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THE APPLICATION OF AIR-COUPLED ULTRASONIC SYSTEMS AND SIGNAL PROCESSING TO THE INTERROGATION OF CONCRETE'

by

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Declaration

The work contained within this thesis was conducted by the author, except where stated otherwise, in the school of Engineering, University of Warwick, between the dates of April 2002 to October 2004. No part of this work has been previously submitted to the University of Warwick or any other academic institution for admission to a higher degree. Publications from this thesis are listed at the end.

SUMMARY

This thesis describes the application of ultrasound to the interrogation of concrete for the retrieval of quantitative information. In particular the use of air-coupled ultrasound is applied for the first time with recent improvement in ultrasonic technology making this possible. Broadband capacitance transducers are used in tandem with pulse compression to deliver and receive ultrasonic signals with greatly improved SNR’s. Pulse compression involves the cross correlation of a chirp signal to record accurate ultrasonic time of flights.

This metric is used to makes structural inferences about concrete and to compare contact and non-contact ultrasonic systems. This comparison reveals that concrete strength estimation from ultrasonic pulse velocity (UPV), alone is inaccurate. Other metrics such as aggregate content and humidity should also be considered. A study in to the effect of humidity on the UPV is presented and a correction factor obtained that normalises UPV around a humidity that could be considered normal to a temperate climate. Images of reinforcement bars embedded in concrete are presented using the pulse compression technique.

Time-frequency (t-f) analysis is applied to ultrasonic chirp signals. Extensive simulation is carried out and a comparison between three different methods presented. This ensures accurate tracking of the ultrasonic chirp signals, which allows for frequency scattering to be examined. T-f analysis is then applied to real ultrasonic signals and it is shown how frequencies spectrums of received chirps can be de-noised using the Hough transform. Images of embedded defects are then presented.

The Superheterodyne technique is then described and applied to concrete interrogation. Although not overly successful it is shown how energy distributions of received tone burst signals vary with time and the need for further work is discussed.
1.1 INTRODUCTION

The work that comprises this thesis utilises ultrasound in order to retrieve information about concrete. This first chapter introduces the basic properties of ultrasound and the various types of ultrasonic waves. It also discusses the reflection and absorption of ultrasound as well as the scattering processes involved in a heterogeneous material such as concrete.

Sound is the oscillation of particles throughout solid, liquid and gas media. It can be described by a frequency $f$, which has the following relation with the speed of propagation in a medium, $c$, and the wavelength of the oscillation, $\lambda$,

$$f = \frac{c}{\lambda}$$  \hspace{1cm} (1.1)

Sound is classified as ultrasound if its frequency lies in excess of 20kHz. The range of human hearing is between 20Hz and 20kHz so ultrasound is ranged above that of human hearing. Below 20Hz is known as the infrasonic range. Examples of ultrasonic response in the natural world to ultrasound can be seen in animals such as bats [1] and dolphins [2] where it is utilised for communication and navigation. The scarab beetle also responds to ultrasound as a means to avoiding predatory bats [3]. Although humans do not possess the ability to hear ultrasound we have nevertheless utilised it for a number of applications. These have included underwater object detection, (SONAR) [4], vehicle [5] and personal [6] guidance systems, medical imaging [7] and non-destructive testing of civil structures [8].
1.2 A HISTORICAL LOOK AT ULTRASOUND

Acoustics comes from the Greek word for hearing [9]. It was indeed in ancient Greece where the first forays into the understanding of sound began. Pythagorus (6th century B.C.) showed how to produce consistent musical consonant intervals [10] from his work with vibrating strings. Aristotle (4th century B.C.) described sound as a motion through a medium although his approach was philosophical and not experimental [11]. Galileo’s (1564-1642) interest in music led him onto studying vibrations and the relationship between pitch and frequency. It was Galileo who developed the field of acoustics into a science [12] [13]. Marin Mersenne furthered this work by studying the vibrations in stretched strings and provided the basis for modern acoustics [14]. In 1877, Lord Rayleigh published his famous book, the theory of sound, in which he described the fundamentals of wave propagation [15].

Developments in the inaudible sound range came in the beginning of the 19th century when Dr. William H. Wollaston studied the human range of hearing [16]. The development of piezoelectric devices by the Curie brothers in 1880 was the technological breakthrough that would allow for the generation and detection of ultrasound [17] [18]. The first area of ultrasonics to be of popular interest was that of underwater acoustics, spurred on by the sinking of the Titanic and the success of German U boats [19]. Daniel Colladon and Charles Francis Sturm performed the most important experiment with regards to underwater acoustics in 1826 [20]. They provided a value for the speed of sound in water using a bell and an underwater trumpet of 1435 ms⁻¹, which is only 3m, less than the value accepted today. In response to the Titanic sinking the Fessenden oscillator was developed which acted as a warning device for icebergs [21]. The destruction of Allied shipping highlighted the need for active systems for the production of acoustic pulses and a means of effectively analysing the returned echos. In 1918, Langevin presented his ‘sandwich’ transducer, which manipulated the piezoelectric effect to cause the transducer to vibrate in resonance with the driving frequency [22]. The German U-boat menace was thus neutralised and SONAR, (Sound Navigation and Ranging) was born.

Ultrasound was then applied to flaw and void detection in manufactured parts. Sokolov (1929) and then Muhlhauser (1931) developed the premise that material inhomogenities would have a measurable effect on the ultrasonic wave [23]. Sokolov was particularly key in developing the phase-amplitude approach of ultrasonic mapping. The development of the pulse-echo technique by Firestone (1946) allowed for one-sided material inspection [24]. The 1940’s and 50’s saw improvements in valve technology that lead to

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increased frequencies, improved instrumentation sensitivity and shortened pulse lengths. By the 1960’s ultrasound was being used as a valuable medical diagnostic [25] and systems were being commercialised.

The piezoelectric transducer has been the mainstay of the ultrasonic fraternity until recent times. Materials have been historically tested using contact transducers, which are fixed against the sample with a coupling gel to assist the transferral of energy. Recent developments in capacitance transducer technology have sparked interest in non-contact ultrasound for material inspection [26] [27]. This removes the need for expensive couplants or time consuming surface preparation. Piezoelectric transducers are deemed unsuitable in an unmodified state for air-coupled use in that the characteristic impedance of the piezoelectric element is very different to that of air. Although matching layers such as aerogel [28] and silicone rubber [29] have been employed to counteract this problem the overall bandwidth of the devices was still limited. Recent developments have investigated multiple matching layers in an attempt to match standard piezoelectric materials, (such as lead zirconate titanate (PZT) to air. This has led to some applications in air-coupled testing. The alternative capacitance design is discussed in chapter 4. These offer high sensitivities and higher bandwidths and offer material inspection applications in areas as diverse as food and civil structure testing.

1.3 BASIC PROPERTIES OF ULTRASOUND

1.3.1 The Propagation Of Ultrasound Through A Medium

Sound is produced by mechanical vibrations of particles throughout a medium. These oscillations are analogous to a mass-spring system. Once the mass is pulled and released, it will oscillate about the equilibrium position. The displacement from the mean position as a function of time is in the shape of a sine curve. Ultrasonic waves can travel in a variety of modes although they are not supported in all media. Longitudinal (or compression) waves can travel in all three phases of matter. Physically the particles are oscillating about a midpoint moving closer and further apart. The direction of oscillation is perpendicular to the propagation direction. The velocity of the longitudinal wave $C_L$ can be calculated from the elastic constants of the medium it is travelling through using:

\[
C_L = \sqrt{\frac{E}{\rho}}
\]

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Where

\[ E \] is Young's modulus of elasticity.

\[ \rho \] is the density of the medium.

\[ \sigma \] is the Poisson ratio of the material.

Shear waves exist in solids and highly viscous liquids. The direction of oscillation of the particles is perpendicular to the direction of the wave. The velocity of propagation of a shear wave can be calculated from:

\[ C_s = \sqrt{\frac{E}{2\rho(1+\sigma)}} \]  \hspace{1cm} (1.2)

Substitution of equation (1.1) into (1.2) bears the relationship between longitudinal and shear wave velocities:

\[ C_L = C_s \sqrt{\frac{2(1-\sigma)}{1-2\sigma}} \]  \hspace{1cm} (1.3)

Equation (1.3) illustrates that \( \sigma \) can only have values less than 0.5 for a solid, and that \( C_L > C_s \), and hence the shear wave always travels with a lower velocity than the longitudinal wave. A diagram showing the particle movement in longitudinal and shear waves is shown in figure 1.1.

Other wave modes can occur at boundaries between two mediums. Rayleigh waves can exist in the surface of a solid [15] [30]. The particle motion is normal to the propagation path and parallel to the surface. This means that the particles move in an elliptical fashion. Similar waves exist in the boundaries between adjacent materials, (referred to as Stonely waves [31]), and within thin layers coated onto a solid (Love waves [32] [33]). Thin plates can support Lamb waves [34] [35]. They are two type of Lamb wave known as symmetrical (stress) and asymmetric (bending) waves. This thesis does not deal with any other wave types other than the longitudinal and thus further details of any of the above can be found in the cited references.
1.3.2. The Behaviour Of Ultrasound At An Interface

A planar ultrasonic wave undergoes reflection and transmission mechanisms when it impinges on a boundary between materials of different acoustic impedances. When a wave hits such a boundary at normal incidence to the interface, the intensity of the two waves can be expressed in terms of the acoustic impedances of the initial medium of propagation, $Z_i$, and

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that of the medium \( Z_B \), which the sound will travel. The acoustic impedance for a material is defined as:

\[
Z = \rho c
\]  

(1.4)

where \( \rho \) is the density of the material. The transmission and reflection mechanisms can be quantified as coefficients expressed as the ratio of pressure in the second medium over the pressure in the first medium. The transmission coefficient is:

\[
T = \frac{Z_1 Z_2}{Z_1 + Z_2}
\]  

(1.5)

In addition, the coefficient of reflection is:

\[
R = \frac{Z_1 - Z_2}{Z_1 + Z_2}
\]  

(1.6)

![Figure 1.2: Transmission and reflection of perpendicular ultrasonic waves incident on a boundary between materials of different acoustic impedances.](image)

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When the impinging ultrasound is at an angle $\alpha_i$ to the boundary then some part of the energy will be reflected and some will be refracted. The directions of these waves are determined by Snell’s law of refraction, a law originally developed for optics, which is analogous to sound, or indeed any wave propagation phenomenon. Snell’s law is:

$$\frac{\sin \alpha_i}{\sin \alpha_r} = \frac{C_A}{C_B}$$  \hspace{1cm} (1.7)

Where $C_A$ and $C_B$ are the acoustic velocities in materials A and B respectively, $\alpha_i$ is the angle of the incident wave, and $\alpha_r$ is the angle of the transmitted wave to the normal of the boundary.

![Figure 1.3: Reflection and refraction of an incident plane wave at an interface between two media with different acoustic impedances.](image)
1.3.4 Ultrasonic Signal Loss

As ultrasound travels through a medium, it will be attenuated. This attenuation is due to two mechanisms: geometric and material attenuation [36]. Geometric attenuation is a decrease in wave amplitude as the wavefront diffuses over a wider area as it propagates away from the source. The amplitude of a Rayleigh surface wave, which propagates along a cylindrical wavefront, decreases as a function of the inverse square root of its propagation distance [37].

Material attenuation also has an effect on longitudinal wave propagation and in certain circumstances can be the dominant effect on signal amplitude. It is caused by either absorption or scattering. Absorption losses are material effects, which result from internal friction due to the energy expended at material interfaces that are not elastically bonded. They are thus losses due to the transfer of energy. They can be broadly classified as classical losses, which occur due to the conversion of kinetic energy into heat due to viscous and thermal losses. Relaxation losses, in which kinetic energy is converted into internal energy within the particles constituting the medium, also occur [38].

Scattering can be a complicated process and is defined as the phenomenon in which the direction, frequency or polarisation of the wave is changed when it encounters discontinuities in the medium. Scattering losses are dependent upon the intrinsic length scale of the scatterer, number of scatterers per volume, distribution of scatterers and the acoustic properties of scatterers in relation to the bulk material.

Absorption increases linearly with frequency whereas scattering can be divided into three distinct regions. The overriding scattering principle is that it is governed by the ratio of particle size to wavelength (\( \lambda \)). Particle size is characterised as being in the Rayleigh region when the particle diameter is less than \( \lambda/4 \) [36]. In this case, the wave has little interaction with the particle, little scattering occurs, and what does is not directional:

\[
\alpha(f) = a_1 f + a_2 D^3 f^4
\]

(1.8)

Where
- \( a_1 \) is the absorption coefficient
- \( f \) is the frequency
- \( a_2 \) is the scattering coefficient
- \( D \) is the mean diameter of the scatterers.
The second region is known as the stochastic regime. When the particle size is between \( \lambda / 2 \) and \( 6\lambda \), the particle is characterised as being in the resonant region. The wavelength is approximately the same order of magnitude as the mean scatterer diameter \( D \) with the scattering coefficient varying with the square of the frequency.

\[
\alpha(f) = b_1 f + b_2 D f^2
\]  

(1.9)

Where

- \( b_1 \) is the absorption coefficient
- \( b_2 \) is the scattering coefficient

For objects larger than \( 6\lambda \), the oscillatory behaviour damps down and the object is said to be in the diffusion region. The scattered energy seems to be highly directional in a large number of beams. The amplitude of a single beam taking on the form \( f^a \) where \( a \) is the scattering coefficient which is governed by the object shape and the feature causing the scattering.

In the evaluation of concrete, low frequency, (long wavelength) waves are utilised to keep attenuation to a minimum. If the wavelength is less than the size of the aggregate, the mismatch in acoustic impedances between the mortar and the aggregate causes the scattering of incident waves at each mortar-aggregate interface. For example, if the maximum size aggregate is 20mm in concrete with a longitudinal wave speed of 4000ms\(^{-1}\), frequencies lower than \( 4000/0.020=200\)kHz should be used to reduce scattering. The concrete will appear homogeneous at these lower frequencies. However, the disadvantage of this is that low frequency waves reduce the sensitivity of the propagating waves to smalls flaws. Thus, there is an inherent limitation in the flaw size that can be detected within concrete using longitudinal wave methods.
1.4 OUTLINE OF THE THESIS

This thesis presents advances in the use of air-coupled ultrasound for the non-contact interrogation of concrete. Air-coupled and contacting ultrasonic systems are compared and images of steel reinforcement bars embedded in concrete are obtained. The effect of humidity on the ultrasonic pulse velocity in concrete is also investigated and quantified. Different signal processing techniques are investigated with a view to information retrieval from ultrasonic signals. The superheterodyne technique is assessed with application to air-coupled concrete interrogation and time-frequency signal processing techniques are developed.

Chapter 2 gives an overview of concrete. A description of the material properties of concrete is given and its chemical composition is discussed. The hydration process is described in detail and an overview of common defects found in concrete structures is given.

Chapter 3 is a literature review of the Non-Destructive Testing (NDT) of concrete. The importance of developing adequate NDT techniques is discussed with particular relevance placed on concrete structures. Ultrasonic, RADAR, and radioactive methods are discussed, and their associated advantages and limitations. Other methods are mentioned briefly and the justification for the work contained in the thesis is presented.

Chapter 4 introduces the experimental work of the thesis. An in-depth description of the air-coupled ultrasonic system is presented with attention paid to the transducer design and the pulse compression signal processing technique that the system utilises in order to increase signal to noise ratios. A contact system (the PUNDIT) is also described and a subsequent experimental comparison is performed using a range of concrete samples. Images of steel reinforcement bars in concrete were produced using the air-coupled system.

In chapter 5 the effect on the ultrasonic wave speed of storing concrete samples, made with the same water/cement ratio, at different humidity levels is investigated. The results from the non-contact system are compared with that from a contact system. It is shown that the two systems return different results, and explanations for these interesting effects are given.

Chapter 6 describes the use of the superheterodyne technique in ultrasonic signals as applied to concrete. Simulations are provided and subsequent measurements are performed on the Ritec™ advanced measurement system (RAM-5000). Preliminary measurements show how this system can be applied to air-coupled ultrasonic evaluation of concrete.

Chapter 7 provides an introduction into time-frequency techniques, which have been applied for use with ultrasonic chirp signals. An overview of the Short-term Fourier
Transform, the Wigner-Ville distribution and Wavelet analysis is presented with simulations of each. An image processing technique is explained and applied to data retrieval from the time-frequency plane. An imaging program is then simulated that utilises the time-frequency software and the chirp signal so that different frequency bands of the same data set can imaged separately.

Chapter 8 applies time-frequency analysis to real ultrasonic signal. Accurate tracking of the chirp signal is achieved and attenuation measurements performed on a set of concrete samples. Images of defects in Perspex and concrete are presented and the problems encountered with this work explained.

The thesis concludes with suggestions for further work.
1.5 REFERENCES


Chapter 2

THE MATERIALS AND PROPERTIES OF CONCRETE

2.1 INTRODUCTION

Concrete in its simplest form is a mixture of paste and aggregates [1]. It is non-uniform and non-isotropic [2]. Aggregates are divided into two types, coarse and fine. Coarse aggregates are typically stone pebbles of diameter greater than 4.5mm. Fine aggregates are usually sand. The cement paste is made from Portland cement, water and entrapped air voids. This acts like a glue to bind together the aggregate into a rocklike mass during hydration, the chemical reaction between cement and water. This reaction process holds the key to concrete’s greatest characteristic, namely that it is plastic and malleable when freshly mixed and strong and durable when hardened [3]. Therefore concrete can be used to construct a variety of different shaped structures such as bridges, skyscrapers etc.

The careful design of the concrete mix is imperative to achieve a strong, durable concrete. Although a mixture of excess paste will be easy to place, the resulting concrete will be more likely to shrink and become uneconomical. Conversely, a mixture with not enough paste to fill the voids between the aggregates will be difficult to place and will produce a rough honeycombed surfaces and porous concrete. A well-designed concrete mix will have good workability when fresh and harden to achieve a high strength. Typically a mix contains about 15 to 20% water, 60 to 75% aggregate and 10 to 15% cement. 5 to 8% may be taken up by air if the mix hasn’t been vibrated enough pre-placement. The quality of the concrete is determined by the water to cement ratio. The water to cement ratio is the weight of the mixing water divided by the weight of the cement used. Making the water to cement ratio as low as it possibly can be, while maintaining workability produces high quality concrete.
This chapter considers the materials commonly used in the construction of concretes, the properties of concrete and the hydration reaction. It then goes on to describe the various defects that can materialise in concrete.

2.2 MATERIALS USED IN CONCRETE MIX DESIGN

2.2.1 Cement

Portland cement is essentially made from of calcium oxide and silicon dioxide. These both occur naturally in very large quantities in the form of calcareous calcium carbonate, e.g. chalk and limestone, and argillaceous clay or shale [4]. Other compounds present in cement are alumina and iron oxide. Gypsum is also added in the final grinding process to regulate the setting time. 85% of cement however consists of Lime and Silica. Portland cement is a fine grey powder with a particle size of between 2 and 80μm with a specific gravity of approximately 3.14.

There are two different processes used for the manufacture of Portland cement. These are known as dry and wet processes. The first step in both processes is the raw material acquisition. These materials are typically obtained from open face quarries, underground mines or dredging operations. The materials are then crushed to particle sizes of typically less than 75mm by hammer mills. The so-called kiln feed is then ready for the pyro-processing operations [5]. In the dry process, the raw materials are ground, mixed to the required proportions and fed to the kiln in a dry state. In the wet process, water is added to the raw mill during the process of grinding producing slurry, (approximately 65% solid). The slurry is agitated, mixed and then fed to the kiln.

The pyro-processing system converts the raw mix into clinkers, which are grey and glass hard resembling marbles. These range from 0.32 to 5.1cms in diameter. This process can be subdivided into four stages. Figure 1 shows the processes taking place in the rotary Portland cement kiln. The stages can be described as

1. Evaporation of free water from the raw materials, (material temperature increases to 250°C).
2. Dehydration; the decomposition of the clay minerals yields oxides of silicon, aluminium and iron. (250°C to 650°C).
3. Calcination; the formation of lime and carbon dioxide, (650°C to 950°C).
4. Clinkering; this is the reaction of the oxides that produces calcium silicates, calcium aluminates and calcium aluminoferrites.

![Diagram of pyro-processing in the rotary Portland cement kiln]

Figure 1: Pyro-processing for the wet process in the rotary Portland cement kiln.

The process shown in figure 1 differs from the dry process only in that the drying does not take place. Therefore the dry process requires less energy as the heat transfer to the powder is more efficient. Improvements in grinding technology and environmental concerns have seen the use of the dry process increase significantly in the last two decades [6]. Information on both the semi wet, and the semi dry process can be found in the Cembureau literature [7].

The next process step to be used regardless of pyro-processing is the clinker cooler. The clinkers are cooled from about 1100°C by ambient air that passes through the clinker and into the rotary kiln for use as combustion air. The last step involves a series of blending and grinding operations that turn clinker into Portland cement. Up to 5% of gypsum is then added to control the cement setting time. Finished Portland cement is almost always exclusively comprised of clinker and gypsum. Table 2.1 shows the main oxide components found in Portland cement.
### Table 2.1: Main components in Portland cement.

<table>
<thead>
<tr>
<th>Compound</th>
<th>Oxide composition</th>
<th>Abbreviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tricalcium silicate</td>
<td>3CaO·SiO₂</td>
<td>C₃S</td>
</tr>
<tr>
<td>Dicalcium silicate</td>
<td>2CaO·SiO₂</td>
<td>C₂S</td>
</tr>
<tr>
<td>Tricalcium aluminate</td>
<td>3CaO·Al₂O₃</td>
<td>C₃A</td>
</tr>
<tr>
<td>Tetracalcium aluminoferrite</td>
<td>4CaO·Al₂O₃·Fe₂O₃</td>
<td>C₄AF</td>
</tr>
</tbody>
</table>

#### 2.2.2 Aggregates

Aggregates are inert filling materials such as sand, gravel or crushed stone. They account for 60 to 75% of the total volume of concrete and can be divided into two distinct categories. Fine aggregate consists of sand or crushed stone particles being not more than 5mm, (although this varies internationally [7]). Coarse aggregates are any particles greater than this 5mm division, usually being gravel particles. Natural sand is acquired from pits, rivers or the sea. Crushed aggregate is quarried and crushed. Processing of aggregates takes the form of crushing, screening and washing so that the cleanliness and the sizes can be maintained.

The choice of aggregates is an important factor that can strongly influence the concrete’s freshly mixed and hardened properties [8]. Characteristics that are looked at when considering aggregate choice are:

1. Grading
2. Durability.
3. Particle shape and surface texture.
4. Abrasion and skid resistance.
5. Unit weight and voids.
6. Absorption and surface moisture.

Grading refers to the size classification of the aggregate particle size. Attention is given to this, as it is an influencing factor on the amount of aggregate used, the cement
requirements and the water requirements. The general opinion is that aggregate grading has an indirect affect on strength through water need and the workability of fresh concrete [9]. The durability of the aggregate particles refers to their resistance to the elements. Intuitively one can deduce that the more durable the aggregate the more resistant the concrete will be to corrosion.

Particle shape and surface consistency affects the workability of freshly mixed concrete. Rough textured and elongated aggregates require more water to promote workability than smooth rounded pebbles do. Aggregate choice can be a factor influencing the hardened strength of the concrete, although it is generally only significant when using lightweight aggregates such as pumice or in high strength concretes [10].

Concrete surfaces can be subjected to abrasive wear [11]. Abrasion and skid resistance of an aggregate is essential when the concrete will be used to make heavy-duty floors or pavements. Different minerals have different rates or wear so therefore harder aggregates are selected for abrasive conditions.

Unit weight refers to the volume that graded aggregate and the voids between them will occupy in concrete. The void content indicates the volume of cement required to fill the space between the coarse aggregate particles [12].

Absorption and surface moisture is important as to ensure that there is enough water available for the cement hydration [7]. Aggregates in fresh concrete will either absorb some of the water or will contribute towards it. Therefore to make sure that the required water to cement ratio is obtained it is necessary to allow for the moisture condition of the aggregate. If the aggregate is in a wet state then less mix water is required, if it is in a dry state then more is required.

2.3 THE HYDRATION REACTION

Hydration is in effect the hardening of the concrete structure. Portland cements are hydraulic cements that set and harden through a chemical reaction with water [13]. The silicates and aluminates form products of hydration referred to as hydrates, which in turn produces a hardened mass.

Nodes form on the surfaces of each of the cement particles. These grow and link up either with nodes from other cement particles or with aggregate particles. This
continuing process results in a matrix structure from which the strength and the hardening of the concrete will both develop. The approximate hydration reactions can be written as:

\[
\begin{align*}
2\text{Ca}_3\text{Si}_3\text{O}_9 + 6\text{H}_2\text{O} & \rightarrow 3\text{CaO}.2\text{SiO}_2.3\text{H}_2\text{O} + 3\text{Ca(OH)}_2 \\
2\text{Ca}_3\text{Si}_3\text{O}_9 + 4\text{H}_2\text{O} & \rightarrow 3\text{CaO}.2\text{SiO}_2.3\text{H}_2\text{O} + \text{Ca(OH)}_2
\end{align*}
\]

The two calcium silicates form the bulk of the un-hydrated cement. It is their hydration products shown in equations 2.1 and 2.2 that determine the concrete's strength and stiffness. Therefore, these reactions and reaction rates are extremely important.

