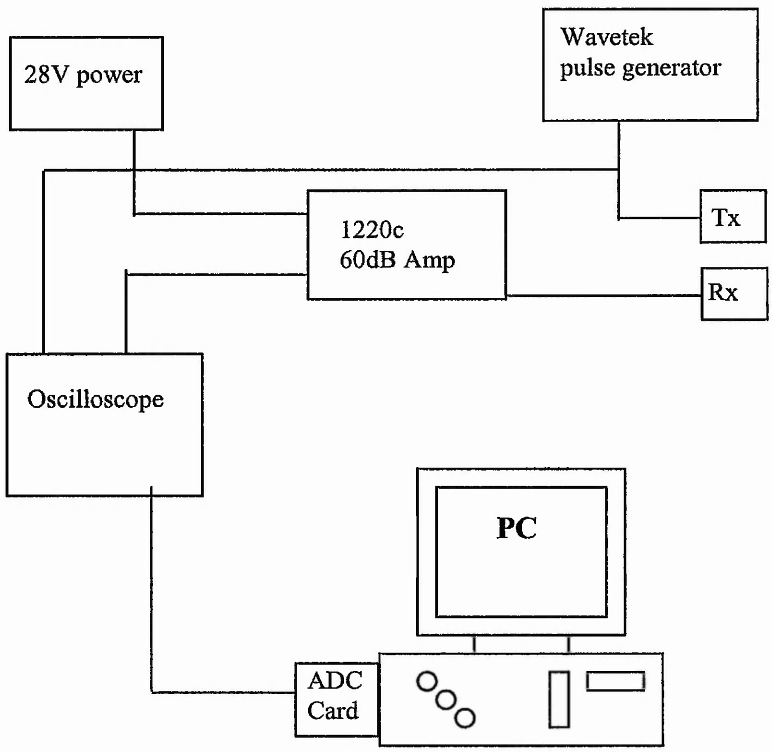


Figure 8.15 Connections of Air Transmission Equipment to a PC

8.5.1 Experiments in Air Transmission: obviating temperature as a variable

To assess the accuracy in using the two signal processing methods, cross-correlation and threshold processing as discussed in sections 8.2 and 8.3, experiments were devised as follows.

8.5.1.1 Key Concepts:

Measurement of small distances.

To accurately measure very small distances, < 0.01mm, a Vernier sliding block was manufactured to the specifications illustrated in Figure 8.16.

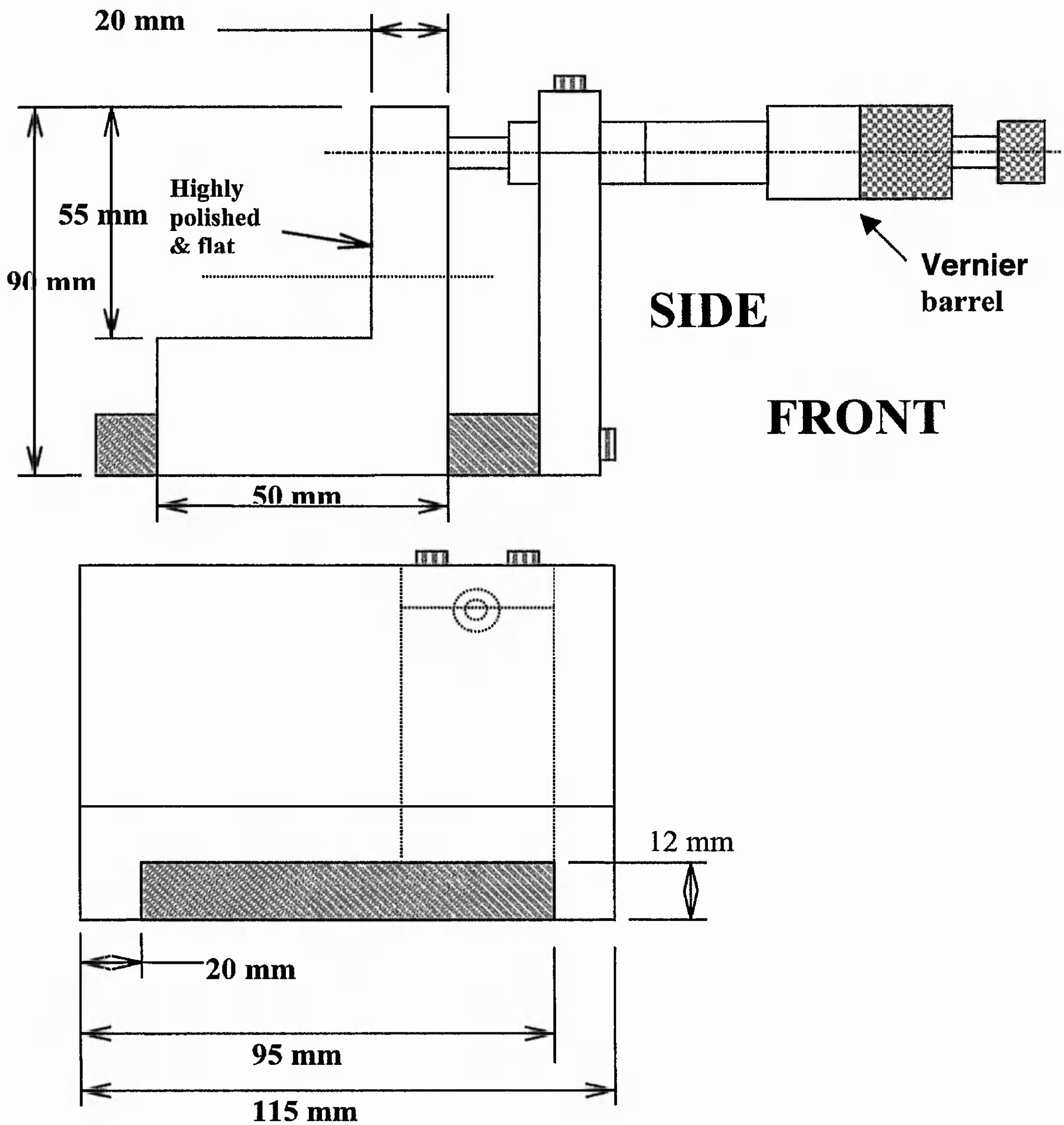


Figure 8.16 Sketch and dimensions of Vernier Sliding Block

As the vernier barrel was rotated the highly polished aluminium block was allowed to slide forward within its tracks. The polished surface of the sliding block acted as a reflector for the ultrasound signals. (Figure 8.17)

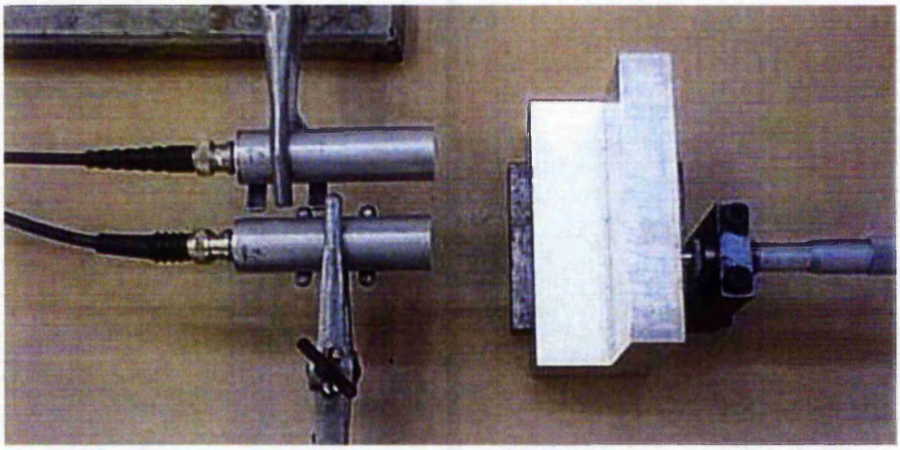


Figure 8.17 Vernier block acting as a reflector for ultrasound

The speed of sound varies in different types of media. Generally, sound travels fastest in solids, slower in liquids, and slowest in gases. The temperature of air (or other gases) affects the speed of sound. For this experiment the following relationships were incorporated into the Matlab® programmes used for data analysis, to obviate temperature as a variable.

The speed of sound in air (accurate only over a relatively small range of temperatures) can be determined by:

$\mathbf{v = (331 + 0.61t)\ m/s}$

where t is the temperature in degrees Celsius, or

$\mathbf{v = 20.0\ ms^{-1}\ K^{-1/2}}$,

where K is the temperature in Kelvin [Vargas et al 1997].

8.5.2 Cross-correlation processing experiment

A reference tone burst was stored as a .dat file to use as the starting point for all accuracy experiments. The environmental temperature was measured using a thermocouple and meter. The thermocouple was positioned to one side of the ultrasound-transmitted beam. This data was used to obviate changes in speed of sound in air based on the relationship given in § 8.5.1.1.

Two ultrasound transducers, one transmitting and one receiving were positioned adjacent to each other in front of the Vernier sliding block at 100mm from the reflecting surface, corresponding to the distance between sensors and fluid level to be measured. At 30-second intervals, five echo signals were captured and stored. The reflecting surface was moved exactly a distance of 2mm and five more echo signals were captured and stored. The first five echoes were cross-correlated with the second set of echoes and detailed in the following table 8-2 of results.

Table 8-2 Cross-correlation results table illustrating data points

Echo data files *.DAT	**1**	**2**	**3**	**4**	**5**
1	18	7	18	8	7
2	29	18	39	19	28
3	18	-3	18	-2	7
4	28	17	38	18	27
5	29	28	29	9	18

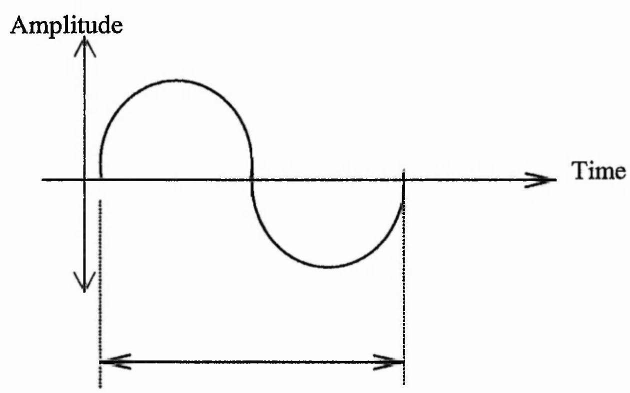
With the ADC card set for a sampling rate of 3.125 MHz, the time allocation for one data point was 1/ 3125000 = 0.32μs.

The table represents the number of data points between the first set and second set of five echoes. All the numbers in the table should be of the same value, corresponding to the number of data points attributed to the change in reflector distance. However, the variations indicate that problems exist with the cross-correlation method of signal processing. These inaccuracies may be attributed to the following observations.

8.5.2.1 Explanation of errors incurred by cross-correlation processing

1. Starting points for cross-correlation mapping.

At 156 KHz, one complete sine wave is represented as in Figure 8.18.



= 1/156000 = 6.4μs

Figure 8.18 156 KHz sine wave

10 data points = 0.32μs ×10 = 3.2μs

20 data points = 0.32μs ×20 = 6.4μs

Cross-correlation between echoes may not always start at the same point. The mapping of one echo to another may not be the same every time resulting in 10 or 20 point jitter.

2. Slight changes in envelope of returning echo.

Figures 8.19 and 8.20 represent the amplification of the middle section of returning echoes at t=0 and t=10 seconds.

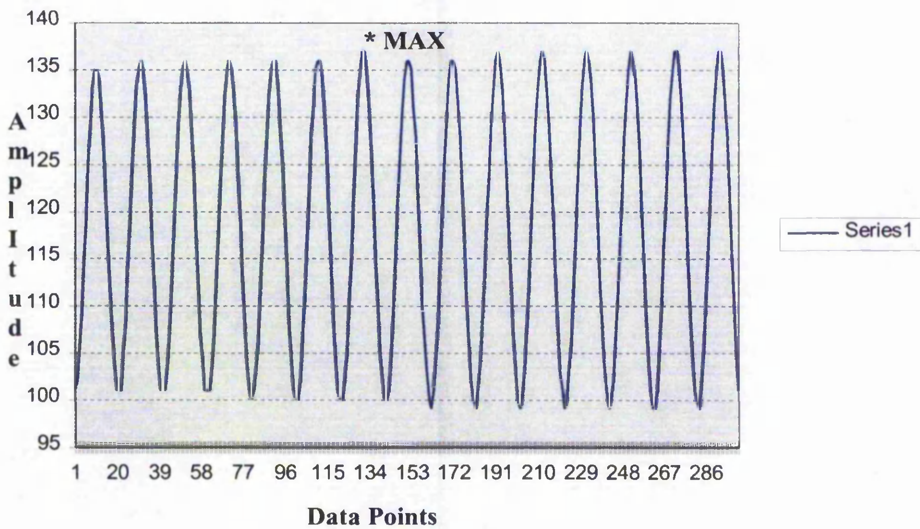


Figure 8.19 Amplification of Returning Echo at t=0.

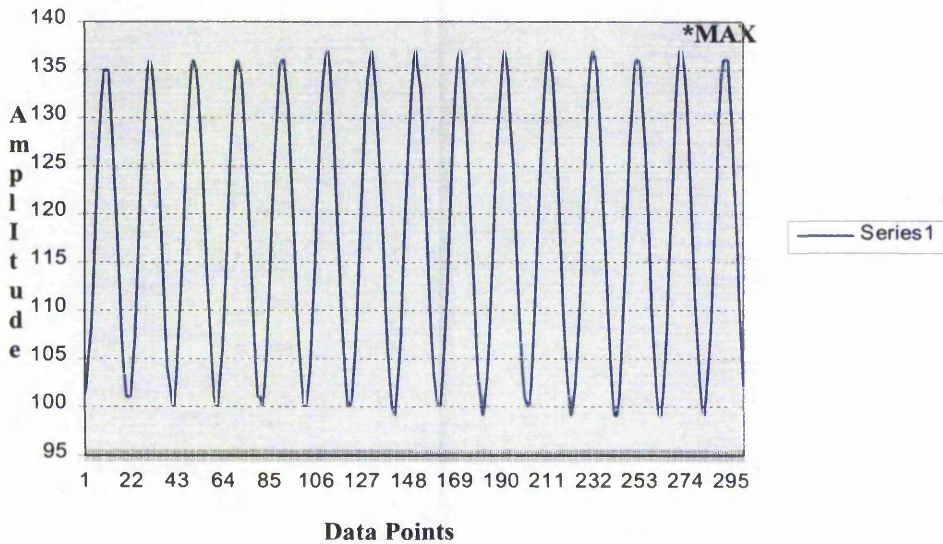


Figure 8.20 Amplification of Returning Echo at t=10 seconds

The slight variation in amplitudes, just visible in figures 8.19 and 8.20 can cause a change in the maximum cross-correlation function, resulting in a difference in the attributed data point time of flight representation.

3. Number of cycles

Is the cross-correlation dependent on the length of the signal? Figure 8.21 illustrates a typical tone burst of 25 cycles, and Figure 8.22 shows the returning echo comprising of 36 cycles.

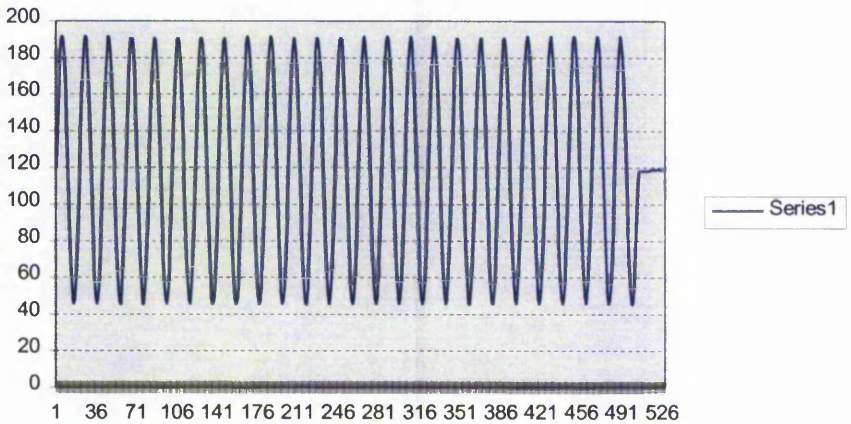


Figure 8.21 Tone Burst, 25 cycles.

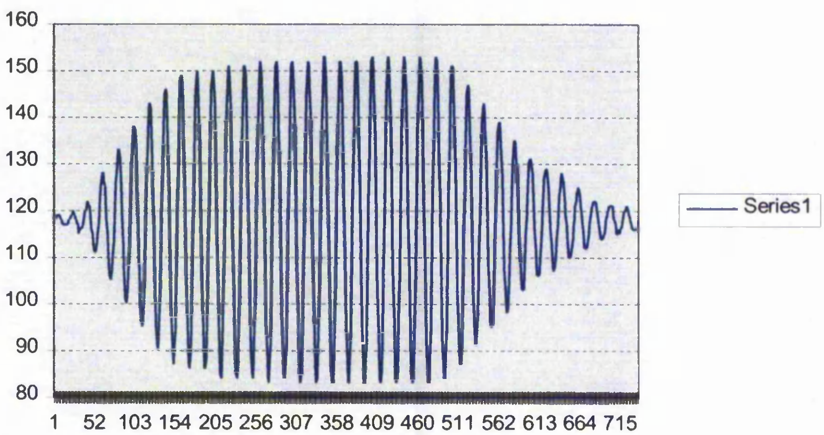


Figure 8.22 Returning Echo, 36 cycles.

An experiment was devised to find out whether the difference in cycles between the transmitting pulse and the echo had an effect on the position of the maximum within the cross-correlation function. This was carried out by adding or subtracting data points from the captured transmitting pulse and comparing the cross-correlation results, as outlined below.

- Cross-correlate the tone burst with the captured echo to determine the distance in terms of data points between them. Result-(4780 data points).
- Add two Ground points (valued at an amplitude 118 units) to the front of tone burst. This adjusted tone burst was cross-correlated with the captured echo. Result-(4778)
- Add ten Ground points (118) to the front of tone burst, cross-correlate. Result-(4770)
- Remove two full cycles from start and end of tone burst, cross-correlate. Result-(4780)
- Add two full cycles to start and end of tone burst, cross-correlate. Result-(4780)

These results clearly show that the number difference in cycles has no bearing on attaining the correct cross-correlation results. Therefore, the number of cycles was eliminated as a possible cause of error.

In conclusion, the slight envelope changes were likely to be the cause of jitter, and therefore cross-correlation was not deemed suitable for processing air-bourne ultrasound in this application. Hence threshold processing was considered as an alternative method.

8.5.3 Threshold Processing experiments

The use of threshold as an alternative method of processing information was examined by using the same data. The start of the returning echo was analysed in more detail by amplifying it within the data viewing software (Microsoft Excell).

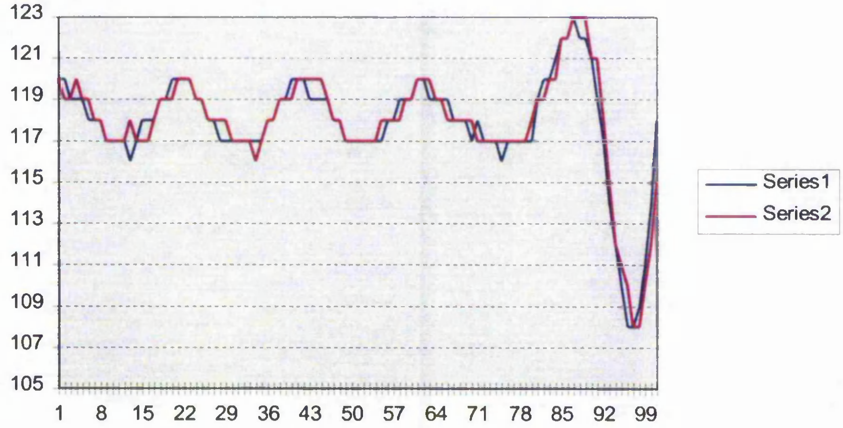


Figure 8.23 Amplification of start of echo

In Figure 8.23, series 1 and 2 are the returning echo signals 1 and 2 from the first set of five signals. These returning signals are near identical as expected. The first rise of the signal breaks through the noise to 123 on the y-axis, five points above the ground signal (118), and then falls to 108 at ten points below the ground signal.

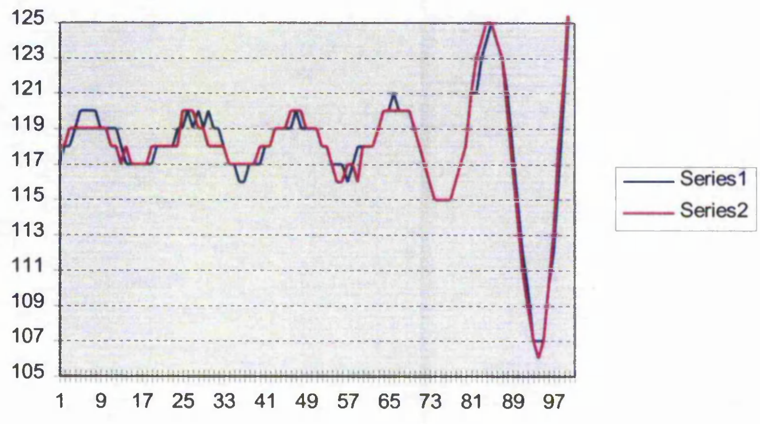


Figure 8.24 Amplification of start of echo after 2mm movement

Series 1 and 2 above are signals 1 and 2 from the second set of returning echoes after a 2mm movement (Figure 8.24). Again they are nearly identical and the first rise breaks through the noise to 125 on the y-axis. This first rise can be considered the start of the signal and the value assigned to it, the threshold.

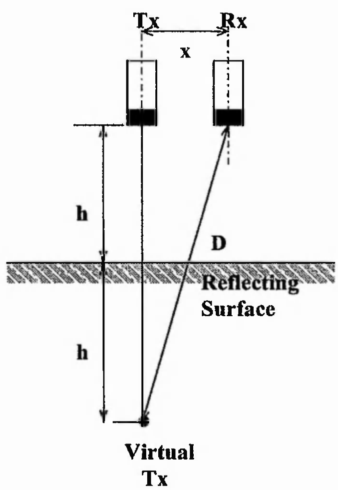
From this threshold value the time of flight can be extrapolated from the data and converted to distance by multiplying by the speed of sound of the transmission medium (346m/s at 25°C). This value,D, when considered in more detail is dependent on the distance between the two transducers.

The following relationship was devised as a more accurate method of determining the distance between the two transducers and the focused reflecting surface.

x = Distance between transducers.

h = Height above reflecting surface.

D = Calculated distance from TOF received.



$$x^2 + (2h)^2 = D^2$$

$$h^2 = \frac{D^2 - x^2}{4}$$

$$\therefore h = \frac{\sqrt{(D^2 - x^2)}}{2}$$

Figure 8.25 Air Transmission Principle [Griffin, 1997].

The geometric relationship illustrated in Figure 8.25 represents the true line of the ultrasound beam. The derived equation [Griffin, 1997] determines the true value h, height above reflector, from the time of flight received from the transducer.

A typical situation was as follows,

for D =202.3mm and for x = 15mm,

$$h=\frac{\sqrt{(202.3mm^2-15mm^2)}}{2}=100.87\text{mm}$$

and without geometric compensation, D/2 = 101.15mm.

This equates to a 0.27% change in the actual distance.

The equation was incorporated into the Matlab processing programme.

8.5.3.1 The Matlab threshold programme.

It was necessary to write a programme within Matlab to manipulate the data:

```
%                          Time

%              Written By Simon J.Griffin 1997

clf reset


disp('Time of flight of Ultrasound Signals')

clear all;                      %clear all variables

format long

load 240497m3\data2.dat;        % Loads data
load 240497m3\data3.dat;


sfreq = input('TIME PER DIVISION (seconds)?');
airtemp = input('AIR TEMPERATURE (C)? ');

seper = input('DISTANCE BETWEEN TRANSDUCERS (metres)?');


test1 = data2;
test2 = data3;

me1= 118 %mean(set_1);          % Removes mirroring of square wave and shifts
test1 = test1-me1;              % base line to centre of signal.
```

```
me2= 118 %mean(set_1);
test2 = test2-me2;


figure(1)                          % Assigns Figure to display plots.
plot(test1(1:4096)), title('Reference signal'), pause
plot(test2(1:4096)), title('Echo signal'), pause

i=1;
while (test1(i)<12) & (I<4096)     %Assigns threshold value, searches data set for
                                   %position of value
i=i+1;
end
i                                  %Displays position

j=1;
while (test2(j)<12) & (j<4096)
j=j+1;
end
j
dist1 = (sfreq*i)*(331+airtemp*0.609);     %Converts data position to distance,
                                           %metres
dist2 = (sfreq*j)*(331+airtemp*0.609);

%strg = sprintf('\nDistance travelled by Ultrasound is %10.6f metres',dist);
%disp(strg)
%pause

height =1000 *(((sqrt(dist1*dist1-seper*seper))/2) - ((sqrt(dist2*dist2-seper*seper))/2));
disp(height)                       %Displays air gap change in mm, from derived equation in
                                   figure 8.25
pause

% disp('End')
```

8.5.3.2 Validation of the threshold method utilising the Matlab threshold programme.

The transducers were clamped and positioned 100mm from the aluminium reflecting block as described in section 8.6.1.1 Key concepts. Three echoes were captured via the A/D card and assigned Data1-3.dat files. The reflector was adjusted to represent a 2mm change in distance, as illustrated in Figure 8.26 and a further three echoes captured and assigned Data4-6.dat. The echoes were run through the Matlab threshold programme and the output from file 1 was compared with the output to that of file 4, file2 with 5 and 3 with 6 respectively.

The value assigned for threshold detection was set at 12 points above the Ground and the sampling frequency at 6.25Mhz.

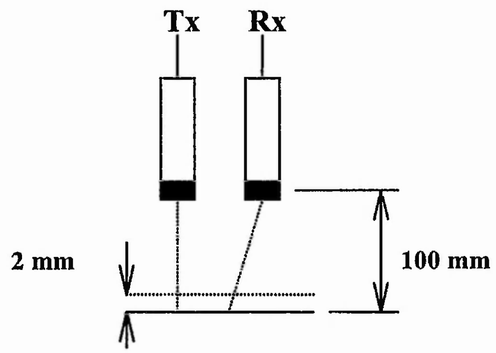


Figure 8.26 Reflector distance change (2 mm)

The results were as shown in Table 8-3, with results converted from data points to millimetres.

Table 8-3 Threshold measurement results mm

	4.dat	**5.dat**	**6.dat**
1.dat	1.906mm	1.850mm	1.824mm
2.dat	2.522mm	2.466mm	2.522mm
3.dat	2.522mm	2.466mm	2.522mm

The results clearly depict a far more consistent spread of measured values with the errors amounting to – 0.176mm to + 0.522mm. A jitter of 2.31mm using cross-correlation (table 8-2) and only 0.69mm utilising the threshold approach.This suggests that threshold processing would be the method of choice but further data processing methodology would be required to improve levels of accuracy.

8.5.4 Summary

The threshold processing method delivered more stable results than cross-correlation. Incorporating a digitiser board to improve the sampling rate advanced the air transmission equipment and data capture resolution for digital signal processing techniques. This system could now be applied to detect fluid levels in a bottling environment. The next chapter describes the development of a carbonating bottling rig.

Chapter 9 - The use of ultrasound for fluid level measurement in a carbonating and bottling system

Introduction

To satisfy the research requirements the use of an industrial scale container filling rig was investigated to test whether on-line ultrasonic measurement of filling levels could be made. To model the filling process as closely as possible to a real industrial situation it was necessary to identify components and relevant processes. An appreciation and understanding of the bottling process was observed at Britvic (Chelmsford, Essex), the main considerations for the development of a bottling rig were as follows :

- Overall size, height, width and depth of rig.
- Design of mounting board, so components can be easily repositioned.
- Type of valve.
- Volume of fluid tank
- Type of pump and flow rate.
- Design of transducer mount.
- Type of container.
- Type of fluid.
- Control action.
- Connections and piping.

However, after considering these requirements it became apparent that a model bottling unit was commercially available. A unit was subsequently purchased from Advanced Bottling UK LTD, suppliers of bottling, brewing and packaging equipment. A photograph of the unit is shown in Figure 9.1.

9.1 Carbonation and bottling system

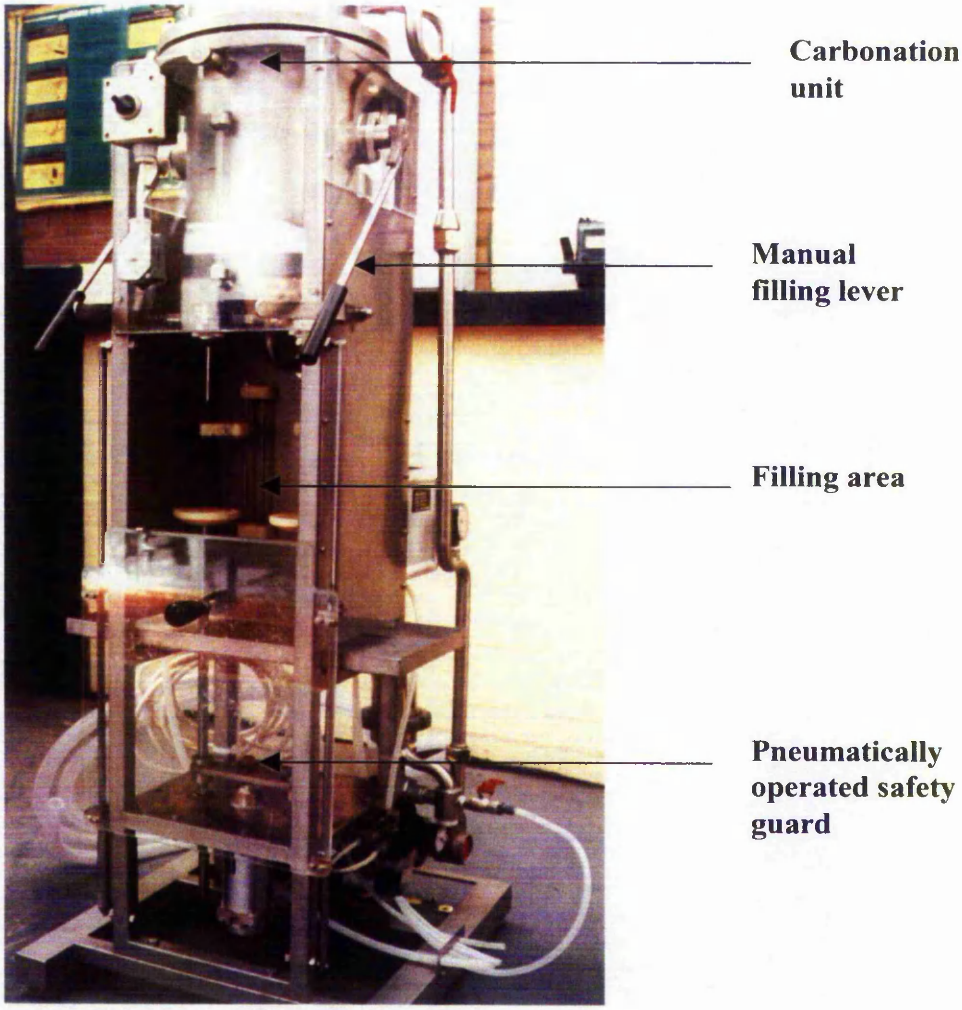


Figure 9.1 CW250 Carbonation and Bottling unit

The carbonation and bottling unit CW250 manufactured by Advanced Bottling UK, is used for carbonation (saturation by carbon dioxide) of wine, water, fruit juices, ciders, mineral waters and for subsequent bottling of manufactured carbonated beverages. An initial process is the drawing in of uncarbonated beverage from an open container (with atmospheric pressure) through a filter that retains any solid particles bigger than 0.1 mm.

The drawing in Appendix F contains the dimensions and descriptions of the main components of the unit. These include a welded frame (1) of steel profiles, carbonation

(2) and bottling (3) sections, carbonation pump (5), filling siphon valves (7), float valve (6), manipulation arms and rods, closing and draining valves, pressure gauges, electric sensors for level control and a switchboard with wiring. The unit is also equipped with pneumatic bottle thrusting and has an air operated cylinder (33) installed above the bottle frame (1).

9.1.1 Operation

The beverage, drawn in by the carbonation pump, is filtered and introduced into the carbonation section of the unit. The beverage is saturated with carbon dioxide in the inner cascade system and then transferred to the bottling section. The level controller in the bottling section attempts to maintain constant level. The level in the carbonation section is kept between maximum and minimum by proximity sensors which switch the pump on and off through an automatic control system.

Bottles are pneumatically positioned under the filling valves, and relief valves are open and closed several times to equalise pressure in the bottles and the bottling section. Bottles are filled with beverage after the filling valves are pressed off.
The pump is protected against running without liquid by the control system and the unit is also supplied with direct reading pressure gauges and a level gauge.

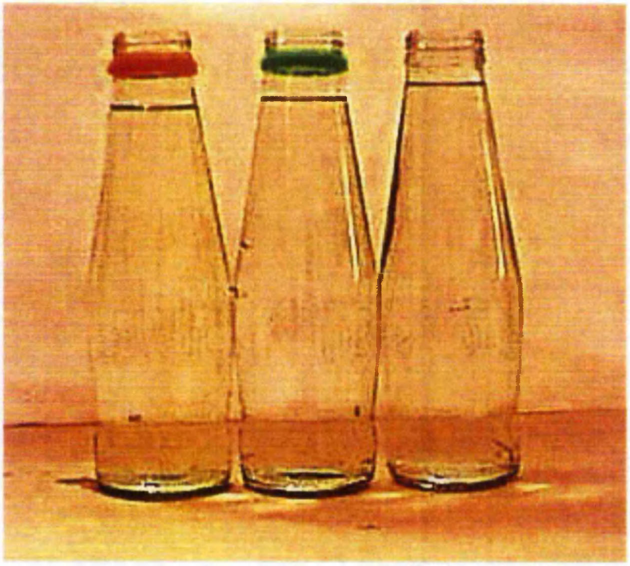


Figure 9.2 A photograph showing typical fill variations

After installing and commisioning the unit in the laboratory, experiments were undertaken to assess the variability in filling levels incurred by the system. Figure 9.2 is a photograph that shows the variability in fill levels that occurred for a typical fill operation.

The extent of this variation was measured by weighing and calculating the volume of contents of a series of bottles filled with 1 pint of carbonated water, as shown in Table 9-1.

