BRUNEL UNIVERSITY

Performance Enhancements in an Ultrasonic Guided Wave Pipe Inspection System

by

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Abstract

Sound has the ability to travel over long distances in structures whose geometry can act as a guide for the sound waves. This phenomenon can be exploited in the use of long range testing of structures, such as oil and gas distribution networks, Storage tank facilities, oil and gas exploration platforms to ships hulls and bridges. Specifically, this technology can be utilised to inspect structures where safety critical evaluation of its structural integrity is of paramount importance to both human and environmental considerations. Therefore, any technique that can aid the inspection process of flaw detection in a structure and possibly reduce the risk of catastrophic failures in industrial installations is highly desirable.

With more and more companies relying on reliable ways to effectively screen for defects in metal pipe lines and structures, namely in the Oil and Gas industries, a solution was found in the use of Ultrasonic Guided Waves (UGWs). These types of Guided Waves have been found to be useful over recent years in the Non-Destructive Testing (NDT) of industrial pipelines. This technology relies on the ability to transfer pre-determined analogue signals into suitable ultrasonic wave modes capable of travelling through test samples, to record any ultrasonic responses that are reflected from anomalies within the sample, these signals are then analyzed using advanced digital signal processing techniques to detect defects.

This research work was carried out with a view to enhance the performance of a commercially available system, marketed as TeletestFocus™, which is designed and manufactured by TWI. Improvements have targeted the ultrasonic transducers and the embedded electronics that control their use.

Improvements to the existing PZT shear mode transducer design were implemented, which resulted in significant improvement in its output characteristics. An experimental setup and testing procedure was developed to facilitate the transducer characterisation. A new transducer manufacturing process was introduced that dramatically reduced production times and improved variations between individual assemblies.

Evaluations on the performance of the previous embedded electronics units (Mk1, Mk2 and Mk3) were accessed. As a result of this evaluation a new embedded electronics unit (Mk4) was designed and manufactured. Newer technologies, namely a more advanced FPGA, interpolation DAC's, Ethernet data transfer protocols and reduced component sizes were introduced to improve the functionality and efficiency of the system but also reduce the overall size of the data collection system. A new approach to the system layout was implemented with new manufacturing processes employed to reduce weight and achieve a reduction in costs.

The design improvements to the next generation of TeletestFocus™ Mk4 significantly enhanced data collection and analysis, compared to the previously available Mk3, unit of over 300%. Improvements to the transducer design also culminated in a 250% increase in output performance. Enhancements to both the electronics unit and transducer resulting from this research enables system operators to cover more test locations within a given time period, therefore, increasing efficiency and reducing costs.

Acknowledgements

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I also would like to thank my good friend Lily for her constant support and encouragement during this research, all my friends in the EAC and a special thought to my late parents for whom this thesis is dedicated.

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Glossary

NDT	Non-Destructive Testing
UT	Ultrasonic Testing
LRUT	Long Range Ultrasonic Testing
MPI	Magnetic Particle Inspection
RT	Radiographic Testing
ASNT	American Society for Non-destructive Testing
PZT	Lead Zirconate Titanate
ASME	American Society of Mechanical Engineers
ATE	Automated test equipment
SPI	Serial peripheral interface

Chapter 1 Introduction

1.1 Overview

This chapter will present the basic concepts for generating ultrasonic sound waves as a form of Non-Destructive Testing (NDT) for the detection of anomalies such as corrosion erosion or even mechanical damage caused by some external or internal influence on a variety of engineering components and structures, either ferrous or non-ferrous. The chapter will also give a brief introduction to some other techniques employed for NDT, and highlight their limitations for rapid inspection of large entities like pipe lines and other structures where speed of inspection is paramount.

The research will primarily focus on guided ultrasound commonly known within industry as Long Range Ultrasonic Testing (LRUT) as one form of NDT, and in particular, on the design of a piezoelectric transducer utilised for LRUT of pipe lines using a commercially available instrument marketed by Plant Integrity Ltd as TeletestFocus™.

Current transducer designs, for use with the TeletestFocus™ system array, and the electronics used to generate the required excitation waveforms and receiver circuits is also discussed, along with recommendations to improve the efficiency of both the transducer and electronics design in order to achieve higher overall system performance and ultimately lower inspection costs.

As a result of the research carried out, a new transducer design was implemented and performance gains of over 240% were achieved compared to the currently commercially available transducer. Also, changes made during this research to the waveform generation and receiving electronics system resulted in an overall data collection time reduction per location greater than 300% compared to the current marketed system (Mk3 TeletestFocus™). Both these design improvements significantly enhanced data collection and analysis, and enables system operators to cover more test locations within a given time period therefore increasing efficiency and reducing costs.