The C₃S alite is the fastest to react producing tricalcium disilicate hydrate and calcium hydroxide. The C₂S reacts more slowly but produces identical products. The hydration of tricalcium aluminate is shown in equation 2.3. This is a very violent reaction, which leads to an immediate stiffening of the paste. This is the reason why gypsum is added to the cement clinker. The product of gypsum and C₃A is calcium sulfoaluminate. This reaction occurs much more slowly than the reaction of C₃A with water alone and therefore the problem of the flash set is avoided.

\[
3\text{CaO}.\text{Al}_2\text{O}_3 + 6\text{H}_2\text{O} \rightarrow 3\text{CaO}.\text{Al}_2\text{O}_3.6\text{H}_2\text{O}
\]

The hydration of cement is an exothermic reaction. The measurement of the heat released at a constant temperature is a direct indication of the rate of reaction. In typical Portland cements about 50% of the total heat is released in between 1 and 3 days, about 75% after 7 days and nearly 90% in six months.

Figure 2.2 is an illustration of the hydration of a single cement grain. It shows a cement particle when fresh and a few weeks after the onset of hydration. The physical processes involved in hydration occur at the interfaces between unhydrated cement and the mix water. Figure 2.2 shows how the unhydrated cement core becomes diminished to form what is known as the gel. This is an amorphous mass consisting mainly of calcium silicate hydrates (C-S-H). They are small irregular fibrous particles typically 0.5-2μm long with a diameter of less than 0.2μm. Throughout the matrix, large hexagonal crystals of calcium hydroxide are interspersed. The gel contains small pores in between the fibrous hydrates.

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that are approximately 0.5nm wide. As hydration continues, new products are deposited throughout these pores decreasing the gel porosity. This reduction in gel porosity marks a decrease in the diffusion of water through the cement matrix meaning that complete hydration of cement particles is not possible for grains larger than 50µm.

![Diagram of hydration process]

Figure 2.2: Illustration of the hydration of a single cement grain.

2.4 PROPERTIES OF CONCRETE

2.4.1 Strength And Transition Zone

Compressive strength appraisal is considered the most common method of determining concrete quality. It gives an overall picture of the concrete as it is directly related to the structure of the cement paste [14]. The maximum value of stress in a loading cell is usually taken as the strength [15]. The compressive strength is taken as the failure load divided by the cross sectional area resisting the load and is measured in

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N/mm². The method for the compressive strength test is included in chapter 4 section 4.5.2 as it viewed as an experimental consideration.

There are numerous factors that have an effect on the strength of concrete. To do so however concrete must be reintroduced as a three phase material, the hardened cement paste, the aggregate and what is known as the transition zone. The transition zone is the area in which the paste is directly in contact with the aggregate. The properties of the paste in these areas are substantially different to that of the bulk paste resulting in this becoming an area of weakness. It is important to discuss the transition zone in order to highlight the origin of failure in most concretes. As load increase cracking will develop in this transition zone, which propagate into the bulk paste until crack paths are formed in the concrete as shown in figure 2.3.

![Diagram of concrete transition zone with labels for aggregate, hardened cement paste, crack path, and direction of crack propagation.](image)

*Figure 2.3: Cracking pattern along the transition zone in typical concrete.*

There are two lines of thought regarding the mechanisms for the formation of these transition zones. They point to an increased water to cement ratio at the paste aggregate interface due to either:

- Cement particles not being able to pack as efficiently next to the aggregate surface as they can in the bulk paste.

*Chapter 2: The Materials and Properties of Concrete*
• Mix water separation due to the movement of aggregate particles and cement paste during mixing.

### 2.4.2 Factors Affecting Concrete Strength

The strength of the concrete is affected by a number of factors, some of which are listed below. Comments on the more important factors are written below.

- Humidity
- Temperature
- Water to cement ratio
- Air content/porosity
- Aggregate characteristics

Fresh concrete needs moisture during the curing period to hydrate and harden. It is therefore intuitive that concretes stored in water will achieve a higher strength than those cured in air [16]. It has been shown that hydration is greatly reduced when the relative humidity within the capillary pores drops below 80% [17]. Therefore for hydration to continue until the concrete reaches its highest possible strength, it has to be cured in 100% humidity or if in the field regularly sprayed with water.

Exposure to higher temperatures throughout the life of concrete will result in higher short-term strengths but lower long-term strengths [18]. Rapid initial hydration appears to form products of a poorer physical structure, possibly more porous so that portions of the matrix structure shown in figure 2.2 will remain unfulfilled [19].

At full compaction concrete strength is taken to be inversely proportional to the water-cement (w/c) ratio. This was suggested by Feret in 1896 [15], who found concrete strength to be equal to:

\[ f_c = K \left( \frac{c}{c + w + a} \right)^2 \]  

where \( f_c \) is the concrete strength, \( c, w \) and \( a \) are the volumetric proportions of cement, water and air, and \( K \) is a constant. Abrams also suggested a relationship in 1918:

---

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\[ f_c = k_1 \left( \frac{k_2^{w/c}}{k_2} \right) \] (2.5)

This is based on empirical observations and is known as Abrams' law. The constants are empirical and depend on cement type, age, curing regime, aggregate type and size. These rules mean that comparable concretes will provide lower strengths with higher water-cement ratios, higher strengths with lower w/c ratios and the same strength with identical w/c ratios. These rules only hold realistically for a range of w/c ratios between 0.4 and 1. At w/c ratios below 0.4 the concrete becomes less workable and more difficult to compact. Using admixtures such as superplasticisers can reduce this limit to approximately 0.25. At w/c ratios above 1 the paste becomes very fluid and it is difficult to achieve a homogenous, cohesive concrete without segregation.

The effect of porosity on the strength of concrete is well documented [20]. A decrease in porosity of the hardened cement paste matrix causes an increase in strength and vice versa. This is because of three reasons. Firstly the increase in pores decrease the quantity of solid material, secondly this reduces the number of chemical bonds in the paste matrix and lastly the number of stress concentrations increase. The first two reasons are self-explanatory. The third reason postulates that an increase in the air-content in the hardened cement paste matrix can be viewed as an increase in flaws. These flaws are localised areas of stress concentration, which can be much higher than the average stress.

Aggregate strength is only significant in very high strength concretes or when the relatively weaker lightweight aggregates are used [21]. There is evidence that the structure and chemistry of the transition zone can be altered by the use of different aggregates. An increase in surface roughness of the aggregate can lead to increase in strength. This is probably due to increased mechanical locking between the aggregates and the hydrates in the cement paste matrix. It has been demonstrated that concretes made with crushed rocks are typically 15% stronger than those made with uncrushed gravels [22].

2.4.3 Durability

The durability of concrete is defined as its resistance to environmental conditions. The most adverse condition is the freezing and thawing of concrete while it is in the early stages of its curing process. The freezing takes place mainly in the hardened cement paste matrix containing the air pores previously discussed. The mechanisms for concrete deterioration by the cycle of freezing and thawing have been fully researched [23] [24].

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An explanation of these is well beyond the scope of this particular work but is due primarily to the damage caused by expanding water on freezing.

Air entrainment of concrete is the most effective method for the prevention of freeze/thaw damage. Entrained air produces billions of microscopic bubbles in the cement paste. This stops the formation of water channels as they provide tiny chambers for the expansion of water when it freezes. This stops the internal pressure of the concrete from increasing to critical levels. Air entrained concrete is produced using admixtures that are added when mixing.

2.4.4 Permeability and Water tightness

The permeability of concrete is its ability to resist the penetration of water or other substances such as gases or other liquids. Water tightness is its ability to retain water. The two properties are obviously interlinked such that an increase in one will mean a decrease in the other. The permeability of concrete is controlled by the porosity within the hardened cement matrix [25] and decreases with hydration. A generally accepted rule is that the permeability is lower both for lower w/c ratios and higher strength concretes. The latter is expected as strength depends on the density of the hydrate products throughout the cement matrix.

2.5 DEFECTS IN CONCRETE STRUCTURES

Most structural concrete has steel reinforcement bars within it to compensate for the low tensile and shear strength of the concrete. They induce stresses that oppose the subsequent loading [26]. Steel has very good tensile and shear properties making it ideal for concrete reinforcement being placed at depths of 30-120mm below the surface [27]. Reinforced concrete has become a universally used building material with life expectancy of structures being 50 years at a minimum. Figure 2.4 shows a concrete beam with reinforcement, highlighting the areas under compressive and tensile load.

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The biggest problem with steel reinforcement is its vulnerability to corrosive agents. Sound concrete provides more than adequate protection but environmental actions and the process of debonding (where the concrete does not adhere sufficiently to the reinforcement) can leave the reinforcement open to corrosion [28]. The rust products occupy more volume than the original steel. This can lead to cracking or spalling of the concrete covering the steel shown in figure 25, which can in turn develop into a loss of structural integrity.
Once corrosion of concrete has commenced its consequences lead to an increase in the rate at which corrosion takes place can increase rapidly. With the increase in volume caused by the generation of rust products, the increased pressure on the surrounding concrete can lead to the defects shown already or delamination shown in figure 2.6. This makes it easier for aggressive agents such as chlorides to get to the steel [29]. The corrosion of the steel reduces its cross sectional area and thus its load carrying capability. This is particularly a problem for bridges in colder climates where salt is used for de-icing. Rainwater mixes with the corrosive salts through the porous concrete causing acceleration in corrosion.

Honeycombing is the presence of a series of air voids, to form a more porous structure. It is caused by using a poorly graded concrete mix, (a good grading of cement has at least 50% of its particles lying between 3 and 30 μm in diameter), by using aggregate particles that are too large or by insufficient vibration at time of placement leading to poor compaction. This can be especially in colder climates, as moisture will work its way deeper into the concrete during freeze-thaw [23].
Bugholes are small holes that form on the surface of the concrete, (sixes generally less than 6.5mm in diameter. Having too much sand in the mix can cause them as can excessive vibration during placement. Bugholes can increase the problems associated with durability discussed in section 2.4.3.

2.6 CONCLUSIONS

The above demonstrates that concrete is a complicated material, and that changes in strength and other properties can be caused by variations in the raw materials and subsequent processing. Inevitably there will be defects within the material, and there are many methods of fault finding and testing concrete. These range from radioactive methods to electrical methods and of course acoustical methods, on which this thesis is based. The next chapter is a review of currently methods employed on site for the non-destructive testing of concrete.
2.7 REFERENCES


Chapter 2: The Materials and Properties of Concrete


Chapter 3

THE NONDESTRUCTIVE TESTING OF CONCRETE

3.1 INTRODUCTION

The variation of the characteristics of concrete and the increased cost of infrastructure maintenance points towards the need for improved methods of non-destructive testing (NDT) with good reliability to cost ratios. The development of NDT techniques will mean that the dependability of concrete structures can be assured while maintaining the tightest possible cost control [1].

The demand for concrete within the construction industry requires high strength, high performance concrete that is workable, self levelling and sometimes retarded. The trend is that there is an increasing quality requirement for durable structures reconciled with a decrease in workmanship available on site. This leads to an increase in the likelihood of the concrete developing faults.

Corrosion of steel reinforcement within concrete structures is the biggest concern within the NDT fraternity [2]. With steel being vulnerable to attack from corrosive agents the tensile strength of the concrete can be compromised. Early detection of damage is therefore of paramount importance. Other defects such as voids and honeycombing have already been discussed in chapter 2.

The estimated number of defective bridges in the United States in 1995 stood at 600,000. This was 40% of all highway bridges in the U.S [3]. An estimate for repair costs in 1993 was $90 billion [4]. This is a huge investment that needs to be allocated accurately. Although complete failure of concrete structures is rare, their deterioration can lead to temporary or permanent closure. The implication of this is an increased economic and social cost. The cost could be greatly reduced if the defective areas of concrete were identified in their infancy. An accurate method of NDT could be used to identify structures that are in need of structural work. It could also be used to prioritise resources so that more critical structures were seen to quickly.
There has been a huge amount of work completed on the subject of NDT of concrete. There is also agreement, however, among engineers that present available methods for the determination of concrete strength are inadequate [5]. The standard method still uses empirical calculations based on wave propagation [6]. These methods have been used since the 1930's and have a significant error associated with them [7]. This chapter introduces the various means of the non-destructive testing of concrete and highlights their advantages and disadvantages.

3.2 ULTRASOUND

The standard for the quality evaluation of concrete in the last 50 years has been the ultrasonic pulse velocity method [8]. It is based on the principle that factors that increase the concrete strength usually increase the pulse velocity of the ultrasonic waves. This method is popular because it is cost effective and simple [9]. Ultrasound is used instead of audible sound because of the large sound generators that would be needed. The higher frequency of ultrasound means that smaller defects can be detected at greater resolution. However, the heterogeneous and anisotropic nature of concrete means that the ultrasonic signal is heavily attenuated. The mechanism for the ultrasonic signal loss due to interfacial reflection and attenuation is discussed previously in chapter 1. These signal losses increase with higher frequencies, which invokes a trade-off between resolution and signal retrieval. Relatively low ultrasonic frequencies of 50-200kHz are used in practical applications [10][7].

3.2.1 The Pulse Velocity Method

Ultrasonic evaluation of concrete is historically performed using the transducers in contact with the specimen [11]. Air-coupled ultrasound is currently being developed [12], see chapter 4. When the transducers are in contact with the specimen, the energy is directly coupled in to it. To ensure good contact and to decrease loss in the signal a coupling is used such as grease, honey or petroleum jelly. This layer should be as thin as possible. Repeated readings at one location are taken until a minimum transit time is recorded. This transit time is derived from the longitudinal pulse velocity ($V$), and the distance ($D$) it has travelled by the simple relationship:

$$V = \frac{D}{T}$$

(3.1)
The heterogeneous nature of concrete ensures that any interrogative ultrasonic wave will undergo numerous reflections at paste/aggregate boundaries. This coupled with attenuation and absorption serves to transform it into a complex waveform by the time it reaches the receiver. This waveform is likely to contain both longitudinal and shear waves.

The wave propagation in concrete has itself become an area of keen research [13][14]. For example EFIT, (Elastodynamic Finite Integration Technique), uses a FIT discretization of the integral form of the basic equations of linear elasticity. Spherical scatterers and attenuation are then added to the code to simulate the ultrasonic propagation though the concrete media. These models are specifically used to investigate the effect of porosity in the cement matrix to highlight its usefulness. It is worth mentioning that these modelling techniques have very little application to existing structure appraisal and could only be used to determine ultrasonic signal degradation through the different material ratios used in the concrete mix.

The standard mode for the ultrasonic testing of concrete is through transmission shown in figure 3.1. This arrangement ensures that most of the energy is transmitted and received although the wide beam width of the transducers can mean that they do not have to be directly opposite each other.

![Figure 3.1: Schematic diagram of ultrasonic testing apparatus.](image-url)
The transducers can also be arranged in a semi direct or pitch catch mode shown in figure 3.2. The semi-direct mode can be effective for onsite measurements although care has to be taken so that the transducers are not too far apart so that the signal is completely attenuated. The pitch catch method is useful for single sided access but it is the mode in which one can expect the least amount of signal back. The disadvantage of using pitch catch is that the calculation of the pulse velocity may become more complicated. The location of the transmitter if fixed while the receiver’s location is varied in increments across the concrete surface. The direct distance between the transducers is plotted against the corresponding pulse velocity. The slope of the line is the surface pulse velocity. This is a disadvantage because the pulse velocity is being measured on the surface of the concrete.

![Figure 3.2: Schematics showing semi direct and pitch catch modes (left to right).](image)

This can give a disproportionate view of the pulse velocity, (and thus strength), as the properties of the concrete at the surface can be different from that of the bulk material. There are a higher proportion of fine aggregates in the surface layer of the concrete than in the bulk of the material. This would give a lower reading for the surface pulse velocity than one that would be taken using the through transmission mode as the speed of sound in stone (coarse aggregate), is higher than that in the paste matrix. A pulse echo transducer configuration can be used but is not very common. Multiple reflections for multiple scatterers results in bad imagery.

The calculation of strength is inferred from the ultrasonic pulse velocity through empirical methods [7]. This has historically been tied in with the determination of the elastic
modulus [15] [16]. The velocity of a longitudinal wave propagating in three dimensions in a homogenous elastic media is given by [17]:

\[ C_L = \sqrt{\frac{E(1-\sigma)}{\rho(1+\sigma)(1-2\sigma)}} \]  

(3.2)

where

- $E$ is Young’s modulus of elasticity.
- $\rho$ is the density of the medium.
- $\sigma$ is the Poisson ratio of the material.

In laboratory conditions the $E/d$ ratio can be obtained by the implementation of what is known as a longitudinal resonance test [9]. The ratio is given by:

\[ \frac{E_d}{d} = (4f^2l^2)10^{-6} \]  

(3.3)

where $E_d$ is the dynamic elastic modulus, $f$ is the resonant frequency, $d$ is the width, and $l$ is the length of the test specimen. The experimental set up is shown in figure 3.3 [18]. An electronic audio-frequency oscillator is excited on the concrete specimen using a monocomponent sinusoid from a function generator. The signal is then detected using a piezo-electric crystal, amplified and then outputted to an oscilloscope. The frequency spectrum of the waveform then reveals a sharp peak at the specimen’s resonance. This is then fed into equation 3.3 to obtain the dynamic elastic modulus.

Figure 3.3: Schematic showing the experimental set-up for the determination of the dynamic elastic constants for a concrete specimen.
Thus, for a range of concrete samples, the ultrasonic pulse velocity can be plotted against the dynamic elastic modulus. The strengths of the concrete specimens are then ascertained using standard cube crushing tests and plotted against the complementary elastic modulus values. This gives the graph shown in figure 3.4, which is taken straight from reference [7].

![Graph of pulse velocity vs. elastic modulus and cube strength](image)

**Figure 3.4: Curves relating pulse velocity with static and dynamic elastic modulus and cube strength. From reference [7].**

One can see how a particular pulse velocity can be now directly related to concrete strength. It has been shown however that the error involved can be as much as 25% [19]. This value is high and therefore this technique for predicting strength can only really be used as a guide. It has been pointed out that no attempt should be made to infer compressive strengths of concretes in the field unless similar correlations have already been established on similar concretes [20]. There are plenty of reasons for this including variations incurring conditions and moisture content.

Strength and the modulus of elasticity are theoretically related [15]. This is because the atomic and molecular bonds control both. This has thrown up a number of empirical formula including [21]:

\[ E = \alpha \sqrt{s} \]  

(3.4)
where $\alpha$ is an empirically derived number and $s$ is the concrete strength. Under laboratory conditions empirical formulas such as these are reported to have a 20% error associated with them [22]. This is a large error that will increase in field conditions. This error comes from the assumption that equation 3.2 is derived for a homogenous, linearly elastic material. Concrete however is a heterogeneous, viscoelastic material and from the standpoint of strength prediction equation 3.2 has to be viewed as an oversimplification.

### 3.2.2 Factors Affecting The Ultrasonic Pulse Velocity (UPV)

The amount of aggregate within a concrete specimen will affect the UPV. This has been reported by the author [23], following on from previous work carried out on the pulse velocities in concretes with different aggregate contents [24]. The higher the aggregate content, the higher the UPV. This is intuitive as the speed of sound through the aggregate stones is higher than that in the cement paste matrix. The UPV through cement paste is approximately 3,300 ms$^{-1}$ after a 28-day cure whilst the velocity through concrete samples has been found to be from between 3,900 to 4,500 ms$^{-1}$ [20].

Water content has a significant effect on the ultrasonic propagation in concrete [25][26]. It has been demonstrated that an increase in water content will have an associated increase in UPV. This is also intuitive as the speed of sound through water (1480 ms$^{-1}$) is faster than that in air (343 ms$^{-1}$).

The UPV through concrete samples varies with age [24][20]. The UPV increases very quickly with age and flattens out after approximately 10 days. It is a very similar relationship to that of strength versus age [8]. The quality control of fresh concrete by continuous monitoring with ultrasound has been of recent interest reiterating the velocity increase mentioned above [27][28].

### 3.2.3 Advantages and Limitations

Ultrasonic appraisal of concrete structures can be carried out in both the laboratory and onsite. It is also the only available method for delineating both surface and internal cracks [18]. A limitation of using conventional ultrasound is that it requires the transducers to be effectively coupled to the area of concrete under test. Couplants such as petroleum jelly have to be employed to temporarily adhere the transducers to the concrete surface. This makes the
process slow and laborious, especially if a large area needs to be examined. It can also be difficult to achieve efficient coupling on uneven surfaces.

The signal loss associated with the ultrasonic propagation in concrete is another limiting factor. The physical process of scattering described in chapter 1 means that the ultrasonic signal can be un-intelligible. This makes it difficult to identify defects among the noise. There can also be confusion between the arrival of surface and longitudinal waves. Strength estimation using ultrasound can give a good indication of structural integrity. The large amount of variables affects the relationship between strength and the pulse velocity resulting in the 25% error discussed previously. Strength estimation therefore needs to be carried out after correlation testing has been performed.

3.3 GROUND PENETRATING RADAR

Radar technology was heavily developed during World War 2 due to its military application [29]. Subsurface applications were subsequently applied to ice location in permafrost, profiling river and lakebeds and finding sewer lines and buried cables [30] [31] [32]. Recent attention has been given to civil engineering applications such as finding locations of steel reinforcement bars and voids and also assessing the deterioration of concrete [33] [34].

Ground Penetrating Radar (GPR) is used to examine the reflections of short pulses from interfaces between materials with different dielectric constants [2]. These reflections come from the defects previously discussed such as steel reinforcement bars and voids. Frequencies of around 1GHz are typically employed and have been used to examine concretes with thickness of around 500mm [35]. Lower frequency GPR has been used to examine thicker specimens but this is complemented with a decrease in resolution.

3.3.1 Operation and Procedure

The use of GPR allows for one-sided evaluation of specimens as illustrated in figure 3.5. A transducer incorporating transmitting and receiving antenna is scanned manually across the specimen’s surface. The electromagnetic beam of radiation is reflected from interfaces between differing materials and are captured and analysed. Results are presented in
the form of a trace in which received signals are depicted with reference to their positions on the surface.

![Diagram of antenna and reflections](image)

Figure 3.5: Propagation of electromagnetic waves though the different dielectric boundaries of a concrete sample (assuming homogeneity).

The trace is usually presented in a grey scale format [36]. Grey scale intensity represents the amplitude of the reflected signal components. Areas in which defects are present can be located as the return time of the reflected signal will be at its' smallest when the antenna is directly above the feature. For more detailed analysis of these areas individual reflected waveforms could be utilised.

Figure 3.6 shows a schematic for a typical short-pulsed radar system. The transmitter sends a single pulse that is followed by a dead time in which the reflected signals are returned to the receiver. The system is comprised of a monostatic antenna, an oscilloscope and a power converter for DC operation. The control unit generates a trigger pulse signal at a rate of 50kHz [29]. Each trigger pulse causes a solid-state impulse generator in the in the antenna to produce a pulse with a very fast rise time. This is then electrically discharged as a short burst of electromagnetic energy. The pulse then radiates into the concrete. The receiver circuit reconstructs the reflected pulses at an expanded time scale using time domain sampling. This
signal replica is then amplified and then fed to the oscilloscope or a grey scale graphic recorder.

Figure 3.6: Schematic showing the experimental set-up for a typical short pulse radar system.

3.3.2 Theory

GPR is the electromagnetic analogy of the ultrasonic pulse velocity method. The theory behind the transmission, reception and image generation in GPR is complex. A good overview is provided by Bungey and Millard [37]. The processes involved in the electromagnetic radiation propagation through materials of different dielectric constants govern GPR. As with ultrasound, an electromagnetic wave will be reflected and refracted at an interface between two materials. The electromagnetic impedance of a material is given by

$$Z_0 = \sqrt{\frac{\mu_0}{\varepsilon_0 \varepsilon_r}}$$  \hspace{1cm} (3.5)

where $\mu_0$ is the magnetic permeability of free space, $\varepsilon_0$ is the dielectric permittivity of free space and $\varepsilon_r$ is the relative dielectric permittivity of the medium given by

$$\varepsilon_r = \frac{\varepsilon}{\varepsilon_0}$$  \hspace{1cm} (3.6)

The equation for the reflection coefficient between two media with impedances $z_1$ and $z_2$ is in the same form as that used with ultrasound, shown previously in section 1., but repeated here for completeness.

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\[ R = \frac{Z_1 - Z_2}{Z_1 + Z_2} \]  

(3.7)

This indicates that if the second material had a larger dielectric constant than material 1 then \( R \) would be negative. The absolute value is the amplitude of the reflected energy and the sign represents its polarity. The propagation velocity for low loss materials such as concrete is given by

\[ v = \frac{c}{\sqrt{\varepsilon, m_r}} \]  

(3.8)

where \( c \) is the velocity of light in vacuo and \( m_r \) is the relative magnetic permeability. The propagation velocity for electromagnetic radiation is between \( 0.87 \times 10^8 \) and \( 1.22 \times 10^8 \) ms\(^{-1}\). This depends on the moisture content of the material [37]. This gives a wavelength of between 87 and 122 mm for a GPR system operating at 1 GHz.

### 3.3.3 Advantages and Limitations

GPR is quick, can give good penetration and can give a good image of the internal structures. This includes images of steel reinforcement bars and voids. GPR can give good depth estimation of defects and can provide information on bonding between asphalt and concrete. The non-contact nature of the antenna ensures traffic disruption can be kept to a minimum.

GPR however has been reported to give faulty readings. Readings have been taken on sound concrete specimens that gave an indication of delamination [38]. GPR also failed to locate delaminations under 0.3m wide. This is thought to be because the strong reflections from the rebars mask reflections from the delaminations. This inaccuracy is partly due to the limitation of current antenna in that they can not resolve consecutive reflections arriving at time intervals that are shorter than the it’s characteristic pulse width.