Table 9-1 Variations in volume of carbonated water

Bottles	1	2	3	4	5	6
Calculated volume ml	560	564	572	561	575	559

It is clear that using the bottling system can introduce a wide variability in fill levels. In a more in depth study, Hull et al [1995] demonstrated that in the filling of 211 soft drinks bottles, 11 were under-filled, 44 were filled accurately and the remaining were overfilled.

9.1.2 Design considerations (constraints)

One of the first requirements in applying ultrasound for fill level detection was the positioning of the transducer. It was clear at this stage that considering the dimensions of the filling valve, as depicted in Figure 9.3, and the size of the ultrasonic transducers (Diameter 25mm), that there was insufficient space to mount the transducers at the appropriate position for air transmission to the liquid level surface (bottle neck diameter 20mm).

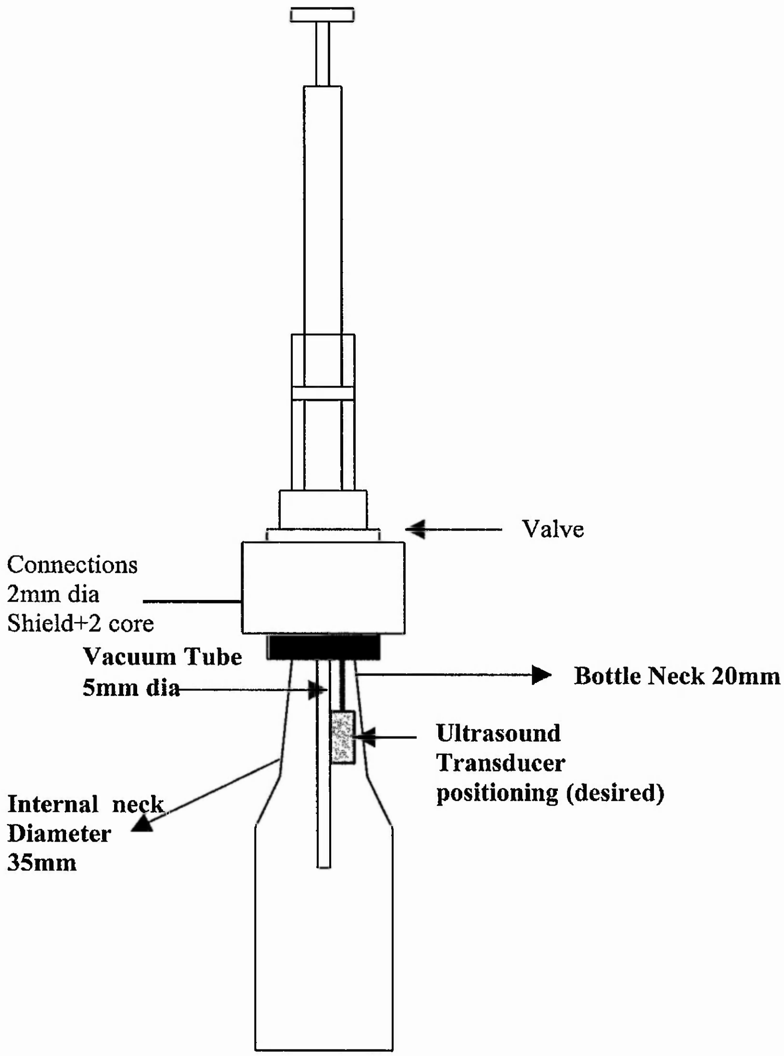


Figure 9.3 Filling valve dimensions and proposed transducer position

It was necessary to consider the use of smaller transducers or a single transducer before any further work using the bottling rig could be carried out.

9.2 Development of a transceiver module

9.2.1 Introduction

Due to the physical design constraints associated with the transducer mounting access, smaller transducers were required. Having unsuccessfully attempted to purchase smaller air transmission type transducers commercially from companies such as Phoenix Inspection Systems Ltd, a small sensor was manufactured by Stresswave Technology. These transducers had to be manufactured to a specified operational frequency so as to transmit ultrasound through air successfully, yet be small enough to be incorporated into the filling head, Figure 9.3, to not disturb the inflow of product.

The sensor comprised the smallest PZT PE elements available that were fitted inside two equal lengths of tubular Tufnol. Electrodes were connected to the PZT PE element and rear damping applied. In addition, a front acoustic impedance matching layer was incorporated into the design. The custom built transducers, as shown in Figure 9.4, were shielded in aluminium tubes and correctly earthed to minimise cross-talk.

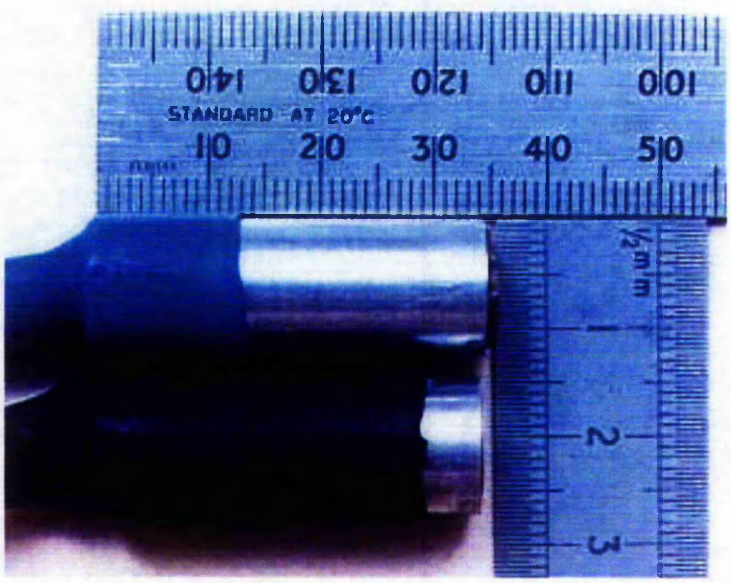


Figure 9.4 A photograph of the two small custom-built 'air-transmission' type transducers

The two transducers just fitted inside the neck of a standard bottle, as shown in the photograph Figure 9.5, but the close proximity of the transmitter and receiver caused excessive cross-talk , illustrated in Figure 9.6.

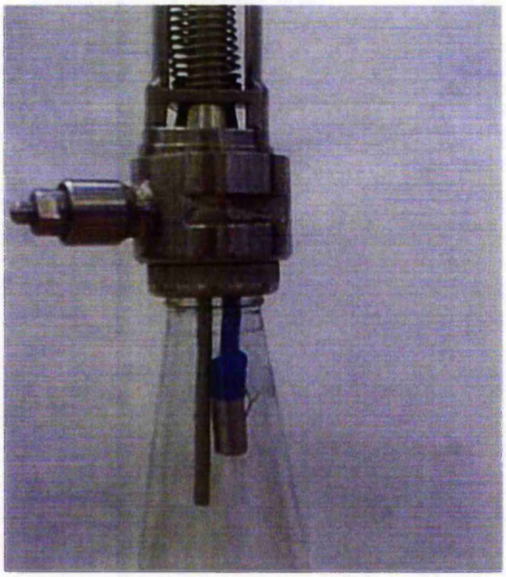


Figure 9.5 Transducers fitted inside bottle

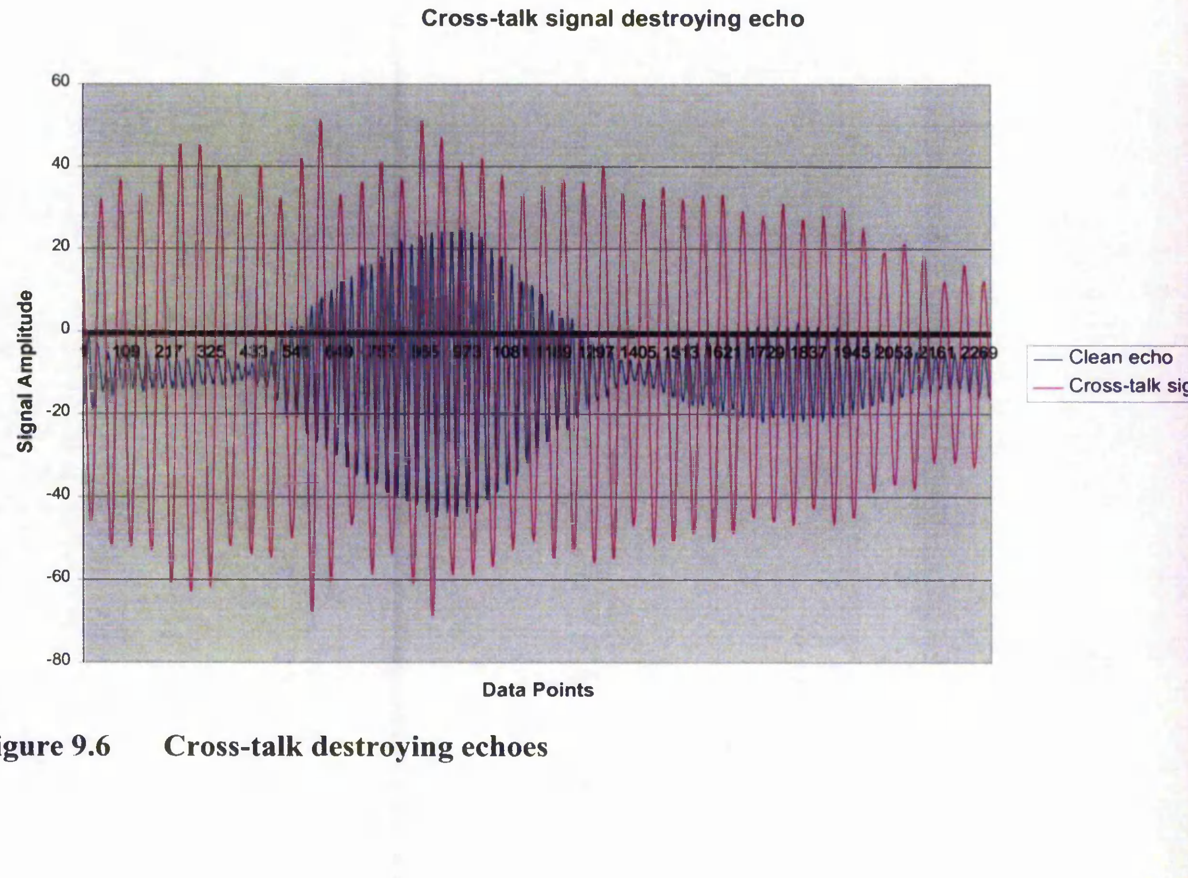


Figure 9.6 Cross-talk destroying echoes

Therefore, it was clear, that the transmitter and receiver would have to be incorporated into one single unit. This could potentially be achieved by transmitting and receiving ultrasound from a single transducer.

9.2.2 Development of single transducer operation

9.2.2.1 Methodology

Figure 9.7 shows a block diagram of the desired function of the single transducer. One of the main objectives is to isolate the receiving duration (or listening period) of the sensor from the excitation pulse.

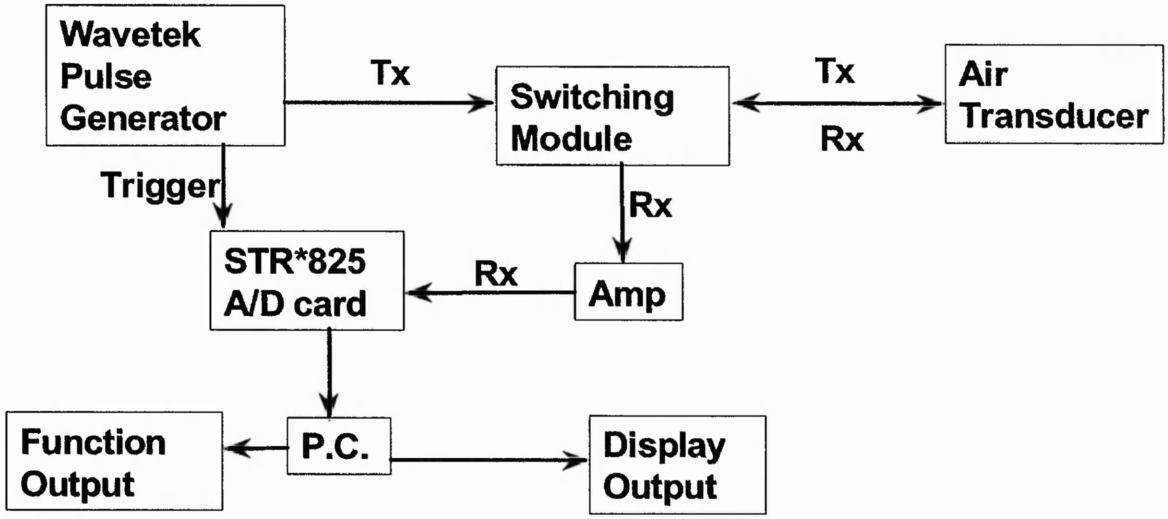


Figure 9.7 Block diagram of transceiver switch network

The proposed method of isolating the receiving and the transmission phases was to incorporate a switch, allowing the single transducer to act as a transceiver. A transceiver module for this specification was not commercially available at this specific frequency and energy of interest at this time. It was necessary to develop a switch. Figure 9.8 shows a typical circuit diagram of the nature of the switching concept, developed with the assistance of Dr. Noel Kerr (formerly of Stresswave Technology Ltd and Mr. Detlef Plantenberg (Research student, Nottingham Trent University). Appendix G shows alternative concepts and circuit diagrams investigated.

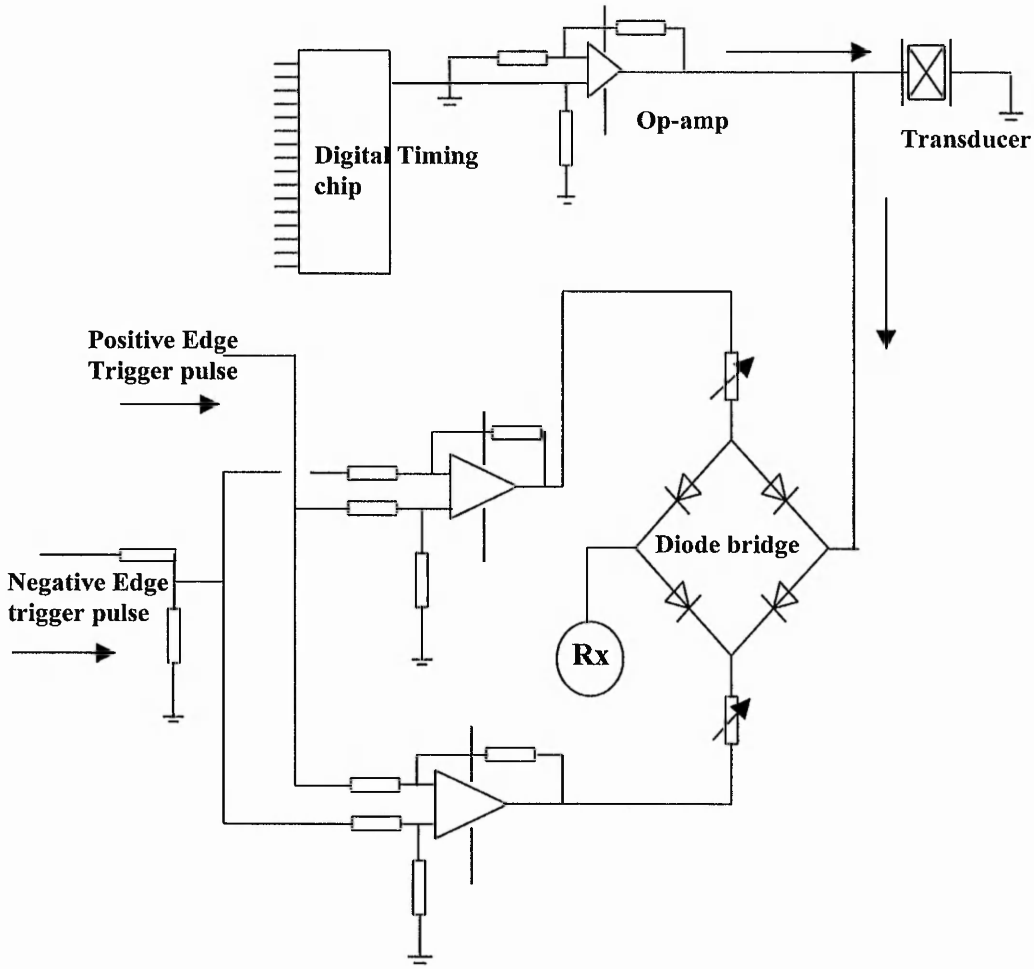


Figure 9.8 Circuit diagram based on the Diode Bridge for switching action.

9.2.2.2 Operation of the switching circuit

The operation of the switch circuit is as follows.

As a excitation pulse is triggered, the same rising trigger is used to energise the diode bridge and this in turn blocks the path of the excitation pulse to the receiving circuits. This block stops high energy reaching the display or digitiser. As the excitation pulse ends, having delivered 24 cycles of the resonant frequency of the transducer at 30 Vpp, the falling edge of the trigger pulse is channelled to invert the energising on the diode bridge and therefore allow any echoes to reach the receiving circuits, in effect opening the switch. This operation happens many times a second.

9.2.2.3 Testing the circuits

A variety of circuits were built and tested on this theme (Appendix G). Components were tried and adjusted, in an attempt to reduce spurious signals, operational-amplifier switching interference and impedance mismatches between equipment such as function generators, oscilloscopes, transducers and connections.

None of the circuits tested at this current time were able to demonstrate the desired switching effect. This was due to a variety of reasons, including:

- Impedance mismatches
- Response time of individual components
- Transducer damping characteristics

Unfortunately to date, non of the circuits were capable of blocking the influence of the excitation pulse on the 'listening period' of the single transducer.

The understanding of the complex combination and affects of these three variables alone would require a separate and extensive further project (see recommendations).

9.3 Summary

It was not possible to complete on-line fluid level detection using ultrasound in the carbonating and bottling unit at this stage. This was due to the cross talk of transducers, the unavailability of a switch mechanism and development of a single transducer. It was decided to pursue the research objectives off-line in another experimental model system. This would enable further research objectives to be carried out to:

1. Improve the accuracy of the data processing technique.
2. Understand and characterise the variables associated with carbonation and their effects on the ultrasound signal.

Chapter 10 describes further processing and chapter 11 investigates the variables associated with the process.

Chapter 10 - Further Signal Processing

10.1 Introduction

In Chapter 8 the threshold approach was defined and chosen as a successful process of measuring TOF. However because of the variation in calculated measurement (Table 8-3) which does not correspond to likely ultrasound signal frequency errors, further investigation was considered necessary to develop a more stable result. There are certain factors associated with the validity of the final output as a result of processing. These factors are a consequence of attempting to increase the accuracy of the threshold technique. The following section introduces digital processing applied to returning echoes in order to improve variations in TOF measurement associated with changing envelope and ultrasound frequency limitations.

The first investigation objective therefore was to investigate different threshold timing methods by digitally manipulating a 'snapshot' of a returning echo.

The means by which the following techniques are presented can be more fully understood by comparing the distribution of TOF results for a given threshold processing technique. The second objective was to establish the number of echoes (snapshots) required to obtain a confident result by determining the number of shots to obtain a steady state.

Investigations were undertaken to establish the best possible threshold timing technique of ultrasound signals through air, in order to determine the most confident distance measurement. To achieve these objectives the following methods were employed.

10.2 Methods to assess different threshold timing approaches

Two piezoceramic (PZT) air-transmission type transducers were mounted adjacent to each other and focused to transmit and receive ultrasound signals reflected by the face of an aluminium block. This block was positioned to within 0.01 mm of the transducers by adjustment of a Vernier gauge. For the following experiments the block was statically set at approximately 70 mm from the transducer surfaces. Air temperature was monitored with a thermocouple and meter. A Wavetek function generator was set to pulse mode and calibrated to emit a 24 cycle pulse of a 116 KHz (resonant frequency of smaller transducers) sine wave of 30 Vpp amplitude. The receiver detected reflected ultrasound signals through air and this signal was filtered and amplified. The signal was converted to a digital signal via the analogue/digital converter card which was set to receive data at a sampling frequency of 6.25 MHz. The card was also set-up through its C programme command lines, to store a threshold value together with the returning echo signal to file. This process was accomplished either manually or automatically by the addition of a loop command within the C programme. Each file was stored as a sequentially numbered data file. These files were viewed in Microsoft Excell or processed further by Matlab software.

10.2.1 Investigations

The following investigations were carried out:

1. Distribution experiments on the threshold result from the ADC card (raw data).
2. Determinations of measuring a step 1mm distance change over 20mm.
3. Normalising the raw data and plotting the distribution.
4. Normalising the raw data and plotting 1mm step change.
5. Normalising and absolving the raw data and plotting distribution.
6. Normalising and absolving the raw data and plotting a 1mm step change.
7. Interpolating normalised absolved raw data, plotting distribution and step change.
8. Determination of the minimum number of shots required for a confident result.
9. Fitting a normal curve to a distribution plot to give more information on standard deviation for control purposes.

10.3 Objectives and discussion of progression of investigations

Further to results presented in chapter 8, the raw data illustrated a broad spread of results highlighting wavelength limitations and other noise sources which are illustrated in Figure 10.1. The raw data does not take into account the change in signal intensity over a distance change. Therefore normalising the data is a possible solution to give a more uniform threshold result at varying distances. Absolving the data, which effectively reduces the wavelength errors by half, was investigated as a method to minimise the spread of results. The concept of interpolating an imposed carrier wave to reduce the spread even further was also investigated and is presented in section 10.3.4

10.3.1 Distribution investigation on the threshold result from the ADC card (raw data)

The aim of this preliminary investigation was to test the reproducibility/reliability of the threshold timing method. As described in the methods above, the A/D card was programmed to output a threshold value that was then incorporated into Matlab. The discriminator value within the A/D card was set to zero. At a fixed reflector distance, a pulse generated echoes of which 100 were transferred to file. A histogram of the distribution of thresholds was generated.

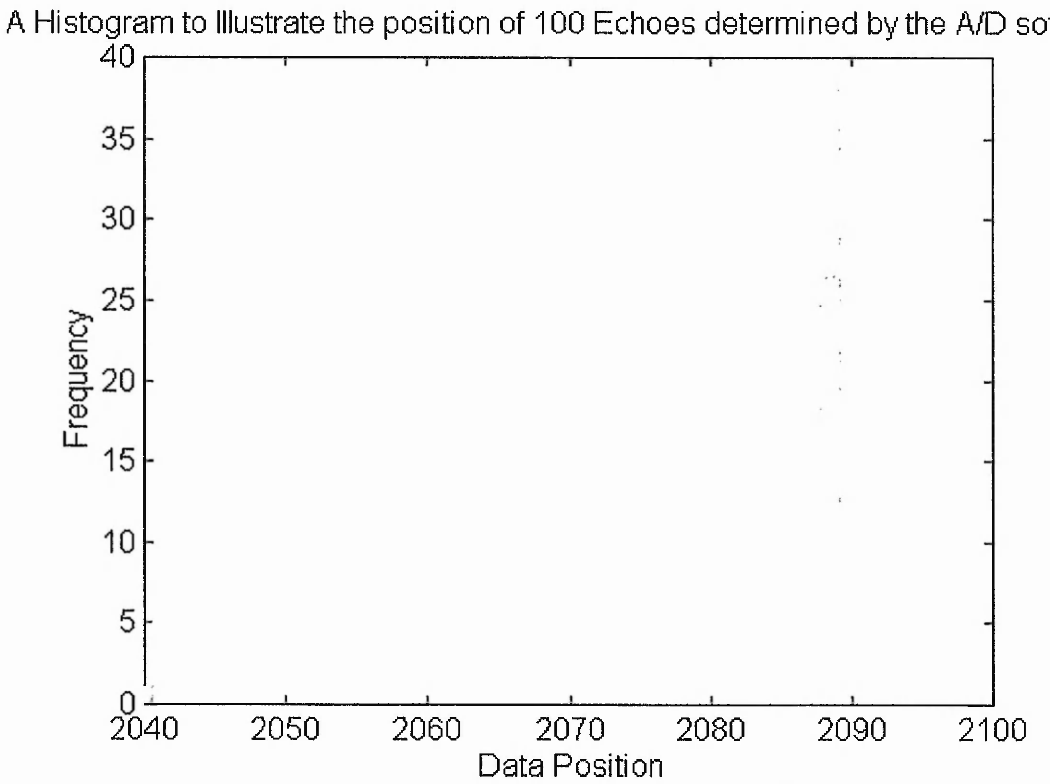


Figure 10.1 Histogram of threshold data values of 100 consecutive echoes determined by the ADC software.

It can be clearly seen that there are two predominant areas of distribution. The smaller area is approximately 50 data points from the larger area. These 50 data points coincides with one complete wave cycle at the ultrasound frequency used in the experiments and the sampling frequency of the AD card. From further investigation Figure 10.2 illustrates the magnification of two echoes; in this case the first and fourth of 100. It can be seen that there is a slight difference in the two wave forms. From further magnification, Figure 10.3, the discrepancy of threshold values is visible due to echo 1 not breaking the discriminator value "zero" as echo four. In this instance, echo four returned a value of threshold of 2041, and echo 1 returned a value of 2088.

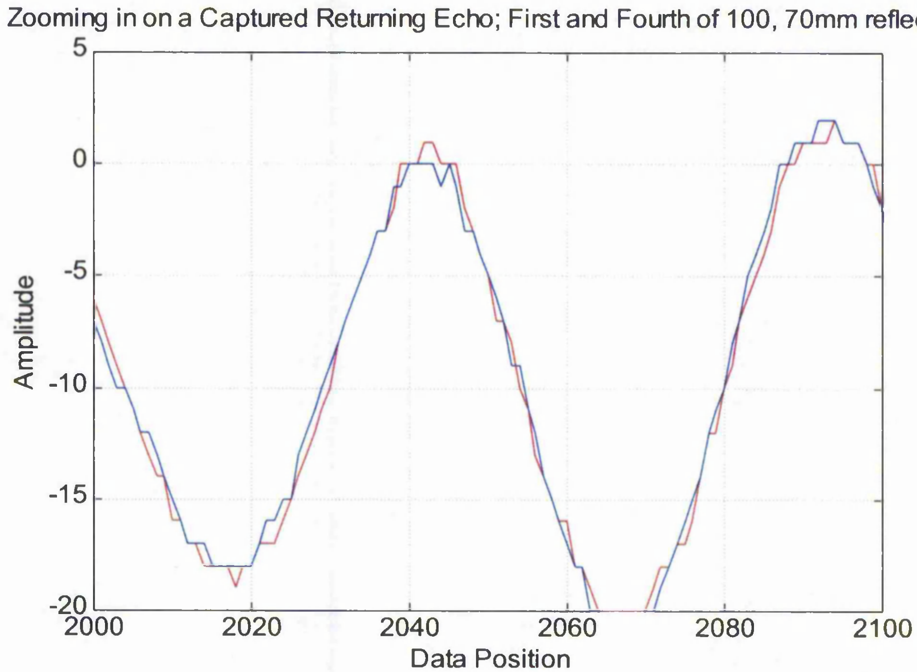


Figure 10.2 Magnification of two typical echoes out of a series of 100.

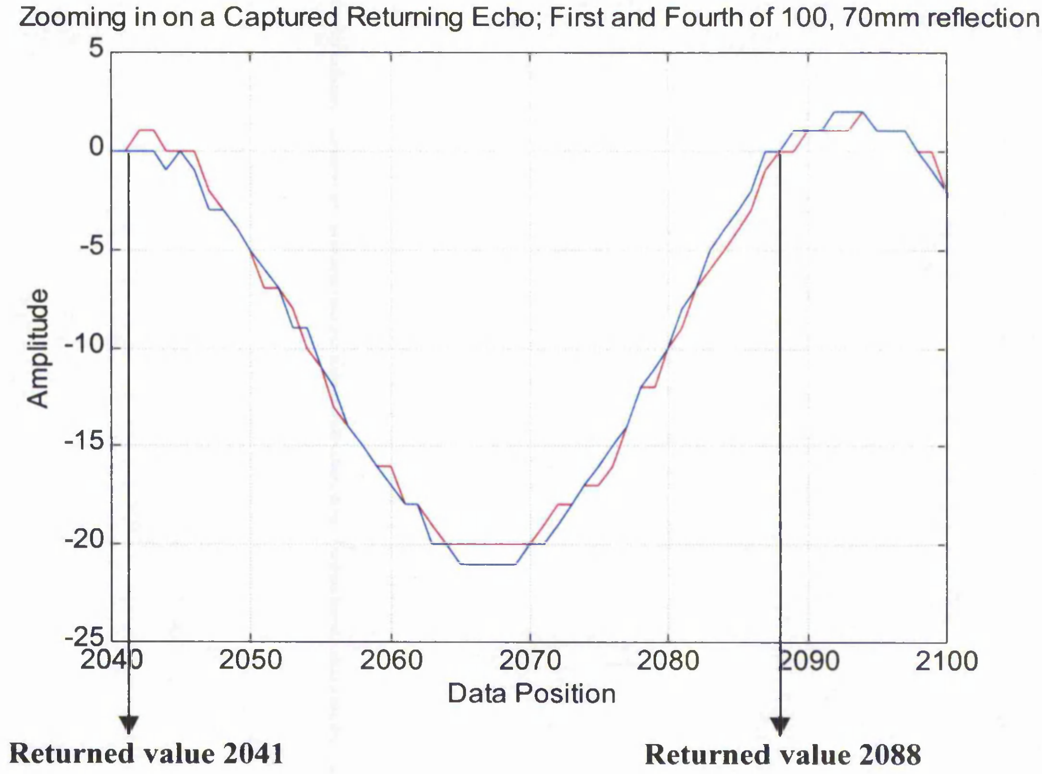


Figure 10.3 Further Magnification

To conclude, the vanishingly small variations in amplitudes between consecutive echoes, caused by intrinsic noise, produces an ultrasound frequency cycle discrepancy. This results in possible errors up to 2.93mm distance at the ultrasound frequency 116 KHz and sampling frequency 6.25 MHz.

i.e.,

$$\frac{1}{f} \times C = D$$

Where, f is the ultrasound frequency, C is the speed of sound in the transmission medium and D is the distance,

$$\therefore \frac{1}{116KHz} \times 340ms^{-1} = 2.93mm$$

The question at this time was is it possible to filter out or ignore the smaller distribution. The conclusions were that in other measured distances the migration of results would result in a more equal spread of distribution and therefore any control system would not be able to make a definite decision between the two separated distributions. The investigations that follow attempt to reduce the spread of results.

10.3.1.1 Determination of measuring a step 1mm distance change over 20mm

The objective of this investigation was to determine the confidence of the mean of 100 echoes per step change of 1 mm over a 20 mm range.

Figure 10.4 is a graph representing the actual measured values compared to an ultrasound detection using the ADC threshold method. The graph shows a strong correlation between the actual distance change and the ultrasonic detected value (R^2 = 0.9685). The trailing off of the "best fit" line over distance may be attributed to changes in the envelope shape of the echo over distance.

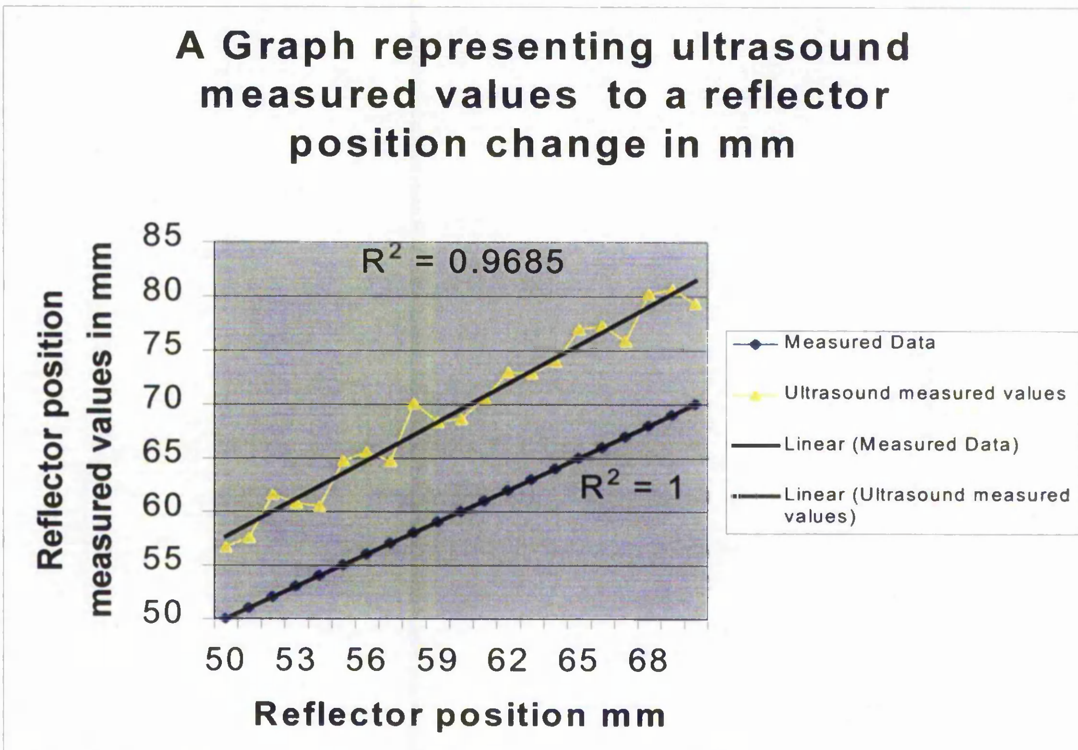


Figure 10.4 Comparison of actual measured distances and ultrasonically determined distances

The results demonstrate that ultrasonic measurement is strongly related to a stepwise change in distance.

10.3.2 Normalising the raw data and plotting the distribution

The aim of this investigation was to normalise the data to compensate for changes in the envelope of the returning echo over reflective distance changes observed above.

It was now necessary to use a macro within Matlab (Appendix E) to calculate the threshold value from returning echoes delivered by the ADC card. This was a more convenient means of manipulating returning echo data as opposed to writing detailed C programmes within the ADC structure. However it should be noted that, all the macros would eventually be written in C++ and incorporated into the A/D card to reduce processing time.

Figure 10.5 is a histogram of the distribution of thresholds of 100 echoes at a fixed distance. The threshold values are determined by a "threshold timing macro" applied to normalised echo data. In normalising the data the maximum value of amplitude attained in one data file for one echo is assigned the value 1 and the minimum 0. These results are identical to those obtained previously (Fig 10.1), and this demonstrates that the timing macro within Matlab operates correctly.