1.2 Commercial relevance

This research has been conducted with support from the sponsor company TWI Ltd. The research has been aimed at improving the technology for industrial use of guided ultrasonic sound waves in the field of non-destructive testing NDT. These systems are now being commercially marketed by Plant Integrity Ltd as the TeletestFocus™ LRUT system and are being successfully used throughout the world for the inspection and monitoring of structures, such as oil and gas pipe line, bridges, railroad lines, and above ground storage tanks.

1.2.1 Background to Non-destructive testing

The following sections give a brief overview of some commonly used techniques used for the non-invasive inspection for components or structures without the requirement to alter their integrity in any way. The inception of modern NDT can be traced as far back to the beginning of the 20^{th} century but it wasn't until the twenties that awareness to different methods truly came into being. During this time, developments were being made into the fields of Magnetic Particle Inspection (MPI) for industrial usage and X-radiography (RT) for mainly medical applications.

Prior to the second world war design engineers had to incorporate high safety factors into designs for the vast majority of products such as pressure vessels, oil exploration platforms and other complex applications where a relatively long life cycle was expected. As a result of documented catastrophic failures due to discontinuities and imperfections either introduced during the manufacturing process, or later in the products life cycle, brought quality to the forefront in the field of engineering culminating in 1941 with the formation of the American Society for Non-destructive Testing (ASNT).

During, and after the Second World War, NDT saw a rapid increase in research and development of techniques. The primary purpose of the research was for the detection of defects and to establish procedure that would ultimately result in higher integrity of components and more cost effective testing.

From the end of the fifties to the present day NDT has undergone exponential advancements in its field of research and has spawn various new techniques that have had a direct relationship to safety of products, product reliability and even the development of new materials. Many of today's industries wouldn't have been possible without some form of NDT to validate the integrity of a construction or the safely of a piece of equipment.

Today, NDT takes on many forms with most of us having experienced some form of NDT during our lives; one example would be an X-ray. Industry uses a much broader range of techniques including chemistry (Liquid Penetrant Testing), magnetism (Magnetic Particle Inspection), microwaves (Ground Penetrating Radar), and sound waves (Guided Ultrasound) to achieve the concept of NDT. All of these techniques would facilitate the inspection of components in a timely, efficient and cost effective manner.

1.2.2 Available techniques for NDT

At present, there are many different procedures using a variety of techniques for the non-invasive inspection of components assemblies and whole plants. Depending on the type of inspection required, and the available access to the operator, an appropriate technique will be deployed.

Each technique has its own limitations, be it physical restraints of the material under inspection or the practical deployment of the system that is being used. For safety critical applications periodic inspection is paramount and schedules must be maintained.

Systems designers are therefore required to develop instruments that are, in most cases, commercially viable to smaller inspection companies and relatively easy for an operator to use and interpret the results on-site. Not only does the physics behind the technique need to be understood by the system designer, but also consideration must be given to the type of environment the equipment has to operate in.

As previously mentioned all techniques are not necessarily suited for every given application. The summary below briefly explains some of the various techniques commonly used today for NDT and highlights the advantages and disadvantages.

1.2.2.1 Eddy current testing

The basic principle of an Electromagnetic Transducer system relies on large alternating electrical currents to pass through a coil located in the head of the probe, this alternating current then produces a magnetic field, which in turn produces eddy currents in the test sample (Figure 1-1a) Probes can either be mounted on a test station as part of a quality control procedure during the components manufacturing stage, or as a hand held instrument (Figure 1-1b) for inspection of components later on in the products life cycle.

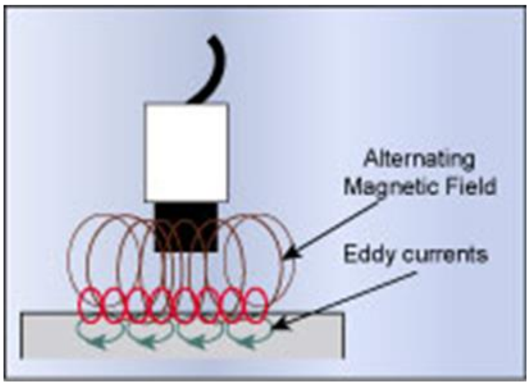


Figure 1-1. (a) Eddy current probe operation (www.ndt-ed.org) **(b) Typical commercially hand held Eddy current probe (www. lionprecision.com)**

Placing the probe head near to conductive materials small amounts of electrical eddy currents are induced into the test sample under inspection. These eddy currents generate a magnetic field in the sample that opposes the field generated by the probe. These opposing magnetic fields can be measured and analysed to produce information relating to the integrity of the sample.