It is also important to recognise that GPR is a comparative technique, which requires the user to have expert knowledge of interpretation of the signal patterns returned. To quantify this technique detailed knowledge of the electrical properties of the concrete specimen, which would mean invasive drilling out of a test block for analysis [35]. There is also an
aforementioned trade off between resolution and penetration. However even at higher frequency GPR (>1GHz), the resolution is not high enough to determine if cracking or minor voids have occurred [39].

3.4 RADIOACTIVE/NUCLEAR METHODS

X-rays and gamma-rays are classes of electromagnetic radiation with extremely short wavelengths, ranging from $10^{-10}$ to $10^{-14}$ cm for X rays and $10^{-13}$ to $10^{-16}$ cm for gamma rays (in vacuo) [40]. The radiation energy of waves is expressed in the electron volt, eV, and intuitively the greater the energy the greater the penetration power. Energy levels for the use of radiography in structural appraisal are typically in the range of 100keV to several MeV [2]. There will be a level of absorption associated with the concrete under examination. This will depend on the specimen’s thickness and density as well as the characteristics of the radiation [41].

The radiographic methods of NDT can be split into three groups, (1) radiometry, (2) radiography and (3) neutron-gamma techniques. In radiometry a radiation source and a detector and placed either on opposite or on the same side of a concrete specimen. The radiation passes from the source through the concrete to the detector where it produces a series of electrical pulses. These pulses are counted and the resulting count rate is a measure of the physical characteristics of the sample, i.e. density. In radiography a radiation source and photographic film are placed on opposite sides of the specimen under test. After exposure a photographic image of the specimen’s interior is produced. Neutron-gamma techniques are rarely used for NDT purposes. The concrete sample is irradiated with neutrons, and then a second type of radiation, gamma-rays is emitted upon interaction with the atoms and neutrons, and detected. This produces a series of counts, which provides a measure of physical characteristics.

A detailed revision of these techniques is well beyond the scope of this review. To this end a brief description of the physical processes in radiography is presented. The description of the radiation propagation through the specimen is transferable between the three subject areas. Detailed literature on the subject can be found in [42][43].

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3.4.1 Radiography

Figure 3.6 shows a typical radiography system comprising of an X-ray source, the object being examined and the X-ray sensitive film. The radiation source is an X-ray tube [40]. When a high voltage is applied to the tube, X-rays are emitted with energies proportional to the voltage. Once generated the X-rays are collimated, with the resulting beam then directed against the concrete sample.

![Radiography System Diagram](image)

*Figure 3.7: Schematic showing the typical experimental set-up for radiography NDT system.*

The intensity $I_z$ of this beam after passing through the concrete specimen is given by

$$I_z = I_0 e^{-\mu Z} \quad (3.9)$$

where $I_0$ is the intensity of the initial beam, $Z$ is the thickness of the specimen and $\mu$ is the linear absorption coefficient. Scattering processes that can be categorised into three main types govern the signal attenuation illustrated by the above equation. These are Rayleigh, Photoelectric absorption and Crompton scattering. Rayleigh scattering has been discussed in...
chapter 1. The mean diameter of the scatterers is very small compared to the wavelength $\lambda$ of the radiation beam and has a descriptive coefficient that is proportional to the fourth power of frequency [44]. Crompton scattering is when an X-ray loses energy and is deflected into a new direction by a free electron [40]. It is the dominant process that X-rays undergo in the energy range from 60keV to 15 MeV and increases with material density. Photoelectric absorption [40] is the absorption of an X-ray into an atom, which then emits a previously bound electron. This process dominates below 60keV and is dependant upon the chemical composition of the sample. It increases as the fourth power of the atomic number of the elements present.

The thickness of the concrete will have an obvious effect on the attenuation. The thickness of a typical concrete that will reduce the intensity of a radiation beam by $\frac{1}{2}$ is 48mm for Ir$^{192}$, 53mm for Cs$^{137}$ and 69mm for Co$^{60}$ [40]. This effect is multiplicative. At a certain thickness the beam intensity is reduced to a level whereby clear images cannot be resolved and image formation times may be impractically long.

The radiation beam, having traversed the concrete sample, is then collected and turned into an image on photographic film. Steel, used for reinforcement, attenuates X-rays much more than the bulk concrete material does, while attenuation air is less. These differences in attenuation give rise to a photographic image of the internal structure of the concrete specimen.

3.4.2 Advantages and Limitations

Radioactive methods offer a tool for visually assessing the internal microstructure of concrete and are superficially great for quality inspection. These techniques are fast and can give high quality pictures of structural interiors by generating radiation at the optimal level for a given specimen thickness. These can be of concretes up to 3 ft in thickness [40]. These methods can be used for assessing cracks and steel reinforcement [45] [40].

To analyse concrete structures of more than 1m in width, high radiation energies are required [2]. This provides a hazard as the general public usually frequently access the structures under test. Therefore it is recommended that restrictive access should be enforced. Radiography systems are costly to emplace and demand access to both sides of the structure. The personnel will require retraining and have to be licensed, as the systems are relatively complex and hazardous. The images returned from radiography are two-dimensional which means that due care has to be taken to the orientation of the system. Corroded tendons may be
located behind sound tendons. In short the high voltages and radiation levels means that radioactive methods role in the NDT of structures will be not be widely exploited.

3.5 OTHER METHODS AND NEED FOR FURTHER RESEARCH

There are many additional methods available for the NDT of concrete structures. These include magnetic and electrical techniques such Electrical Time Domain Reflectrometry [2] and conductivity [41] [46]. Inductive sensors have been developed with the possibility of detecting and imaging steel reinforcement bars [47][48]. Surface waves methods have also been investigated to assess structural integrity by way of estimating concrete strength [49][50]. Combined methods of NDT using ultrasound with laser vibrometer detection have also been researched as a means of imaging defects although this remains a laboratory based technique [51].

It is correct to point out that there is still no definitive NDT technique for the appraisal of concrete structures and its associated strength estimation [41] [20]. It is an accepted point that impressive results have been obtained from laboratory-based experiments without any regard for the complexities involved in on site applications [2]. Efforts are currently underway to combine NDT techniques such as radar and ultrasound [52] but this is very much work in progress.

The development of broadband air-coupled ultrasonic transducers has removed the need for contact in material inspection [53]. A Preliminary investigation revealed that diagnostics could be performed through concrete with a thickness of 75 mm [54]. With no accepted method for the strength estimation of concrete available further research into this technique seemed logical. This thesis thus investigates this approach. As will be seen, the approach gives some interesting results, which seem to give a greater insight into the changes that occur within concrete, especially strength.
3.6 REFERENCES


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Chapter 4

ULTRASONIC NON-DESTRUCTIVE TESTING OF CONCRETE

4.1 INTRODUCTION

Various methods for the NDT of concrete have been reviewed in chapter 3. This Chapter considers the application of ultrasound to the interrogation of concrete, with a view to the development of a non-contacting instrument. The system utilizes transducers with a capacitive design in order to deliver broadband ultrasonic pulses in air. This is used in conjunction with an NCA1000 unit, which generates chirped ultrasonic broadband pulses. The results are then compared to a second system using the PUNDIT (Portable Ultrasonic Non-Destructive Indicating Tester) [1]. The PUNDIT is the industry standard for ultrasonic NDT [2] and differs from the air-coupled system as it uses piezoelectric transducers that are held in contact with the material under evaluation.

The work presented in this Chapter deals firstly with the application of the air-coupled system to concrete to show that it is possible to transmit a signal through laboratory specimens of concrete. A comparison between the two systems was then carried out over a range of specifically mixed concretes. It will be demonstrated that there are potential differences in the results from the two techniques on complicated materials such as concrete. In addition, air-coupled imaging of concrete was carried out, with a view to determining the location of steel reinforcement bar. This work has been the subject of several publications [3-5].

4.2 THE AIR-COUPLED EXPERIMENTAL SETUP

4.2.1 Capacitive Transducers

Ultrasonic analysis has been historically carried out using piezoelectric transducers that are placed in contact with the material under investigation [6-8]. Recent work in the
development of alternative air-coupled transducers has received a lot of attention because of the excellent bandwidths that can be achieved [9]. These are designed using the capacitance or electrostatic principle. The construction of these transducers consist of a thin flexible polymer membrane (~10 μm), metallised on one side and fixed with its insulating surface against a ridged contoured conducting backplate, as illustrated in figure 4.1 [10]. A DC biasing voltage is applied between the backplate and the membrane during operation. This electrostatically attracts it to the backplate, trapping air pockets. When excited with a voltage pulse, the capacitance of the device will change, causing the membrane to vibrate and hence generating ultrasound. The pulsed voltages are often superimposed onto a DC bias voltage to improve bandwidth. The relatively low acoustic impedance between the air/membrane interfaces means that the capacitive design is well suited for the transduction of ultrasound into air. The design of the backplate surface topology has been investigated by several authors, and it has been found that this can affect the response [11-13]. Some early designs had a metallic grooved design [11,12], whereas others used micromachined silicon [13]. The careful control of these features leads to improvements in acoustic properties. As a receiver, impinging ultrasonic waves cause the membrane to deflect, changing the capacitance of the device. Due to the applied DC bias voltage the change in capacitance can be thought of as a redistribution of charge on and off the membrane and backplate, and can be amplified with a charge amplifier.

Figure 4.1: Schematic of a micro machined capacitance back plate transducer.
The polished backplate used in the present design was made of (110) silicon wafer that was coated in silicon nitride and silicon dioxide [14]. Photolithographic techniques were used to produce small patterns of holes with a depth of 40μm and a distance of 80μm between the centres of the holes. These holes help to trap air beneath the membrane reducing its rigidity and thus producing a wider bandwidth and enhanced sensitivities [13]. The silicon nitrate and silicon dioxide layers are then removed using phosphoric and hydrofluoric acid respectively [15]. Finally 1000Å of gold was coated on to the undulating surface to form a conducting layer.

Assuming a basic parallel plate capacitor model, with air as the dielectric, the capacitance, \( C \), of the device would be given by the following:

\[
C = \frac{A\varepsilon_0}{x}
\]  
(4.1)

where, \( A \) is the area of one of the plates, \( \varepsilon_0 \) is the relative permittivity of free space, and \( x \) is the plate separation. Changes in the plate separation, caused in our case by movement of the membrane, when the device is operated as a receiver, will cause a change in the capacitance of the device. This is given by the differentiation of equation (4.1) to give:

\[
\Delta C = -\frac{A\varepsilon}{x^2}\Delta x
\]  
(4.2)

where \( \Delta C \) and \( \Delta x \) are the changes in capacitance and plate separation respectively. Assuming a constant biasing voltage, \( V_p \), the observed change in charge, \( \Delta Q \), on the plates, due to this change in capacitance, \( \Delta C \), is given by:

\[
\Delta Q = \Delta C.V_p = -\frac{A\varepsilon_0}{x^2}\Delta x V_p
\]  
(4.3)

Thus the change in charge, and therefore the signal from the transducer, is proportional to the applied bias voltage and the plate area. There is also an inverse proportional relationship to the square of the initial plate separation. Figure 2.1 illustrates that these transducers will be a good approximation to ideal parallel plate capacitors, as long as the surface features are small compared to the overall dimensions. However, with surface
topography where the air gap behind the membrane can vary in proportional terms across the backplate, the local response may also vary. This is used in the silicon backplate devices deliberately. The peak frequency response increases with a decrease in the air gap. Hence, over regions of the device where the membrane is attracted to the polished silicon flat surface by the DC bias, the peak response is higher than over the cylindrical holes (where the air gap is larger). This effectively increases the bandwidth of the device, which is needed in our case. Thus, while these equations are indicative of the physical relationships between the variables discussed, the variables contained in them may have different values across the device.

4.2.2 The Pulse Compression Technique

Discussion in Chapter 3 conjectured that the signal loss attributed to both air-coupled and contact ultrasound could be improved by using a high power tone-burst signal. Gated power amplifiers can be used to deliver high powers and the frequency of operation can be varied when using a broad bandwidth transducer. For piezoelectric transducers, tone burst excitation can lead to considerable improvements as the frequency of operation can be tuned to the material under interrogation's through-thickness resonance leading to a vast improvement in the signal level. Indeed, the use of a tone-burst in conjunction with a superheterodyne technique is discussed later in this thesis. However, the use of tone-burst excitation does have its disadvantages. First the transducer type limits the voltage excitation level. In the case of the capacitance transducers the voltage level must be restricted in order to avoid dielectric breakdown the thin polymer membranes. Second for maximum SNR's through a sample the exact frequency of excitation must match its through thickness resonance. This is a problem when scanning over a sample with an undulating topology. The main disadvantage when using a tone burst system for defect detection is that the time resolution can be poor [16]. This can lead to scenarios where defects are difficult to resolve because of multiple ultrasonic reflections overlapping in time. Cross-correlation can improve the accuracy of the time of flight measurements.

The wide bandwidth of the capacitance transducers allows for the use of a swept frequency signal instead of a single transient. This is a high power, broad bandwidth signal that can be post processed upon reception to obtain excellent time resolution. This
attribute is the basis for the pulse compression technique [17,18]. Although a tone burst signal tuned to the through-thickness resonance is still more likely to return a greater signal for air-coupled ultrasound, the advantage of using a broadband ‘chirp’ is that a more comprehensive spectral response can be obtained instantly. This eliminates the need for frequency scanning [19].

Pulse compression has the capacity to increase time of flight accuracy and retrieve small signals from below the noise floor as will be demonstrated by simulation in the next section. It has previously been used to improve resolution in medical [20] and radar applications [21]. The ultrasonic source is driven by a chirp signal of predefined parameters. The chirp is an elongated waveform with the duration, rate of frequency change and bandwidth defining the chirp characteristics. The chirp pulse is transmitted and received across the air gap and whatever material is under evaluation. The received signal is then cross-correlated with the input signal to give a single peak.

4.2.3 Simulation of the Pulse Compression Technique

The chirp signal is a cosine function described by:

\[ C(t) = \sin \left( \omega_0 t + \frac{\pi B t^2}{T} \right) \quad 0 \leq t \leq T \]  (4.4)

where \( \omega_0 \) is the starting angular frequency, \( B \) is the bandwidth and \( T \) is the duration of the pulse. The following simulation was completed using Matlab™.

Figure 4.2(a) shows the chirp signal plotted from equation (4.4) with its associated frequency spectrum in 4.2(b). The duration of the pulse was set to 200\( \mu \)s and the starting frequency was set to 150kHz \( f_c = \omega_0 / 2\pi \), and the bandwidth \( (B) \) to 500kHz. The FFT shows that the signal has a wide bandwidth and also some ripples on the band edges. These are Fresnel ripples [22] and are caused by the instantaneous jumps from one frequency to another with a relatively large difference in amplitude. It was found that the time-bandwidth product had to be increased to reduce these ripples. The problem with this is that the bandwidth is extended. In figure 4.2(b) the upper cut off frequency has been extended from 650kHz to approximately 750kHz. Thus using this chirp would give an inaccurate depiction of the frequencies involved. This problem can be avoided however
by the application of a modulation function such as a bandpass Hanning or Gaussian filter to the time waveform.

\[ C(t) = H(T) \sin \left( \omega_s t + \frac{\pi B t^2}{T} \right) \quad 0 \leq t \leq T \]  \hspace{1cm} (4.5)

where \( H(t) \) is the Hanning window function given by

\[ H(t) = \frac{1}{2} \left[ 1 - \cos \left( \frac{2\pi t}{T} \right) \right] \]  \hspace{1cm} (4.6)

The Hanning window modulated chirp signal is shown in figure 4.3(a).

Figure 4.2: (a) Simulated broadband chirp signal of duration 200\( \mu \)s, (b) Frequency spectrum of the broadband chirp signal.

Figure 4.3: (a) Simulated broadband chirp signal with duration of 200\( \mu \)s after a Hanning window is applied, (b) Frequency spectrum of the signal in (a).

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This is the distinctive bell shaped chirp. This shape is important as it ensures experimental accuracy. Figure 4.3(b) shows the corresponding frequency spectrum, from which it can be noted that the Fresnel ripples have been removed. The use of the Hanning amplitude weightings to remove side lobes is an accepted method in the signal processing of chirps [23]. It shows that the originally set bandwidth of the chirp has been maintained at 150kHz and 650kHz with the signal being centred on 400kHz. The removal of the edge ripples dictates that the Hanning chirp is used in most applications for pulse compression.

The strength of the pulse compression system is in its retrieval of small signals. The cross correlation can give accurate time of flight determination from noisy signals. Figure 4.4(a) shows a chirp signal mixed into random noise of 1.5 times the chirp signal amplitude. In order to produce the compressed pulse signal $P(t)$ the received waveform $C_T(t)$ is band-pass filtered above and below the bandwidth of the chirp. This produces figure 4.4(b). The noise levels outside the range of the chirp’s bandwidth have now been removed. The bell shape of the chirp is now more visible. This waveform is then cross-correlated with the reference signal $C(t)$. This can be referred to as matched filtering [24] and is described by:

$$P(t) = C(t) * [C_T(t)]$$

(4.7)

The compressed pulse output, $P(t)$ is the result of cross correlating the received signal $C_T(t)$ with the original reference signal, $C(t)$. The cross correlated result is shown in figure 4.4(c). The peak represents the time taken for the chirp pulse to travel from the ultrasonic transmitter to receiver arriving at 100μs. The SNR has improved greatly but the main attribute of the technique is that the time of flight can is presented as a single definite peak. This greatly improves the accuracy of this metric. The width of the compressed pulse peak can be reduced to give greater time resolution by increasing the bandwidth of the generated chirp. Increasing the duration of the chirp for the same bandwidth will generate a greater cross-correlated peak amplitude. Maximisation of both duration and bandwidth is therefore advantageous. Note the point of interest that to both obtain better time resolution, and to improve SNRs, the length in time of the pulse is increased. This will inevitably mean that such pulses overlap in the time domain in some experiments. However, the cross correlation can separate these successfully after processing, provided the amplitudes are of the same order of magnitude.
The amplitude of the compressed pulse is related to that of the received chirp signal, although most data in this thesis deals with travel time, and hence it is only the location of the peak along the time axis that is of interest in these cases. Note that the exact shape of the pulse will be modified as the chirp travels through concrete. The attenuative, heterogeneous nature of concrete has a low pass filter effect on the interrogative ultrasound depending on its path [24]. The effect of the scatterers on ultrasound was discussed in chapter 2. Due to the randomness of the concrete matrix any correlation of compressed pulse shapes with concrete samples would give a lot of information concerning the internal structure. However, this would be a laborious task. A better method for determining the received frequency components comes under the
general heading of time-frequency analysis, and this approach is discussed in more detail in Chapters 7 and 8.

**4.2.4 Experimental set-up for air-coupled testing**

The experimental set-up is shown in Figure 4.5. The nucleus of the system is the NCA1000 pulser/receiver unit from VN Instruments Limited. This contained a digital signal processor that generates tuned ultrasonic Hanning ‘chirp’ pulses that the capacitance transducers can accurately mimic.

![Figure 4.5: Schematic of the air-coupled ultrasonic testing apparatus.](image)

The pulse generator contained a 200W broadband variable-gain power amplifier and the receiver contained a variable-gain low-noise amplifier (maximum gain of 90Db), followed by an A/D converter. Upon signal reception its embedded software within the digital signal processor performed online pulse compression processing. The output of the NCA1000 was then superimposed upon a +200V dc bias voltage. A Cooknell charge amplifier model CA6/C, which had a gain of 250-mV pC-1, amplified the output from the receiver transducer before being fed into the NCA1000 input. The transducers used are the capacitive type previously explained.

Figure 4.6 show waveforms obtained from the described system measured over an air gap (without sample). Figure 4.6(a) is an example of a typical unfiltered Hanning-modulated broadband chirp pulse that is transmitted across the air gap. It has a chirp centre frequency of 450 kHz, a bandwidth of 300 kHz with a pulse duration of 200 μs. Fig.
4.6(b) is the time waveform after application of band pass filtering. This is utilised to reduce low frequency oscillations that occur either as a result of small traverse dimensions, (allowing a low frequency airwave to bypass the sample), or as a consequence of using a thin plate like sample in which low frequency flexural modes can be stimulated. Fig. 4.6(c) is the FFT of the filtered time waveform. This waveform depicts the wideband frequency response of the capacitance transducer air-coupled system, but limited by the 300 kHz bandwidth of the applied chirp. Finally the waveform of fig. 4.6(d) shows the pulse compression output from the NCA1000 pulser/receiver unit. The single peak is the result of the cross-correlation discussed in section 4.2.2.

![Figure 4.6: Ultrasonic signals obtained across an air gap using pulse compression: (a) unfiltered time waveform, (b) filtered time waveform, (c) FFT spectrum of the filtered waveform, (d) compressed pulse output.](image-url)
4.3 CONTACT EXPERIMENTAL SETUP FOR CONCRETE TESTING USING THE PUNDIT

The PUNDIT is the industry standard for the on site testing of concrete structures, and hence has been used in this work as a device against which the performance of the air-coupled system can be compared. Derived from the initial letters of the full title of "Portable Ultrasonic Non-destructive Digital Indicating Tester" it was designed to be fully portable and simple to operate. It generates low frequency ultrasonic pulses and measures the time taken for them to pass from one transducer to the other. The transit time is displayed in the form of three digits on the user interface shown in figure 4.7.

![Figure 4.7: The PUNDIT](image)

The transducers supplied with the PUNDIT [1] are resonant piezoelectric devices with a centre frequency of 54 kHz. They are driven with a large transient or delta function pulse, shown in figure 4.9, which causes the transmitter to vibrate at the quoted resonant centre frequency. The PUNDIT is a contact measurement device. This means that there has to be physical contact between the sample under test and the transducers. Depending on the surface roughness of the sample, the use of extensive surface preparation may be required. For use with concrete specimens the use of a coupling gel with any ultrasonic contact measurement system is assumed. The system is used in the direct transmission mode illustrated in figure 4.8. The Direct transmission arrangement is the most efficient
since the longitudinal pulses leaving the transmitter are propagated most strongly in the plane, which is normal to the transmitter face.

![Diagram](image)

*Figure 4.8: Schematic for the use of the PUNDIT showing the direct transmission configuration.*

The Pundit has an incorporated zero control since the zero is likely to change when different transducers and lengths of cable are used. This control is used in conjunction with a standard copper reference bar supplied with the instrument. This has an accurately known acoustic transmission time of 26\(\mu\)s. Figure 4.10(a) shows the received voltage output from the PUNDIT through the reference bar. The time of flight is taken as the point at which the voltage begins to change. One can see that the waveform is very oscillatory, as multiple ultrasonic reflections exist within the material that decay with time. Figure 4.10(b) shows the frequency spectrum associated with the PUNDIT’s output. It can be seen that the system’s response is quite narrowband centring on approximately 50 kHz.

![Graph](image)

*Figure 4.9: Transient drive signal for the PUNDIT.*

*Chapter 4: Ultrasonic Non-Destructive Testing Of Concrete*
4.4 CALIBRATION OF THE TWO SYSTEMS USING HOMOGENEOUS BLOCKS

In order to begin the comparison between the air-coupled non-contact system based NCA 1000 and the PUNDIT system when measuring concrete, a calibration was carried out by testing homogeneous blocks. To this end a steel block of thickness 31.54 mm and a Perspex block of 20.69 mm were used. Figure 4.11(a) shows the output waveform from the NCA1000 system measuring the speed of sound within the Perspex sample. The NCA used a chirp with a centre frequency of 400 kHz, a bandwidth of 300 kHz and duration of 600 μs. It gave a time of flight of 198 μs correlating to a speed within the sample of 2,769±69 ms⁻¹. The Pundit recorded a time of flight of 7.6 μs, shown in figure 4.11 (b), which corresponded well to the NCA system with a sample speed of 2,722 ms⁻¹. The longitudinal velocity through the steel was measured by the NCA1000 as 6,005±150 ms⁻¹ corresponding to a speed of 5,951 ms⁻¹ measured with the PUNDIT. This is enough evidence to stipulate that the two systems measure similar speeds through homogenous materials. This is a reassuring result that served as a prelude to examining the two systems analysis of concrete, a notoriously heterogeneous material. Note that it is common in concrete research to use the words “speed of sound” and “pulse velocity” instead of longitudinal velocity. Throughout this thesis, this convention has been followed, and hence mention of an acoustic velocity should be taken to mean the longitudinal...
velocity, unless a different wave mode is specifically quoted. In addition, "non-contact"

![Image](image_url)

**Figure 4.11:** Ultrasonic signals recorded after transmission through a Perspex block: (a) Non-contact waveform, (b) Contact (PUNDIT) waveform. The arrows signify the position from which the time of flight was recorded in each case.

will refer to the air-coupled experiments throughout, and “contact” to those using the PUNDIT.

### 4.5 RESULTS AND DISCUSSION

#### 4.5.1 Preliminary Experiments

Preliminary experiments were conducted, to examine and compare the performance of both the NCA 1000 (non-contact) and PUNDIT (contact) systems for the testing of concrete in the laboratory. The results were also compared to other physical measurements (such as strength) on the concrete samples, to find relationships between the measured ultrasonic values of both systems and the variables affecting the structure and performance of the concrete.

Figure 4.12 shows the respective frequency spectra obtained for the NCA 1000 and PUNDIT systems from experiments performed on two such concrete samples. Figure 4.12(a)-(b) shows the spectrum for a cement paste sample, figure 4.12(c)-(d) shows the spectrums for a concrete sample with aggregate. Figure 4.12(a)-(c) show the response of the NCA system to be broadband around the centre frequency of 400kHz. Figure 4.12(b)-(d) show the PUNDIT system to be narrowband around the piezoelectric transducers.
resonant frequency of 50 Hz. This is performed as a verification of the characteristics of the two systems.