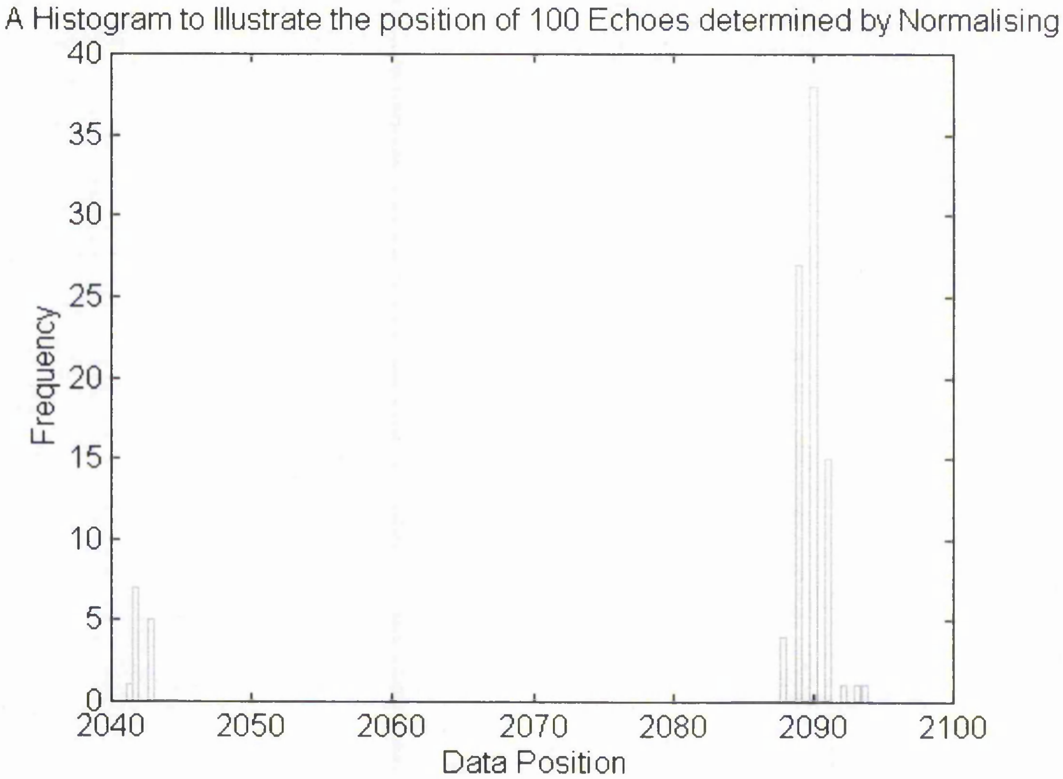


Figure 10.5 A histogram of the distribution of thresholds of 100 echoes at a fixed distance

The objective of the following investigation was to determine whether normalising the data reduces the trailing off of the linear line fitted to the ultrasound measured values in Figure 10.4.

10.3.2.1 Normalising and plotting step change

The echo data already obtained for the step change experiment was normalised by the Matlab macro. Figure 10.6 is a graph representing actual values, normalised and un-normalised ultrasound values. It is clear that by normalising the data the trend line does not trail off, and therefore the R^2 value shows an even stronger relationship.

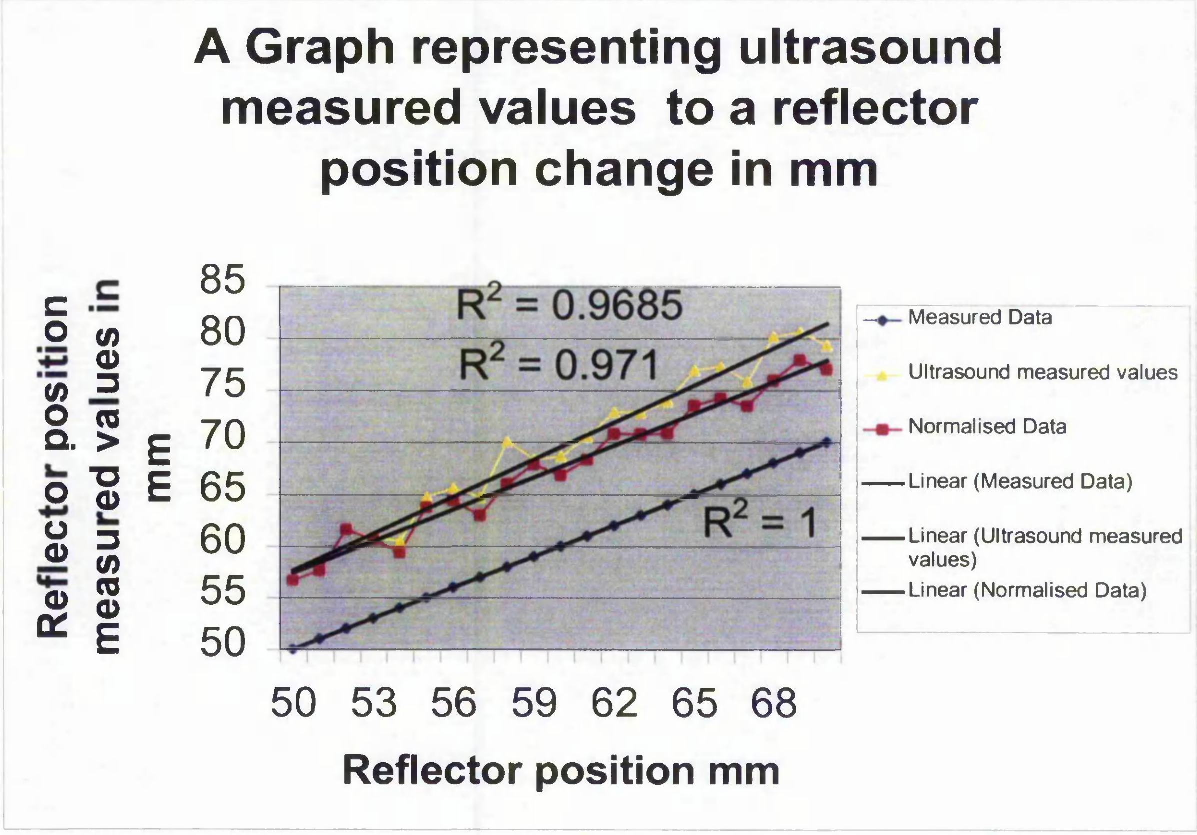


Figure 10.6. A comparison of raw data and normalised data representing measured values to a step change in mm

To conclude, normalising the data is therefore an important factor when determining time of flight measurements through air over a changing distance. The change in amplitude of the returning echo over the distance change is obviated.

10.3.3 Normalising and rectifying the data, plotting distribution

The aim of this investigation was to characterise more fully the nature of the wavelength problem.

With reference to the wavelength fluctuation problem as concluded in investigation (1), a Macro was written to rectify the negative wave length data onto the positive Y axis, thus absolving the data (Diagram to illustrate rectified data Figure 10.7).

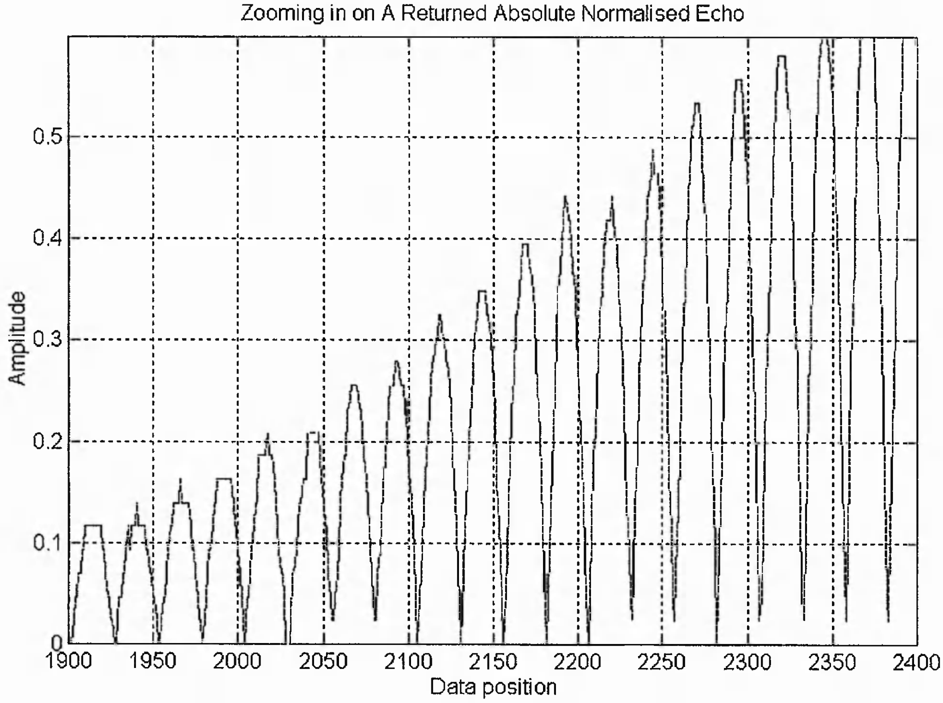


Figure 10.7 The start of a normalised and absolved ultrasonic echo

By rectifying the data, analysis of the histogram of threshold distribution (Figure 10.8) reveals that the number of data points between the two predominant data sets equals half a wavelength. As previously mentioned in §10.3.1 the minute variations in amplitudes over time, which is caused by intrinsic noise, produces distribution clusters resulting in $\lambda/2$ or 21.5 data points for a sampling frequency of 6.25 MHz at an ultrasonic frequency of 116 KHz.

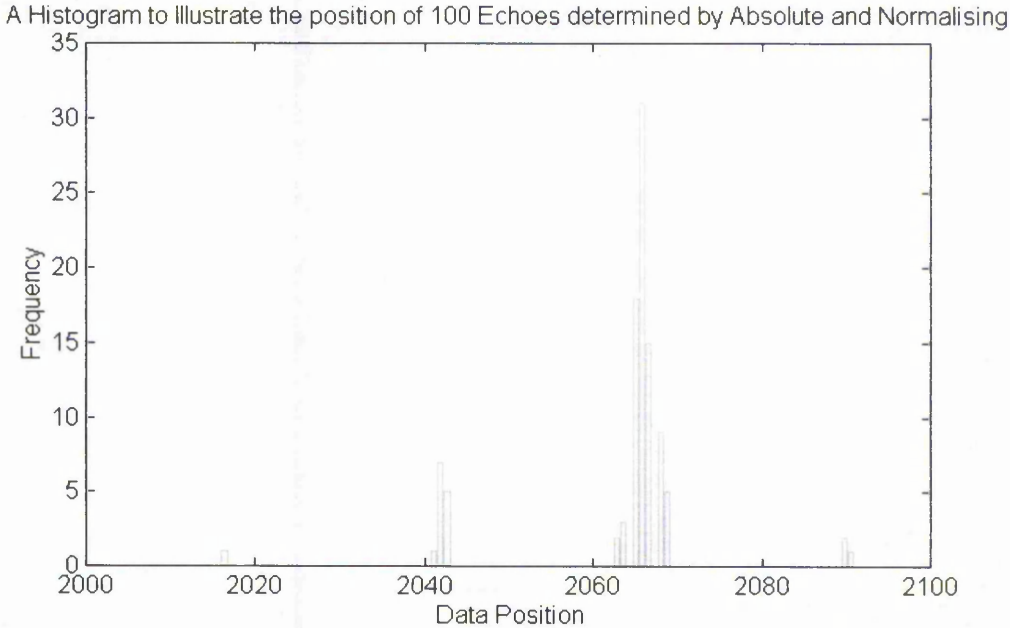


Figure 10.8 Reduced echo data spread by normalising and rectifying the raw data

10.3.3.1 Step change for normalised, absolute data

This investigation tested the impact of normalising and absolving the data on a step change. Figure 10.9 shows a comparison of normalised data and absolved normalised data. There was no dramatic improvement in the R^2 value by these procedures.

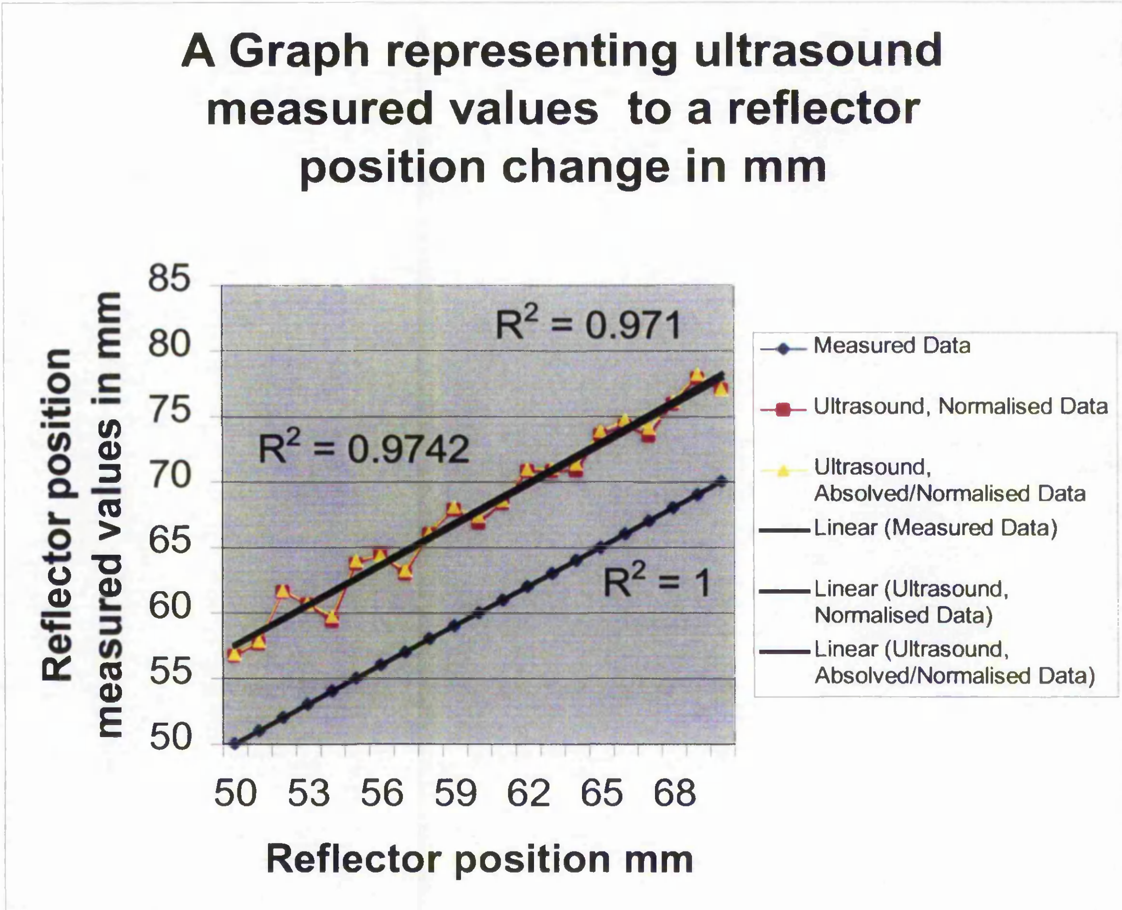


Figure 10.9 A comparison of the relationship between actual distance change and ultrasound measured value for normalised and rectified data.

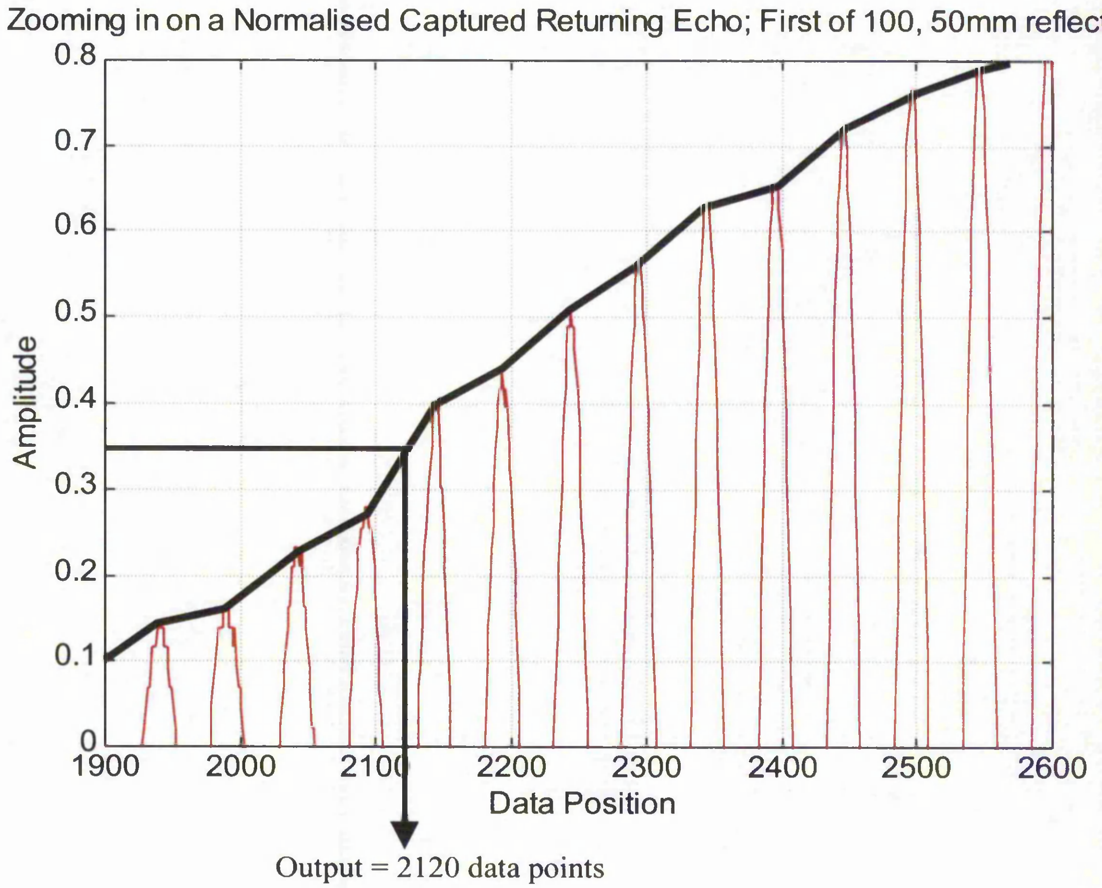
However, there was a slight improvement on the R^2 value (0.9742) of the rectified ultrasound data. The reduction in spread of rectified normalised echo data, of that shown in Figure 10.8, had an impact on the step change ultrasound measured data. The linear line R^2 value tends towards the R^2 value of 1 presented by the physically measured data.

10.3.4 Interpolating normalised absolute data, plotting distribution and step change

Since both absolving and normalising the data generated no great improvements, an additional step of interpolating the data was introduced. The aim of this experiment was to test the effects of the three combined methods on the threshold distribution and step change.

The principles of interpolation are to draw an imposed carrier signal or best fit line along the gradient generated by the maximum individual amplitudes of the half frequency cycles. Figure 10.10 illustrates this.

Refer to macros in Appendix E for the calculations and programming for this procedure.



Discriminator set at 0.35

Data position result 2120

Figure 10.10 Principles of interpolation.

Figure 10.11 is a histogram to illustrate the distribution of 100 threshold positions determined by interpolating the echo. It can be seen from the diagram that the spread of results is now reduced considerably over the data position range. Now the distribution is more uniform over the data range, and outlying data points have been removed, statistical significant quotations can be successfully given by the normal distribution with the contribution of all echoes.

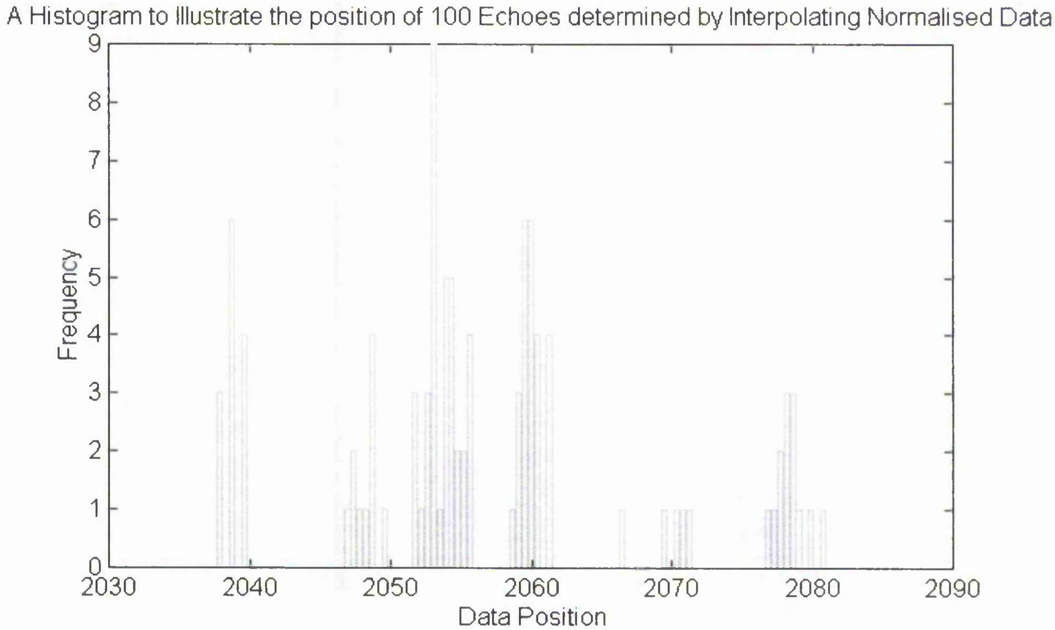


Figure 10.10 A histogram to illustrate the distribution of 100 threshold positions determined by interpolating the echo

10.4 Determination of the minimum number of shots required for a confident result

The objective of the following investigation was to determine the minimum number of echoes (shots) required to give a confident time of flight when taking the mean of the echoes. Currently in all previous investigations 100 shots were taken for each measurement. In order to determine the minimum number of shots required for confidence, a macro was written within Matlab to extract the mean value (m) from the four threshold processing methods; the ADC card, normalised data (Matlab), absolute normalised data (Matlab) and interpolated, absolute, normalised data (Matlab). A graph (Figure 10.12) was constructed to illustrate the steady state of the mean to the number of shots taken (1 to 100) at a fixed distance of 50 mm. The graph shows that after only

20 shots all four processes reach a plateau indicating a confident result. This experiment was repeated at varying reflection distances

KEY

Yellow x = A/D software threshold, set at zero.
Green + = Normalised data, threshold set at 0.4, Matlab processing.
Blue* = Normalised and Absolute data, threshold set at 0.4, Matlab processing.
Red o = Normalised Interpolated data, threshold set at 0.4, Matlab processing.

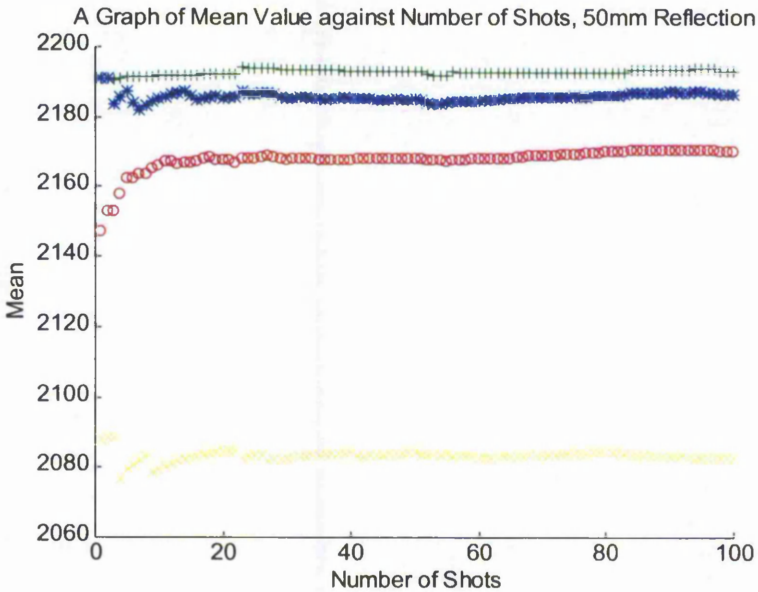


Figure 10.12 Number of shots at a fixed distance (50 mm).

Figure 10.13 and 10.14 show the same results for a 60 mm reflection and a 70 mm reflection respectively. At these longer reflection distances confidence in the mean occurs after 20 shots, therefore a minimum number of shots required for a confident mean result in all further experiments will be 40.

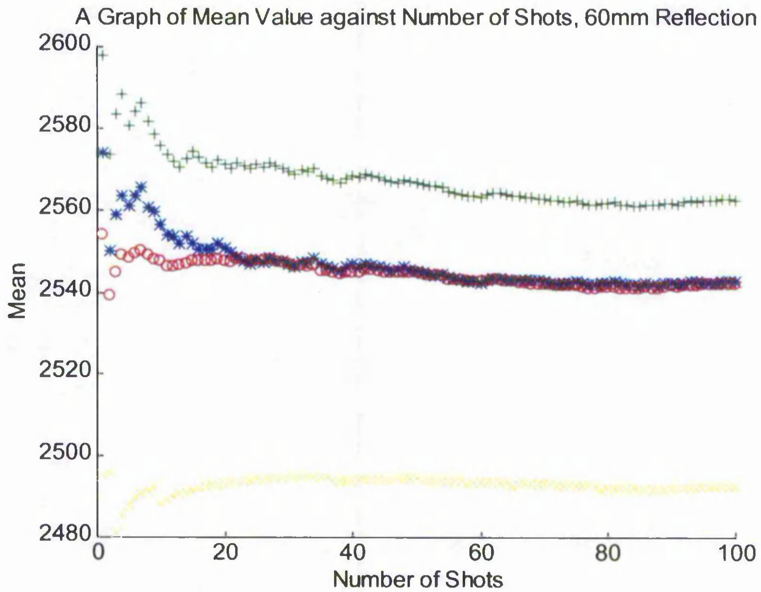


Figure 10.12 Number of shots at a fixed distance (60 mm).

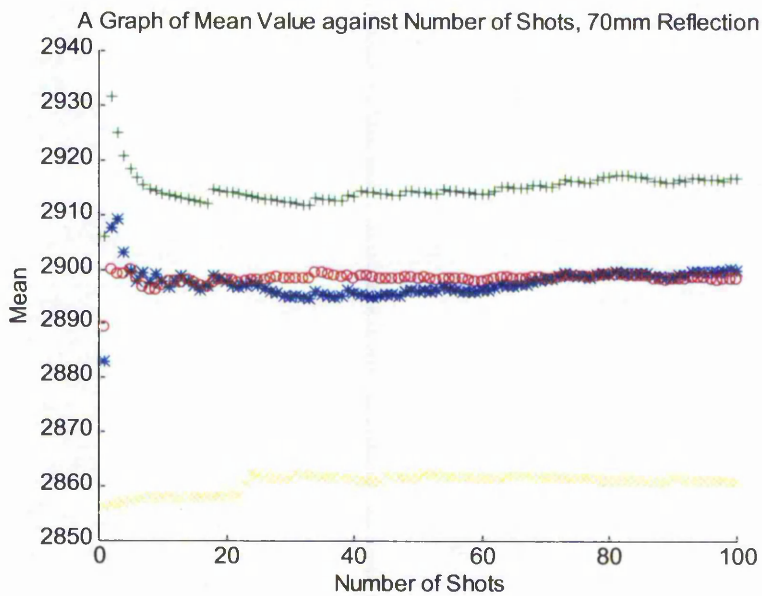


Figure 10.13 Number of shots at a fixed distance (70 mm).

10.5 Fitting a normal distribution curve to a histogram plot to give statistical information

The objective of this investigation was to establish a professionally accepted way of representing the spread of the data. A macro was written in Matlab to fit a normal distribution curve to a histogram plot of mean threshold measurements. Figure 10.15 illustrates the normal distribution curve fit. From this curve it is possible to determine values of the mean and standard deviation which can be quoted for control purposes.

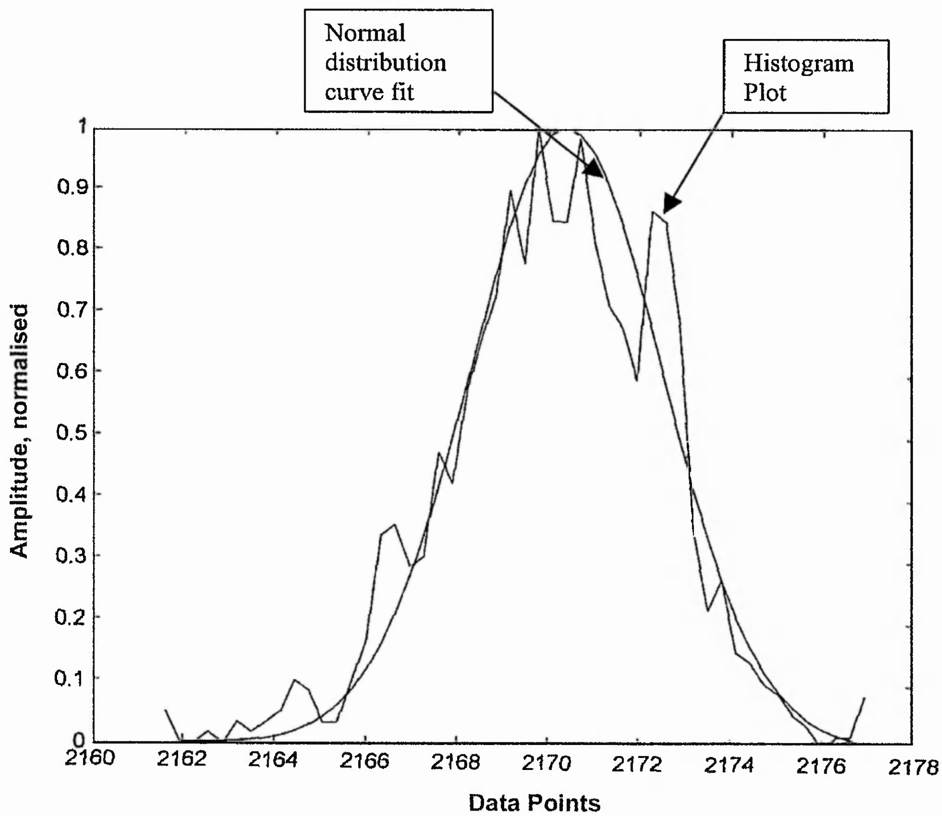


Figure 10.15 Normal distribution curve fit to a histogram plot.

10.6 Conclusions

- Normalising captured returning echo data significantly reduced the 'trail-off' of time-of-flight measurements over distance, thus improving the sensitivity.

- By absolving, normalising and interpolating the raw data to determine a time-of-flight measurement utilising the threshold technique, the spread of results was significantly reduced. In future investigations this technique written as a macro in Matlab would be used.

- The number of echoes (shots) required to obtain a confident mean measurement of a fixed reflector distance was chosen to be 40.

- A normal distribution curve fit programme has been developed to give statistical information on the distribution of ultrasonic threshold measurements for incorporation into a control strategy (See chapter 12, discussion of results).

The development and validation of an experimental model for the use of ultrasound to measure distances of a reflecting surface was now complete, incorporating, the development of appropriate ultrasonic air transmission type sensors, sensitive means of digital processing and temperature compensation

The next objective was to determine the influence of environmental variables, typical of the carbonating and bottling process, on the ultrasound signal and to determine the accuracy of ultrasonic technique in determining changes in fluid level measurement.

Chapter 11 - Modelling the filling environment/investigation of variables

Introduction

There are many variables that are likely to influence the ultrasound signal. These include gas, temperature and pressure. In order to investigate the influence of the variables on the ultrasound signal an off-line model-filling environment was developed using the air transmission ultrasound equipment described previously (Chapter 7). Understanding the influence of these variables on the ultrasonic signal would enable the suitability of this technique, and its ability to measure fluid level in real-time in a carbonating and bottling system, to be finally discussed.
No attempt was made to study the influence of temperature in any further detail of that obtained by Vargas [1997]. However, as described in § 8.5.1.1, compensation has been included into the signal processing software to obviate its effect.

11.1 Development of model filling environment

In order to develop the model system, several factors were taken into consideration including the operating principles of the carbonation and bottling research facility. These factors included operating within the parameters of the maximum working pressure of the carbonation bottling environment; the size of the environmental chamber, and development of equipment fittings to withstand high pressures, gas mixtures and temperature changes.

The technical data supplied with the CW250 carbonating and bottle-filling equipment stipulates that the operating carbonating pressure is of a minimum 7 Psi and maximum 70 Psi. It was therefore necessary to choose a pressure chamber that fell into this range.

For the purpose of these investigations, gas pressure, temperature and ultrasound transmission were monitored within the chamber. Therefore, gas tight fittings were incorporated into the design. The other major design constraint was the mounting of 'air transmission' type ultrasonic transducers within the chamber.

A model 74-05 stainless steel pressure vessel was purchased from Newson Gale Ltd (Nottingham). This chamber had a volume of 19 litres with a certified maximum working pressure of 8.9 bar / 130 Psi at 100 degrees F / 37.8 degrees C. It was supplied with a pressure gauge that was fitted to one of four pressure ports. Access could be made to the inside of the vessel via the quick opening closure lid, Figure 11.2. A photograph of the pressure chamber can be seen in Figure 11.1.