Eddy current systems are primarily used for inspection of surface or near surface flaws in materials such as metals, thin sheet and nonconductive coatings such as paint, as long as there is a conductive substrate near to the surface that will allow eddy currents to form.

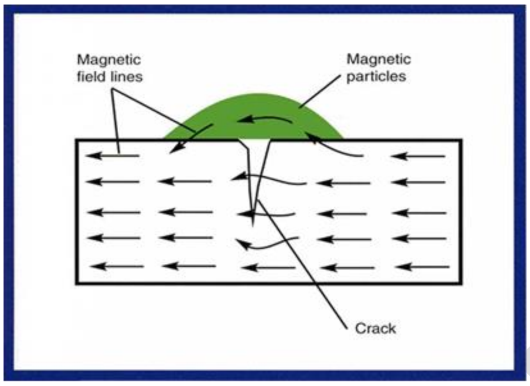
Advantages of using eddy current devices allow surface or near surface flaws to be easily tested. Sample material depth can range from 0.5 to 15mm using frequencies ranging from 250Hz to 15kHz (information based on Lion Precision data sheets). Point contact to the test sample is not necessary so probes can be more easily used in an automated conveyor belt production facility.

However, eddy current systems do have some disadvantages; techniques can only be used where either the sample or substrate is conductive. The penetration of eddy currents is dependent on the coil size and driving current to the probe so inspection of large thickness materials is constrained by the physical size of the equipment.

Due to the nature of the induced currents and the magnetic fields produced any flaws that lie parallel to the probe coil windings can go undetected. Surface preparation of the test sample may be required to reduce interference. Also, eddy current techniques are only appropriate for local inspection and can't be used for testing over long distances, unless the complete system is mobilised in some form.

1.2.2.2 Magnetic particle inspection:

Magnetic Particle Inspection (MPI) is an NDT method used for defect detection. MPI is fast and relatively easy to apply, and part surface preparation is not as critical as it is for some other NDT methods. These characteristics make MPI one of the most widely utilized NDT methods for localised inspection.



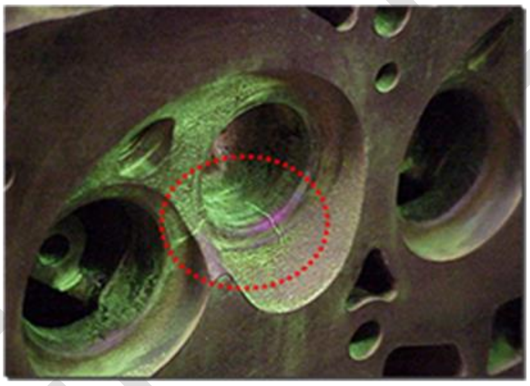


Figure 1-2. (a) Magnetic partial inspection technique (b) Example of fluorescent magnetic particle inspection using UV light, with indications highlighted

MPI uses magnetic fields and small magnetic particles (i.e. iron filings) to detect flaws in components (Figure 1-2a). The only requirement from an inspection ability standpoint is that the component being inspected must be made of a ferromagnetic material such as iron, nickel, cobalt, or some of their alloys. Ferromagnetic materials are materials that can be magnetized to a level that will allow the inspection to be effective.

The method is used to inspect a variety of product forms including castings (Figure 1-2b), forgings and welds. Many different industries use MPI for determining a component's fitness-for-use. Some examples of industries that use MPI are the structural steel, automotive, petrochemical, power generation, and aerospace industries. Underwater inspection is another area where MPI may be used to test items such as offshore structures and underwater pipelines. MPI is a visual inspection method and therefore, it requires no sophisticated software to analyse the results, the operator has instant visual results. As with eddy currents, this type of technique is not suitable for long distance test inspection.

1.2.2.3 Ultrasonic testing

The principle of Ultrasonic Testing (UT) relies on the elasticity of a material to allow stress waves to propagate through an object (Rose and Nagy 1999). As these stress waves travel thorough the object they may encounter features within the object that will reflect the transmitted wave. These reflected waves can be sensed and the resulting data analysed and interpreted to show the characteristics of the object (Figure 1-3).

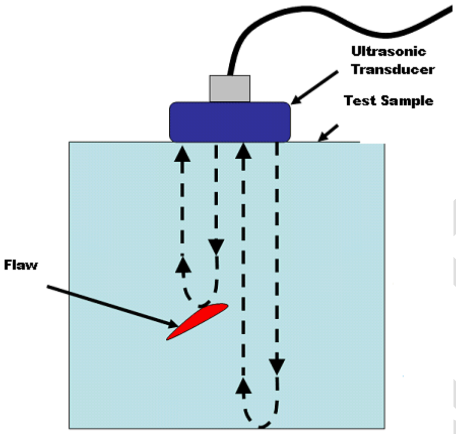


Figure 1-3. Principle of reflected sound wave through a test sample using a compression mode transducer.