Four concrete prisms were used with target 28-day strengths of 50, 60, 70 and 80 MPa respectively, prepared with Tarmec cement (33%) sand and 30% gravel aggregate. The materials were mixed by using a Hobart mixer to a homogeneous consistency. Cubes, 100 mm by side, were cast and then removed from the curing tank after 24 hours. The concrete prisms were then cured in the curing tank at 90% humidity and 23°C. The prisms were then sawed to size, and the surface of each was treated with a water-based sanding compound to finish the surface. The tensile beams were then applied to a pair of these that were placed against the molds. This ensures that the concrete is firmly attached to the upper plate, while the lower plate is free to move. The beams were then subjected to a range of stresses that were then recorded as the stress. The stress is then recorded as the stress, while the beam is free to move. The pressure applied to the stress is recorded as the stress. The pressure applied to the stress is recorded as the stress. The pressure applied to the stress is recorded as the stress.

Figure 4.12(a) Frequency spectrum of NCA system analysing cement paste, (b) Frequency spectrum of PUNDIT analysing cement paste, (c) Frequency spectrum of NCA 1000 system analysing concrete, (d) Frequency spectrum of PUNDIT analysing concrete.
4.5.2 Further Experiments with a Range of Concrete Samples

Four concrete mixes with target 28-day strengths of 30, 40, 50 and 60 N mm\(^{-2}\) were prepared with Portland cement [25], sand and 20mm coarse aggregate. The specific concrete mixes are shown in Table 4.1. The ultrasonic tests were carried out on slices with varying thickness up to 75mm, and lateral dimensions of 100mm x 100mm. These were performed after 7 and 28 days of water curing.

<table>
<thead>
<tr>
<th>Target Strengths (Nmm(^{-2}))</th>
<th>60*</th>
<th>60</th>
<th>50</th>
<th>40</th>
<th>30</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water (Kg)</td>
<td>2.364</td>
<td>1.876</td>
<td>2.142</td>
<td>2.520</td>
<td>3.066</td>
</tr>
<tr>
<td>Portland Cement (Kg)</td>
<td>6.192</td>
<td>4.914</td>
<td>4.914</td>
<td>4.914</td>
<td>4.914</td>
</tr>
<tr>
<td>Sand (Kg)</td>
<td>7.350</td>
<td>7.000</td>
<td>7.812</td>
<td>8.890</td>
<td>8.932</td>
</tr>
<tr>
<td>20mm Aggregate (Kg)</td>
<td>19.213</td>
<td>18.298</td>
<td>16.884</td>
<td>14.952</td>
<td>13.692</td>
</tr>
</tbody>
</table>

Table 4.1: Concrete mixes for target strengths of 30, 40, 50 and 60 Nmm\(^{-2}\).

Compressive strength tests were also carried out in triplicate after 7 and 28 days. The compressive strength tests were carried out using a Denison 7231 conforming to British Standard 1881. This is a hydraulic servo-controlled compression testing machine. It has two heavy platens through which the load is applied to the concrete. The upper one has a ball seating which allows rotation to match surface orientation at the start of loading while the bottom one is fixed. The upper platen locks into position during testing. The load is then applied to a pair of faces that were cast against the mould. This ensures that the measurement does not give falsely low average failure stresses. A few minutes are required to reach the maximum loading as a very high loading gives over high strengths.

At least six measurements per sample were taken with the non-contact set-up. The PUNDIT is much less sensitive to variations in repeat experiments, with almost no variation in the recorded time of flight. The higher variability between measurements of the non-contact system, compared to those of the PUNDIT, was thought to be due primarily to the fact that the PUNDIT transducers were 50mm wide, and hence spatial averaging over many stones in the aggregate would occur. The air-coupled transducers were 10mm in diameter, resulting in greater variability in this respect. In addition, the air-
coupled system had a higher frequency range of operation, meaning that these signals of smaller wavelength would interact more significantly with the aggregate.

The speeds of sound in the samples were measured by both systems at room temperature and correlated with cube strength as shown in figure 4.13. The PUNDIT tests returned an approximately linear relationship between strength, $S$, and speed of sound, $c$, in the samples with $\Delta c/\Delta S$ of about 13 m/s/MPa. The non-contact tests also recorded a strong correlation, but with considerably greater scatter, (obvious at higher strengths) and a $\Delta c/\Delta S$ value of approximately 45 m/s/MPa. The non-contact method returned much lower values of $c$ for low strength (<50MPa) concrete than the PUNDIT but both systems returned similar values for higher strength concrete.

![Figure 4.13: Speed of sound in concrete vs. strength, air-coupled (NCA) and contact (PUNDIT).](image)

This result clearly shows that the two systems are producing different values for the ultrasonic speed through non-homogeneous materials. One possible explanation for the discrepancy is a coupling effect. It is thought that preferential acoustic coupling occurs between the steel PUNDIT transducers and the stiffest/densest of the two phases in concrete, i.e. the aggregate. Thus the ultrasonic pulse will tend to be transmitted along paths that maximise aggregate content. Since the speed of sound is greater in the aggregate than the paste then the measured speed is relatively high.
Conversely it was thought that preferential acoustic coupling would occur between the non-contact system and the paste phase of the concrete returning a lower measured speed of sound. This is due to the contacting medium being air, which is less stiff/dense than either concrete phase. As the PUNDIT is the standard for the ultrasonic testing of concrete, it was felt that this was a significant result. If the above thesis is correct, then the air-coupled system would be much more sensitive to changes in the paste, and it is this phase (rather than the aggregate) whose properties could change with time. It was thus felt that further measurements were of interest.

4.5.3 Experiments with Concrete Samples of Constant Water-Cement Ratio.

To test the above thesis a number of concrete samples were produced with different aggregate but constant water-cement ratio contents (0.5), giving the samples constant paste properties. This was seen as important due to the proposed preferential coupling between the non-contact system and the paste phase of the concrete. The samples were tested after 8 days of water curing with both systems. Table 4.2 shows the specific concrete mixes with their associated 8-day strengths.

<table>
<thead>
<tr>
<th>Sample</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strengths (Nmm⁻²)</td>
<td>32.66</td>
<td>38.28</td>
<td>42.35</td>
<td>45.33</td>
<td>45.61</td>
</tr>
<tr>
<td>Water (Kg)</td>
<td>2.10</td>
<td>1.8</td>
<td>1.74</td>
<td>1.51</td>
<td>1.277</td>
</tr>
<tr>
<td>Portland Cement (Kg)</td>
<td>4.22</td>
<td>3.79</td>
<td>3.49</td>
<td>3.024</td>
<td>2.570</td>
</tr>
<tr>
<td>Sand (Kg)</td>
<td>4.96</td>
<td>5.31</td>
<td>5.54</td>
<td>5.40</td>
<td>5.586</td>
</tr>
<tr>
<td>20mm Aggregate (Kg)</td>
<td>8.45</td>
<td>9.03</td>
<td>9.46</td>
<td>10.114</td>
<td>11.483</td>
</tr>
</tbody>
</table>

Table 4.2: Concrete mixes with constant Water-Cement ratio (8-day strengths shown).

Figure 4.14 shows the measured speed of sound in the samples against the aggregate-paste ratios in the different samples. It was found that there was little correlation between aggregate content and the speed of sound measured using the air...
coupled NCA system. However a strong positive correlation is evident between aggregate content and speed of sound measured using the PUNDIT. As before, the increased scatter in the results of the air-coupled system is due primarily to the smaller aperture of the capacitance transducers (10mm). The larger PUNDIT transducers, (50mm), average out the in-homogeneities in the relatively large area under inspection whereas the non-contact capacitance transducers are sensitive to local effects e.g. large aggregate particles.

![Graph showing speed of sound in concrete at constant water: cement ratio](image)

**Figure 4.14: Speed of sound in concrete at constant water: cement ratio**

### 4.5.4 Time dependent comparison of systems with concrete samples of differing aggregate/paste ratios

In light of the positive result obtained from the testing of samples with a constant water/ cement ratio, it was deemed necessary to investigate the changes in the measured speed of ultrasound in a newly specified range of samples over a 50 day time period. Six different concrete mixes were prepared with target weights of 1.75 kg using Portland cement and 10mm coarse aggregate. The constituents of the concrete mixes were specified such that the range of samples would have varying amounts of aggregate. It was decided to keep the concrete paste properties constant and thus the water/ cement ratio was set to 0.5. Table 4.3 shows the target ratios for the six mixes and table 4.4 shows the actual

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weights in kilograms corresponding to these targets. The samples were tested every day for seven days and five more sporadically up to a concrete age of 49 days using both ultrasonic systems. This was designed to demonstrate changes in the speed of sound through the thickness of the concrete with time as curing proceeded.

<table>
<thead>
<tr>
<th>Mix No.</th>
<th>OPC (kg)</th>
<th>Water (kg)</th>
<th>10mm Agg (kg)</th>
<th>Sand (Kg)</th>
<th>Total kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>8.8</td>
<td>4.4</td>
<td>0</td>
<td>0</td>
<td>13.2</td>
</tr>
<tr>
<td>2</td>
<td>8.0</td>
<td>4.0</td>
<td>8.0</td>
<td>0</td>
<td>20.0</td>
</tr>
<tr>
<td>3</td>
<td>5.8</td>
<td>2.9</td>
<td>11.6</td>
<td>0</td>
<td>20.3</td>
</tr>
<tr>
<td>4</td>
<td>5.8</td>
<td>2.9</td>
<td>0</td>
<td>11.6</td>
<td>20.3</td>
</tr>
<tr>
<td>5</td>
<td>4.6</td>
<td>2.3</td>
<td>4.6</td>
<td>9.2</td>
<td>20.7</td>
</tr>
<tr>
<td>6</td>
<td>3.6</td>
<td>1.8</td>
<td>7.2</td>
<td>7.2</td>
<td>19.8</td>
</tr>
</tbody>
</table>

Table 4.3: Relative target ratios by weight for the concrete samples used in this study. OPC is Ordinary Portland Cement, Agg is standard concreting gravel aggregate and Sand is a standard concreting sand.

Table 4.4: Actual weights in kilograms corresponding to the relative target ratios in table 4.3.

The results that were obtained for the samples of Tables 4.3 and 4.4, using both air-coupled and PUNDIT systems are shown in figure 4.14 for all six samples. The chirp for the non-contact tests was set to a centre frequency of 400 kHz with a bandwidth of 500
kHz. The first, figure 4.15(a), was just paste with no aggregate or sand. As can be seen, both transducer types measured the expected increase in longitudinal velocity with time, as the material hardened. It is interesting to note that for some of the measurements there is reasonably good agreement between the air-coupled and PUNDIT systems, whereas at intermediate times, the PUNDIT seems to produce a lower value for the velocity. In samples 2 and 3, a greater proportion of aggregate was present, and in these cases it was observed that the PUNDIT now measured a higher velocity than the air-coupled system, and that this discrepancy increased with the greater proportion of aggregate. The addition of sand in samples 4-6 (figures 4.15(d)-(f)) caused a similar phenomenon. The above results may be summarised in figure 4.16, where the difference between the velocities measured by the air-coupled and PUNDIT systems are compared. It will be seen that the addition of aggregate in particular has led to a difference in velocity being measured by the two methods, with the air-coupled approach routinely measuring a lower velocity than the PUNDIT.

The reasons for this difference are thought to be due to the nature of the coupling between the transducers themselves and the concrete samples. The air-coupled systems have to get energy into and out of the samples via the air/sample interface. The amount of energy transmitted across the interfaces is strongly dependent on the acoustic impedance $Z$ of the sample, noting that $Z = \rho c$, where $\rho$ is density and $c$ acoustic velocity. Air has a very low value of $Z$ compared to concrete. More energy is transmitted as the impedance mismatch to air gets smaller or as the impedance of the concrete decreases. Paste has lower values of both $\rho$ and $c$, and hence for a sample containing aggregate, it would be expected for the energy to be initially transmitted from the air into the paste primarily, and not into the aggregate. The converse would be true for the PUNDIT system, which uses a piezoelectric element in a metallic case. Here the impedance is higher than the paste, and more closely matched to that of the aggregate; hence, we would expect energy to couple better to the aggregate initially.

The data of figures 4.15 and 4.16 can be explained by these changes in coupling. The PUNDIT would couple energy into the aggregate primarily, and signals would pass through the concrete sample with a bias towards measuring the aggregate properties. Conversely, the air-coupled system couples preferentially into the paste, and hence would be expected to be more sensitive to changes in the paste as it cures. This is indeed what is observed, with a greater range of acoustic velocities, at lower values, being observed in the air-coupled data.

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Figure 4.16: Speed of sound in various concretes vs. time measured using PUNDIT and NCA systems. (a) to (f): mixes 1 to 6 respectively (Tables 4.3 and 4.4).
The important feature of the above is that the PUNDIT may be underestimating the changes in acoustic properties (and hence the elastic moduli) of the concrete samples during the curing cycle. Conversely, it may be measuring more about the aggregate properties. In both cases, it is recognised that a complicated wave propagation path is followed.

Figure 4.16: Variation in discrepancy between PUNDIT and NCA1000 readings with aggregate/cement ratio and time.
4.6 AIR-COUPLED IMAGING

4.6.1 Experimental Set-up

An advantage of the air-coupled system over conventional piezoelectric transducers is that it is relatively easy to scan the transducers parallel to the sample surface. This means that the technique lends itself to imaging. In the present case, the arrangement is for through-transmission, with transducers aligned on either side of the sample, but there are many other possibilities.

To demonstrate these imaging capabilities, three concrete samples with parallel faces were made, incorporating 10mm diameter cylindrical steel reinforcement bars for the purposes of air-coupled imaging. The target mix specifications and the actual mix weight values are shown in Tables 4.5 and 4.6 respectively. The samples were set in purpose-built wooden moulds to give 30mm thick plates with lateral dimensions of 300mm x 300mm. The experimental set-up using the scanning stage is shown in figure 4.17. The scans were completed using a variation on the capacitance transducers described earlier in section 4.2.1. This was to attempt to increase the lateral resolution of images, and involved a focussed transmitter. This contained a built-in parabolic mirror to focus the ultrasonic beams to increase the resultant pressure field at a particular point [27]. This in turn increases the signal to noise ratio of the pulse compression output leading to more accurate time of flight appraisals and sharper images.

<table>
<thead>
<tr>
<th>Mix No.</th>
<th>OPC (kg)</th>
<th>Water (kg)</th>
<th>10mm Aggregate (kg)</th>
<th>Sand (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>1</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

Table 4.5: Relative target ratios by weight for the concrete samples used for ultrasonic imaging.
Table 4.6: Relative target ratios by weight for the concrete samples used for ultrasonic imaging.

<table>
<thead>
<tr>
<th>Mix No.</th>
<th>OPC (kg)</th>
<th>Water (kg)</th>
<th>10mm Aggregate (kg)</th>
<th>Sand (kg)</th>
<th>Total (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3</td>
<td>1.5</td>
<td>0</td>
<td>3</td>
<td>7.5</td>
</tr>
<tr>
<td>2</td>
<td>2.4</td>
<td>1.2</td>
<td>1.2</td>
<td>2.4</td>
<td>7.2</td>
</tr>
<tr>
<td>3</td>
<td>2.2</td>
<td>1.1</td>
<td>2.2</td>
<td>2.2</td>
<td>7.7</td>
</tr>
</tbody>
</table>

The beam convergence of this source is illustrated using simple ray tracing in Figure 4.18. This device has been shown in previous work [27] to have a lateral resolution at the surface at which it was focused of approximately 0.4 mm.
4.6.2 Images of Steel Reinforcement Bars

Figure 4.19 shows three images of the same area of the cement paste mix, (mix 1 in Tables 4.5 and 4.6). Each scan was performed at a different chirp centre frequency so that a brief appraisal of optimal scanning conditions could be ascertained. The centre frequency returning the best result would then be used to scan the concrete samples. Figure 4.19(a) was scanned at 300 kHz, (b) at 400 kHz and (c) at 500 kHz. The chirp had a bandwidth of 500 kHz in each of the scans. Figure 4.19(b) seems to have the best resolution; this corresponds to a wavelength of approximately 10mm. It is fair to hypothesise that at 300kHz, (wavelength of 13mm), that this wavelength is too large to

![Image of steel reinforcement bars](image)

Figure 4.19: Images of steel reinforcement bars in cement paste, (a) at 300kHz, (b) 400kHz, (c) 500kHz.
produce sharp images. Conversely at 500 kHz, (wavelength at 8mm), the wavelength is becoming too small, and is being scattered by the aggregate more than at the other centre frequencies. Thus a 400 kHz centre frequency was used to scan the concrete samples, (mixes 2 and 3 of Table 4.5). The reinforcement bar can clearly be seen to have a width of approximately 10mm with the contrast between the bar and the paste being relatively clear.

Figure 4.20 shows the concrete scan for mix 2. The reinforcement bar can clearly be seen, as can some of the larger aggregate. The smaller particles can be attributed to noise. There is generally good agreement in terms of location and size of the rebar. Figure 4.21 shows the concrete scan for mix 3. Although the rebar is partially obscured by the amount of aggregate in the sample it can be distinguished. These results are viewed as preliminary. At the moment it is obvious that reinforcement bars embedded in concretes with high aggregate content will be hard to image. By combining different metrics (e.g. time of flight, amplitude, frequency attenuation) it should be possible to increase the selectivity and resolution of the technique.

![Figure 4.20: Image of concrete with rebar for mix 2 in tables 4.5 and 4.6.](image-url)
4.7 CONCLUSIONS

It has been demonstrated that air-coupled systems can be used to test concrete samples, and that the longitudinal acoustic velocity can be measured. It has also been shown that the results show a difference to that from a contacting PUNDIT system. It is thought that these differences arise from the coupling to the sample in each case. It is suspected, however, that the air-coupled system may be more sensitive to changes in properties of the paste as it cures, and this may be of interest to researchers in this area. It has also been shown that non-contact ultrasonic NDT can be used to resolve images of subsurface features in concrete.

It is thought that with further developments in selectivity, resolution and power, such a technique might find widespread use in industry in similar materials.
4.8 REFERENCES


Chapter 4: Ultrasonic Non-Destructive Testing Of Concrete


Chapter 5

HUMIDITY AND AGGREGATE CORRECTION FACTORS FOR ULTRASONIC EVALUATION OF CONCRETE

5.1 INTRODUCTION

Concrete strength estimation can be achieved using the ultrasonic pulse velocity method [1]. The strength can be estimated from the pulse velocity using an existing graphical correlation between the two parameters. The pulse velocity is historically measured using a contact ultrasonic measuring system such as the PUNDIT, discussed in chapter x [2]. The time taken for the ultrasonic pulse to travel through a known distance in concrete is recorded and the velocity calculated. The velocity of the longitudinal ultrasonic pulse depends on the material’s dynamic elastic modulus \(E\), Poisson’s ratio \(\nu\) and density \(\rho\) [3]:

\[
C_L = \sqrt{\frac{E(1-\nu)}{\rho(1+\nu)(1-2\nu)}}
\]

Therefore ultrasonic pulse velocity is related to the elastic properties. Like the elastic properties, the pulse velocity can be correlated to strength using empirical relations between elastic modulus and strength [3].

The concrete strength is measured using the compressive strength test, also discussed in chapter 4, in triplicate. The average is taken as the strength reading. Figure 5.1 shows the relationship between elastic modulus and ultrasonic pulse velocity that is used in conjunction with the pundit apparatus. This figure is taken directly from reference [4]. The elastic modulus and cube strength increase non-linearly with pulse velocity. The pulse velocity is related empirically to cube strength. The interdependence between compressive cube strength and pulse velocity has been studied further [5] [6].

The relationship between cube strength and pulse velocity is relatively weak, leading to a large amount of uncertainty in prediction. An examination of figure 5.1 (also shown in
chapter 3), reveals that for a certain measured pulse velocity the predicted cube strength may vary between +/- 30 N/mm². This is an error margin of approximately 50% represented by the shaded region of the graph. A large range of other variables other than strength are likely to have a significant effect on the speed of sound within concrete. These include water/cement ratio [w/c], aggregate type and content and moisture content. It has been noted that concretes with similar strengths but different aggregate contents gave different pulse velocities [7].

![Figure 5.1: Curves relating pulse velocity with static and dynamic elastic modulus and cube strength.](image)

It is known that water content affects the ultrasonic pulse velocity. Etsuzo et al [8], proposes a linear dependence on the pulse velocity in terms of water content. Relative humidity has an affect on the hydration on concrete [9]. This governs the water content that in turn governs the pulse velocity. This can lead to a scenario in which two samples with the similar strengths can return different pulse velocities. The main objectives of this study were to examine the effect of variables other than strength on the speed of sound in concrete, focussing on the effects of aggregate content and storage humidity.
5.2 EXPERIMENTATION

The ultrasonic means of evaluation for the humidity-controlled experiments were the PUNDIT and the NCA1000 system. Both have been described previously in chapter 4. It is worth restating that the PUNDIT uses resonant piezoelectric with a centre frequency of 54kHz. It is driven with a large delta function that causes the transmitter to resonant. The NCA1000 system delivers a chirped ultrasonic signal. This is primarily for use in air-coupled ultrasound and is used in conjunction with broadband capacitance transducers to deliver a chirp with a bandwidth of 400kHz in this case. The chirp had a duration of 600\(\mu\)s with the centre frequency being 400kHz also. Refer back to chapter 4 for further information.

Five different concrete mixes were prepared using Portland cement, sand and 10mm aggregate in the proportions shown in Table 5.1. Each mix was split into four samples. The constituents of the mixes were specified such that a range of concrete mixes was produced with varying aggregate to concrete ratios. The w/c was kept constant at 0.5 and thus the strength range of the concretes was deliberately narrow in order that the effect of aggregate content and storage humidity could be more easily assessed. The samples were mixed using a pan mixer, cast into standard 100mm cube moulds, de-moulded after 24 hours and cured for a further 27 days in water at ambient laboratory temperature. Their saturated weights were then recorded.

Samples from each mix were then kept in sealed containers, shown in figure 2, at different humidities, controlled by placing and maintaining saturated solutions of the salts shown in Table 5.3 in the base of the containers [10]. Four chambers were created with approximate relative humidities of 95, 75, 50 and 35%. The salts relating to these are shown in table 5.3. If water is placed in an airtight container it will evaporate until 100% relative humidity is reached. If any salt is added to the water, the humidity will be reduced depending upon the solubility of the salt. If each salt is mixed to the saturation point with the water then a constant relative humidity is maintained, (at a constant temperature), within the airtight chambers. If air of high relative humidity is introduced to the chamber then the solution will absorb water molecules from the air until the constant relative humidity is reached again. In the scenario of adding air of low relative humidity to the chamber water molecules from the saturated solution will evaporate until the characteristic relative humidity is achieved.

---

*Chapter 5: Humidity And Aggregate Correction Factors For Ultrasonic Evaluation Of Concrete*
Table 5.1: Relative target ratios by weight for the concrete samples used in this study. OPC is Ordinary Portland Cement, Agg is a standard concreting gravel aggregate and Sand is a standard concreting sand.

<table>
<thead>
<tr>
<th>Mix No.</th>
<th>OPC (kg)</th>
<th>Water (kg)</th>
<th>10mm Agg (kg)</th>
<th>Sand (Agg)</th>
<th>Total kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>8.0</td>
<td>4.0</td>
<td>8.0</td>
<td>0</td>
<td>20.0</td>
</tr>
<tr>
<td>2</td>
<td>5.8</td>
<td>2.9</td>
<td>11.6</td>
<td>0</td>
<td>20.3</td>
</tr>
<tr>
<td>3</td>
<td>5.8</td>
<td>2.9</td>
<td>0</td>
<td>11.6</td>
<td>20.3</td>
</tr>
<tr>
<td>4</td>
<td>4.6</td>
<td>2.3</td>
<td>4.6</td>
<td>9.2</td>
<td>20.7</td>
</tr>
<tr>
<td>5</td>
<td>3.6</td>
<td>1.8</td>
<td>7.2</td>
<td>7.2</td>
<td>19.8</td>
</tr>
</tbody>
</table>

Table 5.2: Actual weights in kilograms corresponding to the relative target ratios in table 5.1.