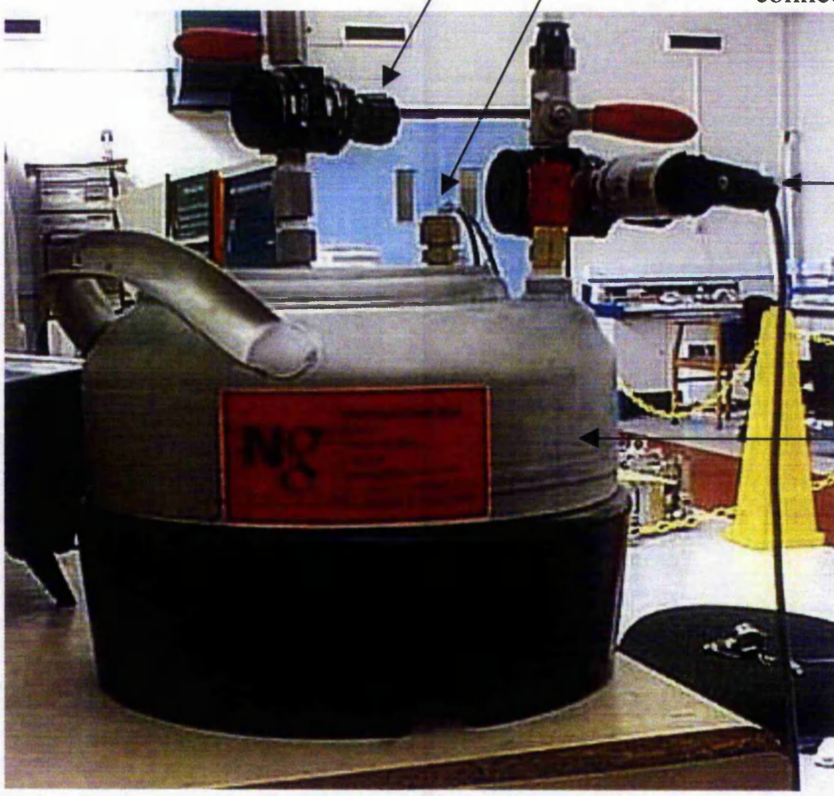


Figure 11.1 A photograph of the 74-05 stainless steel pressure chamber

11.1.1 Fitting the transducers and thermocouple

The transducers were fitted to the inside of the quick opening closure (lid). A vice mechanism was manufactured and welded to the inside of the lid so that the transducers could be clamped or removed easily, a photograph of this arrangement can be seen in

Figure 11.2. Electrical connections were made inside the chamber and passed out of the vessel via one of the ports. This port was specially designed to seal and clamp the wires and this device is shown in Figure 11.1. A blank pressure plug was drilled twice, one hole to allow an interference fit of the ultrasonic cables and the other for the thermocouple. To maintain a gas tight seal, epoxy resin was injected into the ports. The plug was screwed into the chamber.

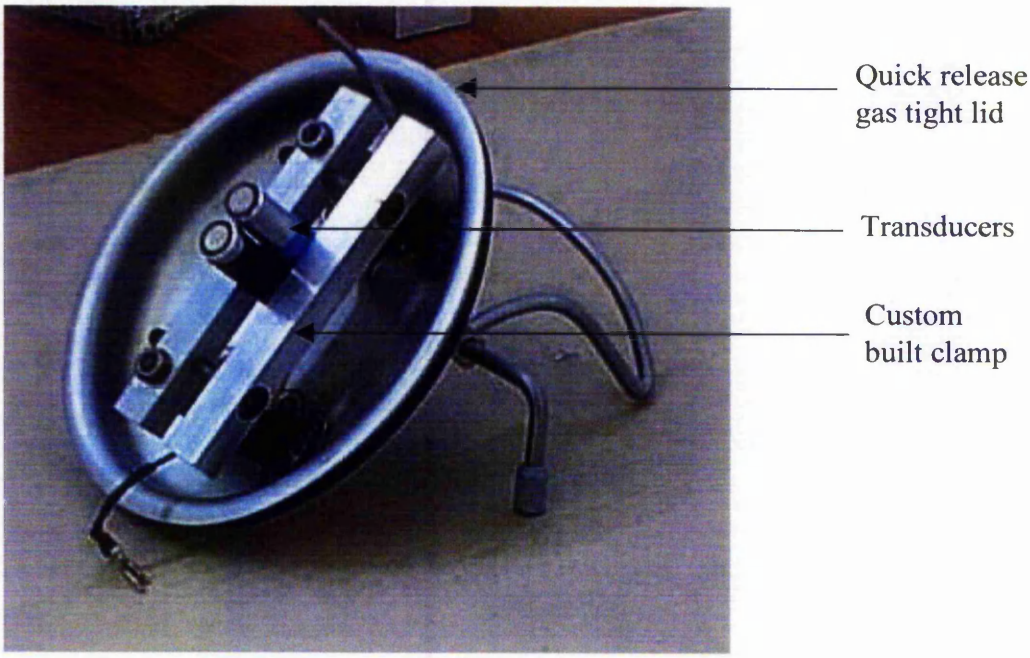


Figure 11.2 A photograph of the clamp and transducers secured to the pressure chamber lid.

11.1.2 Electronic pressure gauge

In order to measure the pressure within the chamber accurately a pressure transducer was fitted to another of the pressure ports, as illustrated in Figure 11.1. This pressure transducer was connected to an LED readout that was calibrated to 100ths of a bar. In conjunction with the pressure transducer a pressure regulator was fitted and connected to different gas supplies that were required for the investigations.

A second pressure regulator and gauge was connected via a third port to enable the gas supplies to be mixed.

11.1.3 Installation of a Safety Relief Valve

A relief valve was fitted to the fourth port as a requirement of Health and Safety for this type of equipment. Before the equipment could be used for investigations, a detailed risk assessment was carried out considering electrical, mechanical, air supply, low to medium carbon dioxide and nitrogen gas supply and instrumentation. Details of this risk assessment are shown in Appendix H.

Information regarding the specification and assembly of the chamber, and certificate of compliance can also be found in Appendix H, together with properties of the two gases carbon dioxide and nitrogen.

11.1.4 Connecting the equipment

Figure 11.3 illustrates the way in which the gas chamber was set up with the ultrasound analysis equipment.

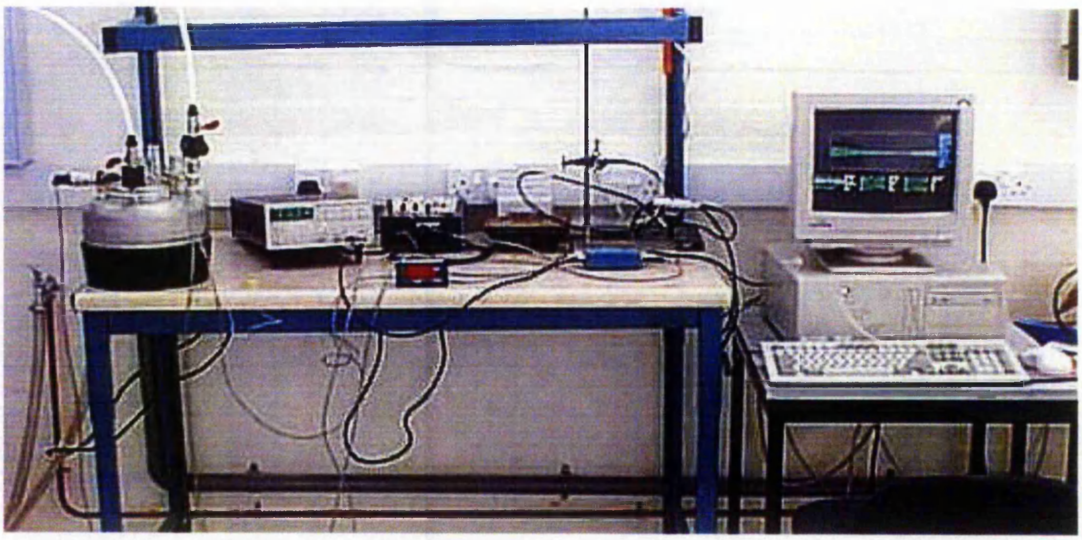


Figure 11.3 Connections of pressure chamber to ultrasound analysis equipment.

Using this system, investigations were carried out to measure the variables of gas pressure, gas temperature and gas mixture, and their impact on ultrasonic echo amplitude and time of flight.

11.2 Investigation programme to interrogate variables associated with carbonation of bottle filling.

The main objectives of these investigations were to determine the impact of a range of pressures and gas mixtures on echo data. For these investigations it was necessary to obviate temperature as described in § 8.5.1.1 "Key concepts".

An initial study was conducted to determine how the strength of ultrasound signals were affected by carbon dioxide content and whether this would affect the ultrasound analysis equipment capability for analysing data.

11.2.1 Impact of variables on amplitude

11.2.1.1 Defining carbon dioxide content in a fixed volume from gauge pressure.

Before investigations were carried out to analyse the effects of carbon dioxide content on ultrasonic signals, it was necessary to define the CO_2 content within a fixed volume of air/CO_2 mixture. An appreciation of the ideal gas law equations and the mole fraction relation between gases was required. This would enable the percentage of carbon dioxide (with respect to mole percent) to be defined from the partial pressures of the system gas mixtures.

Applying the real gas law equations

In the experimental setup, a fixed volume of gas (19 litres) had a mixture of carbon dioxide and compressed air at 4 bar pressure. From Dalton's Law of partial pressures, for a mixture of gases in a container, the total pressure exerted is the sum of the pressures that each gas would exert if it were alone.

$$P = P_1 + P_2 + P_3 + \ldots.. \qquad [11\text{-}1]$$

Where P is the total pressure and P_1, P_2, are the partial pressures of the individual gases. For air, an appropriate form of Dalton's law would be:

$$P_{(air)} = P_{(Nitrogen)} + P_{(Oxygen)} + P_{(Carbon\ Dioxide)} + \ldots\ldots$$

At temperatures near ordinary room temperature the partial pressures of each of the components of air is directly proportional to the number of moles of that component in any volume of air. When the total pressure of air is 100Kpa or one bar, the partial pressures of each of its components are numerically equal to the mole percent of that component. Table 11-1 shows the composition of dry air at sea level.

Table 11-1: Composition of Dry Air at Sea Level

Component	Mole Per Cent	Molar Mass
N_2	78.084	28.013
O_2	20.948	31.998
Ar	0.934	29.948
CO_2	0.0314	44.010
Ne	0.001818	20.183
He	0.000524	4.003
CH_4	0.002	16.043
Kr	0.000114	83.80
H_2	0.00005	2.016
N_2O	0.00005	44.013
Xe	0.0000087	131.30

For the purpose of this investigation the gravimetric analysis of air was taken as 23.3% Oxygen and 76.7% Nitrogen. The traces of CO_2 found in air (0.0314 mole per cent) were ignored.

For a mixture of air at 2 bar gauge pressure and applied CO_2 resulting in a total of 4 bar gauge pressure the mole percent of CO_2 was calculated thus:

$$P_{(4\text{ bar mix})} = P_{(\text{air at 2bar})} + P_{(\text{Carbon dioxide at 2bar})}$$

Because the container was not pre-evacuated there was also one atmosphere (1 bar) of air within the chamber, therefore;

3 bar of air = 230.1 kPa Nitrogen and 69.9 kPa Oxygen,

2 bar CO_2 = 200 kPa Carbon dioxide.

Carbon dioxide as a mole percentage of the system,

$$\frac{P_{(CarbonDioxide)}}{P_{(Total)}} \times 100 = \frac{200kPa}{500kPa} \times 100 = 40\%$$

Table 11-2 shows the CO_2 and air gauge pressures and corresponding mole per cent of CO_2.

Table 11-2: Gauge pressure and Mole per cent

Gauge pressure air bars	Gauge pressure CO_2 bars	Mole per cent CO_2
0	4.0	80
0.5	3.5	70
1	3.0	60
1.5	2.5	50
2.0	2.0	40
2.5	1.5	30
3.0	1.0	20
3.5	0.5	10
4.0	0	0

The table shows that it is not possible to achieve 100% CO_2 content and therefore to achieve higher concentrations of CO_2 pre-evacuative or purging measures would be required.

11.2.1.2 Initial observations of the effect of CO_2 content on ultrasound signal amplitude

Investigations were carried out using the pressure vessel and allied measuring equipment to study the relationship between CO_2 content and the ultrasonic signal. For these investigations a fixed reflecting surface at a distance of 100 mm from the transducer surface was used. Ultrasound transmitting frequency was set to 116 kHz and sampling frequency 6.5 MHz. The voltage peak to peak was 30 v and the gain of the amplifier was set at 60 dB. The discriminator value to determine a threshold was set at 0.4 within the Matlab macro.

The temperature of the internal environment was recorded for every ultrasound measurement. The temperature recording was incorporated into the Matlab threshold timing macro to obviate its effects on the time of flight measurements. (However, the temperature was kept as constant as possible for all measurements to minimise its effect).

The CO_2 used was beverage standard (as supplied by BOC) with a purity minimum of 99.98%.

Initial observations indicated that the presence of CO_2 attenuated ultrasound significantly, and therefore weaker signals needed to be boosted by the switchable gain on the pre-amplifier. At the other end of the spectrum, at very low concentrations of CO_2 the signals were so large at 60 dB that these signals needed attenuating by the switchable gain on the pre-amplifier to 40 dB. This effect is shown diagrammatically in Figure 11.5.

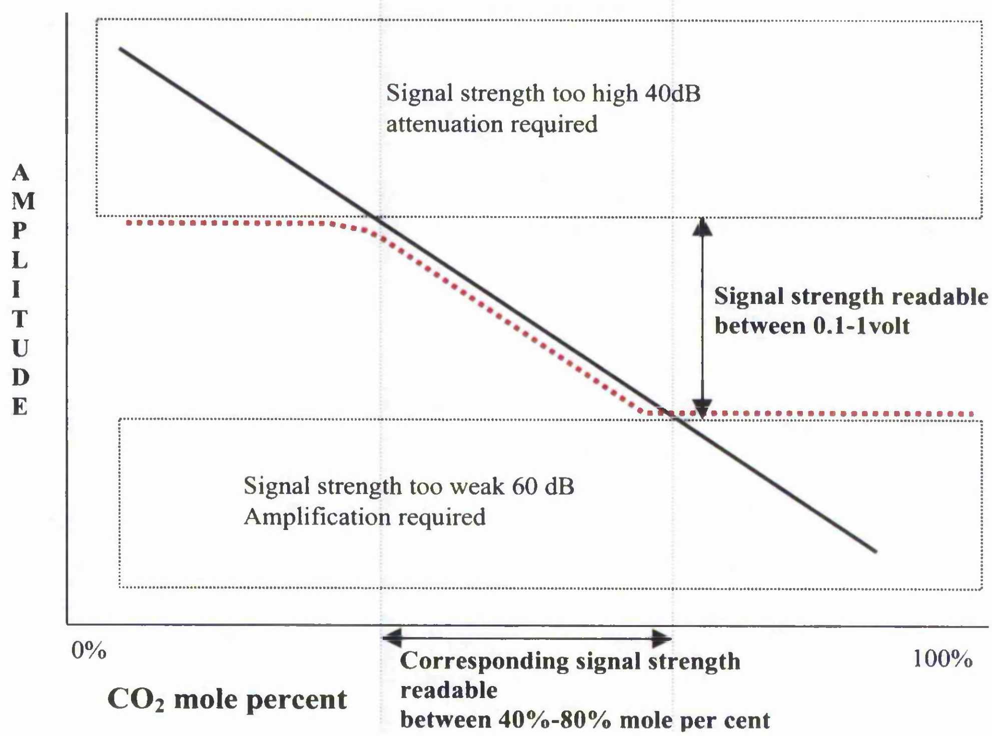


Figure 11.5 The effect of carbon dioxide on ultrasound signal amplitude

It was also noted that due to the limitations of the A/D card, its programmable height and width determines the window in which data can be transferred to file. If too much information is directed to this window, 'clipping' occurs. If too little information is directed to this window, there is a lack of detail resulting in insufficient amplitude and time of flight measurements for presentation.

It was possible to compensate for some of the 'clipping' and the lack of detail by observant use of the switchable gain. The switchable gain on the acoustic pre-amplifier allows weak signals to be amplified and strong signals to be attenuated. This amplification-attenuation (40 dB - 60 dB switching) affects the continuity of signal amplitude and time of flight measurements. In an attempt to minimise this problem, an experiment was carried out to determine the characteristics, and hence, a mathematical relationship between the switching of the amplifier and its effect on signal amplitude.

11.2.1.3 Acoustic pre-amplifier switchable gain characteristics

A standard air reflection was set up. The voltage for the transmission pulse was adjusted between 5 v and 15 v in 1 v steps. At each voltage two returning echoes were captured, one at 40 dB and one at 60 dB. The maximum amplitude of these returning echoes was plotted against each voltage step as illustrated in Figure 11.6.

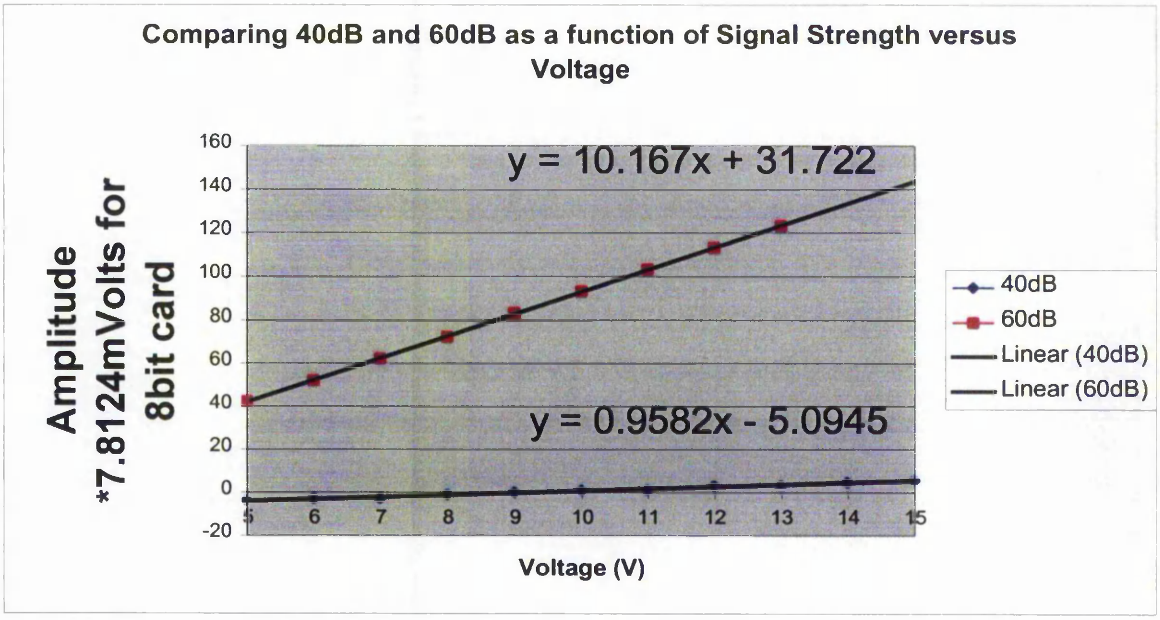


Figure 11.6 Relationship between ultrasound signal amplitude and excitation voltage.

A trend line and corresponding equation to that line was fitted to the data points. It was now possible to combine the line equations in order to calculate the corresponding amplitude for a signal amplitude conversion from 40 dB to 60 dB or vice versa.

The single equations for the 60 and 40 dB lines respectively are,

$Y_1 = 10.167x + 31.722$

$Y_2 = 0.9582x - 5.0945$

Combining these equations,

$Y_1 = 10.167 (Y_2 + 5.0945/0.9582) + 31.722$

In all following experiments this equation was used to adjust weak signals or very strong signals so that all data was presented uniformly.

11.2.1.4 Investigating the relationship between CO_2 content and ultrasound signal amplitude using the combined equation.

The impact of carbon dioxide content on the amplitude of ultrasound echo signal is shown in Figure 11.7. As CO_2 content increased there was a reduction in signal amplitude. However between 60 and 80% content the signal amplitude reached a minimum and then increased as the content neared 80%. An explanation of this phenomenon is given in the discussions Chapter 12.

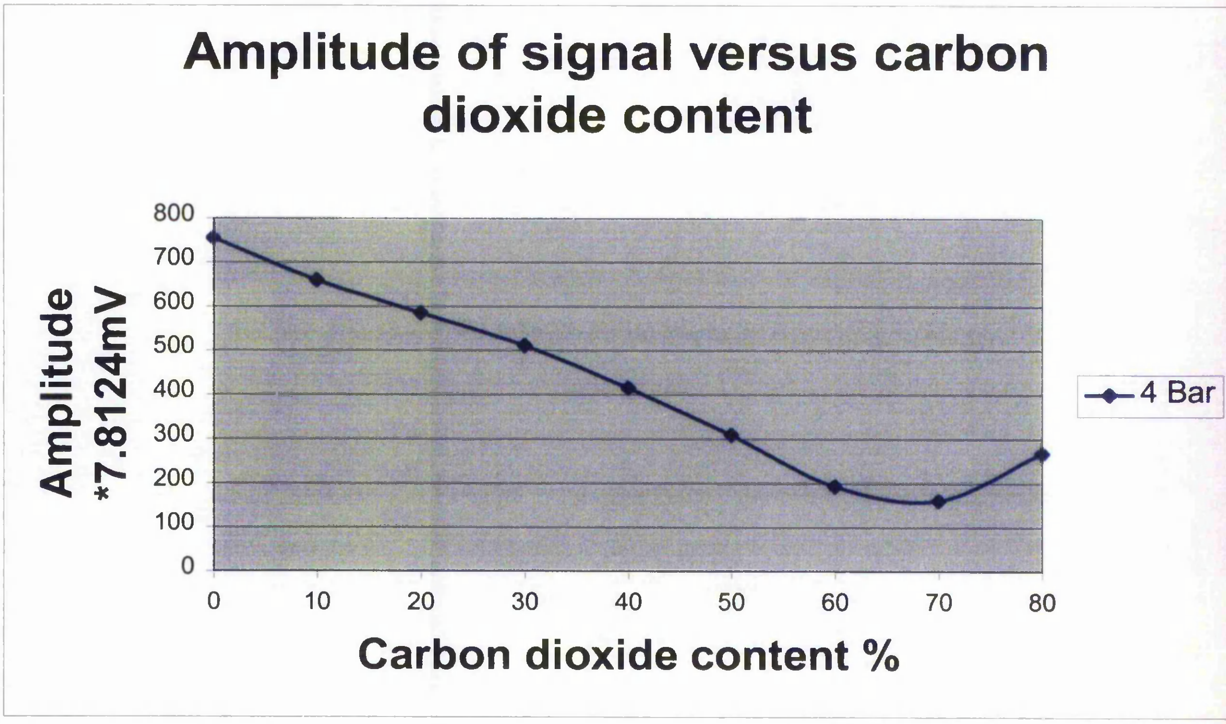


Figure 11.7 A graph showing the relationship of ultrasound amplitude to carbon dioxide content at a pressure of 4 bar.

11.2.1.5 Investigating the relationship between pressure and ultrasound signal amplitude.

A compressed air line was connected to the pressure vessel. The pressure vessel was charged with compressed air to 4 bar. A returning echo was captured at this pressure and at subsequent 1 bar reductions in pressure down to atmospheric. Figure 11.8

represents a graph of pressure versus signal amplitude. The maximum amplitude occurs at 4 bar and reduces linearly as the pressure decreases.

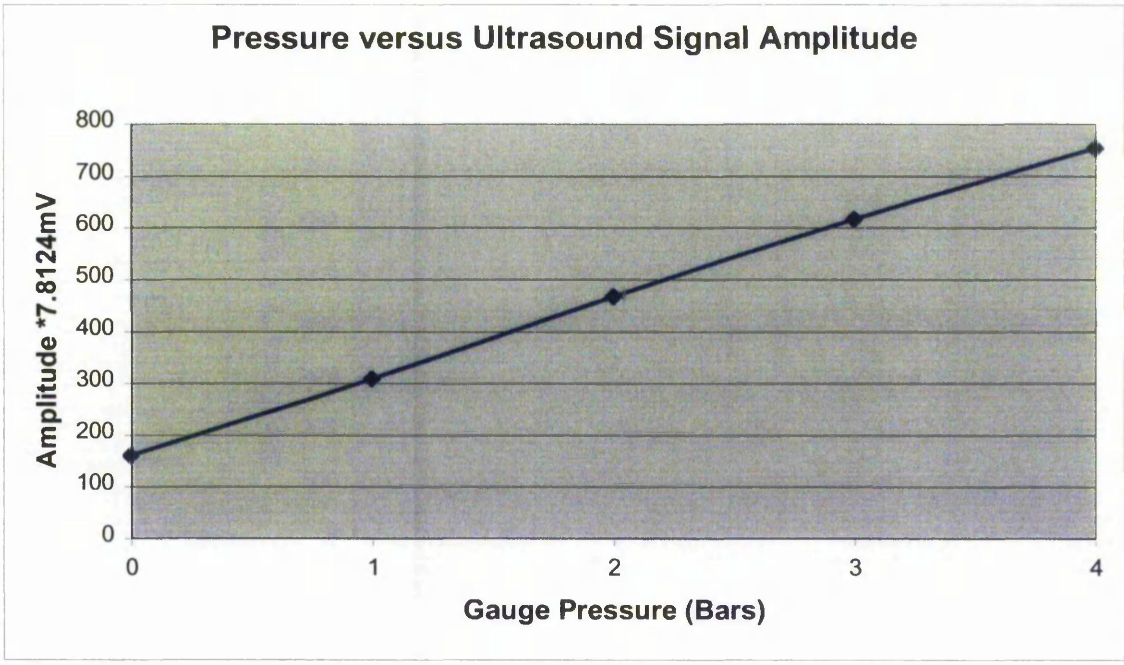


Figure 11.8 A graph showing the relationship of the amplitude of ultrasound signals and pressure of compressed air.

11.2.1.6 Relationships between ultrasound signal amplitude with varying CO_2 content and varying pressure.

To illustrate the relationship between the amplitude of the returning ultrasound echoes through a variety of CO_2 contents (%) and pressures, a 3-dimensional plot was created within Matlab. The purpose of designing surface plots was to build signatures of these variations so that they may be accommodated within a control strategy. The principle was that ultrasound signals captured in real time could be referenced to a database containing surface plots. The objective of this would be to assist in the correct interpretation of the signal, consideration being made to its environment.

The amplitude of the ultrasound signal was initially recorded at 80% CO_2 content and 4 bar pressure. The pressure was then reduced in 1 bar intervals to atmospheric pressure (0 bar gauge pressure) and the amplitude of the signal noted. This procedure was then repeated for intervals of 10% CO_2 content. Figure 11.9 is a surface plot to illustrate the relationships between CO_2 content/pressure and amplitudes of ultrasound echoes.

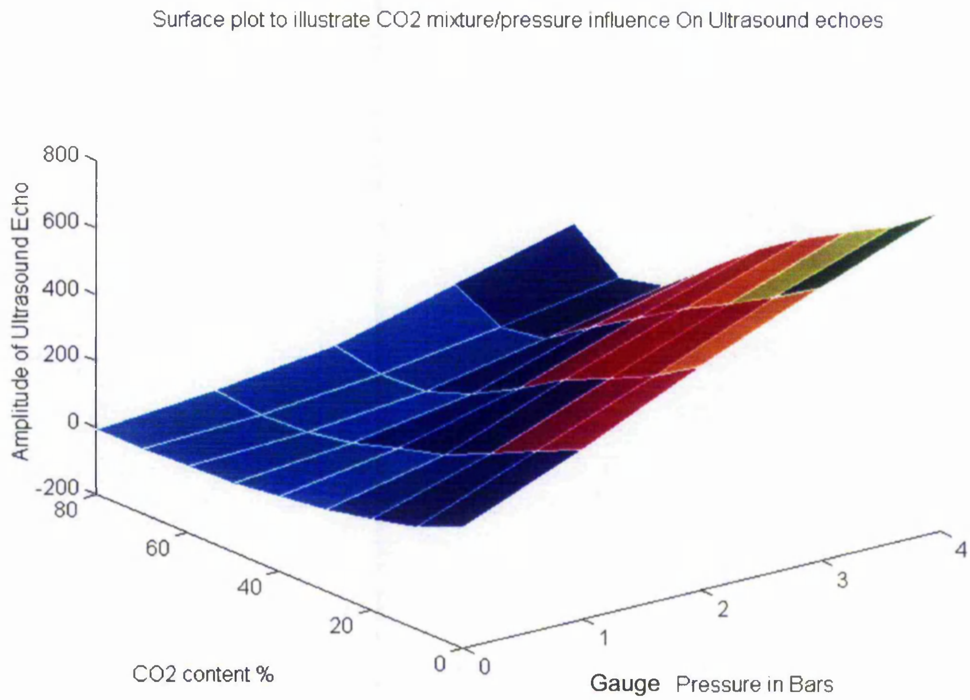


Figure 11.9 3-D plot to illustrate the relationships between CO_2 content/pressure and their effect on amplitudes of ultrasound echoes.

The surface plot shows that amplitude increases with increasing pressure, and decreases with increasing CO_2 content. This surface plot shows that at higher pressures, the attenuation caused by CO_2 is greater.

It is clear that there are no major irregularities within the surface. The signal strength remains relatively uniform so could be used effectively to gain time of flight information. If large irregularities were evident, the signal may be too large or too small at times to successfully interpret time of flight information through the digital processing methods proposed.

11.2.2 Effect of variables on time of flight.

Using the echo data obtained in previous experiments, the time of flight (TOF) was calculated using the interpolating, absolute, normalising macro within Matlab. The problem encountered with the preamplifier gain switching does not have a bearing on the uniformity of presented results. Even if clipping occurs at high signal strength, TOF measurements can still be accomplished. Therefore, all experiments on TOF measurements were carried out at a 60 dB gain.

11.2.2.1 Effect of CO_2 content on TOF.

The CO_2 content of the vessel was altered as described in the previous experiments. Figure 11.10 illustrates the time-of flight measurements converted to mm versus CO_2 content, at a pressure of 4 bar. There is a strong linear relationship ($R^2 = 0.9749$) between the TOF value and CO_2 content; as the CO_2 content increases the TOF measurement (converted to distance by multiplication of the temperature obviated speed of sound) increases.

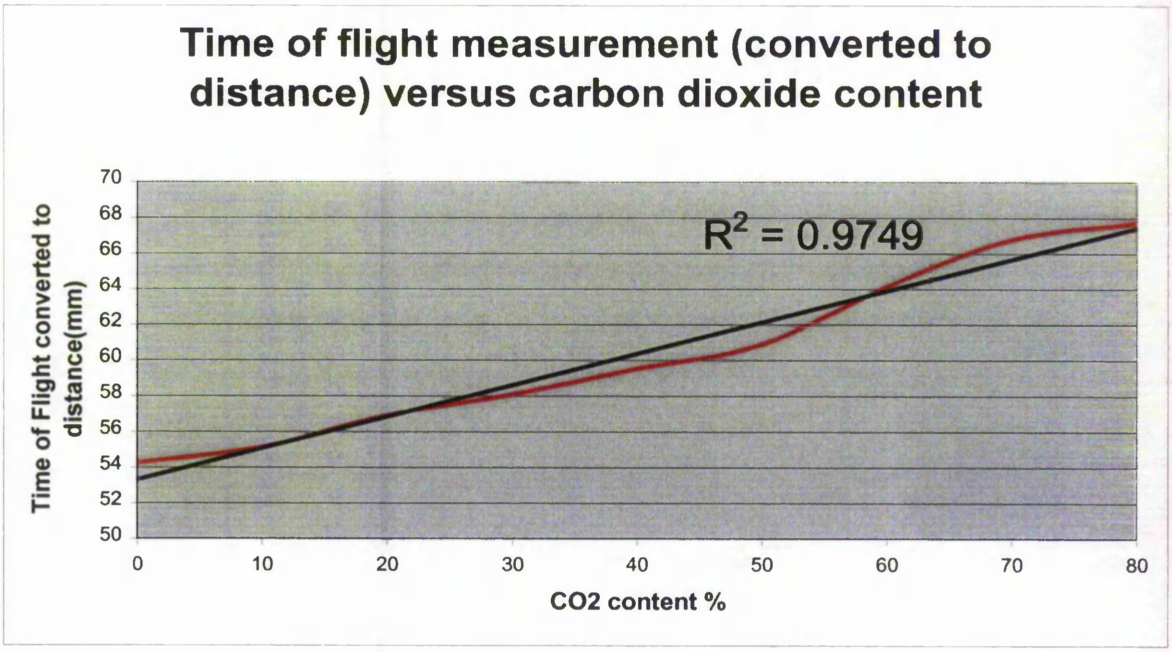


Figure 11.10 The effect of varying CO_2 content on TOF showing a strong linear relationship (black line).

11.2.2.2 Effect of pressure on TOF.

As previously described, the pressure vessel was charged with compressed air to 4 bar. A returning echo was captured at this pressure and at 1 bar reductions down to atmospheric. Figure 11.11 represents a graph of pressure versus TOF (converted to distance). Pressure has very little influence on TOF measurements.

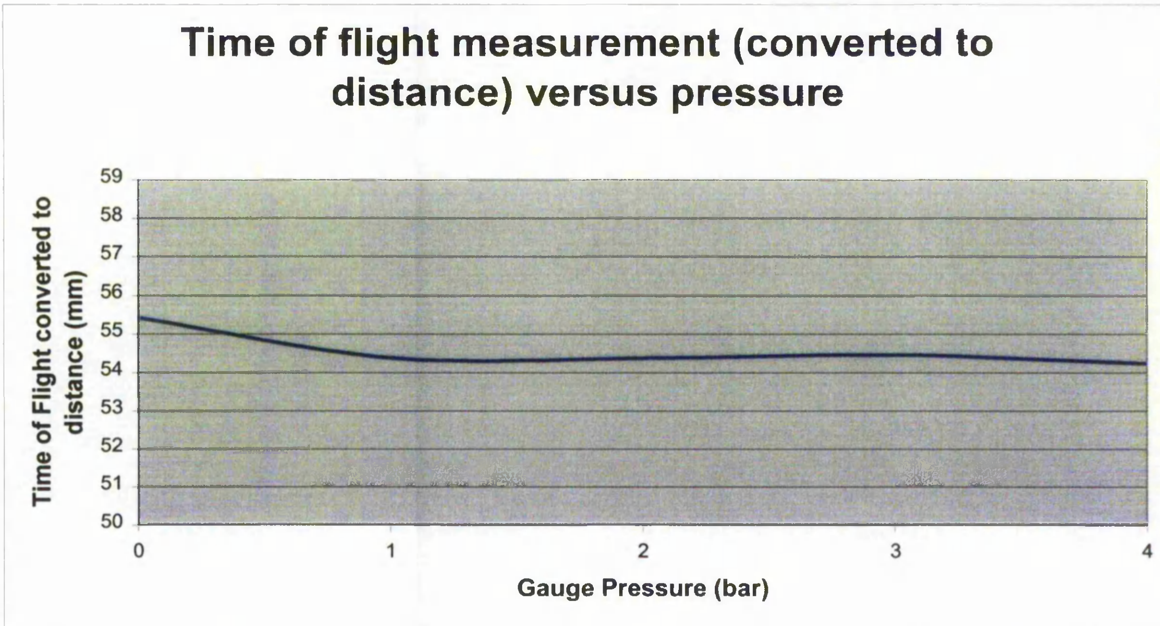


Figure 11.11 Impact of varying pressure of compressed air on TOF.

11.2.2.3 Relationships between TOF, varying CO_2 content and varying pressure.

To illustrate the relationship between the TOF and a range of CO_2 contents (%) and pressures, a 3-dimensional plot was created within Matlab. Figure 12.12.is a surface plot to illustrate CO_2 content and pressure, and their influence on ultrasound echo TOF measurements. The surface looks very much like a ramp, demonstrating that pressure over a range of CO_2 contents has little impact on TOF measurements. However, an increase in CO_2 content elevates the ultrasonic echo TOF measurement.

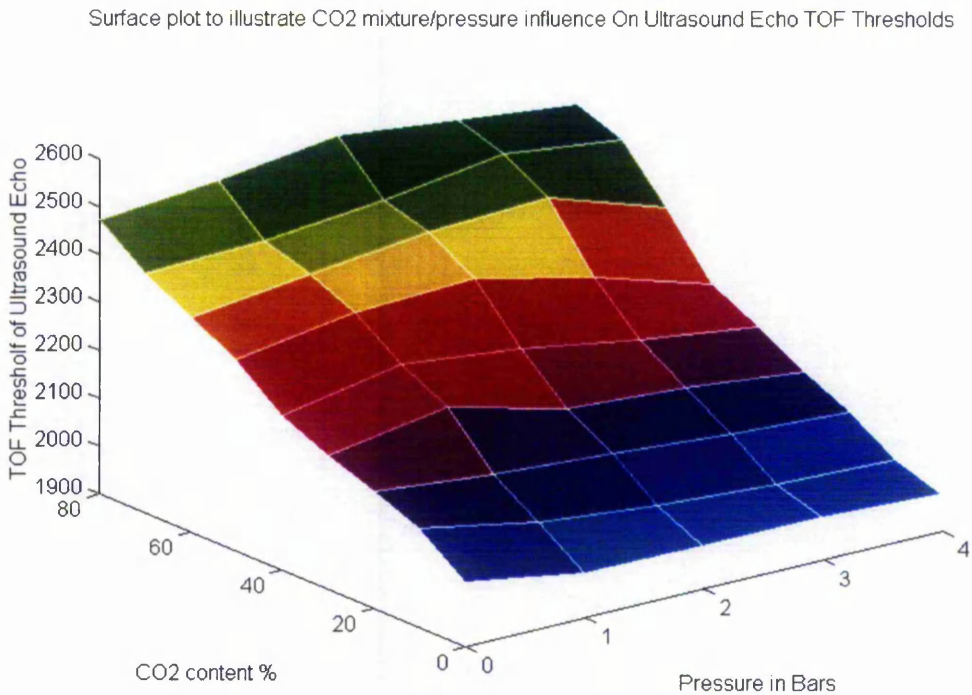


Figure 11.12 3-D plot to illustrate the relaitionship between CO_2 content/pressure on time of flight.

11.3 The industrial carbonation and bottling environment

A variety of carbonation and pressure relationships and their effect on ultrasound signals have now been illustrated. The next phase of the research programme was to carry out investigations to represent more closely the actual environment for the carbonation and bottling of a soft drink.

In order to establish the quantities and pressures of gas within the bottle as it is filled, further contact was made with Advance Bottling (UK). AB UK was recently involved in projects designing bottling apparatus for Budweiser and Cola. It was clear that one important consideration was the elimination of any sources of bacterial contamination, the major one being air as an oxidiser. As a result, the bottling industry incorporates nitrogen as a de-oxidiser process. The nitrogen flushing process can reduce the contents of air within the filling phase from 1.2 parts per million to 0.25 ppm, thus increasing the shelf life of the bottled product. However, carbon dioxide can also used as a deoxidising gas.

When considering pressure, the operational and servicing instructions supplied with the CW 250 carbonation and bottling unit suggests the operational carbonation pressure as 70 psi.

11.3.1 Determining the ultrasonic amplitude at 100% CO_2 content (0% air) purging with CO_2 and N_2.

The objective of this investigation was to determine whether strong enough ultrasound signals in 100% CO_2 could be received for processing. The chamber was purged with either CO_2 or N_2. In order to achieve CO_2 purging the pressure chamber was flushed with CO_2 for 30 seconds and rapidly sealed. CO_2 gas was allowed to fill the system until 4 bar pressure was achieved. When purging with nitrogen, N_2 was flushed through the system for 30 seconds, and the chamber rapidly closed. At the same time, the N_2 supply was closed and CO_2 then allowed to fill the chamber until 4 bar pressure was achieved.

The returning echo data was collected at half bar intervals from 4 bars to atmospheric pressure and processed to gain ultrasound echo signal amplitude. Figure 11.13 illustrates the ultrasound signal strength at very low amplitudes versus pressure for different de-oxidising gases.

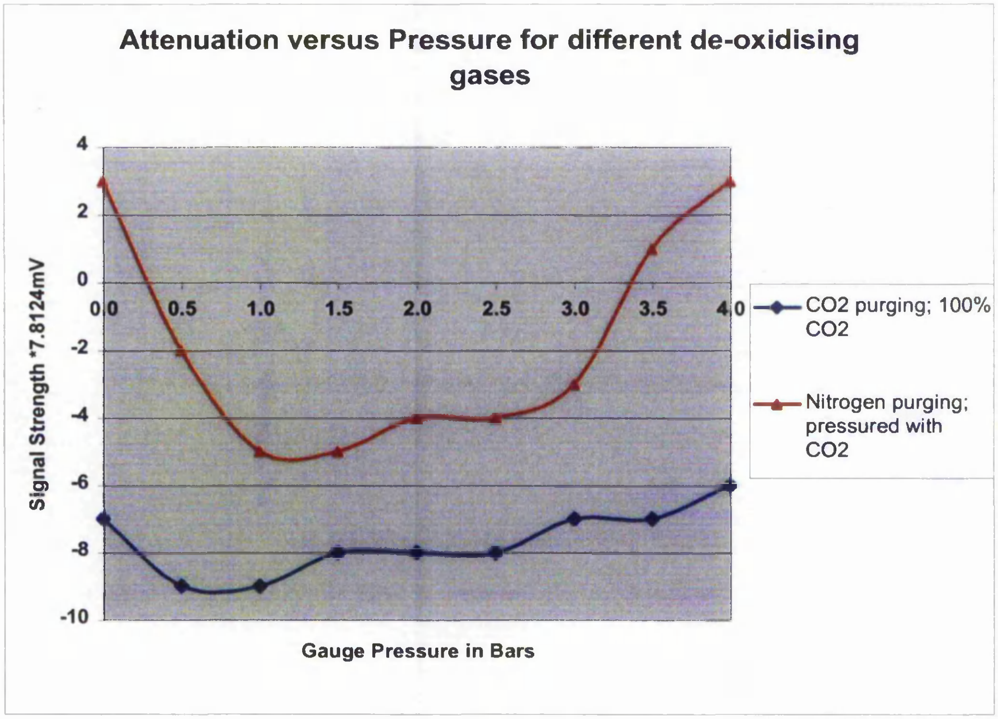


Figure 11.13 Impact of different de-oxidising gases on signal strength at varying pressures.

At 100% CO_2 the signal strength was greatly attenuated over the range of pressures investigated. However, with the N_2 purged CO_2, the signal was stronger over the range of pressures investigated. In conclusion, more information would be available for digital signal processing from the stronger ultrasound echoes transmitted through a medium of 100% CO_2 purged with N_2, that appropriately is in-line with the preferred industrial method for the bottling of carbonated beverages.

11.3.2 Analysing returning echo data using a fluid reflection (surface of fluid fill level)

In order to fulfil the main research objective of measuring fluid levels using ultrasound, the solid reflecting surface was replaced with a fluid, namely water. The aims of the following investigations was to determine the amplitudes of ultrasound returning echoes and time of flight (TOF) transmitted through 100% CO_2 and reflected from a fluid surface. The chamber was purged with CO_2 and N_2.

11.3.2.1 Impact of purging with CO_2 and N_2 on ultrasound signal amplitude.

For these investigations the solid reflecting surface was replaced with a 250 ml beaker half filled with water, with the fluid surface approximately 60 mm from the ultrasound sensors. Initially, the carbonating environment chamber was flushed with CO_2. Single reflected echoes were obtained over a range of pressures from atmospheric to 4 bar, at approximately 1 second intervals. The strength of the signal was plotted for each pressure over the time period. The time course of results are shown in Figure 11.14.

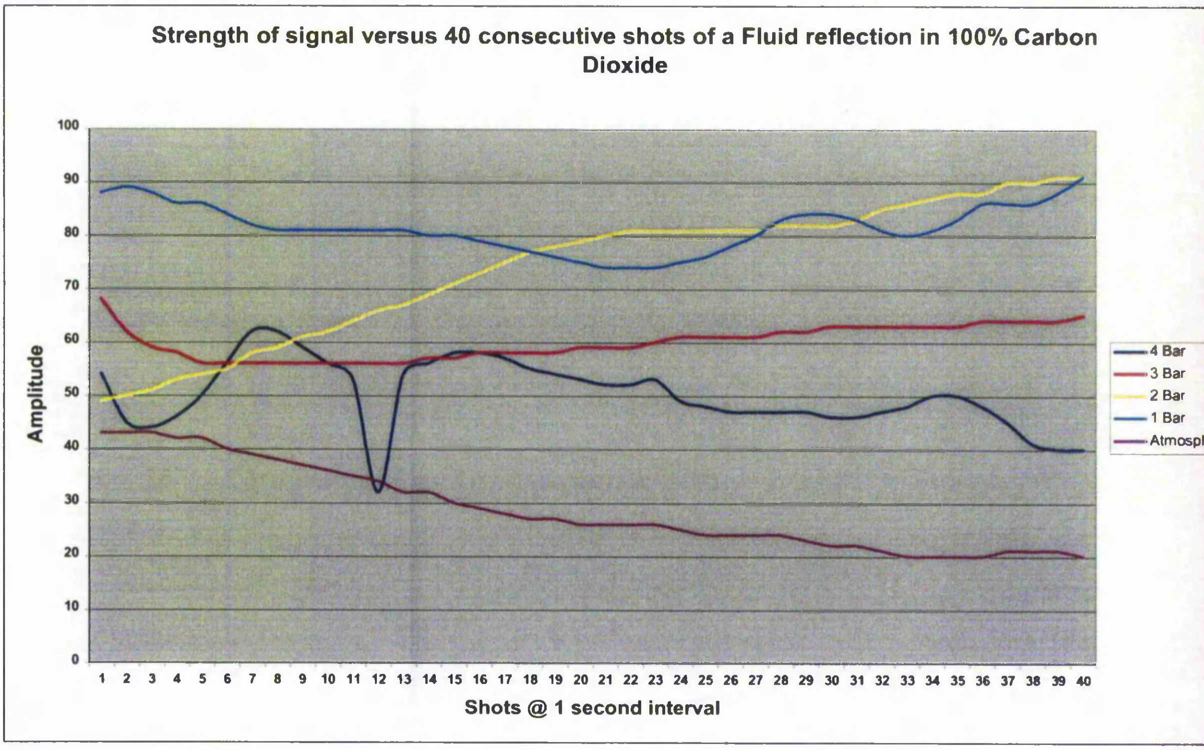


Figure 11.14 The relationship between amplitude and time for varying pressures.

Although variation can be seen in the plotted lines, the signals are still strong and therefore TOF measurements in this complex environment can be successfully gained. The variations in amplitudes were attributed to humidity effects created by the introduction of the fluid reflection.

Purging with Nitrogen

The previous investigation was repeated after purging the chamber with N_2. Figure 11.15 shows that at atmospheric pressure the amplitude is of a similar value to that of the previous experiment, but there is a dramatic increase in amplitude. Individual pressure lines display less noise.

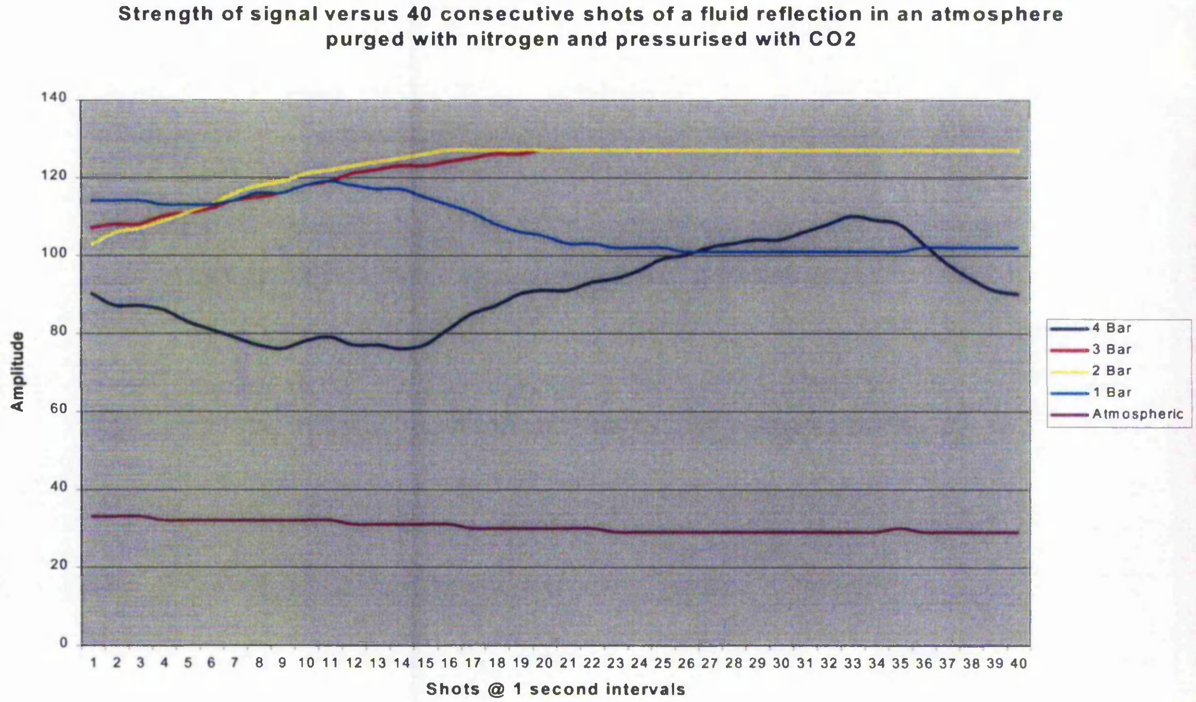


Figure 11.15 The relationship between amplitude and time for varying pressures purged with N_2.

11.3.2.2 Impact of purging with CO_2 and N_2 on ultrasound signal time-of-flight.

As previously described, the pressure vessel was purged with either CO_2 or N_2 and charged with CO_2 to 4 bar. A returning echo was captured at 1 second intervals for a duration of 40 seconds. This procedure was repeated for pressure changes of 1 bar down to atmospheric pressure. Returning echoes were processed within the threshold Matlab macro to determine the TOF. All TOF data was converted to distance.

An analysis of TOF data after CO_2 purging is illustrated in Figure 11.16. The consistency of results was excellent, with minimal noise equating to 0.2 mm. As the overall pressure within the chamber was increased, the TOF measurement increased but stabilisation occurred after 2 bar. On the whole, purging with CO_2 generated TOF measurements within the range of 58.5 to 59.5 mm, excluding atmospheric pressure.

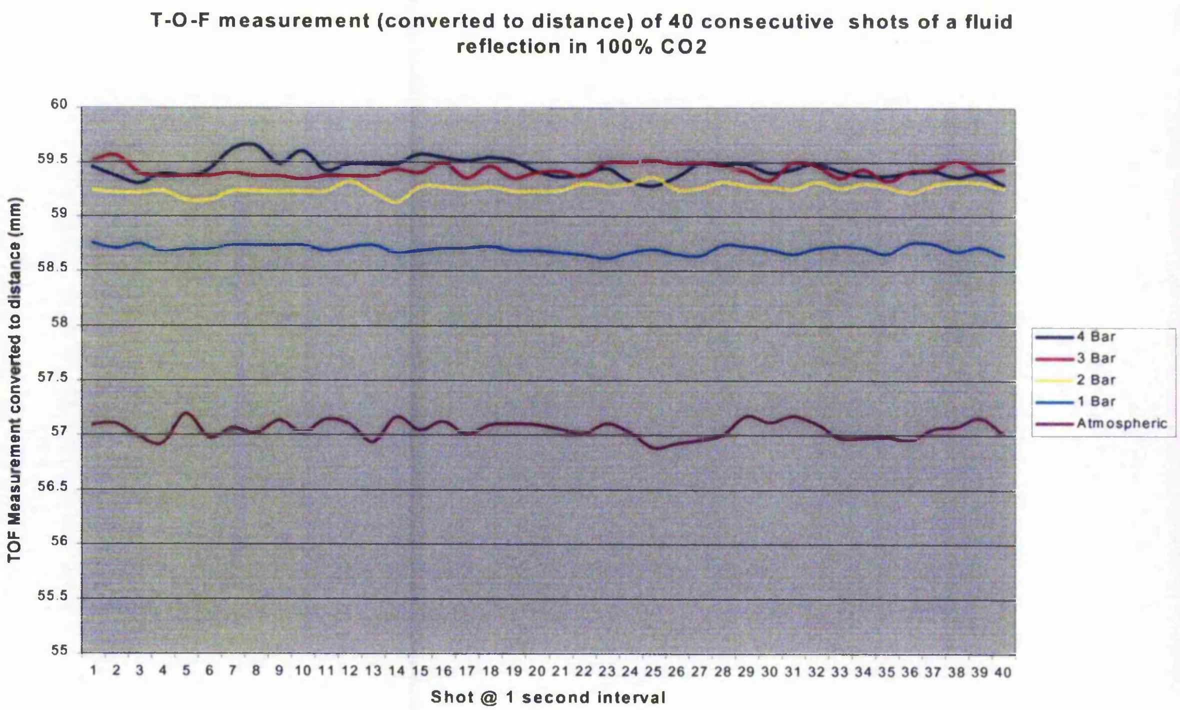


Figure 11.16 TOF – CO_2 purging.

TOF of fluid reflection with 100% CO_2 (N_2 purging).

The above experiment was repeated with N_2 purging. The results, shown in Figure 11.17 clearly show similarities to the results obtained with CO_2 purging. However, there are differences in the calculated measurement of the TOF. This TOF difference is attributed to the influence of the N_2 within the chamber. Therefore, further experiments could be conducted to establish gas mixture and quantity analysis using this novel method of ultrasound. Purging with N_2 generated TOF measurements within the range of 55.0 to 55.8, excluding atmospheric pressure. The ranking of the position of the pressure lines mirrors those observed purging with CO_2 with the 1 bar pressure line consistently lower.

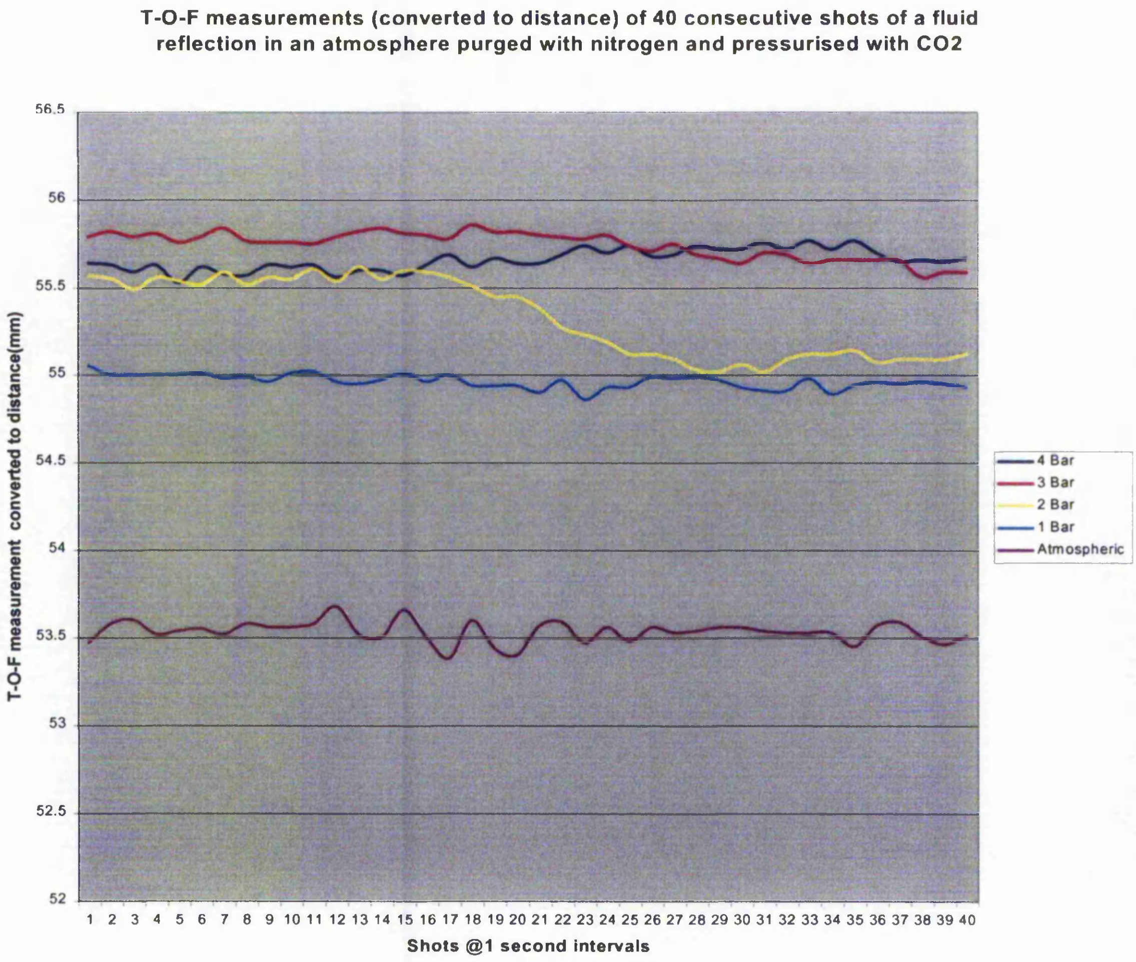


Figure 11.17 TOF – N_2 purging.

11.4 Use of ultrasound to detect changes in fluid levels

A final investigation was undertaken to detect a change in fluid level within the environment of CO_2 pre-evacuated with N_2, at a pressure of 4 bar to represent the nominal working pressure for carbonation of soft drinks. 5ml of fluid was added to the beaker within the pressure vessel. This 5ml quantity equated to a 1 mm change in height of the fluid level. Ultrasound echoes were captured for ten such additions. Figure 11.18 is a graph that shows the TOF measurement in mm of the change in fluid level.

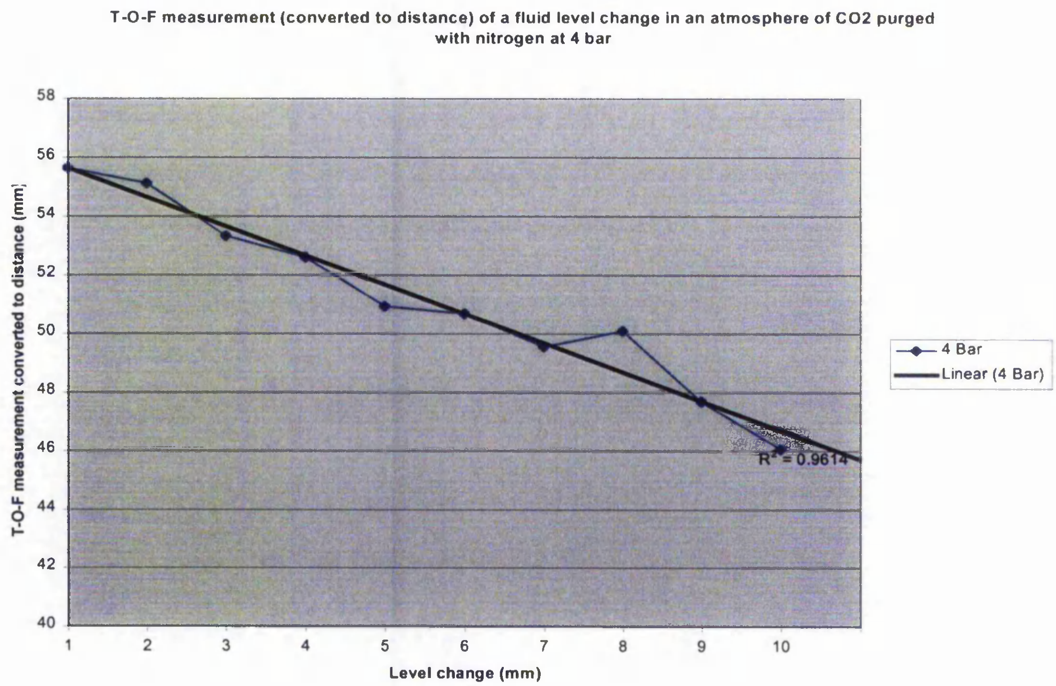


Figure 11.18 A graph showing the TOF measurement of a fluid level change in an atmosphere of carbon dioxide purged with nitrogen at a pressure of 4 bar.

The trend line shows an excellent linear relationship ($R^2 = 0.9614$) between change in fluid level and TOF. The TOF decreases with increasing fluid level. This investigation demonstrated that 'air-transmission' type ultrasound could be used to measure a change in fluid level within the carbonating environment.

Chapter 12 – Discussion of results

12.1 Background

Food and drink production represents the largest manufacturing sector in the UK economy, and companies are among the largest UK exporters. It has been estimated that the industry looses substantial revenue each year due to the inefficient methods of container filling. For example, loss to the dairy industry has been estimated at approximately 12 million pounds per annum [Hull & Muumbo 1995] in the UK alone.

The Government funded Technology Fore*sight* Panel on Food and Drink has stressed the need for increased investment in R & D to maintain the UK in the first division of food manufacture. Food processing represents a field of rapid development and implementation of new approaches in process technology, in particular, automation systems, quality procedures, efficiency improvements and sensor systems for in process monitoring and control.

12.1.1 Aim

The overall aim of this research was to design and develop a prototype system for rapid on-line measurement of fluid dispensing levels in food containers.

The research was approached by exploring all available methods for fluid level measurement, and assessing their suitability for high-speed on-line level measurement of bottle and container filling. The characteristics of available industrial bottling and container filling processes were investigated to enable the design and manufacture of a filling rig for experimental monitoring purposes. The operation of dispensing equipment was studied, with particular attention given to the filling process and associated variables. The various methods of ultrasonic techniques for fluid level measurement were investigated. The performance of the available methods of measuring the fluid levels using ultrasound sensors was assessed. The returning echo data was processed to accurately interpret the fluid level measurement environment.

Initial work involved justifying the use of ultrasound and various other level measurement techniques were considered. In comparison, ultrasound offered considerable benefits such as;

- Non-contact and non-invasive approaches,
- Increased accuracy and speed,
- Robust and reliable and mechanically simple.

12.1.2 The choice of ultrasound

Ultrasound technology presents a unique opportunity to the advancement of sensor technology for process monitoring in the food processing industry. As part of the research, ultrasound technology was chosen and an appreciation of alternative monitoring techniques was completed. The choice of ultrasound was made for the following reasons. Ultrasonic energies used for level detection were low with no health hazards [Suslick 1989]. In engineering terms, ultrasound was advantageous over all other techniques in that it combined non-contact and non-invasive possibilities of monitoring. Ultrasound was accurate and relatively inexpensive in comparison to infrared/microwave detectors. It contains no mechanical working parts and was therefore maintenance free and largely impervious to harsh environments. Ultrasound was a fast process and suitable for real time measurement.

12.1.3 Variability of fluid levels currently

Different methods for container filling exists for beverages that are viscous, non-carbonated and carbonated. There are currently no high-speed on-line monitoring techniques to control the final level requirement as the filling process takes place. The overfilling of containers and variability in volume has been identified as a common occurrence in the food processing industry.

The filling operation for viscous fluids is predetermined by the volumetric fill mechanical operation. Level changes occur due to mechanical wearing of the internal components of the pre-metering cylinder caused by coarse particulates that exist within the type of viscous fluid metered. Milk, which is classified as a non-carbonated product has its filling controlled by vacuum and the corresponding level of milk in header tank. Problems associated with fill level have been identified as air getting into the vacuum and the formation of "cheese" on the surface of the milk. The process of filling relies on vacuum-fill as a means of stopping the process, which is in itself, inaccurate. It has also been identified that the fill rate variability depends on the depth of vacuum in the header tank, and the corresponding hydrostatic pressure changes effect the fill rate. In addition, the flow of milk is controlled by a rubber diaphragm, and this flexibility introduces errors and the diaphragms response dictates the speed of the filling operation. In the filling of carbonated fluids, which is a similar mechanical process to that of the filling of milk, containers/bottles to be filled are charged with gas in order to reach equilibrium with the carbonating header tank and then fluid is allowed to flow. The gas under pressure returns to header tank through a stainless steel tube. It is the length of this tube that is the only means of controlling the level. As soon as the tube is covered with carbonated fluid, the inlet valve closes.

12.2 Industrial Situation

12.2.1 Modelling of bottling and carbonation process

To overcome engineering problems associated with the application of ultrasound monitoring to a real industrial scale container filling operation, a dedicated piece of research equipment (CW250) was obtained to model the bottling and carbonation process.

This model supported the previous findings of [Zeng et al 1994] and general acceptance in the bottling industry that there is variability of fill level in carbonated and non-carbonated products which is exasperated over time.

The use of the carbonating and bottling equipment in this project illustrated the physical design constraints concerned with transducer mounting possibilities. This lead the exploration of different ultrasound techniques based on contact or non-contact/non-invasive methods. Three sensing techniques were identified and explored. The wall resonance and far wall echo approach relied on contact transducers for sound transmission; strong contact between object and sensor is essential for successful operation. However, this creates mechanical design problems when considering individual bottle filling operations on high speed bottling plant.

1. It was therefore concluded that an air transmission approach was more favourable for the purpose of this research. Not only are the non-contact characteristics beneficial in this situation, but also that an ultrasound approach would enable a clear signal in terms of real time control.

2. In order to carry out these investigations using air transmission methods, the interpretation and processing of the ultrasound signals required extensive research and the development of more specialised equipment to produce useable results.

3. The main problems that may be encountered with the air transmission approach include air temperature effects on the speed of sound, and attenuation problems associated with turbulence in filling, bubbles and the carbonating environment. The presence of gas mixtures means that the ultrasound signal would be propagating thorough medium involved in the filling process.

12.3 Control Requirements

The bottling industry has relied on mechanical means to facilitate control of liquid levels ever since its inception. However, as the need to reduce waste becomes an increasingly dominant force in the modern manufacturing world, the search for a reliable and accurate method to control container filling has been brought to the fore. Although modern bottling plants are sophisticated in mechanical design, the employed principles no longer provide sufficient scope for the optimisation necessary to meet waste reduction targets. However, the introduction of modern control theory and new technologies could allow for further improvements to be made [Hull et al 1995].

Ultrasound monitoring has the potential to be an accurate measurement technique which is capable of being combined with an appropriate control strategy to provide the most suitable method of reducing or eliminating the waste problem. The objective of the research undertaken by [Ridgway et al 1999] was to investigate controller design methodologies for a bottling process. The bottling process was modelled using MATLAB® and SIMULINK® packages and controller designs were implemented to improve the response characteristics of the process. Both digital control and fuzzy logic controller design methods were investigated. The digital controller was designed using the direct digital design method and resulted in an improved system performance. Fuzzy logic control operated with a pre-determined set of rules has been shown to function very well with a bottling system. Bottle fill times and the resulting stability with respect to changing carousel delays were improved. Available data indicated that fuzzy logic could be used efficiently and effectively, which could provide a valuable asset to the food processing and allied industries.

Other research undertaken by [Jeffries et al 1998] has shown that currently, measurements are often made at a position away from the filling valve, giving an indication on overall fill level and allowing rejection of under-filled bottles, but the information does not feedback to the filling valve. It was demonstrated that a non-contact method was preferred as the bottles were moving past the sensor at relatively high speeds. It was clear that to improve the bottling process closed-loop control of some kind must be used, and placing the sensor as close to the actual filling would reduce any process lag. Given the flexibility to design a plant around a sensor technology almost all the previously mentioned methods were viable, however applying a new approach to an existing plant would result in both less sensor choice and a reduction of the capabilities of the sensors. This necessitates a control system accommodating imperfections in the sensor technology.

A well-tested solution to the problem of imperfect or noisy measurements is the Kalman Filter [Kalman, 1960], [Kalman and Bucy 1961]. By filtering measurements before the control system has chance to make decisions, inadequacies in the accuracy of sensors can be de-coupled from control actions. This is achieved by modelling the process within the filter and comparing measurements and modelled values to form a dynamic estimation of the process state.

Jeffries (1998) concluded that the approach has great potential to improve the filling process, with implementation on a range of different configurations possible by utilising the rule-based inference engine of the fuzzy logic to provide overall control.

12.4 Development of Equipment

12.4.1 Development of air transmission detection equipment.

In order to develop ultrasound air transmission equipment, several factors were taken into consideration, namely the transducer composition and characteristics, the excitation requirements, receiving ultrasound signals and the successful processing of the data

It was necessary to understand the composition of the transducers (Physical design), the properties of the piezoelement, the damping characteristics and the incorporation of acoustic matching layers to reduce acoustic impedance mismatch when transmitting into the highly attenuating medium of air/gas.

It was necessary to appreciate the way in which the piezoceramic needed to be energised to transmit ultrasound through the air-gas medium, and to make informed choices of the type of PZT crystal required. A low energy excitation pulse was required to propagate ultrasound compressional waves that could be transmitted reflected and consequently received for analysis.

An integral pre-amplifier and narrow band filter (around the resonant frequency of the piezoceramic crystal) was developed to give clean strong useable signals. The returning signals were converted from analogue to digital signals via an ADC card, specifically designed for acoustic analysis. The card was programmed to attain a fast sampling rate and incorporated a spectrum analyser for a high transient sampling rate, it also included a powerful wave form digitiser, and a real time digital signal processor that was consequently developed for the time-of flight calculations required for the particular application.

After initial trials using the equipment, the accuracy of air transmission was improved by investigating alternative methods to analyse signals by assessing time of flight data in an off-line situation. Two methods of signal processing were investigated, cross-correlation and the threshold approach. Encoding the signal and using DSP techniques, the resolution of the measurement was improved.

Research demonstrated that the threshold approach was the most accurate method of determining time of flight, producing errors of −0.176mm and + 0.466mm when measuring a 2mm distance. In addition, the threshold processing method delivered more stable results than cross-correlation, with a jitter of 2.31mm using cross-correlation compared to only 0.69mm utilising the threshold approach [Griffin 1997]. Incorporating a digitiser board to improve the sampling rate advanced the air transmission equipment and data capture resolution for digital signal processing techniques. This system was applied to detect fluid levels in a bottling environment

12.4.2 Physical design constraints of transducer mounting positions

In the present investigation, it was realised that it would be necessary to develop smaller transducers, but these were not commercially available. As an alternative option, one transducer was used to transmit and receive ultrasound signals, and the use of a switching circuit (transceiver module) was investigated, and subsequently designed and tested.