The amount of salt to be added to the containers was calculated using Roult’s law [11] as a guideline. This was to make sure that unnecessarily amounts of salt were not used. In order to calculate this, the amount of free water left over in the concrete that is not used in the hydration reaction needs to be ascertained. The calculation for the amount of free water is determined by the two primary chemical reactions that occur in concrete [12].

\[
2[(CaO)_3(SiO_2)] + 6H_2O \rightarrow (CaO)_3(SiO_2)_2(H_2O)_3 + 3Ca[OH]_2 \tag{5.1}
\]

\[
2[(CaO)_2(SiO_2)] + 4H_2O \rightarrow (CaO)_3(SiO_2)_2(H_2O)_3 + Ca[OH]_2 \tag{5.2}
\]

This is a simplified but justified view of the hydration reaction that was used to calculate the approximate amount of salt to be used. \([(CaO_2)(SiO_2)]\) is the cement involved in the above reaction. The same products of tricalcium disilicate hydrate and calcium hydroxide are created from both reactions.
Using the relative atomic masses of elements the amounts of cement and water, O=16, Si=28, Ca=40 and H=1, for the first equation:

\[ 2[(40+16)x3+28+(16x2)]+6[1x2+16]. \]

Therefore 456g of cement will completely react with 108g of water for equation 5.1. For equation 5.2:

\[ 2[(40+16)x2+28+(16x2)+4[1x2+16]. \]

Therefore 344g of cement will react with 72g of water for equation 5.2. Looking at equations 5.1 and 5.2 one can see that they occur with a ratio of 60% to 40%. This means that 411.2g of cement will react with 93.6g of water. So therefore 0.23g of water will react with 1g of cement. Given the water to cement ratio is 0.5 in the samples that were prepared shown in tables 5.1 and 5.2 the water not used up in the hydration reaction can be given as:

\[ \%_{\text{free}} = \frac{x-0.23}{x} \times 100 \] (5.3)

This works out as 54%. So what this means is that the saturated salt solution has to be able absorb 54% of the total amount of the water that was used to form the concrete in order for the relative humidity’s in table 5.3 to be maintained. This was calculated as 0.28925kg, refer to appendix 1 for the concrete slice weights that are needed for this calculation. Raoult’s law was then used to calculate the amount of salt needed to react with 0.290kg of water. If \( P_0 \) and \( p \) are the vapour pressures of the pure solvent and the solution respectively, and \( n \) and \( N \) are

<table>
<thead>
<tr>
<th>Approximate relative humidity, %</th>
<th>Conditioning salt</th>
</tr>
</thead>
<tbody>
<tr>
<td>95</td>
<td>( \text{K}_2\text{SO}_4 )</td>
</tr>
<tr>
<td>75</td>
<td>( \text{NaCl} )</td>
</tr>
<tr>
<td>50</td>
<td>( \text{Mg(NO}_3\text{)}_2 )</td>
</tr>
<tr>
<td>35</td>
<td>( \text{MgCl}_2 )</td>
</tr>
</tbody>
</table>

*Table 5.3: Conditioning humidities for the concrete samples.*
the respective number (i.e. moles) of molecules of solute and solvent then Raoult’s law can be expressed as:

\[
\frac{(P_0 - p)}{P_0} = \frac{n}{(N + n)}
\]  

(5.4)

In the case of Potassium Sulphate the left hand side of this equation equates to 0.95. With the number of moles of water also known, (mass in grams/formula weight), it was determined that 72.87kg of K₂SO₄ was needed to react with 290kg of water. This amount was then doubled and added to 1 litre of water in the plastic containers that became the humidity chambers. Figure 5.2 shows a picture of one of these containers. To make sure that the correct humidities were maintained in the four containers sensors were employed.
In-situ measurements of humidity were accomplished via a commercially available purpose built humidity sensor, the Honeywell HIH-3610 series. This is basically a simple three-pin (+ Volts, 0V and signal out) capacitative sensing device encapsulated in a micro-porous sheath that relies upon the principle of capillary condensation to gauge the relative humidity of the environment in which it is placed [13]. Figure 5.3 shows the devices output in response to varying levels of humidity. The voltage is read from the multi-meter shown in the right of figure 5.2 and the corresponding humidity is read off the above graph. The electronic schematic of the connectivity of the sensor is shown below.

![Figure 5.3: Output voltage vs. relative humidity at 0°C, 25°C and 85°C.](image)

![Figure 5.4: Schematic of the connectivity of the HIH-3610 humidity sensor.](image)
Samples were weighed periodically until it was apparent that the moisture content in the samples had reached equilibrium with the atmosphere in the containers. These equilibrium weights are displayed in appendix 1. The samples were then tested using the ultrasonic systems previously discussed. Each sample was tested 3 times through different points in the concrete slices using the NCA 1000. Only one reading was recorded using the contact system, as the large transducer tends to perform 'natural averaging' such that readings taken at different points tend to be identical in samples of this size.

5.3 RESULTS

Figure 5.5 (a-d) shows the speed of sound in the concrete samples against aggregate/concrete ratio for the four humidities. The first point of note is that the PUNDIT records a higher reading than the air-coupled system in almost every case. This is in accordance with the results obtained in chapter 4. The reasons for this were covered in that chapter but can be briefly reiterated. It is the author's belief that a preferential coupling mechanism exists between the ultrasonic pulse and the materials that constitute the concrete [14][15]. More energy is traversed between two materials if their impedances are similar. As the acoustic impedance of the steel-cased PUNDIT transmitter is closer to that of the aggregate, (the stronger phase), than that of the paste, more energy will travel through the aggregate returning a faster ultrasonic time of flight. With the non-contact system, coupling is via the air, and the impedance of air is more closely matched to that of the paste. Therefore more energy will be transferred into this weaker phase. It is noted that there appears to be a positive correlation between the aggregate/concrete ratio and the speed of sound.

Figure 5.6 shows the speed of sound versus the relative humidity that the samples were stored at for the five mixes shown in tables 1 and 2. The ultrasonic speeds were recorded using the air-coupled system. The increase in ultrasonic pulse velocity with humidity is obvious in all five graphs and is highlighted with a linear regression courtesy of Sigmaplot™. Comparing between graphs, the effect that aggregate content within the mixes has on the pulse velocity can once again be noted. The extreme examples being that the values shown for mix 1 are substantially lower than that in mix 5.
Figure 5.7 shows the speed of sound versus the relative humidity for the five mixes using the contacting PUNDIT system. The increase of ultrasonic pulse velocity with humidity is noted, as is the increase in speed generally with aggregate content. The linear regression tool has been utilized once again so that the upward trend is more obvious.

Figure 5.5: Ultrasonic speed vs. Agg/Conc ratio: (a) 35% humidity, (b) 50% humidity, (c) 75% humidity, (d) 95% humidity. Error bars are ±1 standard deviation.

Chapter 5: Humidity And Aggregate Correction Factors For Ultrasonic Evaluation Of Concrete
Figure 5.6: Ultrasonic pulse velocity vs. Humidity recorded using the NCA1000 air-coupled system, (a)-(e) mixes 1 to 5 shown in table 1. Error bars are ±1 standard deviation.
Figure 5.7: Ultrasonic pulse velocity vs. Humidity recorded using the PUNDIT contact system, (a)-(e) mixes 1 to 5 shown in table 1.
Figure 5.8 plots the results shown in figures 5.6 and 5.7 on the same graph so that a comparison of ultrasonic pulse velocity for each mix can be made. It was seen that using both systems a positive correlation was recorded between storage humidity and the pulse velocity. The correlation was virtually the same for both systems, at about 2.4 (SD 0.77) % per %RH for the non-contact and contact systems respectively i.e. a change in storage RH from 30 to 70% would add 10% onto the measured value of speed of sound.

This correlation was used to combine the speed of sound data from samples stored at various humidities. A correction was applied such that the measured speed for each sample was adjusted to that which would have been expected for the same sample stored at 75.5% RH. For example, for samples stored at 33.6% RH, a correction of +(75.5-33.6)×2.4%o = 0.101 (or +10.1%) was applied to the measured speed of sound. The choice of 'baseline' RH is of course arbitrary but 75.5% RH was chosen, as it is probably the closest of the four to an in-service environment. The combined results are shown in Fig. 5.9.
Figure 5.9, Speed of sound (adjusted to equivalent at 75.5% RH) vs. aggregate/paste ratio by mass. Error bars are ± 1 standard deviation.

Figure 5.9 shows that the contact system consistently returns higher values for the speed of sound than the non-contact system. This is again indicative of the preferential coupling mechanism discussed before. There appears to be a strong positive correlation between the aggregate paste ratio and the speed of sound. For comparison, Fig. 5.10 presents the same speed of sound results against compressive strength. The correlation with aggregate-paste ratio is much stronger than that with compressive strength. Table 5.4 shows the strengths and standard deviations of each mix.

5.4 DISCUSSION

A correlation between speed of sound with humidity was expected. Hardened cement paste (hpc) has a complex porosity system, the structure of which is highly dependent on the water-cement ratio used during manufacture [3]. At the w/c used here (0.5), the total porosity of the hcp would be about 0.2 cm³/gm or 30%. Most of this porosity will be 'capillary porosity', ranging in size from a maximum pore diameter of 100 nm down to 10 nm, which controls the properties of cement paste (and thus concrete); the remainder will be <10nm 'gel porosity' which is intrinsic to the structure of the paste. The addition of aggregate will introduce small amounts of gross porosity (air bubbles), which can be avoided with good
manufacture, and some further capillary porosity associated with the paste/aggregate interface (the transition zone).

<table>
<thead>
<tr>
<th>Mix No.</th>
<th>Strength (Standard deviation), N mm²</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>46 (2.5)</td>
</tr>
<tr>
<td>2</td>
<td>47 (0.9)</td>
</tr>
<tr>
<td>3</td>
<td>60 (0.8)</td>
</tr>
<tr>
<td>4</td>
<td>59 (1.8)</td>
</tr>
<tr>
<td>5</td>
<td>54 (0.5)</td>
</tr>
</tbody>
</table>

*Table 5.4: Mix No. with associated strengths.*

*Figure 5.10:* Speed of sound (adjusted to equivalent at 75.5% RH) vs. compressive strength. Error bars are ±1 standard deviation.
The free water content of concrete after hardening is largely contained within the capillary porosity. Changes in storage humidity will affect the extent to which the capillary porosity is saturated with water - smaller pores becoming saturated at lower humidity than larger ones - and thus the relative amounts of water and air through which the ultrasonic waves must propagate. The results of this study are in broad agreement with previous studies relating speed of sound to water content [16]. It should be noted that for in-service concrete, there is no direct correlation between w/c (i.e. original water content) and the water content at any given time as the concrete will imbibe water from, or release water to its environment depending on the relative humidity thereof.

The correlations between aggregate content and speed of sound confirm our original hypothesis concerning preferential coupling [14], [15], on two counts. First, the non-contact system consistently returned a lower value for speed of sound than the contact system. Secondly, the dependence on aggregate content is stronger for the contact system than the non-contact system; the corresponding slopes of the best-fit lines in Fig. 5.9 being 261 and 218 m/s respectively.

The aggregate/paste ratio is expressed in terms of total aggregate i.e. no distinction is made between fine and coarse aggregate. This appears to be justified; the results for mixes 2 and 3 (see Table 5.1), which contain only coarse and fine aggregate respectively in the same proportion to the other constituents, are very similar (the two points at aggregate/paste ratio = 1.33 on Fig. 5.10) for both systems.

Comparing Figs. 5.8, 5.9 and 5.10 sheds some light on the reasons why the 'scatter' encountered in the published graphs which purport to relate, in a general sense, strength to speed of sound, [4], [17], can be considerable. For a given w/c, the relationships between aggregate content and storage humidity (or water content) on speed of sound are stronger than that with compressive strength. Thus it follows that for more accurate strength prediction, pulse velocity measurements, however obtained, need to be augmented with measurements of other physical properties of the concrete. Aggregate content can be measured using point-counting, image analysis or chemical means but requires sampling of the concrete. Moisture content is very difficult to measure in-situ but could possibly be inferred from in-service humidity histories, if available.
Of course, since this study was performed at a constant w/c, the range of strength values obtained was quite narrow, as w/c is the primary process variable controlling concrete strength.

It is possible that, using further advanced signal processing techniques that combine time and frequency domain analysis, metrics other than speed of sound can be deduced from a single signal. This could allow concrete samples with different strengths but similar pulse velocities to be distinguished, either without the need to directly deduce aggregate or moisture contents, or by in some way indirectly inferring these properties. The application of time-frequency analysis to ultrasound is covered in chap 6.

5.5 CONCLUSIONS

A number of concrete samples were prepared at constant w/c with different aggregate contents, stored at a range of relative humidities and the speed of sound therein measured using contact and non-contact systems. It was shown that there is a positive correlation between storage humidity and the speed of sound in concrete and a correction factor for humidity was employed. A strong positive linear correlation between aggregate content and speed of sound was observed; there was no obvious correlation between compressive strength and speed of sound. The contact system returned higher values and a stronger dependence on aggregate content than the non-contact system, confirming the hypothesis that preferential coupling occurs when using ultrasonic NDT with concrete.
5.6 REFERENCES


Chapter 5: Humidity And Aggregate Correction Factors For Ultrasonic Evaluation Of Concrete

6.1 INTRODUCTION

It is evident from Chapters 4 and 5 that the use of the cross-correlation technique in pulse compression was a successful approach to the improvement of SNRs in air-coupled measurements. There are other approaches to the problem that could also help in the analysis of ultrasonic signals from complicated media such as concrete. In particular, the use of chirp drive waveforms in air-coupled testing allows the information to be analysed in a different way.

In this Chapter, time-frequency methods are considered as an analysis tool for air-coupled signals, and as will be seen, some interesting features result. As in many such approaches, the technique is based on mathematical transforms, a general technique that is applied to signals when further information than that readily available in the raw signal is required. The Fourier transform is the most popular of these techniques and has been of great value in many areas of science and engineering [1]. It is a tool for the determination of the energy distribution of the signal within the frequency or Fourier domain. In ultrasound its use is well documented with applications ranging from polymer composite material characterisation [2] to attenuation measurements within dispersive materials [3]. Fourier analysis does, however, have limitations when dealing with practical signals.

The Fourier transform is defined over infinite time with a global cosine basis function [4]. A transformation of a finite duration time signal to the frequency domain has the effect of convolving the Fourier transform of the signal with the Fourier transform of the window function. This can reduce the power of the resultant frequency spectra and introduce leakage, a loss in resolution of the frequency components.

Another deficiency of the Fourier transform is its inability to satisfactorily analyse non-stationary signals such as the chirp signal used to drive the air-coupled transducers discussed previously. Fourier transforms assume that the signals under analysis are stationary, having constant statistical properties (such as average and variance). This
approach is only applicable when either the signal occurs for a short duration so that its time of occurrence is known, or when time is a non-specific issue. The location information of frequencies is contained within the phase spectrum of the Fourier transform. Even simple signals, however, have very complicated phase spectra, in which time localisation of frequency components is not intuitive.

A chirp signal is comprised of frequencies that constantly change in time. Fourier analysis gives frequency content but not time localisation. To perform a more meaningful analysis in many situations, ultrasonic chirp signals need to be resolved into a time-frequency representation. This has been the subject of intensive research and is known as Joint Time-Frequency Analysis (JFTA) [5]. Within these mathematical frameworks, the energy of time varying signals is considered as a joint function of time and frequency.

The simplest approach to this problem is to use time-shifted windows along the signal when performing the Fourier analysis. This Short Term Fourier Transform (or spectrogram) gives bands of frequencies over time increments [6]. It does however suffer from a trade off between window length and resolution, which will be covered in more detail later on in this chapter. Recent developments in JFTA have yielded useful alternatives. The Wigner distribution (WD) was introduced within quantum mechanics [7] and revived by Ville for signal analysis [8]. This gives the energy density of various frequency components at given points in time although trade off does exist here in terms of computational complexity and interference [9]. These two JTFA techniques are described as members of Cohen’s class of distributions [10]. These are known as the class of quadratic shift invariant representations.

Wavelet transforms offer an alternative to Cohen's class of distributions [11-12]. They were developed as an alternative to the STFT completely independently of any of the other more complicated distributions defined by Cohen such as the WD. The Wavelet transform uses multi-resolution analysis (MRA), which interrogates the signal at different frequencies using a basis function of a particular shape but with varying scales. This flexible windowing strategy allows the resolution problem associated with the STFT to be tackled effectively. This chapter aims to discuss these techniques with particular attention to applicability to chirp signals. A comparison of the three techniques is made including computer simulations. Cross correlation will also be mentioned, as it is the existing technique for post processing of real time chirped ultrasonic signals. The following sections describe the characteristics of each method in turn, highlighting their relative strengths and weaknesses. Time-frequency analysis is then applied to real air-coupled signals.
6.2 THE SHORT-TERM FOURIER TRANSFORM

6.2.1 Basic Principles

The Short Term Fourier Transform is the intuitive solution to the problem of representing time varying signals in terms of time and frequency. It is an extension of the ubiquitous Fourier Transform, a mathematical procedure to decompose signals into their constituent frequencies \cite{13}\cite{14}. This uses a basis of sines and cosines of different frequencies to determine how much of each frequency the signal contains. The minor difference between the Fourier Transform (FT) and the Short Term Fourier Transform (STFT) is that STFT divides the signal into smaller segments, whereby the signal within these segments can be assumed to be stationary, (frequency non-variant). The mathematical definitions for the FT and the STFT are shown in Equations 6.1 and 6.2 respectively.

\[
S_s(\omega) = \frac{1}{\sqrt{2\pi}} \int e^{-j\omega t} s_s(t) dt
\]  

(6.1)

\[
S_f(\omega) = \frac{1}{\sqrt{2\pi}} \int e^{-j\omega t} s(t) h(t) dt
\]  

(6.2)

Here,

- \(S_s(\omega)\) is the frequency spectrum.
- \(s_s(t)\) is the time varying signal.
- \(h(t)\) is the window function in time.

These equations lead on to the Fourier Spectrogram defined in Equation 6.3, which gives the energy density spectrum at time \(t\).

\[
P_{SP}(t, \omega) = |S_f(\omega)|^2 = \frac{1}{\sqrt{2\pi}} \left| \int e^{-j\omega t} s(t) h(t) dt \right|^2
\]  

(6.3)

The resolution of the STFT is limited due to the relationship between time and frequency. This dictates that the product of the standard deviation in time and frequency is limited by:

\[
\Delta \omega \Delta t \geq \frac{1}{2}
\]  

(6.4)
An increase in resolution in the frequency band must result in a decrease in the resolution of time. As a consequence large frequency windows offer good frequency resolution but poor time resolution. Short time windows give poor frequency resolution. Time and frequency windows cannot be both arbitrarily narrow. The effect to changes in window length on the time-frequency spectrum is shown later in simulation.

The STFT suffers from another problem in obtaining frequency resolution. Side lobes or ‘frequency spreading’ are introduced to the spectra due to the transforms lack of finite support. Due to the localisation of a finite time signal one would expect a distribution to be zero before the signal starts and after the signal ends. This is referred to as the finite support property. The convolution of the Fourier Transform of the signal with the Fourier Transform of the window function (mentioned in the introduction), determines that the value of the distribution will not be zero outside the signal’s duration.

6.2.2 Simulation of the Short-Term Fourier Transform

The JFTA distributions applied within this chapter are for use in ultrasonic chirp signal analysis. The STFT is studied initially using software simulation. The simulations involve creating an example chirp waveform and displaying it simultaneously in the time-frequency domain. The Fourier spectrums are also displayed in order to compare resolution across the frequency band. Figure 6.1(a) shows a Hanning window modulated chirp signal [15] typical of the ultrasonic response produced by the NCA1000 pulser/receiver from VN instruments, outlined earlier in Chapters 4 and 5. It has a centre frequency of 400 kHz and a bandwidth of 500 kHz. It has been delayed by 100 μs to simulate the propagation path, and has a duration of 200 μs. Figures 6.1(b) and 6.1(c) show the frequency spectrum and the STFT time-frequency spectrum of the chirp signal respectively. The STFT displays the simulated chirp ranging from 200kHz to 600kHz. The effect of the Hanning window, (length 32μs), is to reduce side lobes present in the frequency spectrum of the un-modulated signal [16]. This amplitude modulation is visible in both 6.1(b) and 6.1(c). Both the low and the high-end frequencies have been attenuated. Figure 6.1(d) shows the cross correlated pulse obtained from applying the pulse compression technique discussed in chapter 4 to the modulated chirp. The delay time of the chirp can be read as 100 μs as stated above. Figure 6.1(c) can therefore
be seen to deliver the same information that is prevalent within both Figures 6.1(b) and 6.1(d), halving the post processing procedures.

![Graphs of chirp signals](image)

Figure 6.1: Simulation of the STFT: (a) modulated chirp with delay, (b) Frequency spectrum of the chirp, (c) STFT of the chirp, (d) pulse compression technique applied to the same chirp.

Figure 6.2 shows an un-modulated chirp and its associated time-frequency spectrum created from the STFT. This emphasizes the effect of the Hanning window in attenuating the low and high-end frequencies. The pulse compression instrumentation used in earlier Chapters includes this windowing for the removal of side lobes - this is a feature of the instrumentation used, and is not a problem created by windowing the time varying signal in order to perform time-frequency analysis.

Chapter 3: Time-Frequency Analysis Of Ultrasonic Signals
The simulations shown so far are unrealistic although good for proof of concept. Real time signals will have noise added to them [17]. The delayed modulated chirp of Figure 6.1(a) was mixed into random noise of twice the signal's amplitude. This is typical of noise levels that may be encountered when using air-coupled ultrasound for material evaluation. This is shown in Figure 6.3(a). The NCA1000 pulser/receiver initially band-pass filters the received time varying signal within the bandwidth specified by the chirp. The filtered signal is shown in Figure 6.3(b). This has an SNR of around 5dB. The band-pass filter removes the noise present below and above the bandwidth of the transmitted chirp. The shape of the chirp signal is not easily recognisable. The noise added to the chirp has an obvious adverse effect on the frequency spectrum shown in Figure 6.3(c). When compared with the frequency spectrum of the clean chirp signal in Figure 6.1(b) it can be seen that the lower frequency bound has become distorted. Figure 6.3(d) shows the STFT time-frequency spectrum. The evolution of the chirp signal is clearly visible from approximately 120μs to 280μs. This compares favourably with the time-frequency spectrum of the clean chirp in Figure 6.2(c). Although the added noise has affected resolution, the chirp rate angle can easily be seen and time-frequency information obtained that we can have confidence in. The cross-correlated pulse in Figure 6.3(e) is similar to that simulated from the clean chirp. This demonstrates the potential of this technique in small signal retrieval.
Figure 6.3: Simulation of the STFT on a noisy chirp: (a) modulated noisy chirp with delay, (b) band pass filtered noisy signal SNR ~5dB, (c) frequency spectrum of the noisy chirp, (d) STFT of the noisy chirp, (e) result of applying the pulse compression technique to the noisy chirp.

Chapter 3: Time-Frequency Analysis Of Ultrasonic Signals
The STFT suffers from the aforementioned trade-off between window length and resolution. It is advantageous to use the window length that outputs the most accurate information. The solution to this problem when applied to the ultrasonic signals under evaluation is not intuitive. Figure 6.4 shows a series of simulations in which the chirp signal of Figure 6.1 (a) is analysed by the STFT with four different window lengths. These were 1024 frequency bins (0.39μs), 512 frequency bins, (0.781μs), 256 frequency bins, (1.562μs) and 128 frequency bins, (3.125μs).

Figure 6.4: Changing the window length of the STFT: (a) 1024 windows, (b) 512 windows, (c) 256 windows, (d) 128 windows.
6.3 THE WIGNER-VILLE DISTRIBUTION

6.3.1 Basic Principles

The Wigner-Ville distribution is the simplest of Cohen's class of time-frequency (t-f) distributions [18]. These are known as the time-shift and frequency-shift invariant t-f distributions. This means that if a signal is delayed in time and/or shifted in frequency, then its t-f representation will be shifted by the same time delay and/or frequency modulation [1]. Different distributions are obtained by selecting different kernel functions in Cohen's class defined to be

\[ S_x(t, \omega, \phi) = \iint e^{j(\omega - \phi)t} \phi(\phi, \tau) s(u + \tau/2) s^*(u - \tau/2) du \, d\tau \]  

(6.5)

where \( s(u) \) is the time signal, \( s(u)^* \) is its complex conjugate, and \( \phi(\theta, \tau) \) is the kernel of the distribution. The Wigner-Ville (WV) distribution is the simplest of the Cohen class [19]. It uses the kernel \( \phi(\theta, \tau) = 1 \), which simplifies equation 6.5 to 6.6, the definition of the WV distribution.

\[ W_x(t, \omega) = \int_{-\infty}^{\infty} s(t + \tau/2) s^*(t - \tau/2) e^{-j\omega \tau} d\tau \]  

(6.6)

The WV method can be obtained by breaking the process down into two steps. Firstly the signal is converted into pseudo time. This conversion can be thought of as a folding of the signal to see if there is any overlap [6]. This is performed for every pseudo-time point in turn. The second step is a Fourier Transform of the pseudo-time signal at time \( t \) into the frequency domain. This provides the frequency estimation at the given time.

An important difference between the WV distribution and both the STFT and wavelet analysis is that the WV distribution does not require any windowing and that only the signal itself is required. Therefore the WV distribution does not suffer from the windowing effects inherent to the STFT. The major difference between the WV distribution and wavelet analysis is that a basis function is not needed, (This will be covered in the next section).
The WV distribution has two important properties. The first is that it is always real, even if the signal being analyzed is complex [6]. This is desirable as it reduces computational complexity and subsequent processing time. The second is that integrating the WV distribution over time, over frequency and over time and frequency yields respectively the power density at a given frequency, the instantaneous power at a given time, and the total energy of the signal [6].

The major disadvantage of the WV distribution is cross-term interference [20]. These arise because the WV distribution of the sum of two signals is not the linear sum of the respective WV distributions. Two terms exist which can obscure the regions of interest in the t-f plane. For a signal \( s(t) = s_1(t) + s_2(t) \), the WV distribution that is obtained is:

\[
WVS(t, \omega) = WV_{S_11}(t, \omega) + WV_{S_22}(t, \omega) + WV_{S_12}(t, \omega) + WV_{S_21}(t, \omega)
\]

with

\[
WV_{stij} = \int s_i(t - \tau/2) s_j^*(t - \tau/2) e^{-j\omega \tau} d\tau \quad (i=1,2, \ j=1,2)
\]

The two main terms are \( WV_{S_11} \) and \( WV_{S_22} \), the cross terms \( WV_{S_12} \) and \( WV_{S_21} \) are a direct result of the quadratic nature of the t-f representations [21]. These cross terms can obscure the useful terms and limit the effectiveness of the WV distribution in reproducing accurate representations of time varying signals in the t-f plane. One method for the reduction of these cross terms is to localize the WV distribution [6]. This will place an emphasis on the properties of the signal around the time instant of interest. The definition of the pseudo WV distribution is thus to include a window function in equation (6.6).

\[
W_s(t, \omega) = \int h(\tau) s(t + \tau/2) s^*(t - \tau/2) e^{-j\omega \tau} d\tau
\]

This window can be used to suppress cross terms between signal components that are separated in time. It calculates the auto-correlation for smaller time-shifts and removes cross terms that are created between signal components that are spaced further apart than the length of the window. There has been considerable work done on the removal of cross terms [5], [6], and the use of different windowing methods and kernels to achieve this [22], [23].