The use of the switching circuit generated several problems, notably problems associated with the impedance mismatch of the equipment and individual component characteristics of the electronic circuit, and the time constraints of this process. Further research would be required to eliminate/investigate these problems in order to fulfil the research objective (see recommendations for further work).

12.4.3 Development of Equipment...switch mechanisms

Due to the unavailability of a switching mechanism, it was not possible to complete on-line fluid level detection using ultrasound in the carbonating and bottling unit. This was due to the fact that further extensive research was required, that did not necessarily fit into the main research objectives. In addition, the characteristics of the transducer were such that there was an acoustic impedance mismatch, and more in-depth investigations would be required to enhance its ability to transmit in air over short distances in order to reduce excitation pulse ringing and cross-talk interference.

12.4.4 Signal Processing

In the present research, it was concluded that the air transmission technique was to be pursued using two transducers. In an experimental situation, the received signal from a single transducer would be the same as the received signal from a dual acting transducer. Therefore, further work was conducted on time of flight and threshold processing techniques within the digital processing software on board the ADC card as well as the introduction of Matlab ® software.

The processing of returning echo data was improved by using Matlab ® macros. The macros were written to normalise, rectify and impose a carrier wave onto returning echoes. The process of threshold timing using the 'interpolating' method significantly reduced the spread of results. The number of echoes required for a confident individual measurement if averaging the TOF macro calculations was 40. A normal distribution curve fit program was written to give statistical information on the average data.

12.5 Discussion of results from modelling the filling environment

The effect of environmental variables on ultrasound signals was assessed using a through air monitoring system comprising of a model pressure chamber. The impact of environmental pressure and CO_2 content the ultrasonic signal was determined. For these investigations a fixed reflecting surface at a distance of 100 mm from the transducer surface was used. Ultrasound transmitting frequency was set to 116 kHz and sampling frequency 6.5 MHz. The discriminator value to determine a threshold was set at 0.4 within the Matlab macro.

The temperature of the internal environment was recorded for every ultrasound measurement. The temperature recording was incorporated into the Matlab threshold timing macro to obviate its effects on the time of flight measurements. (However, the temperature was kept as constant as possible for all measurements to minimise its effect).

12.5.1 Impact of pressure effects on amplitude and TOF

The present work demonstrated that the received ultrasound signal amplitude increased as the transmission environment air/gas pressure increased from 0 to 4 bar (the maximum operating pressure of the bottling unit). As the pressure increased, the gas density increased and therefore gas molecules were more tightly packed hence increasing transmission of the ultrasonic signal. In contrast, increasing environmental pressure had little impact on the recorded time of flight (velocity of sound). Hence, the ultrasound signal was louder but not transmitted faster. It can be noted that for an ideal gas (or "perfect"), where the conditions of pressure and temperature are well away from those under which condensation to a liquid would occur, the velocity of ultrasound is independent of pressure. In the carbonating environment, the understanding of the sophistication of the processes of absorption for a non ideal gas is not necessary. However, as the most recent information describes [Asher 1997], the response of ultrasound signals to pressure within these conditions needs to be confirmed experimentally.

The current transducer was designed to transmit through air. When transmitting through different gases, different damping characteristics are required to achieve the strongest possible ultrasound signal transmission. A question that became clear was that when using the same transducer to transmit ultrasound through a combination of pressures and gas mixtures, further development of the transducers would be necessary, in terms of, impedance matching layers and damping to particular piezoceramic crystals, so that the sensors were finely tuned for the environmental variations.

12.5.2 Impact of carbon dioxide content on ultrasound amplitude and TOF

The impact of carbon dioxide content on the amplitude of ultrasound echo signal and time of flight were investigated at constant (4 bar) pressure. The results show that as CO_2 content increased there was a reduction in signal amplitude. However, between 60% and 80% content the signal amplitude reached a minimum and then increased as the content neared 80%. The attenuation of ultrasound signal amplitude in increasing carbon dioxide concentrations is a well-recognised phenomenon.

However, the reason for increasing magnitude in signal amplitude at contents higher than 80% is unclear but could be explained as follows. The mechanism of attenuation within a gas can be termed classical absorption, in the case of monatomic gases. In the case of polyatomic gases other sources of relaxational absorption take place. For carbon dioxide, the presence of small amounts of water vapour catalyses the vibrational thermal relaxation process [Asher 1997]. The relaxation frequency of thermal relaxation is often low but still within the range of ultrasonic frequencies which are used for stronger transmission capabilities. Under normal conditions, the thermal relaxation frequency of carbon dioxide is about 30 kHz, and at this frequency the absorption co-efficient at the peak is about 1200 times greater than that predicted from classical mechanisms. For example, 1% of water vapour increases the frequency corresponding to the maximum molecular absorption per wavelength from approximately 30 kHz to 2 MHz. Hence, instead of working above the relaxation frequency, levels below this frequency may have been achieved under the current investigations. The increase in amplitude may correspond to the purity of beverage standard carbon dioxide used in the experiment. As the content of carbon dioxide increases, the levels of water vapour increase. This probably leads to a shift on the maximum vibrational relaxation frequency that leads to an increase in ultrasound signal amplitude.

In order to fully substantiate these observations, further investigations are required to explore the phenomenon at varying excitation frequencies, which were not possible with the transducers developed for the purpose of this research. In addition, it is interesting to note that the ultrasonic detection system developed as part of the current research is sensitive enough to detect impurities in gases.

The impact of carbon dioxide content on time of flight data was also assessed at a constant 4 bar pressure. There was a strong linear relationship ($R^2 = 0.97$) between the TOF value and CO_2 content; as the CO_2 content increased the TOF measurement increased. The increase in TOF measurement corresponds to a decrease in transmission time of the ultrasound pulse. At higher concentrations of carbon dioxide the speed of sound decreases (267 m/s in carbon dioxide compared to 330 m/s in air). Unlike signal amplitude, the TOF data showed no diversion at high carbon dioxide content. This was because the explanation of classical relaxation was only appropriate to signal amplitude and has no bearing on determining the time at which the signal is received with respect to its excitation.

12.5.3 Surface plot relationships between pressure, carbon dioxide content and ultrasound signal amplitude and time of flight.

The relationship between the amplitude of the returning ultrasound echoes through a range of CO_2 contents (%) and pressures was determined by creating a 3-dimensional plot within Matlab. The purpose of designing surface plots was to build signatures of these variations so that they may be accommodated within a control strategy. The principle was that ultrasound signals captured in real time could be referenced to a database containing surface plots. The objective of this would be to assist in the correct interpretation of the signal, consideration being given to the environment.

The amplitude of the ultrasound signal was initially recorded at 80% CO_2 content and 4 bar pressure, and then pressure was reduced in 1 bar intervals to atmospheric pressure. This procedure was then repeated for intervals of 10% CO_2 content. As previously discussed, the surface plot illustrated that amplitude increased with raised levels of pressure, and amplitude decreased with increasing CO_2 content. To conclude, the attenuation of amplitude caused by high CO_2 content was of greater magnitude at high pressures.

No irregularities within the surface plot were apparent, with the signal strength remaining relatively uniform, so this could be used effectively to gain time of flight information. If large irregularities were evident, the signal may be too large or too small at times to successfully interpret time of flight information through the digital processing methods.

A further three dimensional plot was generated replacing the y-axis with TOF data. The surface plot had the appearance of a ramp, with increased CO_2 content elevating the ultrasonic echo TOF measurement, but pressure having little effect, as discussed previously. In accordance with the amplitude surface plot data, these surfaces would be successful in describing the impact of carbonating variables on ultrasound signals and therefore could be incorporated to intelligently control their effects.

12.6 The industrial carbonation and bottling environment

The next phase of the research programme was to investigate more intimately the actual environment for the carbonation and bottling of a soft drink, at 100% carbon dioxide and 4 bar pressure (70 Psi), and to ultimately process ultrasound signals reflecting off a fluid surface.

As outlined in Chapter 11, the most recent methods applied by industry to minimise bacterial contamination, and hence, improve shelf life of products, incorporated nitrogen pre-flushing prior to pre-evacuation. However, carbon dioxide is the most common gas used to minimise oxidation.

Initial data was obtained to determine whether strong ultrasound signals in an environment of 100% CO_2 could be received for processing. The chamber was flushed with either CO_2 or N_2 in order to purge the system of oxygen. The returning echo data was collected at half bar intervals from 4 bars to atmospheric pressure and processed to gain ultrasound echo signal amplitude.

At 100% CO_2 the signal strength was greatly attenuated over the range of pressures investigated. However, with CO_2 pre-flushed with N_2, the signal was stronger over the range of pressures investigated. It is interesting to observe from the data the strong correlation between the CO_2 flushed and the N_2 flushed data. Each line follows a similar path. As expected, within an environment of 100% CO_2 the signal amplitude is greatly attenuated, disappearing into background noise. However, with the minute quantity of N_2 introduced at the flushing stage, the amplitude of ultrasound signals is increased and for all investigative pressures rises out of the noise. This works in favour of the preferred industrial practice for the bottling of carbonated beverages.

The current data demonstrates that the developed ultrasound air transmission equipment, if calibrated correctly, could define minute concentrations of gas mixtures based on ultrasound signal strength.

12.6.1 Analysing returning echo data using a fluid reflection

In order to fulfil the main research objective of measuring fluid levels using ultrasound, the solid reflecting surface was replaced with a fluid, namely water. The amplitudes of ultrasound returning echoes and time of flight (TOF) transmitted through 100% CO_2 were determined. The chamber was pre-flushed with CO_2 and N_2.

A fluid surface was positioned 60 mm from the ultrasound sensors. Initially, the carbonating environment chamber was flushed with CO_2. Single reflected echoes were obtained over a range of pressures at approximately 1 second intervals. The results illustrated an excellent degree of consistency of signal strength at varying pressures. Although variation was apparent in the plotted lines, the signals were strong and therefore measurements in this complex environment can be successfully made. When considering the 2 bar pressure line result the amplitude of the signal at t=1 second is represented by 50 units. After 20 seconds, there is a gradual increase in strength of signal to 80 units. At t=40 seconds the signal strength plateau's at approximately 90 units. The rise in signal strength over the first 20 seconds may be due to a number of factors. Although every step was taken to obviate temperature effect, when pressurising or de-pressurising a fixed volume, there are major (± 20 °C) temperature fluctuations. Much work focussed on the necessity to design the chamber so that it was completely gas tight. It became apparent through these investigations that at higher pressures gas leaked through the transducer-electrical connection cables, between the wire and its insulation. This discovery, although deemed non-influential, was highlighted by immersing the external ends of the cable under water, and bubbles were visible as the gas escaped. Steps were taken to minimise this problem by encasing the internal connections in a suitable sealant.

Upon repeating the experiment with N_2 flushing the results were similar, however, as previously described, there was an increase in signal amplitude of the range of pressures investigated.

An analysis of TOF data after CO_2 flushing showed an excellent consistency of results, with minimal noise that equated to determining a measured level to within 0.2 mm (± 0.1mm). As the overall pressure within the chamber was increased, the TOF measurement increased, but a degree of stabilisation occurred in the TOF measurement when the pressure within the chamber was in excess of 2 bar. On the whole, flushing with CO_2 generated TOF measurements within the range of 58.5 to 59.5 mm, excluding the atmospheric pressure data.

The results obtained with N_2 flushing showed extreme similarities to those obtained with CO_2 purging. These similarities are twofold. Firstly the degree of accuracy obtained is again ± 0.1mm. Secondly, the distance between the five pressure data lines are exactly the same. This shows without doubt not only the capabilities of ultrasound to determine level extremely accurately within complex gas pressure environments, but also its potential application for the analysis of gases.

There were differences observed in the calculated measurement of the TOF. This TOF difference was attributed to the influence of the N_2 within the chamber. Therefore, further experiments could be conducted to establish gas mixture and quantity analysis using this novel method of ultrasound analysis utilising the measurement of changes in the speed of sound.

12.6.2 Use of ultrasound to detect changes in fluid levels in a carbonation environment.

The changes in fluid level were detected within the N_2 pre-flushed CO_2 environment at a pressure of 4 bar, in order to represent the nominal working pressure for carbonation of soft drinks. A volume of fluid was added to the beaker within the pressure vessel. A 5ml quantity equated to a 1 mm change in height of the fluid level. Ultrasound echoes were captured for ten such additions. The data obtained shows a strong linear relationship (R^2 = 0.96) between ultrasound TOF measured values and the actual changes in fluid level. This final investigation clearly demonstrated that the novel application of ultrasound within the carbonating environment is capable of determining fluid level changes within expected levels of accuracy.

Chapter 13 – Conclusions and Further Work

13.1 Conclusions

- Overfilling of containers and volume irregularities have been identified as a major problem in the food industry. Different methods for container filling exist for beverages that are non-carbonated, viscous in their nature and carbonated. There are currently no high-speed on-line monitoring techniques to control the final level requirement as the filling process takes place.

- Ultrasound was identified as the clear choice for a rapid on-line fluid level detection system offering considerable benefits over other level measurement devices such as its application being non-contact and non-invasive; it is mechanically simple; robust and reliable; potentially highly accurate and imparts a very fast response.

- The air transmission ultrasound approach was found to be the most favourable because of its non-contact characteristics. The wall resonance and far wall echo approach rely on contact transducers for sound transmission. Strong contact between object and sensor is essential for successful operation. This creates mechanical design problems when considering individual bottle filling operations on high speed bottling plant.

- The main problems identified with the air transmission approach include air temperature effects on the speed of sound and attenuation problems associated with turbulence in filling, bubbles in the fluid dispensed and the carbonating environment. The carbonating environment has many intrinsic variables, namely gas, mixture, pressure, humidity and temperature.

- Two methods of interpretation and processing ultrasound signals were developed to provide accurate measurement. The threshold approach was more accurate than cross-correlation methods.

- From an understanding of the physical design constraints of the bottle filling area it was concluded that a single transducer would be required. This would have to be custom built to incorporate a transceiver switch mechanism and could be the subject of future research.

- Normalising captured returning echo data significantly reduced the 'trail-off' of time-of-flight measurements over distance, thus improving the sensitivity. By absolving, normalising and interpolating the raw data to determine a time-of-flight measurement utilising the threshold technique, the spread of results were significantly reduced.

- Further development of piezoelectric transducers would be necessary; incorporating specifically designed back and front damping to optimise sensitivity in a carbonating environment.

- Amplitude of ultrasound signals increased with raised levels of pressure, and amplitude decreased with increasing CO_2 content. The attenuation of amplitude caused by high CO_2 content was of greater magnitude at high pressures.

- Since no irregularities within the constructed 3-D surface plot were apparent, it is concluded that this process could be used effectively to gain time of flight information to build signatures of these variations so that they may be accommodated within a control strategy.

- Increased CO_2 content elevated the ultrasonic echo TOF measurement, but pressure had little effect. The surfaces plots would be successful in describing the impact of carbonating variables on ultrasound signals and therefore could be incorporated to intelligently control their effects.

- Flushing of the model environment with N_2 enhanced the signal over the range of pressures investigated. This works in favour of the preferred industrial practice for the bottling of carbonated beverages.

- There were differences in the ultrasound TOF with the flushing of N_2 compared to CO_2. This data demonstrates that the developed ultrasound air transmission equipment, if calibrated correctly, could define minute concentrations of gas mixtures based on ultrasound signal strength.

- An analysis of TOF data after CO_2 flushing showed good consistency of results, with minimal noise that was similar to that obtained for N_2 flushing. As the overall pressure within the chamber was increased, the TOF measurement increased, but a degree of stabilisation occurred in the TOF measurement when the pressure within the chamber was in excess of 2 bar. This shows the potential of ultrasound to determine fluid level extremely accurately within complex gas pressure environments.

Use of ultrasound to detect changes in fluid levels in a carbonation environment.

- There was a strong linear relationship between ultrasound TOF measured values and the actual changes in fluid level. This final investigation clearly demonstrated that the novel application of ultrasound within the carbonating environment is capable of accurately determining fluid level changes.

In summary

Measurable outcomes of the project would include a new and much needed approach to level measurement and control thereof, for the fluid food industry with transferable possibilities. The equipment designed and developed within this project for air transmission of ultrasound, detection and processing has proven to be a very effective and accurate tool for complex ultrasound signal analysis.

Its capability for the application of non-contact and non-invasive fluid level measurement has been proven through its investigative role when dealing with variables that may effect ultrasound transmission through gases as apposed to the more recognised systems for solid material testing.

The Non-destructive, highly accurate and fast approach to condition monitoring will be of great benefit in facilitating the increased standards required by the food industry in their never ending goal to be more productive.

13.2 Recommendations for Further Work

1) Further work will be required on transducer design. The considerations that need to be addressed are, size of transducer, transmission frequency, impedance matching layers and damping, in order to accomplish the best possible transmission characteristics within the carbonation environment.

2) Development of a working transceiver module based upon proposed requirements and circuit designs. The considerations, individual component response, impedance matching of equipment, response time and development around transducer characteristics.

3) Real time operation combining control strategy..

4) Investigate the effects of turbulence and minimise/obviate its impact by use of stilling tube incorporated into the redesign of the filling head, utilising existing vacuum tube and space constraints.

5) Investigate the impact of humidity effects with different fluids and carbonation requirements.

6) Investigations into gas analysing capabilities of equipment.

7) A database containing the 'signatures' of common contaminants should be developed to demonstrate ultrasound applicability to not only level measurement but also condition monitoring.

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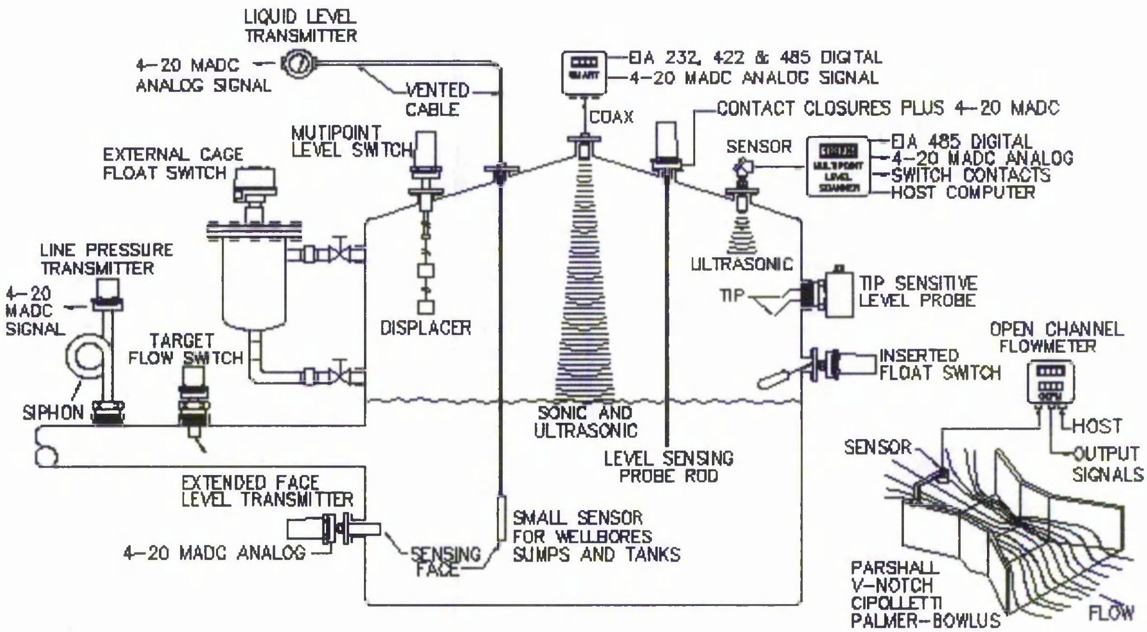
Appendix A – Description of Level Measurement Devices



Pressure/Level Transmitter Model 551, Delta Controls Corporation
Description

The Model 551 Pressure Transmitter incorporates both the sensor and the electronics in a module mounted in a heavy duty body. Its compact size makes it ideal for very limited space conditions.

The sensor includes an oil filled 316-L S.S. or platinum diaphragm which isolates the strain gage bridge from the process liquid or gas. The back of the sensor is usually vented to atmosphere to compensate for barometric pressure changes.

Features

- Small Size For Tight Places

- Two Wire Loop Powered
- 4-20 mADC, Intrinsically Safe
- Integral Electronics/Sensor Module
- Surface Mount Silicon Electronics
- Used For Pressure Or Level Measurement
- NPT, ANSI, DIN, or JIS Process Connection
- Ranges From 12 Inches Water To 3000 PSI
- Zero & Span Pots For Field Recalibration
- Spark & Voltage Surge Protection
- Maintenance Free Operation

Application

The Model 551 is used to measure and transmit the pressure of liquids and gases in pipelines, tanks, ducts and other containments. The 551 is commonly used as a liquid level transmitter in vented tanks. The pressure at the bottom of a vented tank containing a liquid is linearly proportional to the height and density of the liquid.

Specifications

- Technology: Silicon Strain gage.
- Supply Power: 13 to 35 VDC, 2 Wire loop powered
- Output: 4-20 mADC isolated, Intrinsically Safe
- Loop Impedance: 550 ohms @ 24 VDC, 1100 ohms @ 35 VDC
- Adjustments: Span from 30% to 100% of sensor range.
- Zero to 30% basic and to 80% optionally, non-interactive.
- Over Pressure: 2X Range (35 PSI min) without damage, 3X Range (1000 PSI min) without rupture
- Temperature Range
    - 20 to +220 Deg F (Process)
    - -20 to +180 Deg F (Electronics)
    - 30 to +130 Deg F (compensated)
- Accuracy: ±0.25% F.S. or better
- Thermal Error: ±0.02% F.S./Deg F. maximum
- Barometric Effect: None

Probe Type Level Switches, Model 103 and 105, Delta controls Corporation.

Description

The Model 103, 105 probe type switches use RF Admittance technology to produce switching action when a material level crosses the setpoint of its sensing probe. Many probe configurations are available; the proper style is determined by the service.

The interface position between two liquids with different dielectric constants can be accurately detected by the switches. The units will even average out a cloudy interface and produce a precise switching action as its position passes the set point. A limitation is that one of the liquids must be nonconductive. They are not sensitive to SPG (specific gravity) variations. Water/hydrocarbon interfaces produce excellent results. Detecting a liquid interface as it moves down a pipeline is another useful application.

The Model 103, 105 utilizes admittance technology to measure how much of its sensing probe is covered by the liquid. This is accomplished by generating a radio frequency pulse of energy which travels from the sensing probe to the ground reference (usually the tank wall). The amount of liquid between the two determines how much energy is transferred. The amount of energy flowing (very small and low level in all cases) is a highly repeatable measure of the liquid level or interface position. The amount is compared to an internal reference and produces a switching action at a selected material elevation.

Integral mounting on the probe head produces a simple one-piece unit which generally results at the lowest installed cost. Alternately, the Model 105 electronics module may be located 50 feet away from the probe. A coaxial cable then connects the remoted electronics to the sensing probe.

The probe may be mounted in any position; vertical, horizontal, or at an angle. Horizontal mounting is usually preferred for alarm action because it provides the sharpest switch point definition. The Model 105, with adjustable differential action (where the OFF setpoint is different from the ON setpoint) requires that the probe be mounted either vertically or at an angle. The material level must move past the two points on the probe where switch action is to occur.

Features

- R.F. Admittance type circuitry
- Insensitive to process coatings and buildup

- Choice of integral or remoted electronics module
- Design is accurate, simple, and very reliable
- Ambient temperature range -40 to +185°F (-40 to +85°C)
- Corrosion resistant, NACE #MR-01-75 optional
- Heavy duty sealed contacts
- High or Low relay failsafe action
- Adjustable 1-60 second time delay
- High reliability; 100 hour operational quality testing
- Epoxy sealed electronics module survives harsh environments and area vibration
- Process pressure may be as high as 10,000 psig (700 bar)
- Process temperatures may be as high as +750°F (400°C) or as low as -360°F (-215°C)
- Choose from application specific probe shapes, styles, configurations, and process connections
- Wide choice of wetted materials includes Steel, Stainless Steel, Teflon®, Kynar®, Monel, and Ceramics
- Threaded, flanged, or bracket mounting
- Sealed relay for corrosive conditions

Specifications

- Level range: Switching at any point along the length of the probe selected (see Application Note
- #PROB-198 for details). Setable range from 0 to 4,000 Sensing Units (SU) equivalent admittance.
- Differential:
  - Model 103 Fixed 2 SU for alarm service
  - Model 105 Adjustable up to 50% of range.
- Relay Contacts: Sealed for corrosive conditions.
  - Model 103 10A @ 250 VAC SPDT
  - Model 105 5A @ 250 VAC DPDT
- Time Delay: 0.25 to 60 seconds adjustable
- Basic Supply Voltage: 120 VAC, 24 VDC optional
- Operating Temperature: -40 to +185°F (-40 to +85°C) ambient
- Temperature Effect (0-150°F): +- 0.25 SU; typically less than 1/10" (2mm) in water.
- Probe Sensing Circuit: Intrinsically safe on the Model 105, explosionproof on the Model 103
- Electronics Module: Potted for high reliability.
- Housings: 4X Hoseproof; Class 1, Division 1, Groups BCD,EFG Explosionproof; PVC, Aluminum, or
- Stainless Steel material.

Appendix B - External Collaborators and Equipment Manufacturers

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Yorkshire

UK

Canongate Technology

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UK

Delta Model 551 Supplier

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Mapex Inspection Systems

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UK

Milltronics Limited

Customer Support

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Worcester WR4 9ZQ

UK

MONITEK TECHNOLOGIES, INC.

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USA

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Neel Electronics, Inc. / Nick Electronics, Inc.

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Appendix C - Variables associated with transducer construction

Section 1 Piezoelectric materials

There are not many materials that are piezoelectric, with the exception of quartz. However, there is a wide range of materials that are electrostrictive and demonstrate important similarities to the PE effect. These materials are called ferroelectrics and generate an electrostrictive effect large enough to be useful. Many of them are ceramics that can be fabricated into shapes which are convenient for use in piezoelectric transducers. For example lead zirconate titanate (often shortened to PZT) is the best known of the ferroelectric ceramics used in piezoelectric transducers. The polymeric organic plastic material PVDF (polyvinylidene fluoride) is another example.

Criteria for assessing piezoelectric materials

When choosing piezoelectric materials there are many criteria to be taken into account. Some manufacturers list thirty or more. The following section will introduce the important criteria.

The mechanical quality factor Q_m

The mechanical quality factor Q_m is related to the bandwidth. It gives information about the damping of the transducer and its ability to generate short pulses. Q_m is a measure of the ease with which energy is lost from an oscillating system. It is often defined as a function of the ratio of the energy supplied per cycle to the energy dissipated per cycle.

Quartz is notable for having a remarkably high Q_m (exceeding 25000 for some samples). This means that it shows exceptionally sharp resonance frequency (hence its attraction as a means of controlling constant frequency devices, such as watches) and also has a very small damping coefficient.

The plastic material PVDF, in contrast has a very low quality factor.

Curie point (Curie temperature)

At a sufficiently high temperature, PE materials undergo a phase change that destroys the piezoelectric or ferroelectric domain structure. This is known as the Curie temperature or, more strictly the Curie point, of the material. Above the Curie point, the material is no use in a PE transducer. The Curie points of common PE materials range between about 100 °C and over 1100 °C.

Acoustic impedance

The acoustic impedance Z is important since it controls the transmission of the ultrasound out of the PE element into the load and into any damping material.

Piezoelectric Parameters

There are many piezoelectric parameters that have to be considered when choosing a suitable material. The more important ones are listed below.

- The electromechanical coupling coefficient k.
  This quantifies the efficiency of the PE material at converting electrical energy into mechanical energy (or vice versa). Ultrasound is one of the forms of mechanical energy but not the only one.
- The transmitting constant d.
  This is related to the dimensional change to the applied emf.
- The receiving constant g.
  This is another piezoelectric constant, analogous to the transmitting constant and relates the emf generated to the change in dimension

The piezoelectric element

Firstly there is the question of selecting the piezoelectric material. The lead zirconate titanate ceramics (such as a PZT or a similar material from another source) are widely used because these are well known and versatile. The PE parameters for a typical lead zirconate titanate are given in table C.1.

Table C.1. Piezoelectric parameters for a typical lead zirconate titanate, PZT 5A.

Electromechanical coupling coefficient, k, %	71
Transmitting constant, $d \times 10^{12}$ C N^{-1} or mV^{-1}	374
Receiving constant, $g \times 10^{3}$ C N^{-1} or mV^{-1}	24.8
Quality factor, Q_m	75
Acoustic impedance, Z, Mrayls	30
Curie point, °C	365

Reference [Asher 1997].

Before finalising the selection of the PE material it is necessary to check its electrical breakdown field strength to make sure it will tolerate the energising voltages proposed. Compatibility with the environment, for example attack by water or corrosion by chemicals is an important consideration if the PE material was to be exposed to such elements. However, for the proposed air transmission level detection system, being non-contact, corrosion is not a factor.

The dimensions of the PE element are also an important consideration. Firstly the thickness, $t_{PE,}$ has to be selected to give the required resonant frequency. For a given frequency this thickness depends on the material.

For a typical PZT, a 1 MHz PE element would have to be 1.9 mm thick. Thickness requirements for other frequencies are easily calculated since the frequency is inversely proportional to thickness. So a 10 MHz element would be 0.19 mm thick and a 0.25 MHz element 7.6mm. These figures illustrate the mechanical limitations and are one reason why piezoelectric transducers of the type shown in Figure 7.1 cover a range of 0.1 to 50 MHz. Special measures have been taken to make PE transducers work outside this range. Much higher frequencies can be generated using depletion layers and other thin film devices (Gooberman 1968).

A final consideration is the diameter of the radiating surface of the transducer. This determines the beam profile and angle of divergence. A large disc (compared with the wavelength) will give a low beam divergence but a long near field in which there will be a complex variation in intensity. It will also result in a large transducer that may be inconvenient, not only because of its size, but also because of weight and cost.

A small disc will give a highly divergent beam with a short near field, i.e. the transducer will become more omnidirectional. Depending on the application, this may not be desirable.

Section 2

Damping

The damping requirements of a transducer depend on its intended application. When used in a pulsed mode, a damped transducer would be capable of producing shorter pulses than would an undamped transducer. As a receiver, it would be sensitive to a wider range of frequencies. The loss of efficiency caused by damping can be very significant (e.g., as much as 35 dB) and has to be accepted, although attempts can be made to minimise it.

Mechanical damping can be sited either behind or in front of the piezoelectric element ('back-damping' or 'front-damping').

Back-damping

Back-damping is very often achieved by filling the rear cavity of the transducer case with epoxy resin loaded with tungsten powder. The purpose of this backing material is to extract as much energy as possible from the piezoelectric element into the backing material and to absorb it rather than reflect it. It is the aim to choose a material which has a good impedance match to the piezoelectric element and which is also highly attenuative.

In the epoxy resin-tungsten powder mixture, the tungsten is the component which increases the acoustic impedance whereas the epoxy resin exerts its major influence on the attenuation; hence if the epoxy resin concentration is too low the attenuation is not high enough.

Other useful backing materials are plastics and rubber, which are attenuative, although they do not have high acoustic impedance. Lead or lead alloys, either in massive form or as powders incorporated in plastics are other possibilities. Tungsten powder in a matrix of aluminium, copper, lead or tin has also been suggested (Rokhlin et al 1981).

With back-damping, there are other steps which can be taken to improve the absorption of the unwanted ultrasound. Roughening the rear surface of the damping or machining V grooves can have the effect of scattering the echoes so that they have a greater chance of being absorbed in the damping material or in the attenuative material. The backing material can be shaped in such a way that the ultrasonic echo follows a long path and makes multiple reflections with an absorbent material. Alternatively the path length of the unwanted ultrasound can be adjusted to encourage destructive interference between the reflected pulse and the vibration of the PE element.

Most PE materials have acoustic impedance's similar to that of PZT and present the same sort of problem of impedance matching to the backing.

Front-damping

In front-damping a plate is bonded to the front face of the piezoelectric element. The material and thickness of the plate are selected so that interference effects shorten the pulse.

The material is selected to have an acoustic impedance intermediate between that of the PE element and the load. In this case the thickness should be $\frac{\lambda}{4}$, i.e., it is a 'quarter-wave plate'. The use of the thickness means that partial destructive interference occurs between the beam passing through the plate and the successive reverberations within the plate; only the first half cycle of the pulse completely escapes this effect.

Section 3

The behaviour at interfaces: beams at normal incidence

Reflection

The following diagram (Figure C.1) illustrates the mathematical models of ultrasound being reflected.

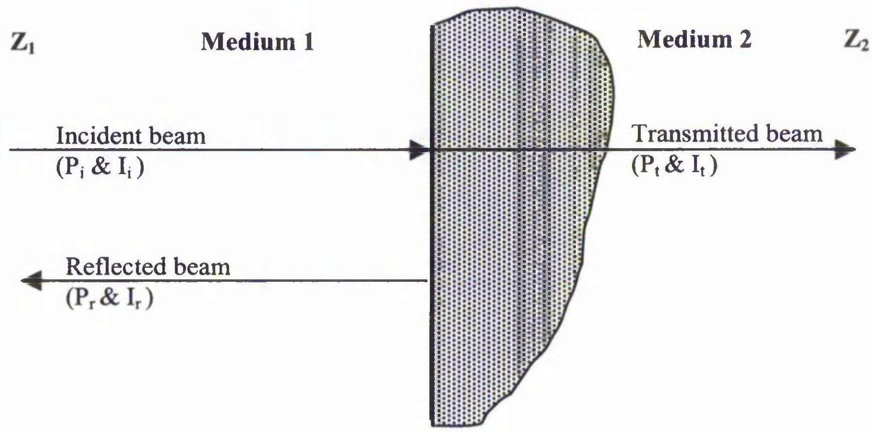


Figure C.1 Reflection and transmission at an interface; normal incidence.

The ratio of the acoustic pressure of the reflected beam to that of the incident beam (p_r and p_i respectively) is given by

$$R_p = \frac{p_r}{p_i} = \frac{Z_2 - Z_1}{Z_2 + Z_1} \qquad \text{(C.1)}$$

where R_p is the pressure reflection coefficient and Z_1 and Z_2 are the acoustic impedances of the two media in the order in which they are encountered by the ultrasound.