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6.3.2 Simulation of the Wigner-Ville Distribution

The simulation for the WV distribution reuses the band pass filtered noisy chirp of figure 6.3(b), shown again in figure as figure 6.5(a) for convenience. The chirp has a bandwidth of 400 kHz, ranging from 200 kHz to 600 kHz with a duration of 200 µs and a delay of 100µs from the origin. Figure 6.5(b) shows the pseudo WV distribution of the chirp. The resolution is excellent in both the time and frequency domains. A comparison with the STFT of figure 6.3(d) shows the WV distribution to be better at coping with added noise. Indeed the WV distribution seems to resolve the noisy chirp signal better than the STFT resolves the noise free chirp of figure 6.2(a).

![Figure 6.5: Simulation of the pseudo Wigner-Ville distribution: (a) band pass filtered noisy signal SNR -5db, (b) WV distribution of the noisy chirp.](image)

For completeness figure 6.6 shows the effect of cross terms on the t-f distribution when analyzing a signal containing two chirps of the same frequency parameters as in the last example. Figure 6.6(a) shows the two chirps, each of a 100 µs duration separated by 200 µs. Figure 6.6(b) shows the WV distribution of this signal. Although the two chirps have been accurately resolved the inclusion of cross terms within the distribution leads to the inclusion of a "ghost" chirp at 200 µs. Although obviously not part of the signal in this example it can be noted that the inclusion of these terms could make data analysis a little more confusing. Figure 6.6(c) shows the pseudo-WV distribution. Localizing the area of analysis removes the
cross term components and boosts the energies of the relevant signals. This is why there is a contrast in sharpness between the two images.

![Cross term components](image) (a)

![WV distribution showing associated cross terms](image) (b)

![Pseudo-WV distribution without cross terms](image) (c)

Figure 6.6: Demonstration of cross-term interference and removal: (a) Signal with sequential chirp signal, (b) WV distribution showing associated cross terms, (c) Pseudo-WV distribution without cross terms.

6.4 The Wavelet Transform

6.4.1 Basic Principles

The Wavelet transform is similar to the STFT in that the signal under analysis is convolved with a basis function in order to produce coefficients that are indicative of
frequency content [24]. A wavelet is a localized function in time, which must be oscillatory. This localization of the basis function is what differs it from the globally infinite cosine basis used in the Fourier analysis. Wavelet families are generated from a mother wavelet \( \psi(t) \) by translation and dilation. A wavelet family can be described by

\[
\psi_{a,b}(t) = |a|^{-1/2} \psi\left(\frac{t-b}{a}\right)
\]  

(6.10)

where \( a \) and \( b \) are the scale and shift parameters respectively. Scale is inversely proportional to frequency. So intuitively frequency can be deduced from any value of scale. There are many kinds of wavelet family, all having to satisfy certain mathematical properties. These include wave shapes known as Gaussian [25], Meyer [26], Daubechies [27] and Coifman [28]. The wavelet that is being used in this study is the Morlet wavelet [29] [30]. The Morlet wavelet is described by

\[
\psi(t) = e^{-|t|^2/2} e^{ik\psi t}
\]  

(6.11)

where \( k_\psi \) is a parameter that is commonly \( 2\pi \). This can be used to change the resolution of the t-f resolution of the wavelet [31], (although it is kept at \( 2\pi \) for the duration of this work). The shape of this wavelet can be seen in figure 6.7.

![Figure 6.7: Real part of the Morlet Wavelet.](image)

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The windowing constraints inherent to the STFT are removed as the translation and dilation of the mother wavelet is used to analyze the signal throughout its duration [12]. The wavelet family is moved along the data resulting in overlap. The transformation from 1D data to 2D data is accomplished with

\[
Wf(a, b) = |a|^{-1/2} \int f(t)\psi^*\left(\frac{t-b}{a}\right)dt
\]  

(6.12)

where \(f(t)\) is the time-varying signal and \(\psi^*\) is the complex conjugate of the wavelet function. The multiplication of \(|a|^{-1/2}\) is for energy normalization purposes so that the transformed signal will have the same energy at every scale. The result is the inner product of the signal \(f(t)\) with the wavelet. In this respect this technique is similar to the STFT. The advantage of the wavelet transform is in the removal of the windowing effects discussed previously.

The wavelet basis functions have to fulfill certain mathematical conditions for it to be used efficiently [32]. Firstly it must integrate to zero, i.e.

\[
\int_{-\infty}^{\infty} \psi(t) dt = 0
\]  

(6.13)

This ensures that the function has a wave like nature with a zero mean. The second condition is that the wavelet must have finite energy, i.e.

\[
\int_{-\infty}^{\infty} |\psi(t)|^2 dt < \infty
\]  

(6.14)

This implies that most of the energy in the basis function is confined to a finite duration. The magnitude of the wavelet transform equation 3.12 is called the scalogram. This is an energy distribution that is similar to the Fourier Spectrogram of equation (6.3). This gives the energy density at time \(t\). It is used for the two dimensional representations of time-varying signals and is described by

\[
E_{\psi}(t, \omega) = |Wf(a, b)|^2 = |a|^{-1/2} \int f(t)\psi^*\left(\frac{t-b}{a}\right)dt
\]  

(6.15)

---

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6.4.2 Simulation of the Wavelet Transform

Figure 6.8(a) once again shows the band pass filtered noisy chirp with the simulation resolving it in the t-f plane shown in figure 6.8(b). Although the signal is defined well in the time plane, the representation does suffer from attenuation in the frequency plane. This appears to put the chirp angle at a slightly different slope than that in the t-f representations obtained from the STFT and the WV distribution. The signal is still highly visible though and can be used for further processing and characterization.

Figure 6.8(b) was calculated using a Morlet wavelet with a half-length of 32 at the coarsest scale. This is 1/sqrt of the signal length, which serves as a good guideline. The length of the Morlet wavelet affects the t-f representation in the same way that the window length affects the STFT. This is because the wavelet is acting as a window function. In the STFT the FFT of the windowed portion of the signal is taken, in wavelet analysis a correlation between the signal and all the dilated versions of the Morlet wavelet at the same time point is calculated. The effect of changing the Morlet wavelet half-length is shown in figure 6.9. Figure 6.9(a) shows a t-f representation calculated with a half-length of 2. The frequency resolution is very poor at this small scale. Figure 6.9(b) is calculated with a half-length of 62. The time resolution here is worse than that of figure 6.8(b). This shows that an increase in wavelet half-length will obtain an increase in frequency resolution, but with an associated decrease in time resolution as was shown in Section 6.2.2 for the STFT.
6.5 The Hough Transform and imaging using t-f methods

6.5.1 Basic Principles

Once the transformation from 1D to 2D data is complete a method of extracting the numerical values from the t-f plane is needed so that the data can be processed further. Work in this field has been done specifically for vibration [25] and interferogram analysis [33]. Using these methods however would be over complicated given the situation. The representation of a chirp signal in the t-f plane is a straight line increasing or decreasing depending on the nature of the chirp itself. The problem is therefore one of line detection in an image. The Hough transform [34] [35], is an image processing technique developed in 1956 to solve this problem.

\[ x \cos \theta + y \sin \theta = \rho \]  

(6.16)

For each point of an image \((x, y)\), the Hough transform associates a sinusoid in the plane \((\rho, \theta)\). This draws a line through the point \((x, y)\) and rotates it through 360°. Integration is performed for each line and the value is affected to the point \((\rho, \theta)\) corresponding to the parameters of the line. Therefore, if some pixels exist with high intensities and are concentrated along a straight line in an image then a peak is observed in the \((\rho, \theta)\) domain directly related to the parameters of the line.
The Hough transform is used in our application to retrieve data values along the line of the chirp resolved in the t-f plane. This gives a matrix of time versus frequency that can be used for further processing. This could be used to image materials at different frequencies from the same data. The use of the Hough transform in the t-f domain has the effect of filtering out any noise existing outside the slope of the chirp.

6.5.2 Simulation of the Hough Transform applied to a noisy chirp

To demonstrate the use of the Hough transform in feature extraction it is applied in figure 6.10 to the WV distribution of a noisy chirp. Figure 6.10(a) shows the noisy chirp again for the use of immediate reference. Figure 6.10(b) shows the t-f plane obtained using the

![Figure 6.10: Simulation of the Hough Transform: (a) band pass filtered noisy chirp signal, (b) Hough Transform tracking WV distribution, (c) FFT of noisy chirp, (d) Frequency points taken along the Hough line.](image)

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WV distribution with the application of the Hough transform. The line through the chirp slope shows that the chirp has been detected. Figure 6.10(c) shows the frequency spectrum of the chirp shown in figure 6.10(a). It is noted that the spectrum has been affected by the random noise that was added to the chirp. Figure 6.10(d) shows the frequency spectrum of the chirp using only the frequency components taken along the line in figure 6.10(b). The spectrum has become smooth and the amplitude increased by approximately a factor of four. It is noted therefore that the process can be thought of as a noise filter provided that the slope of the chirp is distinct. Having extracted the data and turned it back to a 1D format it is possible to obtain images. This technique can image across the spectrum of the inputted chirp and return the images obtained within pre-selected frequency bands. This has applications in imaging steel reinforcement bar in concrete for example.

6.5.3 Image simulation as a software check

To make sure that the imaging software was returning a correct result it was deemed necessary to perform a simulation. To this end a grid of 20x21 chirps were made using Matlab™. A point on the grid corresponds to where a time-varying waveform would have been taken using the NCA 1000 unit described in Chapter 4. The grid of chirp signal was constructed out of two chirp signals. The first would be a perfect Hanning windowed chirp signal, shown in figure 6.11(a), with a bandwidth of 500kHz ranging from 150kHz to 650kHz. This reflects the frequency that used with the air-coupled capacitance devices discussed also in chapter 4. These chirps will run along the x-axis from positions 1 to 9 and 13 to 20. Positions 10 to 12 represent a defect, shown in figure 6.11(b). The simulation assumes that, in this case, the signal has passed through a material with a structure so that high frequencies are attenuated. This would be expected, and was observed in Chapters 4 and 5, when signals were passed through concrete. In the case simulated here, the passed frequencies range from 200 kHz to 400 kHz.
Figure 6.11: Chirps used in the image simulation program: (a) 'Perfect chirp', bandwidth of 500 kHz, (b) defected chirp with higher frequencies attenuated, (c) WV distribution of 'perfect chirp', (d) WV distribution of defected chirp.

Figure 6.12(a)(b) is the frequency components, (essentially the FFT of the signal), taken along the Hough line of the t-f spectrums shown above. Notice the attenuation of the higher frequencies. Figure 6.12(c) show an image produced using the imaging software. It takes the components along the line and sums them, basically a summation of the frequency content along the line. Above the ‘defect’ there is less energy in the frequency spectrum because of the high frequency attenuation. Therefore there is a contrast between these points and the ‘perfect chirp’ points. This can easily be seen.

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The software can image in particular frequency bands. Figure 6.13 shows three images obtained. The first, figure 6.13(a) shows the image of the ‘defect’ using the frequency band of 200-450 kHz. Looking at figure 6.12 it can be seen that there is a lot of energy in these frequency bands, this is reflected in the increased amplitude values of figure 6.12(a) compared with (b) and (c). Figure 6.13(b) shows the image obtained in the frequency band of 450-550 kHz. There is less energy in the frequency spectrums of this band, which again is reflected in the amplitude values. Lastly figure 6.13(c) show the image for the frequency band of 550-600 kHz. There is very little energy in this band. The $x$ and $y$ scales have been rescaled so

*Figure 6.12: (a) frequency components along t-f line for the perfect chirp, (b) frequency components long the t-f line for the defected chirp, (c) image produced using summation of frequency components.*

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that the something can be seen at a z scale that is comparable with (a) and (b). This goes to zero if rescaled to match (a) and (b) as demonstrated in figure 6.13(d).

Figure 6.13: Images obtained using chirp frequency band software: (a) 200-450 kHz, (b) 450-550 kHz, (c) 550-600 kHz, (d) 550-600 kHz rescaled to match (a) and (b).

6.6 CHOICE OF T-F TECHNIQUE FOR ULTRASONIC MEASUREMENTS

The nature of the wavelet algorithms suggest that it will operate better in situations such as small signal retrieval. The decision for the most appropriate method of t-f analysis to
be used on ultrasonic signals could still be considered a matter of debate, and is the subject of current research by the author. However, it has been noted in the above that the Wigner-Ville method has the best resolution throughout the simulations. It was decided to continue the comparison for experimental ultrasonic chirp signals, with a view to producing air-coupled images of steel reinforcement bars in concrete samples.

6.7 EXPERIMENTAL MEASUREMENTS IN CONCRETE USING T-F METHODS

The previous sections described three types of time-frequency analysis that could be applied to ultrasonic signals. Each technique varies the resolution returned in the t-f plane. In this Section, ultrasonic chirp signals will be tracked through concrete samples. The best technique will then be used to image steel reinforcement bars in concrete. The air-coupled imaging has been achieved using the same through-transmission techniques as used in earlier Chapters. The results indicate that these techniques may be of good use in failure mechanism characterisations of concrete structures. Part of this work have been the subject of a recent conference paper and a pending journal paper [36].

To illustrate the use of the three t-f analysis techniques a non-contact through transmission system was set up. This comprised of the broadband capacitive transducers and the NCA1000 system both described in Chapter 4. The superior results demonstrated using the focused transducer, again in Chapter 4, meant that it would be used again. Initially the time-varying waveforms from single measurements were recorded. This meant that t-f analysis could be performed upon them and compared. The capacitive transducers were then scanned across concrete plates to produce image of steel reinforcement bars using the same experimental set up. Figure 6.14 shows this set up, essentially the same arrangement as that used earlier in Figure 4.16. Three 30 mm thick concrete plates were made for imaging. These were mixed and set in specially constructed wooden moulds with dimensions of 300 mm x 300 mm. The concrete plates were each made with varying amounts of aggregate. The mixes are shown in Table 6.1.
Table 6.1: Target ratios for concrete mixes incorporating reinforcement bar.

<table>
<thead>
<tr>
<th>Mix No.</th>
<th>OPC</th>
<th>Water</th>
<th>10mm Aggregate</th>
<th>Sand</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>1</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

The weights of mixes 1, 2 and 3 were 7.13, 7.7 and 7.2kg respectively. Each plate had a 10mm steel reinforcement bar passing through it. The duration of the chirp signal had to be shortened from 600 ms used in Chapter 4 to 200 ms. This is a limitation of the system caused by electromagnetic (EM) pickup in the circuitry of the NCA1000 pulser unit. This effectively means that the reference chirp is superimposed upon the time varying waveform. Solutions to this problem will be discussed in further work. This problem is illustrated in figure 6.15. Figure 6.15(a) shows the output from the NCA 1000 in the form of a time-varying waveform, producing a chirp of 600 µs duration through a concrete plate of 30mm. The cross-correlated output from the NCA1000 in figure 6.15(b) reveals a signal at approximately 200 µs. On first glance this looks like it corresponds to the chirp in figure 6.15(a) well. The duration of the chirp was then shortened to 200 µs. The chirp pulse, shown in figure 6.15(c), seems to have moved to the right. The corresponding cross-correlated output stays the same, (but at a lower...
amplitude). Although not immediately obvious the pulse shown in figures 6.15(a) and (c) are the EM pickup in the circuitry of the NCA1000. On-board processing takes care of this, leaving the cross-correlation to perform its function. It can be seen that the information required to resolve the cross-correlated output of figure 6.15(b) is buried within this EM pickup as the output of figure 4.2(d) is at the same time. Unfortunately the t-f software cannot resolve this buried information. Therefore the pulse had to be shortened and the separation between the transducers had to be sufficient in order for the ‘real’ chirp to be seen so that t-f analysis could be performed upon it. The energy shown to the right of the EM pickup chirp in figure 6.15(c) corresponds to the cross-correlated output of figure 6.15(d).

![Graphs of EM pickup in the NCA1000](image)

Figure 6.15: Demonstration of EM pickup in the NCA1000: (a) EM pulse of 600μs swamping the real chirp signal, (b) cross-correlated output from the 600μs pulse, (c) EM pulse of 200μs with the real chirp signal to the right of it, (d) cross-correlated output from the 200μs pulse.

The problem with shortening the chirp pulse is that less energy is delivered to the samples under interrogation. This effectively means that the signals have more chance of being

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attenuated especially considering the composition of concrete, (see Chapter 3). The best compromise was achieved however. The chirp signal generated by the NCA1000 had a bandwidth of 500 kHz with a centre frequency of 400 kHz.

Figure 6.16(a) shows the chirp signal produced by the NCA1000 across the air gap. Figure 6.16(b) is the STFT representation of this chirp. It has been well reproduced in both the time and frequency planes.

![Figure 6.16: T-f representations of an ultrasonic chirp across an air-gap. (a) Chirp signal across air-gap of 13.7mm, (b) STFT representation of the chirp.](image)

The t-f representations of the Wigner-Ville distribution and the Morlet wavelet are shown in figure 6.17. Both give good results. The resolution of the WV distribution is excellent whereas the wavelet’s resolution does seem to spread a little in time. The energy of the WV distribution is lower than that of the other two t-f representations. This is of course a more significant problem when examining heterogeneous materials as the ultrasonic signals are heavily attenuated.
Figure 6.17: T-f representations of an ultrasonic chirp across an air-gap, (a) Wigner-Ville distribution of the chirp in figure 4.3(a), (b) Morlet-wavelet representation of the chirp in figure 4.3(a).

Figure 6.18 shows the t-f representations taken of the ultrasonic chirps through the paste plate. All three have picked out the chirp signal. The noise introduced by the attenuative nature of the concrete paste can be seen clearly in the STFT, figure 4.18(a). The WV distribution and the Morlet wavelet, (figures 6.18(a) and (b) respectively), seem to do a better job of dealing with this. The resolution of the WV distribution is very good and the second ultrasonic chirp echo from within the plate can clearly be seen to the right of the first chirp coming in at around 530 μs. Energy in this area can be seen in the other two distributions but it is not as prominent. The frequency scale on the Morlet wavelet diagram is reduced in order to cut down on computational time.
Figure 6.18: T-f representations of ultrasonic chirp signal through concrete paste sample, (a) STFT representation (b) Wigner-Ville representation, (c) Morlet wavelet representation.

Figure 6.19 shows the t-f representations through the concrete plate made from mix number 2 in Table 6.1. This contains 10mm aggregate, something that attenuates ultrasound...
The chirp is once again visible in all representations with the echoed chirp being prevalent also. The noise, added by the aggregate, is visible, although does not detract from the chirps. The time-varying waveforms were recorded in three places over the concrete plates. T-f analysis was then performed on all three and the best one saved. It is therefore quite possible that the path of the ultrasound does not take it through any significant
proportion of aggregate. This hypothesis can be arrived at from a comparison of figures 6.18 and 6.19. The energy in the chirp in figure 6.19 does not seem to have diminished in any way. This would suggest that the ultrasound has travelled predominantly through the paste. However, this is not a problem in this study, as the object is to inform on the usefulness of t-f representations on the analysis of ultrasonic signals and not to correlate aggregate content with frequency attenuation.

Figure 6.20 shows the t-f representations for the ultrasonic chirps travelling through

![Figure 6.20: T-f representations through concrete sample of mix 3, (a) STFT representation (b) Wigner-Ville representation, (c) Morlet wavelet representation.](image)

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mix 3 in Table 6.1. Once again all chirps can be visualised. This meant that it could be feasible to image the three concrete plate samples, as the chirp signals could be distinguished after the ultrasonic signal had passed through the concrete.

6.8 Example of Frequency Spectrum Denoising

The use of the Hough transform in the t-f plane allows for clearer frequency spectra as shown previously. Figure 6.21(a) shows a received chirp through concrete specimen mix 6, (see chapter 4), and (b) is its frequency spectrum taken using conventional Fourier means. The transmitted chirp has a 200μs duration and a bandwidth of 500kHz centering upon 400kHz. The frequency spectrum shows information from around 200kHz to 450kHz but cannot be deemed good enough to resolve accurate information about frequency attenuation.

![Figure 6.21](image1.png)

(b) Figure 6.21: (a) Received chirp signal through concrete specimen mix 6, (b) Its associated frequency spectrum.

Figure 6.22(a) show the time-frequency spectrum acquired using the Wigner-Ville method. The chirp signal can clearly be seen. The Hough transform has been utilized in figure 6.22(b) with the chirp line being accurately found. Figure 6.22(c) shows the de-noised frequency spectrum taking the points through the Hough line. It can be seen clearly that the chirp signal has undergone high frequency attenuation and that the passed frequencies range from around 200kHz to 350kHz. The information retrieved from this is clearly more useful than what is presented in figure 6.21(b) which displays the frequency content of the noise also.

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Figure 6.22: Information extraction using the Hough Transform, (a) Time-frequency spectrum of the received chirp shown in figure 6.21(a), (b) The Hough line through the chirp signal, (c) The resultant de-noised frequency spectrum.

6.9 AIR-COUPLED IMAGING USING T-F METHODS

The apparatus shown earlier in Figure 6.14 was now used to collect data for imaging purposes. As before, the source and receiver were scanned in unison over the sample to be imaged, and data collected in the form of time waveforms for later processing using t-f methods.

To ensure that the approach could be used for imaging, data was first collected from a 30 mm thick Perspex plate containing a side-drilled hole of 10 mm diameter. The results are
shown in Figure 6.23. This image was produced with the application of the Hough transform to data mining in the t-f plane. To produce this image, the total integrated amplitude along the chirp line was taken, to provide a single value for each position in the image. Note that this is an untreated image, and the raster scan trajectory can be seen to be producing horizontal artifacts into the resultant image. This is thought to be due to the fact that there was not sufficient overlap spatially between successive horizontal linear scans (an artifact that could easily be removed). Despite this, it is evident that the side-drilled hole has been successfully imaged with a reasonable resolution.

Note that some widening of the lateral dimensions of the hole in the image is expected, because of two factors: diffraction of ultrasonic energy around the drilled hole rather than through the air gap, and the lateral dimensions of the receiving transducer (10 mm diameter). Experiments have shown that this probably contributes a blurring of the image at its edge of approximately 3mm in each case.

The image of Figure 6.24 demonstrates that the approach had some merit. The hole was clearly visible as a reduction in signal amplitude in through-transmission. However, the extension of this method to concrete would involve much lower SNRs, due to the attenuation due to scattering etc within the material. However, as was seen in earlier simulations and experiments with concrete plates, the t-f method could recover sufficient information to give useable data for imaging. Thus, having optimised the scanning system for imaging in Perspex,
and image was now obtained in a concrete plate containing a 10mm diameter steel reinforcement bar. As in previous cases, the concrete sample was 30 mm thick, and in this case used concrete of Mix 1 of Table 6.1. The reinforcement bar (rebar) can clearly be seen and the resolution appears to be affected by the same processes as in figure 6.23. However, the presence of the rebar has been detected successfully, with a reasonable image quality.

![Air-coupled ultrasonic image of a 10mm diameter rebar in a 30 mm thick concrete sample (mix 1), produced by processing of the data by a t-f method based on a Hough transform.](image)

**Figure 6.24:** Air-coupled ultrasonic image of a 10mm diameter rebar in a 30 mm thick concrete sample (mix 1), produced by processing of the data by a t-f method based on a Hough transform.

### 6.9 CONCLUSIONS

This Chapter has demonstrated that time frequency (t-f) methods have merit in the detection and interpretation of air-coupled ultrasonic signals. The work has shown that information concerning the signals can be obtained via a variety of transform methods, all of which show the time-frequency history of the signal. This type of information is not available in pulse compression outputs, where a single peak in time results.
6.10 REFERENCES


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Chapter 7

THE APPLICATION OF THE SUPERHETERODYNE TECHNIQUE TO ULTRASONIC INSPECTION

7.1 INTRODUCTION

The attenuating nature of concrete on ultrasonic signals at frequencies above 100 kHz highlights the need to use signal processing techniques for signal recovery. As seen in earlier chapters, the signal-to-noise ratio in air-coupled ultrasound is low compared to that found when using contact systems. The power that can be supplied to the capacitance transducers is also limited by the commencement of the breakdown of the polymer film. The inclusion of an inherently difficult test material such as concrete means that NDE via ultrasound must be achieved from signals that must be pulled from the noise floor. The use of the pulse compression technique in this regard has been discussed in Chapter 4, and has been seen to return very accurate time-of-flight information. Another well-known signal processing technique used predominantly in telecommunication applications is the superheterodyne technique. It was conceived by Edwin Armstrong in 1918 [1], and has been used in ultrasonic applications such as the identification of bats [2]. It is also a widely-used technique in optical interferometry, useful in the detection of ultrasonic displacements at solid surfaces [3,4].

This chapter describes the application of the superheterodyne technique to the ultrasonic analysis of concrete. A mathematical overview is presented and simulated using Matlab™. An experiment is then conducted using the technique on a range of concrete samples using the Ritec™ SNAP system. This is a high power ultrasonic instrument specifically designed for the study of non-linear properties for the non-destructive evaluation of materials, although here it is used in the linear mode.

The present experiments represent a preliminary investigation into the use of such a system as a possible alternative to pulse compression. As will be seen below,
Superheterodyne techniques are inherently of narrow bandwidth, and hence are in contrast to the broad bandwidth nature of pulse compression. The use of tone bursts has, in fact, been reported in ultrasonic air-coupled inspection systems for use in thin metals and bonded joints [5-7]. Here, the frequency of operation could be tuned to the through-thickness resonance of the sample. The use of tone bursts has also been widely reported using piezoelectric transducers in through-transmission mode [8,9], where again the through-thickness resonance was excited. In the case of concrete, this would not be feasible for real structures at the frequencies of interest. Thus, it was felt interesting to look at this method in concrete, where scattering and attenuation would lead to a totally different type of response.

7.2 THE SUPERHETERODYNE TECHNIQUE

The basis for the application of the superheterodyne technique to ultrasonic testing is to mix the received ultrasonic signal $S(t)$ with a second frequency ($C(t)$) to produce a difference frequency output. A particular frequency in the received signal is translated into sum and difference frequencies. The frequency of the received ultrasound signal is mixed with a signal of a different frequency created by digital frequency synthesizers. This generates a useful beat frequency that can be either the lower or higher side band. A band pass filter then selects the useful beat frequency. This is known as the Intermediate Frequency (I.F). The band-pass filter is effective in noise reduction, which is instrumental in increasing the SNR. In our application the lower band is selected, as it is easier to amplify low frequency signals because of component constraints at high frequencies. Note also that filtering at low frequencies is a good way of reducing noise, because of the narrower band-pass filter bandwidths.

A schematic of a simple superheterodyne receiver is shown in figure 6.1. A capacitive transducer is used to receive the interrogative ultrasonic signal. The signal is then passed on to a band-pass filter stage which helps to boost the received signal and dismiss the noise outside of this range. At the mixing stage the filtered received signal is mixed from a signal created from a local oscillator. This is a piezoelectric crystal that can be used to emit a narrow range of frequencies. The local oscillator is linked to the first bandpass filter, as they must both vary with the frequency of the received signal, (the carrier frequency). The Intermediate frequency is then amplified and passed through...
another filtering stage in order to reduce the noise levels further. The superheterodyne technique is implemented within the Ritec™ SNAP system and is followed by an integrator module that performs a windowed integration over the outputted signal. The following section provides a mathematical overview of the superheterodyne technique as well as a simulation carried out in Matlab™.

![Diagram of a superheterodyne receiver]

Figure 7.1: Schematic representation of a superheterodyne receiver.

### 7.3 MATHEMATICAL OVERVIEW OF THE SUPERHETERODYNE TECHNIQUE

Figure 7.2 is a redraw of the schematic of figure 7.1 with emphasis placed on the operations placed on the frequency of the received signal. This received signal $S(t)$ can be represented by:

$$S(t) = x(t) \cos(2\pi f_r t)$$  \hspace{1cm} (7.1)

Where

- $f_r$ is the frequency of the received signal
- $x(t)$ is the amplitude of the signal

The received signal $S(t)$ is then mixed with a signal from the local oscillator, $L(t)$, the signal from which is given by:
\[ L(t) = A \cos(2\pi f_c t), \]  

(7.2)

where \( A \) is the amplitude and \( f_c \) is the frequency of the local oscillator signal. The mixing process outputs the signal \( Z(t) \), given by:

\[ Z(t) = S(t) L(T) \]  

(7.3)

where

\[ Z(t) = x(t) \cos(2\pi f_c t) A \cos(2\pi f_s t). \]  

(7.4)

Using the following trigonometric identity:

\[ \cos(x) \cos(y) = \frac{1}{2} [\cos(x + y) + \cos(x - y)], \]  

(7.5)

equation (6.4) can be further simplified to give:

\[ Z(t) = \frac{A x(t)}{2} \cos(2\pi (f_c + f_s) t) + \frac{A x(t)}{2} \cos(2\pi (f_c - f_s) t) \]  

(6.6)

As can be seen, the result separates the signal into sum and difference components. The unwanted signal (usually the sum signal) is then filtered out at the subsequent band-pass stage. The resultant signal left after filtering can then be represented as:

\[ Z(t) = \frac{A x(t)}{2} \cos(2\pi (f_c - f_s) t) \]  

(7.7)

This, as expected, is in the form of a single frequency shifted downwards in frequency from the original. The overall process is described by the diagram shown in figure 7.2, for a signal input in the form of a single frequency.
7.4 SIMULATION OF THE SUPERHETERODYNE TECHNIQUE

MATLAB can be used to model the superheterodyne process for a typical tone-burst signal that would be used for ultrasonic testing. The results of such an initial simulation are shown in figure 7.3. The received signal \( S(t) \) that might result from an ultrasonic experiment is shown in figure 6.3(a), and is a narrowband tone-burst signal at a frequency of 250 kHz. Its corresponding frequency spectrum is shown in figure 7.3(b). This received signal is then multiplied by a signal that would have been synthesised from a local oscillator. In this instance this frequency is 100 kHz. This multiplication results in the formation of sum and difference frequencies demonstrating mathematically in the previous section. Figures 7.3(c) and (d) show the heterodyned signal and its associated frequency spectrum respectively. Note the typical modulated appearance of the time waveform, and the expected double frequency peak in the spectrum. The sum and difference frequencies are seen at 150 kHz and 350 kHz, in agreement with equation (7.6).

A band-pass filter is then implemented between the frequencies of 50 kHz and 250 kHz. This allows only the difference frequency of 150 kHz to be passed. The resultant waveform and its frequency spectrum are shown in figures 7.3(e)-(f). While there is some structure to the signal, it is evident that a single lower frequency peak remains at the IF value. The structure noted in the spectra arises from the absence of windowing – this generation of side bands is a well-known feature in such systems (and was noted earlier in pulse compression, where it appears for similar reasons).
Figure 7.3: Simulation of the Superheterodyne technique: (a) The transmitted signal, (b) Its frequency spectrum, (c) The heterodyned signal, (d) Its frequency spectrum, (e) Waveform after bandpass filtering, (f) Its frequency spectrum.
Figure 7.4 shows the more realistic scenario in which the signal is embedded in noise. The signal was mixed into random noise of 75% of the signal amplitude. Figure 7.4(a) shows the resultant transmitted waveform which a signal to noise ratio (SNR) of 2.5 approximately. Its corresponding frequency spectrum is shown in figure 7.4(b). The signal is then mixed with a signal from the local oscillator at 100 kHz again. The heterodyned signal and its frequency spectrum are shown in figure 7.4(c)-(d).

![Figure 7.4: Simulation of the Superheterodyne technique with 75% noise: (a) The transmitted signal, (b) Its frequency spectrum, (c) The heterodyned signal, (d) Its frequency spectrum, (e) Waveform after bandpass filtering, (f) Its frequency spectrum.](image-url)
The bandpass filter is then applied to this signal and the resultant waveform is displayed in figure 7.4(e). It has a SNR of 12 approximately, which is an improvement by a factor of 5. The frequency spectrum of figure 7.4(f) clarifies the 150 kHz content of the waveform.

In reality, ultrasonic signals received using experimental systems such as the Ritec™ to be described below are still under the noise floor, even after superheterodyning. Therefore the system utilises an integrator, so that areas of higher signal density can be distinguished. The heterodyned signal is windowed to a user-defined value and the integration is performed henceforth. The output from a simulated integrator is shown in figure 7.5. This has used the simulated signal shown earlier in figure 7.4(e) as its input. It can be seen that an increase in signal density occurs between the times of 60 and 80\(\mu s\), the time duration over which the tone-burst signal is visible in the figure. The use of integration allows signals to be identified where none is visible by eye, again a feature that it shares with pulse compression. Such types of signal are likely to be encountered routinely in air-coupled ultrasonic experiments, especially in materials such as concrete.

![Figure 7.5: Output resulting from integration of the signal shown in figure 7.4(e).](image)

The above MATLAB simulations demonstrated that the approach had some merit. Thus, in situations where a through-thickness resonance could not be guaranteed, and where the material was likely to be highly attenuating, the technique had a chance at recovering signals from noise. It was thus thought to be a reasonable approach to attempt experimentally for air-coupled ultrasonic experiments. This is described in the next section.

Chapter 6: The Application Of The Superheterodyne Technique To Ultrasonic Inspection
7.5 APPLICATION OF THE SUPERHETERODYNE TECHNIQUE TO AIR-COUPLED ANALYSIS OF CONCRETE

The superheterodyne technique has been effectively demonstrated to increase SNRs in noisy signals. The technique was thus applied to the air-coupled analysis of concrete using the capacitive transducers described earlier in Chapter 4. In the experiments to be described, the signal was transmitted in through-transmission across concrete samples, the mixes of which were as shown previously in Tables 4.3 and 4.4 of Chapter 4.

To illustrate the operation of the Ritec™ SNAP system in generating ton-bursts in combination with the polymer-membrane capacitive transducers described in previous chapters, an 8-cycle tone-burst signal with a frequency of 250 kHz and a duration of 32 µs was first used over an air gap so that a response could be viewed. The Ritec™ SNAP system output voltage was set to 600V peak to peak and the receiver gain was set to 72dB. Figure 7.6(a) shows the tone-burst voltage signal that is generated by the Ritec™ SNAP system. Figure 7.6(b) and (c) show the received ultrasonic waveform and the output from the integrator respectively.

In anticipation of noisy data from the waveform outputs from concrete interrogation, a method of obtaining time of flights from the integrated output needed to be established. A program to locate the centre of the bulge outputted by the integrator was coded and run for the output shown in figure 7.6(c). It returned a value of 257.4 µs, which is approximately the centre. It is worth bearing in mind that this is not looking at local maxima but is looking for the centre of the centre of the signal’s energy density. A maximum value is returned from the Ritec™ when the integrator window is located at the beginning of the bulge. This of course depends on window size so it follows that it must equal the generated pulse duration of 32 µs.

It will be seen from the results presented in figure 7.6 that the received signal was as expected from the earlier simulations, with the superheterodyned output being in the form of a low frequency (IF) time waveform, and the integrated output returning a single peak. However, the received signals in this case are likely to be orders of magnitude larger than those received after travelling through a solid using air-coupling techniques. Experiments were thus performed in real samples. In real situations such as
these, it was found that signal averaging of waveforms was required to improve the SNR to a point where the technique would become of value.

Figure 7.6: (a) 8 cycle 250kHz tone burst signal, (b) Resultant ultrasonic waveform received across an air gap, and (c) the integrated output.

The number of averages used in experiments using the Ritec\textsuperscript{TM} thus had to be ascertained, as a trade off existed between accuracy and time taken for averages. As an illustration, figures 7.7(a) to (d) show the integrated output of the ultrasonic waveform, for experiments using a concrete paste sample (as in mix 1, Chapter 4). This was performed in simple through-transmission, using 5, 20, 50 and 200 averages respectively. A maximum value of 200 averages was chosen for experiments, as the difference between this and using 500 averages was not significant. Note that signal averaging greatly improves the SNR of received integrated outputs, and the SNR improves with the number of averages, as expected. The discrepancy at 200 $\mu$s in figure 7.7(d) can be attributed to a

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Chapter 6: The Application Of The Superheterodyne Technique To Ultrasonic Inspection
system error in the Ritec unit, and is not an artefact of the received ultrasonic signal. In this case, it can be seen that there are a number of maxima within one output. This is due to multiple reflections within the air gap between the receiver transducer and the sample. In this case the time of flight reading cannot be taken using the centre of the energy density, as it is evident that multiple reflections are present. However, the initial peak could still be used as a measure, provided readings were taken at a sufficiently large distance from the sample.

Figure 7.7: Integrated experimental outputs through a paste sample, (a) 5 averages, (b) 20 averages, (c) 50 averages, (d) 200 averages.

Figure 7.8 (a) shows the received waveform through a concrete sample, this being mix 1 of Chapter 4. The time waveform shows a large transient at the left hand side, this being the electrical breakthrough signal from the transmitted signal, and as such is noise. The actual transmitted signal is buried in the noise, but can just be seen by the naked eye as
commencing after about 200 μs in the time waveform. The integrated superheterodyne output is shown in figure 7.8(b), with the local maxima occurring at 226 μs and the energy centre is at 216 μs, which averages to 221 μs. Note now that a single peak is present, making the analysis simpler, although interference from reflections is still evident later in the integrated output.

![Figure 7.8](image)

**Figure 7.8** (a) Received time waveform through mix1 concrete, and (b) the integrated superheterodyne output.

Figure 7.9 shows a similar output for concrete mix 2, where again the general features are observed.

![Figure 7.9](image)

**Figure 7.9**: Superheterodyne results for a concrete sample using mix 2. (a) Received time waveform, (b) sample integrated output.
7.6 DISCUSSION

The above has demonstrated that superheterodyne techniques can be used to provide an air-coupled ultrasonic signal in concrete samples. The basic approach mixes the signal to a lower IF frequency, filters the result, and subsequently integrates the time waveform (with averaging) to get a final output. This leads to a broad peak in time, which in principle represents both the arrival time and the amplitude of the through-transmitted air-coupled ultrasonic waveform.

It will be seen that the output is not as "user-friendly" as that from either pulse compression or time-frequency techniques. Being in the form of a broad time peak means that the accurate measurement of arrival time is difficult. In the above, this was estimated using both the peak and the centre of energy of the peak, and any asymmetry would lead to different values (as was observed). Also, the broad time duration means that overlap between reflections can occur. In pulse compression and time-frequency analysis, this is not a problem. In pulse compression the outputs are narrow in time, and in time-frequency methods the main aim is to display time characteristics for analysis purposes. In superheterodyning, neither is possible.

It has been concluded that, because of these problems, there needs to be more work done before such methods could be recommended for use in air-coupled inspection of concrete.
7.7 REFERENCES


Chapter 6: The Application Of The Superheterodyne Technique To Ultrasonic Inspection
Chapter 8

CONCLUSIONS AND FURTHER WORK

8.1 CONCLUSIONS

This thesis has looked at new methods for the ultrasonic inspection of concrete, and for the first time has used air-coupled techniques to do this. The improvement in air-coupled transducer technology has allowed the transmission and reception of broad bandwidth ultrasonic signals through air. This has led to applications to various types of materials inspection techniques, for example in concrete. This is despite the large difference in acoustic impedance between air and the material under test. Because of the low signal to noise ratios that are still encountered, various signal processing techniques are required to retrieve the ultrasonic signals from beneath the noise floor.

The first technique looked at was cross-correlation. This signal processing method was incorporated into pulse compression, using ultrasonic chirp signals. This enabled us to retrieve very small signal levels, and to obtain accurate time of flight values. This allowed us to compare contact and non-contact ultrasonic systems for use in concrete. In Chapter 4, it was demonstrated that while the two techniques gave similar results for homogeneous blocks (such as Perspex and steel), the PUNDIT contact derived returned higher values of speed than the non-contact system. This was attributed to preferential coupling between the steel outer face of the PUNDIT contact transducers and the aggregate, whereas the air-coupled technique coupled more easily into the paste. The velocity in the paste was lower than that in the aggregate, giving the observed effect.

Pulse compression was shown to be a very successful technique for making measurements in concrete samples with various mixes of aggregate, sand etc. It managed to detect changes in structure, and showed that it was sensitive to changes in paste properties as ageing occurred. It was sufficiently sensitive to also allow non-contact through-transmission imaging to be performed on steel reinforcement bars (rebars).

Chapter 5 continued the work with pulse compression, and looked again at the effect of concrete properties. Again it was confirmed that the contact system returned higher sound velocity values than the non-contact air-coupled system. The work particularly concentrated on the effect of humidity in the concrete. Samples were prepared carefully so that this humidity could be quantified. It was found that the speed of sound...
increased with storage humidity. This is expected, as the concrete has a complex porosity system, which is highly dependent on the moisture content during manufacture. The fact that coupling in non-contact experiments was primarily into the paste was thought to increase sensitivity to humidity. The dependence on sound velocity with humidity was then used to apply a correction factor to velocity measurements in various concrete mixes, so that variations due to humidity could be removed from the data. The sensitivity of the air-coupled system allows this to be done, whereas contacting systems would find this difficult.

Chapter 6 looked at the use of time-frequency analysis to non-contact air-coupled experiments. The development of time-frequency tools allowed us to display the chirp signal in a time-frequency plane, where more information could be extracted (compared to conventional time-of-flight variations). It was also demonstrated that it is an excellent alternative technique to pulse compression in extracting low signal levels from the noise floor. Extensive simulations were presented, and applied to the chirp signals for the case of frequency information extraction and imaging. The application of these tools to real signals allowed us to track the chirps accurately in time and frequency. This led to images of detects in both Perspex and concrete being presented, as well as a practical example of frequency spectra de-noising. It was demonstrated in this work that time-frequency methods could be applied to air-coupled signals in concrete, to give a greater insight into the propagation process.

Chapter 7 investigated superheterodyning as a possible alternative to pulse compression and time-frequency analysis. Instead of using broad bandwidth chirp signals, it used gated tone-bursts and frequency mixing, to again attempt an improvement in SNRs. This was predominantly due to the band-pass filtering of the intermediate frequency (IF) signal. The integrated output shows at what time points there are energy concentrations. Because of the superheterodyne’s lack of efficiency and extended time duration, metrics containing accurate information could not easily be obtained.

8.2 FURTHER WORK

The research into pulse compression using air coupling was very successful in measuring changes in sound speed with changes in internal structure of concrete. This was done by preparing samples with different mix specifications, and by careful control of humidity. There are, however, a range of other constructional materials where the technique could also be used. Examples include fibre-reinforced composites such as
pultruded materials, where there is great concern that damage may occur at bolted joints (where steel points are loaded onto composites). Air-coupled ultrasonic techniques could be applied in this area. Another area to which the same techniques could possibly be applied is acoustic emission (AE), especially the use of time-frequency analysis to look at fracture events.

The technique may also be able to distinguish different strengths of concrete from ultrasonic measurements. While there was some success in this work, further techniques could be applied to differentiate between samples with similar sound velocities but different strengths. This could possibly be achieved using time-frequency analysis. A robust technique to quantify strength of concrete from ultrasonic measurements is currently not available. Further work in this area may lead to such a technique.

The measurements in this thesis were all conducted in through-transmission. This was primarily due to the fact that there is a very large front wall echo, which would return to a transducer in the pulse-echo mode. Current instrumentation does not allow such measurements to be made. It is thought that by paying attention to higher transmission powers, and by applying new techniques such as Independent Component Analysis (ICA), multiple reflections could be split into their individual frequency components. Many applications would open up if single-sided inspections could be carried out, especially with a fully scannable air-coupled system. This could be especially interesting if scanned ultrasound could be combined with ground-penetrating radar techniques. Radar could be used to find big defects, but smaller ones can be difficult to detect; it is also strongly affected by rebar presence. Air-coupled ultrasound could be used to find smaller defect, and to see behind rebar layers.

Chapter 8: Conclusions and Further Work
Publications


- J. BERRIMAN, T. H. Gan, D. A. Hutchins, P. Purnell, ‘Non-contact ultrasonic interrogation of concrete’

- P. Purnell, D. A. Hutchins, J. BERRIMAN, T. H. Gan
  Sounding it out—advances in ultrasonic diagnostics for construction materials, *New Civil Engineer*.

- P. Purnell, D. A. Hutchins, J. BERRIMAN, T. H. Gan,
  Advances in ultrasonic interrogation of concrete—testing without touching. *Concrete in press*.

- P. Purnell, T. H. Gan, D. A. Hutchins, J. Berriman

- J. BERRIMAN, A. Neild, D. A. Hutchins, T. H. Gan, P. Purnell
  Time-frequency analysis of non-contact ultrasonic signals for the NDE of concrete, *Proceeding of the international conference on acoustics, Kyoto, Japan. April, 2004*.

- J. BERRIMAN, A. Neild, T. H. Gan, D. Hutchins, P. Purnell

Pending

- T. H. Gan, J. BERRIMAN, P. Purnell, D. A. Hutchins
  Application of advanced ultrasonic NDT to concrete *Ultrasonics, in prep ETS 6/2004*

- J. BERRIMAN, A. Neild, T. H. Gan, D. Hutchins, P. Purnell
  The application of time-frequency analysis to the field of air-coupled ultrasonic analysis of concrete *Ultrasonics, in prep ETS 7/2004*
## Appendix 1: Sample weights

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<th>after oven</th>
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APPENDIX 2

MATLAB™ program listings

A) CHIRP GENERATION AND SIMULATION

close all;
clear all;
noPoints=500;
signalLength=200e-6;
increment=0.4e-6;%signalLength/noPoints;

f1=150000;
f2=650000;
B=f2-f1;

%generation of chirp
for T=1:signalLength/increment;
    t=(T-1)*increment;
    tm(T)=t;
    normalchirp2(T)=sin(2*pi*f1*t+pi*B*t^2/signalLength);
    hanchirp(T)=0.5*(1-
    cos(2*pi*t/signalLength))*sin(2*pi*f1*t+pi*B*t^2/signalLength);
    frequency=1/2/increment/(noPoints/2)*(1:noPoints/2);
end
%Transmitted chirp. Lengthens signal so the delay can be added.
new_points=noPoints*2.048
plot_time=signalLength*2.048
inc2=plot_time/new_points;
tm1=(1:new_points)*inc2;

newpoints2=2048;
inc3=plot_time/newpoints2;
tm2=(1:newpoints2)*inc3;

size(hanchirp)
%Create ideal signal
new_array(1:new_points)=0;
new_chirp(1:new_points)=0;
new_array(1:noPoints)=hanchirp;
%new_array(1:noPoints)=normalchirp;
new_chirp=new_array;

%Adding delay of noPoints*2
new_array1(1:new_points)=0;
new_array2(1:new_points)=0;
delayed_pos=noPoints*0.512;
delayed_chirp(1:new_points)=0;
normalchirp(1:new_points)=0;
new_array1(delayed_pos:length(hanchirp)+delayed_pos-1)=hanchirp;
new_array2(delayed_pos:length(normalchirp2)+delayed_pos-1)=normalchirp2;
delayed_chirp=new_array1;
normalchirp=new_array2;

%noise_factor=0.01;
%noise=randn(size(1:new_points))*noise_factor; %random noise
noisefactor=1.5;
noise=randn(size(1:new_points))*noise_factor;
noisehan=noise+delayed_chirp;

nh=noisehan;

FFT_delayed_chirp=fftshift(abs(fft(delayed_chirp)));

FFT_delayed_chirp_half=FFT_delayed_chirp(new_points/2+1:new_points);

freq_new=1/2/inc2/(new_points/2)*(1:new_points/2);

[b,a]=ellip(4,0.5,40,[50 400]*1/1024);
[H,w]=freqz(b,a,length(freq_new));
H=H*50;

filter_signal=filter(b,a,nh);

%plot(tm1,delayed_chirp)
size(delayed_chirp)

%plot(tm1,normalchirp)
size(normalchirp)

%subplot(4,1,1)
%plot(tm1,nh)
%subplot(4,1,2)
%plot(tm1,filter_signal)

FFT_filter_signal=fftshift(abs(fft(filter_signal)));

FFT_filter_signal_half=FFT_filter_signal(new_points/2+1:new_points);

freq_new=1/2/inc2/(new_points/2)*(1:new_points/2);

%subplot(4,1,3)
%plot(freq_new,FFT_filter_signal_half)

cc=xcorr(delayed_chirp,new_chirp);
c1=xcorr(nh,new_chirp);
c1=abs(c1);

%subplot(4,1,4)

Appendix 2
%plot(cc)

a=delayed_chirp;
b=[a,a];
size(b)
plot(b)

B) SUPERHETERODYNE SIMULATION CODE

%Sthetodyne program

signal_point= 100;
Fs= 1000000;
t=(1:signal_point)/Fs;

max_freq=1/(2*(t(2)-t(1)));
delta_freq=(1:50)*(max_freq/50);
delta_freq=delta_freq-delta_freq(1); %starts at 0

C_Freq1=100000; %carrier frequency
S_Freq2=250000; %signal frequency
carrier=sin(2*pi*t*C_Freq1); %carrier signal at 100kHz
signal=sin(2*pi*t*S_Freq2); %tone burst signal at 250kHz

fftcARRIER=fftshift(abs(fft(carrier))),
fftsignal=fftshift(abs(M(signal))),

subplot(2,2,1)
plot(t, carrier)
title('Carrier ToneBurst at 100kHz');

subplot(2,2,3)
plot(t, signal)
title('ToneBurst Signal at 250kHz');

subplot(2,2,2)
plot(delta_freq, fftcarrier)
title('Frequency of the Carrier Signal at 100kHz');

subplot(2,2,4)
plot(delta_freq, fftsignal)
title('Frequency of the Toneburst at 250kHz');

for i=1:length(carrier);
hetrodynne(i)=carrier(i)*signal(i):
end:
ffthet = fftshift(abs(M(hetrodyne)));  
ffthet = ffthet(length(signal)/2+1:length(signal));  
[b, a] = ellip(5, 0.5, 40, [130 170]*2/1000);  
[H, w] = freqz(b, a, 50); % 50 is the length of the frequency points  
H = H*max(fftcarrier)/2;  
shifted = filter(b, a, hetrodyne);  
fftfilter = fftshift(abs(fft(shifted)));  
fftfilter = fftfilter(length(shifted)/2+1:length(shifted));

%Figure 2
figure
subplot(4,1,1)
plot(t, hetrodyne)
title('Hetrodyning of Carrier & ToneBurst Signal - 100kHz X 250kHz');

subplot(4,1,2)
plot(delta_freq, ffthet)
title('Frequency of the hetrodyned signal, filter band & carrier frequency');
hold on;
plot(delta_freq, fftcarrier, 'r')
plot(delta_freq, abs(H), 'g'); % filtr shape and its frequency
hold off
subplot(4,1,3)
plot(t, shifted); % filtr shape and its frequency

subplot(4,1,4)
plot(delta_freq, fftfilter); % filtr shape and its frequency of the filtered signal
title('Frequency of the selected Lower band frequency, 150kHz');