Since the intensity is related to the square of the acoustic pressure and to the acoustic impedance then it follows that the intensity reflection coefficient R_I is given by

$$R_I = \frac{I_r}{I_i} = \frac{(Z_2 - Z_1)^2}{(Z_2 + Z_1)^2} \qquad \text{(C.2)}$$

where I_i and I_r are the intensities of the incident and reflected beams respectively.

Transmission

Figure 7.1 also illustrates the mathematical models of ultrasound being transmitted. The pressure transmission coefficient, T_p is related to the acoustic pressure of the transmitted beam (p_t) by the equation

$$T_p = \frac{p_t}{p_i} = \frac{2Z_2}{Z_2 + Z_1} \qquad \text{(C.3)}$$

In terms of intensities, the relationship becomes

$$T_I = \frac{I_t}{I_i} = \frac{4Z_1Z_2}{(Z_2 + Z_1)^2} \qquad \text{(C.4)}$$

where I_t is the intensity of the transmitted beam and T_I is the intensity transmission coefficient.

Calculating the impedance match.

Each layer should have an acoustic impedance which is the geometric mean of those on either side, i.e.,

$$\frac{Z_1}{Z_2} = \frac{Z_2}{Z_3} = \frac{Z_3}{Z_4} \quad \text{and so on} \qquad \text{(C.5)}$$

where Z_n is the acoustic impedance of the *n*th layer.

This gives, for example

$$Z_2^2 = Z_1 \times Z_3 \qquad \text{(C.6)}$$

Matching layers should be $\frac{\lambda}{4}$ thick or an odd integral number of $\frac{\lambda}{4}$ for the reasons outlined in the previous section.

Usually one or two matching layers are used between the PE element and the load; more than that causes complexity and problems with bonding all the layers.

Some materials that might be considered for matching layers are given in table C.2 .and are described in order of decreasing acoustic impedance.

Table C.2. Some materials relevant to acoustic impedance matching layers.

Material	Acoustic impedance, Mrayls (approximate)
Stainless steel (typical)	47
PE ceramics (typical)	30
Aluminium loaded epoxy resin	4-7
Silicon carbide loaded epoxy resin	5
PVDF	2.1-4.7 (average 3.4)
Water	1.5
Silicone rubber	1
Silicone rubber loaded with microspheres	0.3
Air	0.43×10^{-3}

Taking a simple example, the geometric mean of the acoustic impedance of a typical ceramic PE material and that of water is about 6.7 Mrayls. Therefore, a $\frac{\lambda}{4}$ layer of silicone carbide/epoxy resin (impedance 5 Mrayls) should give a significant improvement in the efficiency of the transmission into an aqueous load.

Improving the transmission into a gas is less easy. The geometric mean of the acoustic impedance of a typical ceramic PE material is approximately 0.11 Mrayls; silicone rubber loaded with microspheres (acoustic impedance 0.3 Mrayls) is the best of the materials listed in the table.

In practice it is often possible to get a detectable signal into air from a PE ceramic element faced with more conventional plastics.

If two matching layers were considered, the simple rule of thumb would suggest that their impedances should be approximately 0.73 Mrayls and 1.8×10^{-2} Mrayls respectively.

Appendix D - Detailed specifications of equipment used for air transmission of ultrasound

Specifications of the Wavetek model 81 pulse/function generator

Standard waveforms
Sine, triangle square, positive and negative pulses.

Frequency
Range: 10 mHz to 50 MHz.
Resolution: 4 digits

Accuracy (continous mode)
10 mHZ to 999.9 mHZ: ±3%.
1 Hz to 50 MHz: ±0.1%.
Jitter: ≤ 0.1% ±50 ps.

Pulse & Ramp
Pulse modes: Symmetrical pulse, positive pulse, negative pulse and the complement to all pulse waveforms.
Pulse period:
Range: 20ns to 99.9 s.
Resolution: 4 digits.
Accuracy and Jitter: As for frequency.
Pulse width:
Range: 10ns to 999ms.
Setting accuracy:
10ns to 99.9ns: ±(5% + 2ns).
100ns to 999ms: 3% ± (4% + 2ns).
Resolution: 3digits.
Duty Cycle Range: 1% to 80%. Up to 99% using the complement mode.
PWM Range: 0 to 5V ±20% produces > 10% pulse width change from pulse width setting.
PWM Bandwidth: DC to 70 KHz.
Ramp Modes: Positive and negative going ramp.
Ramp Period:
Range: 7μs to 99.99 s.
Resolution: 4 digits.
Ramp width:
Range: 5μs to 999ms.
Resolution: 3 digits.

Amplitude
Range:
Into 50Ω: 10mV to 16Vp-p.
Into open Circuit: 20mV to 32Vp-p.
Resolution: 3digits.
Accuracy: (at 1KHz): ±4 % reading.

Main Output
Modes: Normal (on) or disabled (off).
Impedance: 50Ω ± 1%
Output Protection: Protected against continuous short to chassis ground.

Sync Output
Level (into 50Ω): 0 to 1V.
Rise/Fall Time: < 3ns

Operating Modes
Continuous, triggered, phaselock and start phase.

Triggered operation
Modes: Single shot, gated and burst.
Sources: Manual (from panel key), internal trigger rate generator and external signal input.
Triggered: For each trigger one output cycle is generated.
Gated: Continuous waveform cycles are generated for the generation of the active portion of the trigger signal. Last cycle is always completed.
Burst: Preset number of waveform cycles are generated by a trigger :1 to 4000.
Internal Trigger Rate Generator: 1 mHz to 50 KHz.
External Input: Via Trig Input BNC.
Impedance: 10Ω ±5%.
Sensitivity: 500 mVp-p.
Max Input Voltage: ±20V.
Min pulse width: 20 ns.
Max Frequency: 50 MHz.
Slope: Positive or negative going leading edges.
Trigger Level: Variable –10V 20 +10V.

General
Remote Operation: GPIB interface is standard and HP8116A emulation mode.
Environment:
Operating temperature: 0° to 50°C, ambient.
For Specified Accuracy: Within ±5°C and 24 hours of last internal calibration.
Power: 115/230Vac, optional 100V, 50 or 60 Hz 60 W max.

The 1220A Preamplifier

Features

- Wide Dynamic Range, 90 dB
- Low Noise (2μV)
- 20Vpp into 50Ω
- Single Power/Signal BNC
- Plug-in Filters
- 40/60 selectable gain
- High Input Impedance

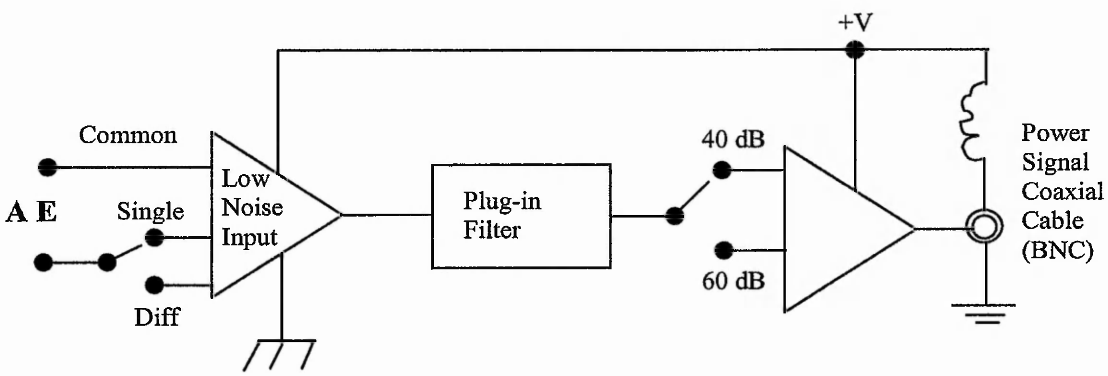
The model 1220A is a second-generation preamplifier that utilises a low noise differential transistor pair. The unit was designed to be used with available acoustic emissions systems and has its power supplied via the output signal BNC, thus providing simplicity and low cost. For versatility it is supplied with 40/60 db gain (switch selectable) and operates in either a single ended or differential mode. Plug in filters provide the flexibility to optimise sensor selectivity and noise rejection. These filters are provided in the Low Pass (LP), High Pass (HP) and Band Pass (BP) configurations, in order to provide broad bandwidths.

Electrical Specifications

Gain: 40/go dB selectable
Bandwidth: 20-1200KHz (-3dB)
Input Impedance: 10KΩ // 15ρf
Output Voltage: 20Vpp into 50Ω
Dynamic range: 90 dB
CMRR (500KHz): 55 dB
Noise (RMS rti): < 2μV
Power Required: 28V (32V max)
Operating Current: 25ma

Standard Plug-in Filters

Lowpass (L)	High pass (H)	Band Pass (B)
-70L 70 KHz	-3H 3 KHz	-50B 30-70 KHz
-100L 100 KHz	-20H 20 KHz	-60B 20-100 KHz
-300L 300 KHz	-30H 30 KHz	-200B 100-300 KHz
- 1200L 1200 KHz	-600H 600 KHz	-800B 600-1200 KHZ



Block Diagram of the 1220A

The Sonix STR*825 Analogue to Digital Converter

The Sonix's STR*825 analogue to digital converter board is an IBM PC /XT/AT compatible instrument featuring a true 25 MHz transient sampling rate. The 16K on board high speed memory buffer provides data acquisition flexibility. All board functions are under software control. These include sampling rate, trigger selection, clock selection, threshold phase and level, channel designation, board select and interrupt enable. Industry standard BNC connectors are used for convenient set up while maintaining maximum signal integrity.

Plugging the STR*825 into a PC transforms the computer into a powerful wave form digitiser, a real time digital signal processor or a spectrum analyser. The ADC boards high speed data acquisition memory is mapped directly into PC memory space. Once the wave form has been captured, the PC can transfer data off the board at approximately 1 byte per microsecond. It is designed with 25 nanosecond static ram and fast bus interface logic.

Using the STR*825 means that processing is no longer locked into the static architecture of a stand alone digital oscilloscope or the unusable slow data transfer rates between a stand alone instrument and the computer. The ability to install additional boards for multi-channel applications increases the options and flexibility of the instrument.

Applications

- Digital Oscilloscopes
- High Speed Measuring
- ATE Equipment
- Transient Capture
- Ultrasonics
- Acoustic Emmision
- Non-destructive Testing
- Mass Spectrometry
- Signal Processing
- Spectrum Analysis
- Communications
- Rada Guidance
- Pattern Recognition
- Video
- Optical/ Laser

Features and Specifications

Analogue

- DC to 35 MHz bandwidth, -3dB.
- -6dB at 50 MHz.
- 50Ω to 1 MΩ input impedance shunted with 15pf.
- Input may be configured for a low impedance (50Ω) and be easily changed to 1MΩ by pulling a single jumper.
- 1 to 10 volt input range through resistor selection.
- Offset trimpots provided to accommodate unipolar or bipolar signals.
- Precision voltage reference and low drift components used to insure long term accuracy and calibration.
- Standard BNC connector inputs.

Analogue to Digital Converter

- 2 independent channels.
- 25 MHz Flash converter, one per channel.
- 8 bits at 5 MHz full power bandwidth.
- Natural Binary output code.
- Integral and Differential nonlinearity +/- ¼ LSB typ, +/- 1 LSB max.

A/D Clock

- 25 MHz crystal oscillator time base.
- 7 software selectable lower rates.
- 50, 100 and 200 Mhz Time Equivalent sampling rate.
- Single time base; both channels fill simultaneously at the selected sampling rate.
- Time Equivalent sampling may be used in the internal trigger mode were the board is providing trigger out to trigger a repetitive event.
- Lowest sampling rate is jumper selectable in 10 steps from 381hz to 195KHz by factors of 2.
- External sample clock input; phase is software selectable.
- Internal sample clock output for multible board systems; one board may act as the master clock source and the others slave off the clock to insure total synchronisation between channels.
- Standard BNC input/output.

Triggers

- Trigger sources can be internally software generated, external ttl or threshold triggering.
- Normal, posttrigger and pretrigger data acquisition modes.
- A BNC connector provides for exteral trigger in.
- The same BNC connector can be software selected to provide a ttl trigger out.
- Trigger in or trigger out will respond to or provide either phase under software control.
- The number of bytes saved after trigger, in the pretrigger mode, is software selectable in 1 byte increments from 1 to 65536.

- The memory will automatically fill at least the required amount of pretrigger data before allowing a trigger to be accepted in the pretrigger mode.
- A 16K memory can be made to appear as a window out to 64K in posttrigger mode.
- Threshold trigger is derived from high speed 8-bit digital comparator for each channel.
- The threshold may be programmed to 256 levels greater or less than the incoming digitised data.
- Both channels have independent threshold logic allowing the trigger to come from CH1, CH2, CH1 or CH2, CH1 and CH2.
- Both channels can store the peak signal in a software generated window or the window may be brought onto the board via a snap on connector.
- The location of the peak (Time of Flight) in one channel may also be stored through jumper selecion.
- A 1525Hz continuos ttl trigger is available at the trigger BNC connector under software control.
- Standard BNC connector inpu/output.

I/O and Memory Map

- I/O is mapped as a 8 byte block on any 8 byte boundary from 100 to 3FF hex through jumper selection.
- Most parameters of the board are written or read using the 8 I/O ports.
- Memory buffer start and length are sent via a memory write.
- The high speed buffer memory may be mapped as either 4, 8, 16, 32 or 64K memory size through jumper selection anywhere in the PC's memory space (4K at D4000 default).

Memory Buffer

- 16, 32, 48 or 64K high-speed static ram per channel.
- All memory is on board eliminating the need fir "piggyback" boards.
- 1 byte to 65536 bytes of data per channel in 1 byte increments may be programmed to be acquired per record sequence.
- Waveforms may be programmed to start filling anywhere in the memory.
- A number of waveforms may be placed one right after the other in the memory so the user need not transfer any data until the entire memory buffer is full.
- Under software control, the high speed memory may not only be read from but may be written to as normal memory, allowing signal processing of the data without having to move it off the board.
- Ch1 or Ch2 or both may be write protected to save previously acquired waveforms.

Appendix E - Matlab macros used for signal processing

ATT.m

```
%Attenuation Conversion
%D = Value to be altered
%B = 40 db, C = 60 db


B = (((D-31.722)/10.167)*0.9582)-5.0945
C = (((D+5.0945)/0.9582)*10.167)+31.722
```

CDc.m

```
%carbon dioxide concentration plot

x= 0: 4/40:4;
Y = (x.*44)./((x.*44)+(((5-x).*29)+4.58))*100;


plot(x,Y)
Xlabel('Pressure of CO2 in Bars')
Ylabel('Percentage concentration of CO2 in Air')
TITLE('A graph to illustrate the relationship between pressure of CO2
and concentration in a fixed volume')
```

Conf.m

```
%determines mean plot

for m=1:40;
      hold on;
      plot(m,mean(x(1,1:m)),'yx');
      plot(m,mean(x(2,1:m)),'g+');
      plot(m,mean(x(3,1:m)),'b*');
      plot(m,mean(x(4,1:m)),'ro');
      xlabel('Number of Shots');
      ylabel('Mean');
      title('A Graph of Mean Value against Number of Shots, 50mm
Reflection');
end;
```

Control.m

```
% ultrasound data file viewer and interpolater
%21.07.98

clear all;
times=input('How many files? ');
airtemp = input('Air Temperature (C)?');
thresh =input('Threshold value?');

for n=1:times
      file=['data' int2str(n)];
      name=[file  '.dat'];
```

```
        eval(['load ' name]);
        X=eval(file);
        X(1:900)=-10*ones(1:900);
        ndata=X(:,1);
        x(1,n)=X(1,2);
        %eval(['x(1,n)=' file '(1,2);']);
        %eval(['ndata=' file '(:,1);']);
        ndata=ndata+10;
        ndata=ndata/max(ndata);
        for s=size(ndata,1):-1:1
              if ndata(s)>=thresh;
                    x(2,n)=s;
              end
        end

        Adata=abs(ndata);
        for s=size(ndata,1):-1:1
              if Adata(s)>=thresh;
                    x(3,n)=s;
              end
        end

        max_value2=0;
        max_value=0;
        max_value1=0;
        max_n1=0;
        max_n2=0;
        max_n=0;
        a=0;
        t=1;
        while max_value2<thresh,

              if ndata(t)>max_value;
                    max_value=ndata(t);
                    max_n=t;
              end
              if a==0;
                    if ndata(t) < 0.03
                          max_value1=max_value2;
                          max_n1=max_n2;
                          max_value2=max_value;
                          max_n2=max_n;
                          max_value=ndata(t);
                          a=1;
                    end
              end
              if ndata(t) > 0.05
                    a=0;

%if Adata(t)>max_value;
                    %max_value=Adata(t);
                    %max_n=t;
              %end
              %if a==0;
                    %if Adata(t) < 0.03
                          %max_value1=max_value2;
                          %max_n1=max_n2;
                          %max_value2=max_value;
                          %max_n2=max_n;
                          %max_value=Adata(t);
                          %a=1;
```

```
                  %end
            %end
            %if Adata(t) > 0.05
                  %a=0;
            end
      t=t+1;

      end
      IV=(((max_n2-max_n1)*(thresh-max_value1)/(max_value2 -
max_value1))+max_n1);
      x(4,n)=IV;

end
%x=(((x/6.25e6)*(331+airtemp*0.609)*1000)/2)
save results.dat x -ascii
```

Fits.m

%Normal Distribution comparer and Error checker

```
function [res,ybest,t] = fits(Z,n_h)
% HELP
%     [res,ybest,t] = fits(Z,n_h)


if nargin < 2,
n_h = 100;
end

log=[];
[h,t]=hist(Z,n_h)
nh=h/max(h);

for s=1:5
      for mu=t
            y=exp(-((t-mu)/s) .^2);
            E=sum((y-nh).^2);
            log=[[mu,s,E];log];
      end
end

res=log(find(log(:,3) == min(log(:,3)) ),:);
ybest=exp(-((t-res(1))/res(2)) .^2);
plot(t,nh,'r',t,ybest);
xlabel('Data Points');
ylabel('Normalised Frequency');
title('Normal Distribution Curve Fit');
```

Inter.m

%Interpolation of threshold

```
%Simon Griffin 4 08 98

max_value2=0;
max_value=0;
max_value1=0;
max_n1=0;
max_n2=0;
max_n=0;
```

```
a=0;
n=1;
while max_value2<thresh,

	if x(n)>max_value;
		max_value=x(n);
		max_n=n;
	end
	if a==0;
		if x(n) < 0.03
			max_value1=max_value2;
			max_n1=max_n2;
			max_value2=max_value;
			max_n2=max_n;
			max_value=x(n);
			a=1;
		end
	end
	if x(n) > 0.05
		a=0;
	end
n=n+1;

end
IV=(((max_n2-max_n1)*(thresh-max_value1)/(max_value2 -
max_value1))+max_n1)
```

Limits.m

```
%Attempt to determine mean tendancy

clear all;
times=input('How many files? ');
airtemp = input('Air Temperature (C)?');
thresh =input('Threshold value?');

for m=1:times
	file=['data' int2str(m)];
	name=[file '.dat'];
	eval(['load  ' name]);
	eval(['x(1,m)=' file '(1,2);']);

	for n=1:m
	eval(['ndata=' file '(:,1);']);

	ndata=ndata+10;
	ndata=ndata/max(ndata);
	for s=size(ndata,1):-1:1
		if ndata(s)>=thresh;
			x(2,n)=s;
		end
	end

	Adata=abs(ndata);
	for s=size(ndata,1):-1:1
		if Adata(s)>=thresh;
			x(3,n)=s;
		end
	end
```

```
        max_value2=0;
        max_value=0;
        max_value1=0;
        max_n1=0;
        max_n2=0;
        max_n=0;
        a=0;
        t=1;
        while max_value2<thresh,

                if ndata(t)>max_value;
                        max_value=ndata(t);
                        max_n=t;
                end
                if a==0;
                        if ndata(t) < 0.03
                                max_value1=max_value2;
                                max_n1=max_n2;
                                max_value2=max_value;
                                max_n2=max_n;
                                max_value=ndata(t);
                                a=1;
                        end
                end
                if ndata(t) > 0.05
                        a=0;
                end
        t=t+1;

        end
        IV=(((max_n2-max_n1)*(thresh-max_value1)/(max_value2 -
max_value1))+max_n1);
        x(4,n)=IV;

end
disp(m)
plot(m,mean(x(4,:)));
Hold on
End
```

Lookat.m

```
% ultrasound data file viewer
%21.07.98

clear all;
times=input('How many files? ');
airtemp = input('Air Temperature (C)?');
thresh =input('Threshold value?');


for n=1:times
        file=['data' int2str(n)];
        name=[file '.dat'];
        eval(['load  ' name]);
        eval(['x(1,n)=' file '(1,2);']);
        eval(['ndata=' file '(:,1);']);
        ndata=ndata+10;
```

```
        ndata=ndata/max(ndata);
        for s=size(ndata,1):-1:1
              if ndata(s)>=thresh;
                    x(2,n)=s-1;
              end
        end

        %ndata=abs(ndata);
        for s=size(ndata,1):-1:1
              if ndata(s)>=thresh;
                    x(3,n)=s-1;
              end
        end
end
%x=(((x/6.25e6)*(331+airtemp*0.609)*1000)/2)
save results.dat x -ascii
```

Mmax.m

```
for k=1:40

             datak = ['data' int2str(k)];
             filename = [datak '.dat'];
             if ~exist(filename), break, end
             eval(['load ' filename]);
             X = eval(datak);
             % Process data in matrix X.

            X(1:900)=-10*ones(1:900);

            maxX = max(X);
            results(k) = maxX(1);

end
```

Nc.m

```
%Nitrogen concentration plot

x= 0: 4/40:4;
Y = (x.*28)./((x.*28)+(((5-x).*29)+4.58))*100;


plot(x,Y)
Xlabel('Pressure of N2 in Bars')
Ylabel('Percentage concentration of N2 in Air')
TITLE('A graph to illustrate the relaitionship between pressure of N2
and concentration in a fixed volume')
```

Surf.m

```
%Surface plots

 x=0:4;
y=80:-80/8:0;
[xx,yy]=meshdom(x,y);
```

```
z=[160 308 467 616 754; 103 245 383 531 658; 69 181 319 457 584; 42
119 255 383 510; 21 80 170 298 414; 5 38 97 213 308; -2 14 47 120 192;
-5 10 42 98 160; -4 27 72 170 266]
surf(xx,yy,zz)
```

Surp.m

```
%Surface plots
clear all

 x=0:4;
y=80:-80/8:0;
[xx,yy]=meshdom(x,y);
zz=[160 308 467 616 754; 103 245 383 531 658; 69 181 319 457 584; 42
119 255 383 510; 21 80 170 298 414; 5 38 97 213 308; -2 14 47 120 192;
-5 10 42 98 160; -4 27 72 170 266];
surf(xx,yy,zz)
title('Surface plot to illustrate CO2 mixture/pressure influence On
Ultrasound echoes');
Xlabel('Pressure in Bars');
Ylabel('CO2 content %');
Zlabel('Amplitude of Ultrasound Echo');
```

Surt.m

```
%Surface plots
clear all

 x=0:4;
y=80:-80/8:0;
[xx,yy]=meshdom(x,y);
%zz=[2035 1995 1990 1991 1979; 2109 2062 2037 2020 2010; 2148 2122
2103 2085 2070; 2181 2224 2159 2141 2112; 2224 2272 2243 2200 2166;
2300 2338 2351 2291 2216; 2350 2380 2407 2417 2336; 2400 2410 2432
2468 2437; 2475 2495 2530 2501 2472];

zz=[55.42 54.37 54.36 54.45 54.22; 57.48 56.25 55.64 55.27 55.11;
58.53 57.88 57.42 57.06 56.88; 59.47 60.71 59.00 58.61 58.06; 60.63
62.01 61.33 60.25 59.50; 62.70 63.80 64.24 62.72 60.85; 64.05 64.89
67.72 66.17 64.10; 65.41 65.70 66.36 67.47 66.76; 67.45 68.04 69.05
68.35 67.67]
surf(xx,yy,zz)
title('Surface plot to illustrate CO2 mixture/pressure influence On
Ultrasound Echo TOF Thresholds');
Xlabel('Pressure in Bars');
Ylabel('CO2 content %');
Zlabel('TOF Threshold of Ultrasound Echo');
```

Twenty.m

```
%Chooses twenty shots and compares 'means'
clear Y;
clear Z;
rand('uniform');
for p=1:1000;

      r=1+round(rand(20,1) .*39);
      Y=x(4,r);
```

```
        Z(p)=mean(Y);
    end
```

Appendix F - Carbonation and Bottling Unit CW 250

General

Applicability

The carbonation and bottling unit CW 250 is intended for carbonation (saturation by carbon dioxide) of wine, water, fruit juices without sedimenting particles, cider, mineral water, beer and all sorts of pre-mixed settled beverages and for subsequent bottling of finished carbonated beverage into bottles. Uncarbonated beverage is drawn in from an open container (with atmospheric pressure), through a filter, which retains any solid particles bigger than 0.1mm.

Operation

The beverage drawn in by the carbonation pump is filtered and introduced in the carbonation section of the unit. The beverage is saturated by carbon dioxide in the inner cascade system and then transferred to the bottling section. The level controller in the bottling section maintains constant level, whereas the level in the carbonation section is kept between the maximum and minimum sensors by switching the pump on/off through a semi-automatic control system.

Bottles are thrusted to the filling valves and the relief valves are opened and closed several times to equalise pressure in the bottles and bottling section. Bottles are filled with beverage after the filling valves are pressed off.

The pump is protected against running dry by the semi-automatic control system. The unit is supplied with direct reading pressure gauges and a level gauge.

Technical Data

Maximum carbonated beverage production	250 LPH
Capacity	110 Psi
Maximum Pressure at Pump exit	190 Psi
Maximium CO_2 concentration in beverage	
- at temperature 5 °C and refraction 4 % RS	5.5 Vols
- at temperature 15 °C and refraction 8 % RS	4.2 Vols
Nominal CO_2 concentration in beverage	
- at temperature 10 °C and refraction 4 % RS	3.5 Vols
Operating carbonation pressure	70 Psi
Minimum carbonation pressure setup	7 Psi
Adjustable height of bottling	200 – 340 mm
Bottle volume	0.25 – 1.5 litres
Noise (equivalent noise level)	max. 70 dB
Supply voltage (standard)	3 x 380 V, 50 Hz
Power consumption	0.6 kW
Dimensions	0.6 x 0.6 x 2.2 m

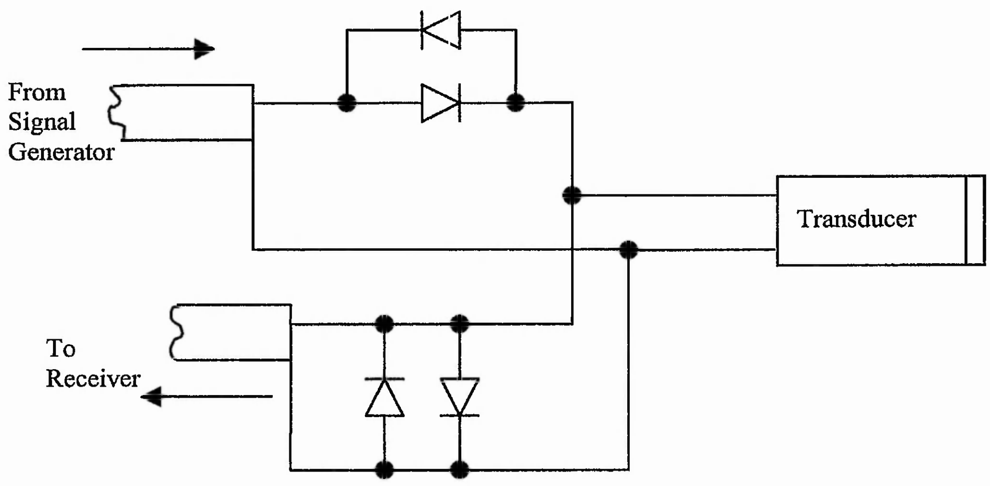
Description of the main parts of the unit CW 250

1	Frame of the machine
2	Carbonation section
3	Filling section
4	Bottle thrusts
5	Carbonation pump
6	Level controller at bottling section – float valve and membrane regulator of filling counter pressure
7	Filling siphon valve
8	Sensor of maximum level at carbonation section
9	Sensor of minimal level at carbonation section
10	Blocking sensor – pump protection against running dry
11	Sleeve of thrust rod with screw and spring
12	Draw bar of thrust control with pedal
13	Level indicator at bottling section
14	Safety valve of pressure tank
15	Pressure gauge of carbonation pressure
16	Control mechanism of filling valve with fork and valve lever
17	Venting valve lever of filling valve
18	Safety guard of bottling space
19	Pressure gauge for showing pressure on the nozzle
20	Inlet filter
21	Non-return valve of carbon dioxide
22	Main switch
23	Non-return valve on pump delivery piping
24	Delivery piping of pump
25	Overflow valve of bottling section
26	Overflow valve of carbonation section
27	Regulation screw of nozzle
28	Closing inlet ball valve CO_2
29	Deaeration ball valve of inlet piping to the machine
30	Discharge ball valve of interconnection piping of carbonation and bottling section
31	Closing valve under level controller of bottling section
32	Thermostat
33	Pneumatic thrust drive
34	Terminal switch of the safety guard
35	Bypass valve
36	Discharge valve of inlet piping
37	Controller of bottle thrust
38	Support of bottle

Appendix G - The transceiver module (switch), Circuits and contacts

Alternative Circuits proposed by external collaborators

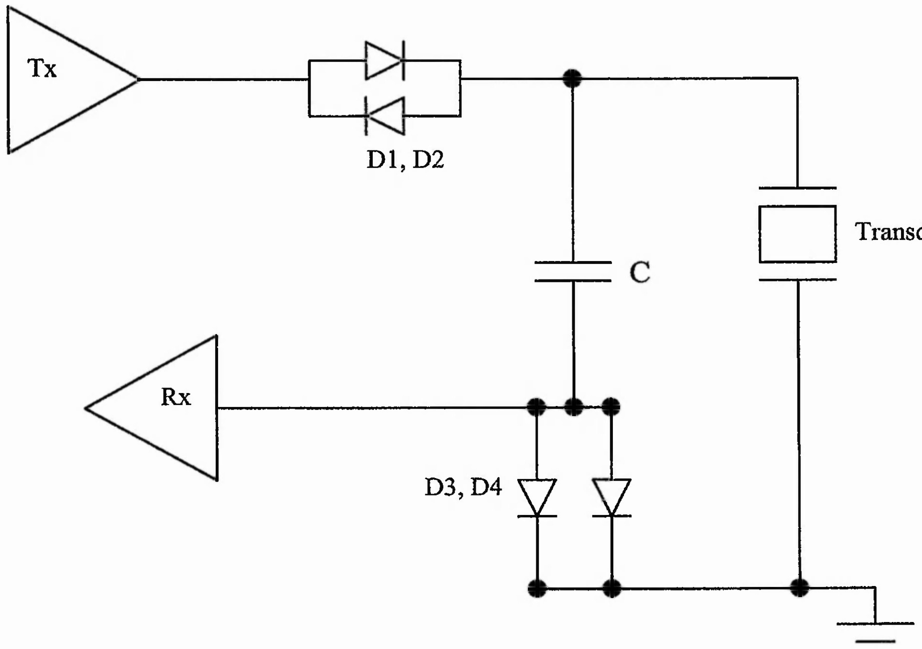
Circuit proposed by Dr Noel Kerr of Stresswave Technology Ltd



4 times IN 4148 type diodes

The idea of this circuit relies on the blocking of the excitation pulse by the diodes. The problems encountered were due to the long ring down period of the transducer and impedance mismatch between the signal generator and the receiver.

The electronics department at Stresswave Technology Ltd came up with another variation on the theme.

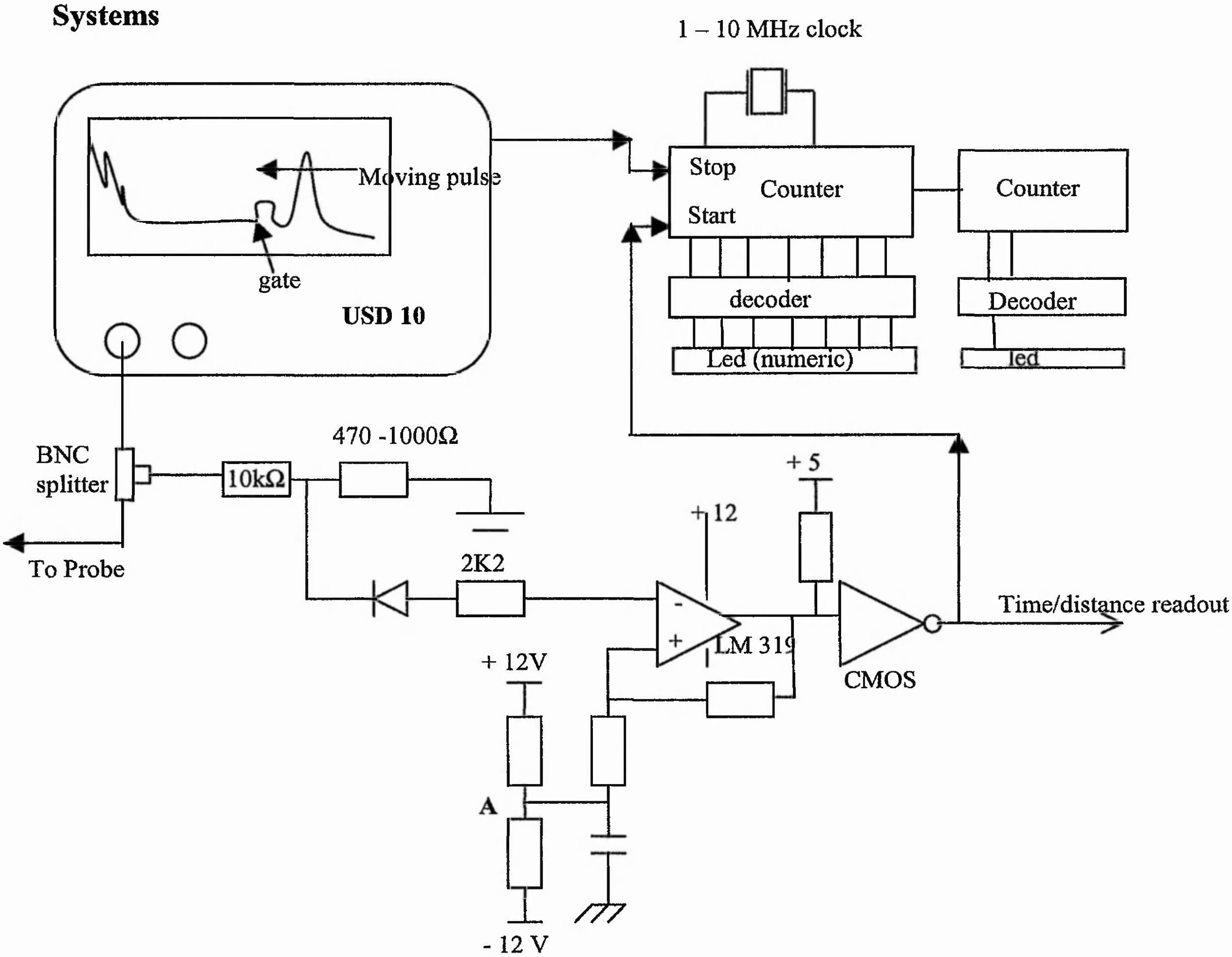


The diodes D1 – D4 were chosen with regard to their back flow voltage characteristics i.e., 4148 type ≤ 0.6 Vpp, BAT 54 S or Schottky ≤ 0.4 Vpp

The desired operation was as follows:

On transmit, The load capacitance is increased by C, which is fine, an extra volt is required to overcome D1, D2, these uncouple the transmit driver during receive. Signal volts are clamped at ± 0.6 V when using Si type diodes. For a faster response Shottky diodes could be used (no storage) but signal then clamped at ± 0.4 V. There is some signal loss due to the potentiometer effect of 1/ωC and transducer output impedance

Circuit proposed from discussions with John L. Turner of Phoenix Inspection Systems



*** threshold voltage on A set by devider between ± 12 V**

This is an external counter circuit utilising a trigger pulse from the USD 10.