%Figure 3
figure;

length_of_waveform=1000;

x=zeros(size(1:length_of_waveform));
y=randn(size(1:length_of_waveform)); % generating random noise
y=y/max(y);
y=y*0.75; % put to 0.5 for noise
signal_shape=sin(2*pi*t*S_Freq2); % 250kHz
generated_signal=x;
generated_signal(1:100)=signal_shape;

subplot(3,1,1)
%generated waveform is then transmitted on a plate as Ao Lam wave of frequency 250kHz
transmitted_signal=x;
transmitted_signal(501:600)=signal_shape;
plot(transmitted_signal,'r')
%title('Transmitted signal across a plate - 250kHz')

%transmitted is now embedded in noise

transmit_noise=y;
transmit_noise(501:600)=y(501:600)+signal_shape;
%transmit_noise(501:600)=signal_shape;
subplot(3,1,2)
plot(transmit_noise)
%title('Transmitted signal (250kHz) across a plate with noise')
subplot(3,1,3)
plot(y)
%title('noise')

ZZ=std(transmitted_signal)
ZZ_noise=std(y)

Fs=1000000;
time=(1:length_of_waveform)/Fs;
max_freq_prac=1/(2*(time(2)-time(1)));
delta_freq_prac=(1:500)*(max_freq_prac/500);
carrier_point=1000;
Fs=1000000;
t=(1:carrier_point)/Fs;
carrier_signal=sin(2*pi*t*C_Freq1); %50Hz

%Filter the transmitted signal to remove noise
%[d1,c1]=ellip(4,0.5,40,[242 257]*2/1000);
[d1,c1]=ellip(4,0.5,40,[235 266]*2/1000);
[H2,w2]=freqz(d1,c1,500);
noise_filter_signal=filter(d1,c1,transmit_noise);

for j=1:length(carrier_signal);
hetrodyne_prac(j)=carrier_signal(j)*transmit_noise(j);
end;

ffthet_prac=fliplr(abs(fft(hetrodyne_prac)));
hfthet_prac=ffthet_prac(length(carrier_signal)/2+1:length(carrier_signal));
[d,c]=ellip(4,0.5,40,[143 159]*2/1000); %filt
function [tfr,t,f] = tfrsp(x,t,N,h,trace);
%TFRSP Spectrogram time-frequency distribution.
% [TFR,T,F]=TFRSP(X,T,N,H,TRACE) computes the Spectrogram
% distribution of a discrete-time signal X.
% %
% % X : signal.
% % T : time instant(s) (default : 1:length(X)).
% % N : number of frequency bins (default : length(X)).
% % H : analysis window, H being normalized so as to
% % be of unit energy. (default : Hamming(N/4)).
% % TRACE : if nonzero, the progression of the algorithm is shown
% % (default : 0).
% % TFR : time-frequency representation.
% % F : vector of normalized frequencies.
% %
% Example:
% % sig=fmlin(128,0.1,0.4);
% % h=window(17,'Kaiser'): tfrsp(sig,1:128,64,h,1);
% %
% [tfr,t,freq]=tfrsp(sig,1:128,64,h,1); plot(fftshift(freq),fftshift(tfr(:,100)))

C) SHORT TERM FOURIER TRANSFORM

[H1,w1]=freqz(d,c,500);
filter_signal=filter(d,c,hetrodyne_prac);
fftfilter_prac=fftshift(abs(fft(filter_signal)));
fftfilter_prac=fftfilter_prac(length(filter_signal)/2+1:length(filter_signal));

gfigure
subplot(4,1,1)
plot(time,hetrodyne_prac)
title('Hetrodyncing of the Transmitted 250kHz Burst with Carrier Signal')
subplot(4,1,2)
plot(delta_freq_prac,fftprac)
title('Frequency of the signal after Hetrodyncing, Carrier Frequency & Filter Band')
hold on;
plot(delta_freq,fftcarr,
H1=H1*50; plot(delta_freq_prac,abs(H1),'g'); %filter shape and its frequency
hold off
subplot(4,1,3)
plot(time,filter_signal), %filter shape and its frequency
title('Waveform Filtered Signal from the Lower Band Frequency (150kHz')
subplot(4,1,4)
plot(delta-freq_prac,fftfilter_prac); %filter shape and its frequency of the filtered signal
title('Frequency Spectrum of the lower band signal')
if (nargin == 0),
    error('At least 1 parameter required');
end;
[xrow,xcol] = size(x);
if (nargin < 1),
    error('At least 1 parameter is required');
elseif (nargin <= 2),
    N=xrow;
end;

hlength=floor(N/4);
hlength=hlength+1-rem(hlength,2);

if (nargin == 1),
    t=1:xrow; h = window(hlength); trace=0;
elseif (nargin == 2) | (nargin == 3),
    h = window(hlength); trace=0;
elseif (nargin == 4),
    trace = 0;
end;

if (N<0),
    error('N must be greater than zero');
end;
[trow,tcol] = size(t);
if (xcol==0) | (xcol>2),
    error('X must have one or two columns');
elseif (trow==1),
    error('T must only have one row');
elseif (2^nextpow2(N)-N),
    fprintf('For a faster computation, N should be a power of two\n');
end;

[hrow,hcol]=size(h); Lh=(hrow-1)/2;
if (hcol==1)|(rem(hrow,2)==0),
    error('H must be a smoothing window with odd length');
end;

tfr= zeros (N,tcol) ;
if trace, disp('Spectrogram'); end;
for icol=1:tcol,
    ti= (icol); tau=-min([round(N/2)-1,Lh,ti-1]): min([round(N/2)-1,Lh,xrow-ti]);
    indices= rem(N+tau,N)+1;
    if trace, disp(icol,tcol,10). end;
    tfr(indices,icol)=x(ti+tau).*conj(h(Lh+1+tau))/norm(h(Lh+1+tau));
end;
tfr=abs(fft(tfr)) ^2;

Appendix 2
if trace, fprintf('n'); end.

if (nargout==0),
tfrqview(tfr,x,t,'tfrsp',h);
elseif (nargout==3),
if rem(N,2)==0,
f=[0:N/2-1 -N/2:-1]/N;
else
f=[0:(N-1)/2 -(N-1)/2:-1]/N;
end;
end;

D) WIGNERVILLE

function [tfr,t,f] = tfrpvw(x,t,N,h,trace);
%TFRPVW Pseudo Wigner-Ville time-frequency distribution.
% [TFR,T,F]=TFRP'VW(X,T,N,H,TRACE) computes the Pseudo Wigner-Ville
% distribution of a discrete-time signal X, or the
% cross Pseudo Wigner-Ville representation between two signals.
% X : signal if auto-PWV, or [X1,X2] if cross-PWV.
% T : time instant(s) (default : 1:length(X)).
% N : number of frequency bins (default : length(X)).
% H : frequency smoothing window, in the time-domain,
% H(0) being forced to 1 (default : Hamming(N/4)).
% TRACE : if nonzero, the progression of the algorithm is shown
% (default : 0).
% TFR : time-frequency representation.
% F : vector of normalized frequencies.
%
% Example:
% sig=fmlin(128,0.1,0.4); tfrpvw(sig);

[xrow,xcol] = size(x);
if (nargin < 1),
error('At least 1 parameter is required');
elseif (nargin <= 2),
N=xrow;
end;

hlength=floor(N/4);
hlength=hlength+1-rem(hlength,2);

if (nargin == 1),
t=1:xrow; h = tftb_window(hlength); trace=0;
elseif (nargin == 2)(nargin == 3).
h = tftb_window(hlength); trace=0;
elseif (nargin == 4),
    trace = 0;
end;

if (N<0),
    error('N must be greater than zero');
end;
[trow,tcol] = size(t);
if (xcol==0) | (xcol>2),
    error('X must have one or two columns');
elseif (trow==1),
    error('T must only have one row');
elseif (2^nextpow2(N)==N & nargin==5),
    fprintf('For a faster computation, N should be a power of two\n');
end;

[hrow,hcol]=size(h); Lh=(hrow-l)/2; h=h/h(Lh+l),
if (hcol==1)j(rem(hrow, 2)==0),
    error('H must be a smoothing window with odd length');
end,
tfr= zeros (N, tcol) ;
if trace, disp('Pseudo Wigner-Ville distribution'); end;
for icol=1:tcol,
    ti= t(icol); taumax=min([ti-1,xrow-ti,round(N/2)-1,Lh]);
tau=-taumax:taumax; indices= rem(N+tau,N)+1;
tfr(indices,icol) = h(Lh+1+tau) * x(ti+tau,1) * conj(x(ti-tau,xcol));
tau=round(N/2);
if (ti<=xrow-tau) & (ti>=tau+1) & (tau<=Lh),
    tfr(tau+1,icol) = 0.5 * (h(Lh+1+tau) * x(ti+tau,1) * conj(x(ti-tau,xcol)) + ... 
    h(Lh+1-tau) * x(ti-tau,1) * conj(x(ti+tau,xcol))) ;
end;
if trace, dispprog(icol,tcol,10); end;
end;
tfr= ffft(tfr);
if (xcol==1), tfr=real(tfr); end ;

if (nargout==0),
tfrqview(tfr,x,t,'tfrpwv',h);
elseif (nargout==3),
f=(0.5*(0:N-1)/N); 
end;

Appendix 2
E) MORLET WAVELET

function [tfr,t,f,wt]=tfrsca(X,time, wave, fmin, fmax, N, trace);
% TFRSCALO Scalogram, for Morlet or Mexican hat wavelet.
% [TFR,T,F,WT]=TFRSCALO(X,T,WAVE,FMIN,FMAX,N,TRACE) computes
% the scalogram (squared magnitude of a continuous wavelet
% transform).
% X : signal (in time) to be analyzed (N=\text{length}(X)). Its
% analytic version is used (z=\text{hilbert}(\text{real}(X))).
% T : time instant(s) on which the TFR is evaluated
% (default : 1:N).
% WAVE : half length of the Morlet analyzing wavelet at coarsest
% scale. If WAVE = 0, the Mexican hat is used. WAVE can also be
% a vector containing the time samples of any bandpass
% function, at any scale. (default : sqrt(N)).
% FMIN,FMAX : respectively lower and upper frequency bounds of
% the analyzed signal. These parameters fix the equivalent
% frequency bandwidth (expressed in Hz). When unspecified, you
% have to enter them at the command line from the plot of the
% spectrum. FMIN and FMAX must be > 0 and <= 0.5.
% N : number of analyzed voices.
% TRACE : if nonzero, the progression of the algorithm is shown
% (default : 0).
% TFR : time-frequency matrix containing the coefficients of the
% decomposition (abscissa correspond to uniformly sampled time,
% and ordinates correspond to a geometrically sampled
% frequency).
% F : vector of normalized frequencies (geometrically sampled
% from FMIN to FMAX).
% WT : Complex matrix containing the corresponding wavelet
% transform. The scalogram TFR is the square modulus of WT.
% Example :
% sig=altes(64,0.1,0.45); tfrsca(sig);

if (nargin == 0),
    error('At least one parameter required');
end;

[xrow,xcol] = size(X);
if nargin<=6, trace=0; end

if (nargin == 1),
time=1:xrow; wave=sqrt(xrow);
elseif (nargin == 2),
    wave=sqrt(xrow);

Appendix 2
elseif nargin==4,  
    disp('FMIN will not be taken into account. Determine it with FMAX');  
    disp('from the following plot of the spectrum.');  
elseif nargin==5,  
    N=xrow;  
end;  

[trow,tcol] = size(time);  
if (xcol==0)|(xcol>2),  
    error('X must have one or two columns');  
elseif (trow>1),  
    error('TIME must only have one row');  
elseif wave<0,  
    error('WAVE must be positive');  
end;  

s = (real(X) - mean(real(X)));  
z = hilbert(s);  

if nargin<=4 % fnin, ftnax, N unspecified  
    STF = fft(fftshift(z(min(time):max(time)))); Nstf=length(STF);  
    sp = (abs(STF(1:round(Nstf/2)))).^2; Maxsp=max(sp);  
    f = linspace(0,0.5,round(Nstf/2)+1); f = f(1:round(Nstf/2));  
    plot(f,sp); grid;  
    xlabel('Normalized frequency');  
    title('Analyzed signal energy spectrum');  
    indmin=min(find(sp>Maxsp/100));  
    indmax=max(find(sp>Maxsp/100));  
    fminflt=max([0.01 0.05*fix(f(indmin)/0.05)]);  
    fmaxdflt=0.05*ceil(f(indmax)/0.05);  
    txtmin=['Lower frequency bound [',num2str(fminflt),'] :'];  
    txtmax=['Upper frequency bound [',num2str(fmaxdflt),'] :'];  
    fmin = input(txtmin); fmax = input(txtmax);  
    if isempty(fmin), fmin=fminflt; end  
    if isempty(fmax), fmax=fmaxdflt; end  
    txt=['Number of frequency samples [',num2str(2^nextpow2(xrow)),'] :'];  
    N=input(txt);  
    if isempty(N), N=2^nextpow2(xrow); end  
end  

fmin_s=num2str(fmin); fmax_s=num2str(fmax);  
N_s=num2str(N);  

if fmin >= fmax  
    error('FMAX must be greater or equal to FMIN');  
elseif fmin<=0.0 | fmin>0.5,  
    error('FMIN must be > 0 and <= 0.5');  
elseif fmax<=0.0 | fmax>0.5.
error('FMAX must be > 0 and <= 0.5');
end
if trace,
disp(['Frequency runs from ', fmin_s, ' to ', fmax_s, ' with ', N_s, ' points']);
end

f = logspace(log10(fmin), log10(fmax), N);
a = logspace(log10(fmax/fmin), log10(1), N);

wt = zeros(N, tcol);
tfr = zeros(N, tcol);

if wave > 0
if trace, disp(['using a Morlet wavelet']); end
for ptr = 1:N,
if trace, disp(ptr, N, 10); end
nha = wave*a(ptr);
tha = -round(nha) : round(nha);
ha = exp(-(2*log(10)/nha^2)*tha^2).*exp(i*2*pi*f(ptr)*tha);
detail = conv(z, ha)/sqrt(a(ptr));
detail = detail(round(nha)+1:length(detail)-round(nha))
wt(ptr,:) = detail(time);
tfr(ptr,:) = detail(time).*conj(detail(time));
end
elseif wave == 0
if trace, disp(['using a Mexican hat wavelet']); end
for ptr = 1:N
if trace, disp(ptr, N, 10); end
ha = mexhat(f(ptr));
Nha = (length(ha)-1)/2 ;
detail = conv(z, ha)/sqrt(a(ptr));
detail = detail(round(nha)+1:length(detail)-round(nha))
wt(ptr,:) = detail(time);
tfr(ptr,:) = detail(time).*conj(detail(time));
end
elseif length(wave) > 1
[rwav, cwav] = size(wave);
if cwav > rwav, wave = wave.', end
wavf = fft(wave);
nwave = length(wave);
f0 = find(abs(wavf(1: nwave/2)) == max(abs(wavf(1: nwave/2))));
f0 = mean(f0-1).*(1/nwave);
if trace, disp(['mother wavelet centered at f0 = ', num2str(f0)]); end
a = logspace(log10(f0/fmin), log10(f0/fmax), N);
B = 0.99;
R = B/((1.001)/2);
nscale = max(128, round((B*nwave*(1+2/R)*log((1+R/2)/(1-R/2))/2));
if trace, disp('Scale computation '); end
wts = scale(wave, a, fmin, fmax, nscale, trace);
for ptr = 1:N,
clear detail
if trace, disprog(ptr,N,10); end
ha = wts(ptr,);
Nha = length(ha)/2;
detail = conv(z,ha)/sqrt(a(ptr));
detai = detail-fix(nha):length(detail)-round(nha));
t = time;
f = f;

SP = fft(z);
indmin = 1+round(fmin*(xrow-2));
indmax = 1+round(fmax*(xrow-2));
SPana = SP(indmin:indmax);
tfr = tfr*norm(SPana)^2/integ2d(tfr,t,f)/N;

if (nargout==0),
tfrqview(tfr,hilbert(real(X)),t,'tfrscalo',wave,N,f);
end;

**F) HOUGH**

%b=tic
%assumes input matrix size is even number by even number
in=tfr;
[xsize,ysize]=size(in);
%locate origin at centre of data set
ox=(xsize+1)/2;
oy=(ysize+1)/2;
%specify size of output matrix as square of magnitude equal to longest tfr dimension
mx=max([xsize,ysize]);
%to speed up:
mx=mx/4,%/2;
%define matrices
houghset=zeros(mx,mx);
datalog=zeros(mx,mx);

%r distance need to consider
rmax=sqrt(xsize^2+ysize^2);
rstep=(rmax+1)/mx; %this means that the last r point will be 0, but retains even size and passes through 0
%angular steps
angstep=pi/mx;

%loop through data rotating line about origin
for al=1:mx %loop through angles (from horizontal rotating anticlockwise)
    ang=(al-1)*angstep;
    al
%assign each data point the nearest r value
for X=1:xsizex
    for Y=1:ysize
        %need to calculate r for the given data point and angle, can be negative
        %assign data point an x, y value from origin
        x=ox-X;
        y=Y-oy;
        %find exact r value (can be negative)
        rext=cos(ang)*(x-y*tan(ang));
        %find nearest available r value
        rfactor=round(rext/rstep);
        rloc=rfactor+mx/2;
        if rloc<=mx & rloc>O
            %log how many data points inputted into each hough bin
            datalog(al, rloc)=datalog(al, rloc)+1;
            %houghset
            houghset(al, rloc)=houghset(al, rloc)+tfr(X,Y);
        end
    end
end
end
orgl=houghset;

%%%%%%%%%%%%%%%%%%%%
%houghset(1:40, :)=0;
%houghset(:, 1:40)=0;
%%%%%%%%%%%%%%%%%%%%

%find location of maximum value
for aa=1:mx
    for bb=1:mx
        if houghset(aa, bb)==max(max(houghset))
            la=aa;
            lb=bb;
        end
    end
end
hello=1
%value of r and ang at max
ang_m=(la-1)*angstep;
r_m=(lb-mx/2)*rstep.

Appendix 2
%refine angle and location (r)
refinefactor=32;

datalogr=zeros(refinefactor*2+1,refinefactor*2+1);
houghsetr=zeros(refinefactor*2+1,refinefactor*2+1);
for angref=1:refinefactor*2+1
  ang=(la-1)*angstep+(angref-refinefactor-1)*angstep/refinefactor*2;  %covers two steps
  at angstep size
lists(angref)=ang;
  for X=1:xsize
    for Y=1:ysize
      %need to calculate r for the given data point and angle, can be negative
      %assign data point an x,y value from origin
      x=ox-X;
      y=oy-Y;
      %find exact r value (can be negative)
      rexact=cos(ang)*(x-y*tan(ang));
      %find nearest available r value
      rfactor=round((rexact-r_m)/rstep*refinefactor/2);  %covers two points at rstep size
      rloc=rfactor+refinefactor;
      if rloc<=refinefactor*2+1 & rloc>0
        %log how many data points inputted into each hough bin
datalogr(angref,rloc)=datalogr(angref,rloc)+1;
%houghset
houghsetr(angref,rloc)=houghsetr(angref,rloc)+tfr(X,Y);
end
  end
end
end

hell=2
%find location of refined maximum value
for aaa=1:refinefactor*2+1
  for bab=1:refinefactor*2+1
    if houghsetr(aaa,bab)==max(max(houghsetr))
      lar=aaa;
      lbr=bab;
    end
  end
end

%value of r and ang at max
ang_mr=(la-1)*angstep+(lar-refinefactor-1)*angstep/refinefactor;
r_mr=(lbr-refinefactor)*rstep/refinefactor+r_m;
%collect data along chirp
tfd=zeros(1,xsize);
tfdn=zeros(1,xsize);
tfrcheck=zeros(mx*2,mx*2);

Appendix 2
tfrch2=tfr;

%set size of time gate in points (odd number)
tgate=3;

for XX=1:ysize %so constant frequency step
    XX
    x=ox-XX;
    %find exact r value (can be negative)
    y=(x-r_min/cos(ang_min))/tan(ang_min);
    Y=ceil(y+oy);
    ylog(XX)=Y;
    list=0;
    for Yoff=1:tgate
        Yoff=Y+tg-(tgate+1)/2;
        if Yoff>0 & Yoff<=ysize
            list(tg)=tfr(XX,Yoff);
        end
    end
    tfd(l, XX)=max(list);
    if Y>0 & Y <=ysize
        tfrcheck(XX, Y)=10;
        tfrch2(XX, Y)=tfr(Y, X, Y)+max(max(tfr))*2;
    end
end
toc

G) WAVELET SCAN

%b=tic
%assumes input matrix size is even number by even number
in=tfr;
[xsize,ysize]=size(in);
%locate origin at centre of data set
ox=(xsize+1)/2;
oy=(ysize+1)/2;
%specify size of output matrix as square of magnitude equal to longest tfr dimension
mx=max([xsize,ysize]);
%to speed up:
mx=mx/4;%/2;
%define matrices
houghset=zeros(mx, mx);
datalog=zeros(nix, mx);

%r distance need to consider
rmax=sqrt((xsize^2+ysize^2);
rstep=(rmax+1)/mx; %this means that the last r point will be 0, but retains even size and passes through 0
%angular steps
angstep=pi/mx;

%loop through data rotating line about origin
for al=1:mx %loop through angles (from horizontal rotating anticlockwise)
    ang=(al-1)*angstep;
    al
%assign each data point the nearest r value
for X=1:xsize
    for Y=1:ysize
        %need to calculate r for the given data point and angle, can be negative
        %assign data point an x,y value from origin
        x=ox-X;
        y=oy-Y;
        %find exact r value (can be negative)
        reexact=cos(ang)*(x-y*tan(ang));
        %find nearest available r value
        rfactor=round(reexact/rstep);
        rloc=rfactor+mx/2;
        if rloc<=mx & rloc>0
            %log how many data points inputted into each hough bin
            datalog(al, rloc)=datalog(al, rloc)+1;
            %houghset
            houghset(al, rloc)=houghset(al, rloc)+tfr(X, Y);
        end
    end
end
orgl=houghset;

%find location of maximum value
for aa=1:mx
    for bb=1:mx
        if houghset(aa, bb)==max(max(houghset))
            la=aa;
            lb=bb;
        end
    end
end
hello=1
%value of r and ang at max
ang_m=(la-1)*angstep;
rm=(lb-mx/2)*rstep;

%refine angle and location (r)
refinefactor=32;

datalogr=zeros(refinefactor*2+1,refinefactor*2+1);
houghsetr=zeros(refinefactor*2+1,refinefactor*2+1);
for angref=1:refinefactor*2+1
    ang=(la-1)*angstep+(angref-refinefactor-1)*angstep/refinefactor*2; %covers two steps at angstep size
    lists(angref)=ang;
    for X=1:xsize
        for Y=1:ysize
            %need to calculate r for the given data point and angle, can be negative
            x=ox-X; y=Y-oy;
            %find exact r value (can be negative)
            rexact=cos(ang)*(x-y*tan(ang));
            %find nearest available r value
            rfactor=round((rexact-r_m)/rstep*refinefactor/2); %covers two points at rstep size
            rloc=rfactor+refinefactor;
            if rloc<=refinefactor*2+1 & rloc>0
                %log how many data points inputted into each hough bin
                datalogr(angref,rloc)=datalogr(angref,rloc)+1;
            end
            houghsetr(angref,rloc)=houghsetr(angref,rloc)+tfr(X, Y);
        end
    end
end
end
hell=2
%find location of refined maximum value
for aaa=1:refinefactor*2+1
    for bab=1:refinefactor*2+1
        if houghsetr(aaa,bab)==max(max(houghsetr))
            lar=aaa; lbr=bab;
        end
    end
end

%value of r and ang at max
ang_mr=(la-1)*angstep+(lar-refinefactor-1)*angstep/refinefactor;;
r_mr=(lbr-refinefactor)*rstep/refinefactor+r_m;
%collect data along chirp
tfd=zeros(1,xsize);
tfdn=zeros(1,xsize);
tfrcheck=zeros(mx*2,mx*2);
tfrch2=tfr;

Appendix 2
%set size of time gate in points (odd number)
tgate=3;

for XX=1:xsize %so constant frequency step
    XX
    x=ox-XX;
    %find exact r value (can be negative)
    y=(x-r_mr/cos(ang_mr))/tan(ang_mr);
    Y=ceil(y+oy);
    ylog(XX)=Y;
    list=0;
    for tg=1:tgate
        Yoff=Y+tg-(tgate+1)/2;
        if Yoff>0 & Yoff<=ysize
            list(tg)=tfr(XX,Yoff);
        end
    end
    tfd(I, XX)=max(list);
    if Y>O & Y<=ysize
        tfrcheck(XX, Y)=10;
        tfrch2(XX, Y)=tfr(XX, Y)+max(max(tfr))*2;
    end
end
toc

H) SURFER CONVERSION PROGRAM

tic
%normalise and scale ready for Surfer
in=ampp;
highest=max(max(in));
norm=in/highest;
[a,b]=size(in);
out=zeros(a*b, 3);
yvalues=0;
xvalues=0;
col1=0;
col2=0;
col3=0;
for aa=1:a
    yvalues(aa, 1:b)=1000*(aa*ystep-((a+1)/2*ystep));
end
for bb=1:b
    xvalues(bb, 1:a)=1000*(bb*xstep-((b+1)/2*xstep));
end
col1=reshape(yvalues,a*b,1);
col2=reshape(xvalues,a*b,1);
for aaa=1:a
    %

Appendix 2
for bbb=1:b
    col3((bbb-1)*a+aaa, 1) = norm(aaa, bbb);
end
end

out = [col1, col2, col3];
save rdatasurfl.dat -ascii out
toc