Companies and people

Transducer

Mr Karl Quirk Engineering Director, Phoenix Inspection Systems.
Dr Noel Kerr, Stresswave Technology.
Dr Roger Hill, Department of Chemistry and Physics, Faculty of Science and Mathematics, The Nottingham Trent University.

Transciever switch circuits

Mr J.L. Turner, Electronics Department Phoenix Inspection Systems Limited.
Dr Noel Kerr, Stresswave Technology.
Mr Christos Mias, Department of Electrical Engineering, The Nottingham Trent University.
Mr D. Plantenberg, Mr V Bartley and Mr J Keeling, Department of Mechanical and Manufacturing Engineering, The Nottingham trent University.
Neel-Electronics Inc USA,
Airmar USA,
Krautkrammer Germany,
Sonatest UK,
Sonix USA

Appendix H - Risk Assessment, Gas Properties and Pressure Vessel Certificate of Compliance

Project work approval and Risk Assessment

Department: Mechanical & Manufacturing Eng   Location: Research Lab M111

Name: Simon John Griffin   Course: F/T Research

Submission: December 1998

Title of Project: Development of a novel ultrasound monitoring system for container filling operations.

The filling rig is situated in the research laboratory M111 and is designed to carbonate and subsequently fill two bottles.

The test equipment, consisting of a 3.8 litre volume stainless steel pressure vessel, two piezoceramic probes, function generator, acoustic amplifier, A/D card and PC, beverage standard carbon dioxide gas bottle and oxygen free nitrogen gas bottle is situated alongside the filling rig in room M111.

Risk Assessment, will be considered under the following classifications.

a) Electrical
b) Mechanical
c) Medium pressure water and air supply
d) Low to medium carbon dioxide and nitrogen gas supply
e) Instrumentation

a) Electrical Risk Assesment

The fluid pump on the bottling rig is supplied by a 3-phase 220V, 10 Amp supply. All wiring is isolated in earthed sheathed cables. The details of the safety procedures for the bottling rig can be found in Appendix 1

b) Mechanical Risk Assessment

The bottling rig is self-contained on three sides by stainless steel plate. The filling area has a high strength transparent polycarbonate interelocking guard that needs to be in place before filling can commence.

c) Medium pressure water and air supply

The system pressure is not expected to exceed 6 bar. This is supplied from an existing air pressure line in the laboratory. The air supply is taken from existing airline via flexible pneumatic tube with a maximum working pressure of 22bar. The water supply is taken from the existing piping via a combination of UPVC pipe and hose rated at 16 bar max working pressure. All drainage of fluid is via UPVC pipe to a drain.

d) Low to medium Carbon Dioxide and Nitrogen gas supply

The filling rig is supplied with Carbon dioxide from a beverage standard CO_2 gas bottle (E290), via a multistage regulator and pneumatic pipe. The regulator has an integral relief valve and the maximum working pressure the pipe can handle is 22bar (see appendix 2) The bottle rig is fitted with an adjustable relief valve set at 10 bar. The test pressure vessel (see appendix 3) is supplied with CO_2 to a maximum pressure of 4 bar. The vessel has a maximum working pressure of 9.8 bar and has a relief valve fitted and adjusted to 6 bar. In addition Nitrogen is supplied to the pressure vessel only via a multistage regulator and pneumatic pipe. The second stage can regulate between 0 and 10 bar and contains an integral pressure relief valve. The gas bottles are secured so that they cannot fall over. See section 2 For information on the gases

e) Instrumentation risk assessment

In the vicinity of the rig and pressure vessel all instrumentation is supplied with low voltage and low current. These are derived from mains (240v) supply and is remote from the rig and test area. The hardware is all subject to the regular P.A.T. tests and the supply is via earth leakage protection.

EMERGENCY PROCEDURE

In the event of a serious gas leak, room M111 would be evacuated and the fire brigade called.

NAME…………………………………………..DATE………………………

SUPERVISOR…………………………………..DATE………………………

SAFETY ADVISOR……………………………..DATE……………………...

Nitrogen N_2

General Characteristics	Health Hazards	Material Recommendations
A colorless, nonflammable and odorless gas	A simple asphyxiant	Normal materials can be used

TLV-TWA	Flammable Limits	DOT Class / Label
None Established	Nonflammable	2.2 / Nonflammable

Molecular Weight	Specific Gravity	Specific Volume
28.0	0.967 @ 77 F	13.8 cu.ft./lb @ 70 F

CGA Valve Outlet	CAS Registry No.	UN Number
580	7727-37-9	1066

Grade Part #	Purity Minimum	Cylinder Size	Volume SCF	Pressure @ 70 F	Comments
Research 406300	99.9995% Min.	049 044 002	304 210 4	2640 2000 2000	None
Ultra High 403700	99.999% Min.	049 044 016 007	304 210 80 34	2640 2000 2000 2000	None

Zero 403800	99.998% <0.5 ppm THC	049 044 016 007	304 210 80 34	2640 2000 2000 2000	None
Oxygen Free 404000	99.98% <0.5 ppm O_2	049 044 016 007	304 210 80 34	2640 2000 2000 2000	None
Prepurified 430900	99.998%	049 044 016 007	304 210 80 34	2640 2000 2000 2000	None
High Purity 403900	99.995%	049 044 016 007	304 210 80 34	2640 2000 2000 2000	None
Industrial/ Welding	99.5%	049 044 016 007	304 210 80 34	2640 2000 2000 2000	

Uses: Nitrogen - N2 - at room temp and atmospheric pressure, nitrogen is a colorless, odorless, nontoxic, nonflammable gas. It constitutes 78% by volume of the atmosphere. Naturally occuring nitrogen contains two isotopes, 14N and 15N. Used as an inert gas in electrical systems, chemical and food packaging industry. Used in the drying and preparation of refrigeration systems.

Carbon Dioxide CO_2

General Characteristics	Health Hazards	Material Recommendations
A colorless, nonflammable, liquified and odorless gas.	In high concentrations can paralyze the respiratory center	Copper, brass, nickel alloys, stell and stainless steel, other normal materials

TLV-TWA	Flammable Limits	DOT Class / Label
5000 ppm	Nonflammable	2.2 / Nonflammable

Molecular Weight	Specific Gravity	Specific Volume
44.0	1.522 @ 70 F	8.74 cu.ft./lb @ 70 F

CGA Valve Outlet	CAS Registry No.	UN Number
320	124-38-9	1013

Grade Part #	Purity Minimum	Cylinder Size	Volume LBS	Pressure @ 70 F psig	Comments
<u>**Research**</u> 4546000	99.996% Min	044 002	60 0.875	830 830	None
Supercritica l Fluid SFC/SFE 407700	99.9995% Min. Liquid Phase	A31	40	830	Can be supplied with 1500 psia helium for higher pressure
Anaerobe 473600	99.99% <20 ppm O_2	044 016	60 18	830 830	None
Coleman 405600	99.99% Min. Liquid Phase	044 016 007	60 18 5	830 830 830	None
Bone Dry 401700	99.8% Min	049 044 LBS	60 18 5	830 830 830	None
Industrial /	99.5% Min.	044	60	830	

Technical		016 LBS	18 0.5	830 830	None

Uses: Carbon Dioxide properties, purities, packaging and CGA Standards including research and supercritical fluid. Used in a variety of areas including refrigeration, carbonation, inerting agent and a neutralising

Appendix - I Determining the content of gas in a fixed volume

John Dalton observed that the Total Pressure of a gas mixture was the sum of the partial pressure of each gas.

$$\mathbf{P\ total = P_1 + P_2 + P_3 + \ldots\ldots\ldots\ldots P_n}$$

There are two ways of determining the Partial Pressure of a gas using the Ideal Gas Law Equation and using the Mole Fraction Relationship.

Ideal Gas Law Equation

The Laws of Boyle and of Gay-Lussac may be combined in an expression that represents the relationship between the pressure, volume and temperature of a given mass of gas; such an expression is described as an **Equation of State.** If a gas has initially a volume V_1 at the pressure P_1 and temperature T_1; then when the pressure is changed to P_2 and the temperature to T_2, the volume will be V_2. The relationship between these quantities may be derived in the following manner. If the temperature is maintained at T_1 while the pressure is changed from P_1 to P_2; if the accompanying volume change is from V_1 to V'_1 then Boyle's Law equation $P_1V_1 = P_2V_2$, which is applicable since the temperature is constant, gives;

$$P_1V_1 = P_2V'_1$$

$$V'_1 = \frac{P_1V_1}{P_2}. \qquad \text{(I.1)}$$

If the pressure is now kept constant at P_2, and the temperature is altered from T_1 to T_2; the volume will then change from V'_1 to the final value of V_2. Applying Gay-Lussac's Law $\frac{V_1}{T_1} = \frac{V_2}{T_2}$ at constant pressure, it follows that;

$$\frac{V'_1}{T_1} = \frac{V_2}{T_2},$$

and upon introducing the value of V'_1 from equation (I.1), it is seen that

$$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2} \qquad \text{(I.2)}$$

A similar result will be obtained from the volume V_3 at pressure P_3 and temperature T_3, and so on; hence,

$$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2} = \frac{P_3V_3}{T_3} = \ldots.$$

or, in general,

$$\frac{PV}{T} = \text{constant}, \qquad \text{(I.3)}$$

for a given mass of gas.

The equation (I.3) is thus a form of the Equation of State for a gas which obeys Boyle's Law and Gay-Lussac's Law. It implies that for a definite mass of gas, *any change of temperature and pressure will be accompanied by an adjustment of volume so that the quantity PV/T remains unaltered.*

Mole Fraction Relation

The value of the constant in equation (I.3) depends upon the mass and nature of the gas, but the introduction of **Avogadro's Law** permits a remarkable simplification. According to this law, equal numbers of molecules of different gases will occupy the same volume, at a given temperature and pressure. In other words, provided equal numbers of molecules are concerned, and P and T are the same, V will be the same for different gases. The constant in equation (I.3) will then be independent of the nature of the gas. In accordance with its definition, one mole or one gram molecular weight of any substance always contains the same number of molecules. Hence, *provided one mole of gas is under consideration, PV/T will be equal to a universal constant R, known* *as the* **gas constant,** *which has the same value for all gases.* The general equation of state for any gas would then be:

$$\frac{PV}{T} = R$$

or

$$\mathrm{PV} = \mathrm{RT} \qquad \text{(I.4)}$$

where V is the volume occupied by 1 mole, i.e., the **molar volume,** at the pressure P and the temperature T. At the same pressure and temperature, the volume of *n moles* would be *n* times as great as for 1 mole; if *v* is the volume, then

$$\mathbf{P}v = n\mathbf{RT} \qquad \text{(I.5)}$$

Diffusion of Gases: Graham's Law.

The phenomenon of diffusion may be described as the tendency for any substance to spread uniformly throughout the space available to it. Diffusion is exhibited by gases, liquids and solids, but is most rapid in gases. Gravity will effect the distribution of the gases, but this is quite negligible unless a long column of gas is under consideration, as in the earth's atmosphere.

Applying the Real Gas Law Equation

In the experimental setup, a fixed volume of gas has a mixture of carbon dioxide and air at 4 Bar pressure. It is necessary to calculate the relationship between the applied pressure of carbon dioxide to the fixed volume and the concentration of carbon dioxide.

The average molecular weight for air, mwa, is 29 g/mol and for carbon dioxide, mwc, 44 g/mol.

Molecular Mass, M = m * *n*

Pv = *n*RT

$$\frac{Pv}{RT} = n \qquad \therefore \frac{Pv}{RT} m = M$$

$$\frac{P_1 V_1}{RT_1} mwc = Mco2 \ , \qquad \frac{P_2 V_2}{RT_2} mwa = Mair \, .$$

Percentage carbon dioxide in air $= \dfrac{Mco2}{Mco2 + Mair}$ (I.6)

$$\textbf{\% Co2} = \frac{\frac{P_1 V_1}{RT} mwc}{\frac{P_1 V_1}{RT} mwc + \frac{P_2 V_2}{RT} mwa}$$

Removing constants, % Co2 $= \dfrac{P_1 \times 44}{P_1 \times 44 + P_2 \times 29}$

The percentage content of gas within a fixed volume from its measured pressure was therefore defined using the Gas Law Equations.

Appendix J – Published Paper

Development of a novel ultrasound monitoring system for container filling operations

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Abstract

Food and drink production represents the largest manufacturing sector in the UK economy and are among the largest UK exporters (£8.2bn in 1995). The industry makes essential contributions to UK wealth creation, to the quality of life within the UK and is seen to add value at each of the major stages of the supply train. Around 45,000 companies are involved in food processing and production in the UK, and 90% of these are classed as small to medium enterprises (SMEs) with less than 250 employees. Most of the SMEs possess little, if any research facilities or research expertise. Food processing represents a field of rapid development and implementation of new approaches in process technology, in particular, automation systems, quality procedures, efficiency improvements and sensor systems for on-line process monitoring and control. The current research programme has been set up to develop an ultrasound monitoring system for container filling. For fluid level measurements, most of the previous research has focused on developing ultrasound monitoring techniques with sensors positioned at the base of the container for ease of operation. The objective of the research described herein was to explore various approaches to ultrasound monitoring to assist determination of the potential benefits of mounting the sensors on the side and top of containers. Three sensing techniques have been identified and explored and two methods of signal processing have been assessed to determine the optimum approach. The central result of this work was the discovery and utilisation of the non-contact air transmission approach to ultrasound sensing. Ultrasound monitoring from the side or top of containers requires a contact approach and therefore is seen as impractical for a high-speed food processing situation.

1.0 Introduction

Food and drink production represents the largest manufacturing sector in the UK economy and are among the largest UK exporters (£8.2bn in 1995). The industry makes essential contributions to UK wealth creation, to the quality of life within the UK and is seen to add value at each of the major stages of the supply train. Around 45,000 companies are involved in food processing and production in the UK, and 90% of these are classed as small to medium enterprises (SMEs) with less than 250 employees. Most of the SMEs possess little, if any research facilities or research expertise.

The UK Technology Foresight Panel on Food and Drink has focused on scientific and technological priorities, and has stressed the need for increased investment in research and development to maintain the UK in the first division of food manufacture. Emphasis has been placed on collaborative research with Government departments working closely with each other, with the industry and academia. There is significant interest in new and innovative research in raw materials, packaging, the supply chain, retailing, safety and processing.

In recent years, world-wide interest in the environment has promoted considerable industrial attention to the elimination and disposal of waste products and hazardous materials. In addition, despite less publicity in the media, there has been a growing research base in the elimination of waste resulting from inefficient production processing [1]. In food processing, considerable waste occurs in the form of "give-aways", in overfilled containers, or through "throwaways" as non-conforming underfilled products that end up in the rubbish bin.

The current methods for measuring the liquid level in containers are often carried out downstream of the filling operation. While these methods ensure that the requirements of Trading Standards legislation are met [2], they contribute very little to improving the real-time control of the filling process. Among the measurement techniques involving the use of non-invasive sensors, ultrasound appears to attract an increasing level of interest in its application in the food industry because of its inherently safe characteristics. A number of ultrasound measurement techniques have been proposed which may form the basis for developing real-time fluid level monitoring systems and for detecting foreign objects in food containers [3,4]. These approaches include, the wall resonance method, which utilises the structural properties of the liquid container. Another approach relies on the impedance mismatches between fluid and container, commonly termed, the far wall echo principle. An air transmission approach is made possible by generating high sound levels combined with the use of high-gain, low noise amplification.

For fluid level measurements, most of the previous research has focused on developing ultrasound monitoring techniques with sensors positioned at the base of the container for ease of operation [5]. The current work explores various approaches to ultrasound monitoring to assist determination of the potential benefits of mounting the sensors on the side and top of containers.

2.0 Basic Concepts

The present study was based around the following concepts. Figure 1 shows a simple set-up of the components that make up the container filling operation.

The filling rig incorporates a fluid tank, dispensing valve, container and ultrasound transducer. Fluid substances are filled to the optimum level, as detected by the transducer, prior to transportation via the conveyor. The conveyor also illustrates the potential of feedback control, in order to regulate the filling.

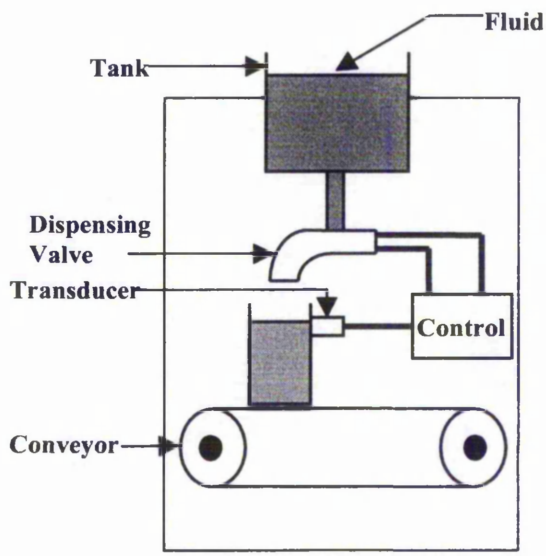


Figure 1 Sketch of fluid filling rig

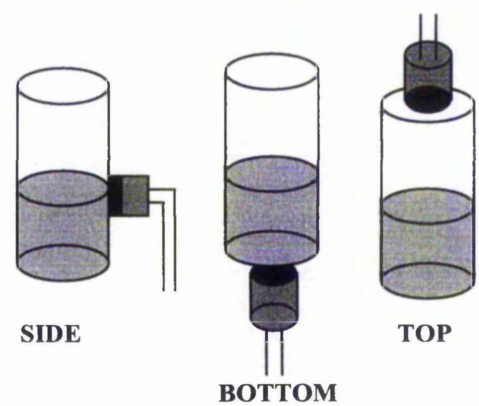
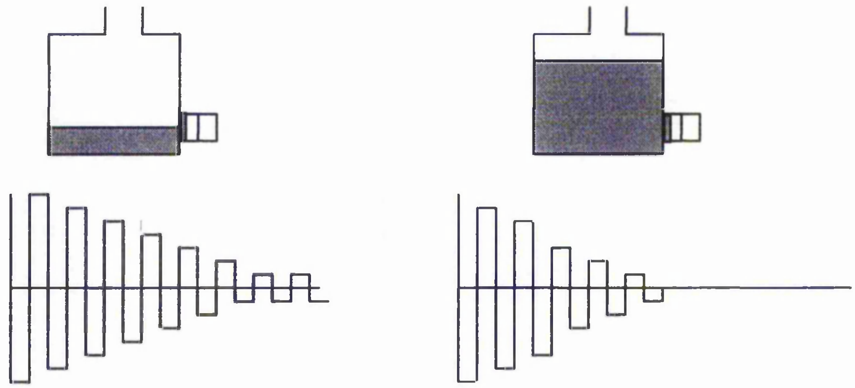


Figure 2 Sensor mounting positions

Figure 2 illustrates the various methods of sensor positioning that are possible, side bottom and top. The transducer positions require different ultrasound monitoring techniques for successful interpretation of the fluid level.

3.0 Sensing Techniques

As indicated in § 2 and illustrated in Figure 2, the positioning of the ultrasound transducers for level measurement may be at the top, bottom and side of the container. Using Ultrasound Technology this leads to different sensing techniques commonly identified as;



Tank empty: long ringing time

Tank full: short ringing time

Figure 3. Wall Resonance Principle

- Wall Resonance Approach
- Far Wall Approach
- Air Transmission Approach

3.1. Wall Resonance Approach

An ultrasound transducer is acoustically coupled to a vessel wall by means of a couplant, Figure 3, and generates a short ultrasonic pulse, which causes a local resonance in the vessel wall. When the pulse ends, the resonance dies away, whereby the ringing time depends upon whether or not the liquid is to be found immediately behind the sensor. The sensor, which now operates as a receiver, measures the ringing time and generates an empty or full signal as appropriate.

If a material is excited with ultrasound, it will reflect at a boundary, the ultrasound with some attenuation to the signal strength.

The intensity of an ultrasonic beam that is sensed by a receiving transducer is considerably less than the intensity of the initial transmission. Primary factors responsible for intensity losses can be classified as transmission loss, interference effects and beam spreading. Transmission losses include absorption, scattering and acoustic impedance effects at interfaces. Interference effects include diffraction and other effects that create wave fringes, phase shift or frequency shift.

Beam spreading involves mainly a transition from plane waves to either spherical or cylindrical waves, depending on the shape of the transducer-element face.[6]

If a material sample is small the energy dissipated will be coincident with the amount of material present. The energy loss (attenuation) will be greater if the sample size is increased.

This technique detects the presence of fluid without relying on the far reflection. Instead the attenuation of the first reflection is measured. From observing different attenuation's, it may be possible to detect the type of liquid present, determined by how well it transmits ultrasound.

Problems associated with the wall resonance approach

- Coupling critical.
- Decay is not a clean exponential.

- Clinging liquids.
- Decay quicker on metals but longer on glass and plastic.
- Signal dependant on container dimensions.

Advantages

- The effect is large, low tech.

3.2. Far Wall Echo Approach

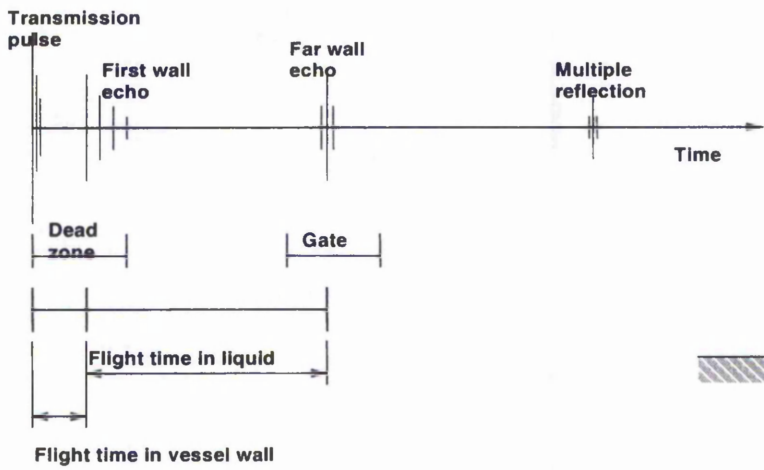


Figure 4. Far Wall Echo Principle

If a contact transducer is acoustically coupled to the side of a container and excited with a pulse, an echo will be detected a short time after denoting the first wall. If a liquid is present between the transducer and the far wall of the container an echo will be detected after a longer time interval, (dependant on the diameter or width of the container) detecting the presence of the far wall.

Problems

- Coupling.
- Alignment over long distances.
- Attenuation problems, due to;
- Bubbles.
- Turbulence (filling, mixing).

Advantages

- Clear effect.
- Relatively low tech.

3.3 Air Transmission Approach

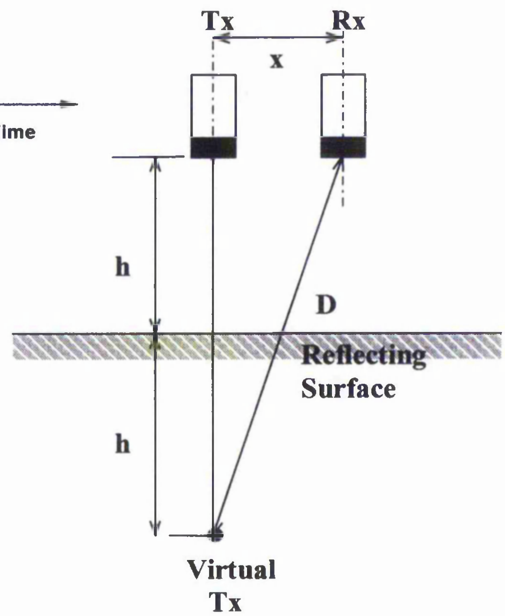


Figure 5. Air Transmission Approach

In the majority of cases Couplants are used as a sound propagation medium between the transducers and the part under inspection. Although air is a reasonably good sound carrier in the frequency region of interest, it poses a major obstacle. The acoustic impedance of air differs so much from the acoustic impedance's of transmitter and test parts, that most acoustic energy is being reflected, and only a very small fraction of that energy penetrates in and out of the part and the transducers.

One solution to overcome this problem without introducing an additional sound transmitting medium consists in generating high enough sound levels and to use high-gain, low-noise amplification.

Transducers for the generation and reception of sound are the most critical components of an air-coupled ultrasonic NDE system. In current commercial applications, thickness-mode type, piezoelectric elements are used [7]. Such transducers are constructed using a circular disk of an efficient piezoelectric material.

Transducers with high mechanical quality factors Q are best suited for operation in the tone-burst mode. In this case, the centre frequency of the driving electrical signal is chosen to correspond exactly to the thickness-mode resonance of the transducer. As a result, the mechanical amplitude of the piezoelectric material is significantly increased and the transmit and receive sensitivities can be increased by as much as 20 dB. Such transducers are necessarily narrow-band and can be operated at one frequency only.

Problems

- Temperature (changes speed of sound).
- Position dependent (dual).
- Attenuation problems.

Advantages

- No couplant required.
- New technology.
- Clear effect.

For the application of fluid level measurement a flat air-coupled transducer, backed by air and with a thin front layer with low impedance, represents the transducers used in this study. A larger beam spread is preferred at this stage of the research in an attempt to gather as much information possible from the returning echo. Focusing transducers will be looked at in greater detail in further work.

4.0 Signal Processing

The signal processing methods utilised for this study are;

- Cross-correlation.
- Threshold technique.

To manipulate the data, Matlab software and the add-on, *Signal Processing Toolbox,* were installed onto a dedicated personal computer.

Cross-correlation is useful in detecting a signal buried in noise and also in applications where delays must be measured [8]. The threshold technique is a well-documented approach for determining signal delay and more specifically for this study, ultrasound flight times.

5.0 Experimental Results

To assess the accuracy in using the two signal processing methods, Cross-correlation and Threshold processing, experiments were devised as follows.

Key Concepts

To accurately measure very small distances, < 0.01mm, a Vernier sliding block was manufactured. An aluminium block was designed to slide on a channelled flat bed. The aluminium block had a highly polished reflecting surface that could be moved toward clamped ultrasound transducers via movement of a vernier barrel that was fastened to the flat.

As the vernier barrel is rotated the highly polished aluminium block slides forward. The polished surface of the sliding block acts as a reflector for the ultrasound signals.

The speed of sound varies in different types of media. Generally, sound travels fastest in solids, slower in liquids, and slowest in gases. The temperature of air (or other gases) affects the speed of sound.

The speed of sound in air (accurate only over a relatively small range of temperatures) can be determined by:

$$\mathbf{v = (331 + 0.610t)\ m/s}$$

where t is the temperature in degrees Celsius, or

$$\mathbf{v = 20.0\ ms^{-1}\ K^{-1/2}},$$

where K is the temperature in Kelvin.

5.1 Cross-correlation processing experiment

Firstly a reference tone burst was stored as a .dat file to use as the starting point for all accuracy experiments. Secondly, the room temperature was measured using a calibrated thermocouple and meter. This data was used to obviate changes in speed of sound in air based on the above relationship.

Two ultrasound transducers, one transmitting and one receiving were positioned adjacent to each other in front of the vernier sliding block at 100mm from the reflecting surface. At 30-second intervals, five echo signals were captured and stored. The sliding block was moved a fixed small distance and five more echo signals were captured and stored. The first five echoes were cross-correlated with the second set of echoes and detailed in Table 1 Cross-correlation processing results.

Table 1. Cross-correlation processing results

	Ref. One	Ref. Two	Ref. Three	Ref. Four	Ref. Five
Echo One	18	39	38	38	29
Echo Two	18	-2	38	38	-22
Echo Three	39	39	-8	18	32
Echo Four	29	19	-22	-2	19
Echo Five	18	39	38	38	39

With the input computer A/D card set for a sampling rate of 3.125 MHz the time allocation for one data point was 1/ 3125000 = 0.32μs.

The numbers in Table 1 represent the number of data points between the first set and second set of five echoes. All the numbers in the table should be the same corresponding to the change in the reflector distance. However, the variations indicate that problems exist with the cross-correlation method of signal processing, which, on examination can be attributed to the slight changes in the envelope shape of the returning echo signal.

5.2 Threshold Processing experiments

Looking at the start of the signals in more detail.

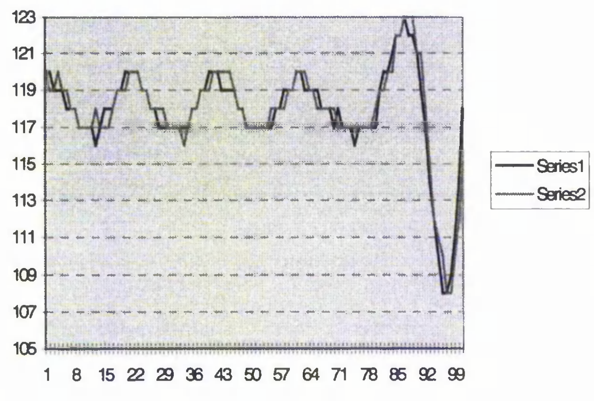


Figure 6. Amplification of start of echo

Series 1 and 2 are the returning echo signals 1 and 2 from the first set of five signals used in the previous experiment (§5.1), nearly identical as expected. The first rise of the signal breaks through the noise to 123 on the y-axis, five points above the ground signal (118) and falls to 108, ten points below ground.

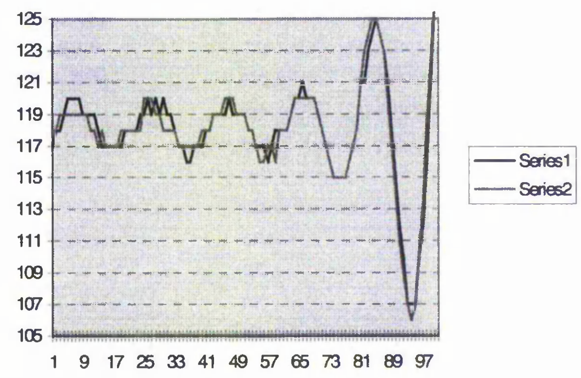


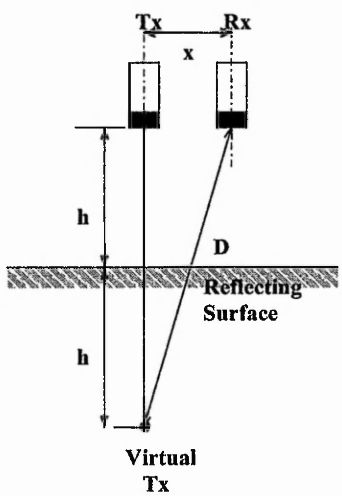
Figure 7. Amplification of start of echo

Series 1 and 2 in Figure 7, are signals 1 and 2 from the second set of returning echoes after a 2mm movement. Again they are nearly identical and the first rise breaks through the noise to 125 on the y-axis.

This first rise can be considered the start of the signal and the value assigned to it, the threshold.

Table2 Threshold Processing Results

	4	5	6
1	**1.906mm**	**1.850mm**	**1.824mm**
2	**2.522mm**	**2.466mm**	**2.522mm**
3	**2.522mm**	**2.466mm**	**2.522mm**



x = Distance between Transducers.
h = Height above reflecting surface.
D = Time of flight received by transducer.

$$x^2 + (2h)^2 = D^2$$

$$h^2 = D^2 - x^2/4$$

$$\boxed{h = \frac{\sqrt{(D^2 - x^2)}}{2}}$$

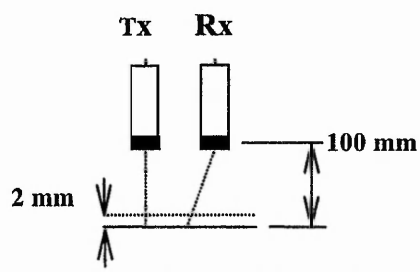
Figure 8. Air Transmission Principle

The trigonometric relationship illustrated in Figure 8 represents the true line of the ultrasound beam. The derived equation determines the true value h, height above the reflecting surface, from the time of flight received from the transducer. This relaitionship is incorporated into the dedicated Matlab processing programme.

Results.

The data from the cross-correlation experiment were used with the new Time Programme.

Threshold set at 12.



These results are shown in Table 2 (Threshold Processing Results).

The results illustrate a far more consistent spread of measured values with the errors amounting to – 0.176mm to + 0.522mm.

6.0 Conclusions

1) Three sensing techniques have been identified and explored. The wall resonance and far wall echo approach rely on contact transducers for sound transmission; strong contact between object and sensor is essential for successful operation, this creates mechanical design problems when

considering individual bottle filling operations on high speed bottling plant. The air transmission approach is the most favourable method for container filling level monitoring; not only for its non-contact characteristics but also that it is new technology and a clear signal effect.

2) The main problems identified with the air transmission approach include air temperature effects on the speed of sound and attenuation problems associated with turbulence in filling, bubbles and the carbonating environment.

3) Two methods of signal processing have been investigated, Cross-correlation and the Threshold approach and following experimental investigations it has been concluded that the Threshold approach is the most accurate method and the distances that can be measured under ideal experimental conditions are within ± 0.5 mm.

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