In conventional UT, compression mode transducers are used that allow for the immediate inspection of an area directly beneath the point of contact of the transducer, as shown in Figure 1-4. These types of probes generally operate in the MHz frequency range and give very good spatial resolution, but the very short wavelength tends to dissipate within a short distance from the emitting transducer. Therefore these types of probes are not ideal for testing over long ranges: conventional ultrasonic transducers are mainly used for localised inspection.

Figure 1-4. Conventional NDT inspection of weld integrity.

1.2.2.4 Teletest guided wave system

The TeletestFocus™ long-range ultrasonic test system provides a means of inspecting long lengths of pipe (tens of metres) from a single access point.

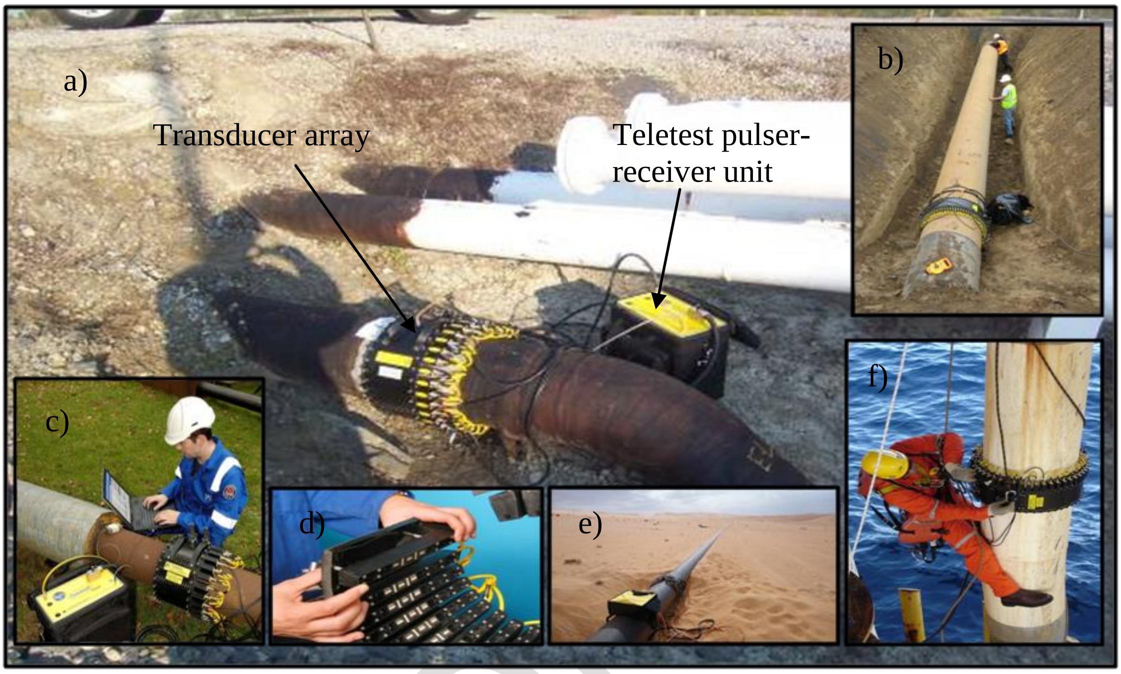


Figure 1-5. Typical applications using Teletest system, a) Inspection of buried pipe line under road crossing, b) Buried line after excavation, c) Inspection of insulated pipe line, d) Transducer array located in inflatable coupling mechanism, e) Long distance above ground inspection, f) Off shore riser inspection

From a single access point, as shown in Figure 1-5, pipes can be inspected in each direction in turn. Thus the inspection length of a pipe tested from the location of the transducer array is twice the range over which it is possible to transmit ultrasound in the pipe. This range varies according to the pipe condition, contents, configuration, surrounding insulation or wrapping, etc, but typically is of the order of 30m. Thus 60m can be tested from one access point. Furthermore the system inspects 100% of the pipe wall. Major cost savings can therefore be achieved compared to other NDT methods.

Figure 1-6 shows the comparison between conventional NDT and guided ultrasonic wave inspections systems. Figure 1-6a) shows how only one single point compression mode transducer is implemented in a conventional NDT inspection system. Inspection coverage for long distances of pipe lines, or structures, can be time consuming and can be prone to error if areas of the structure are missed or are inaccessible to the probe.

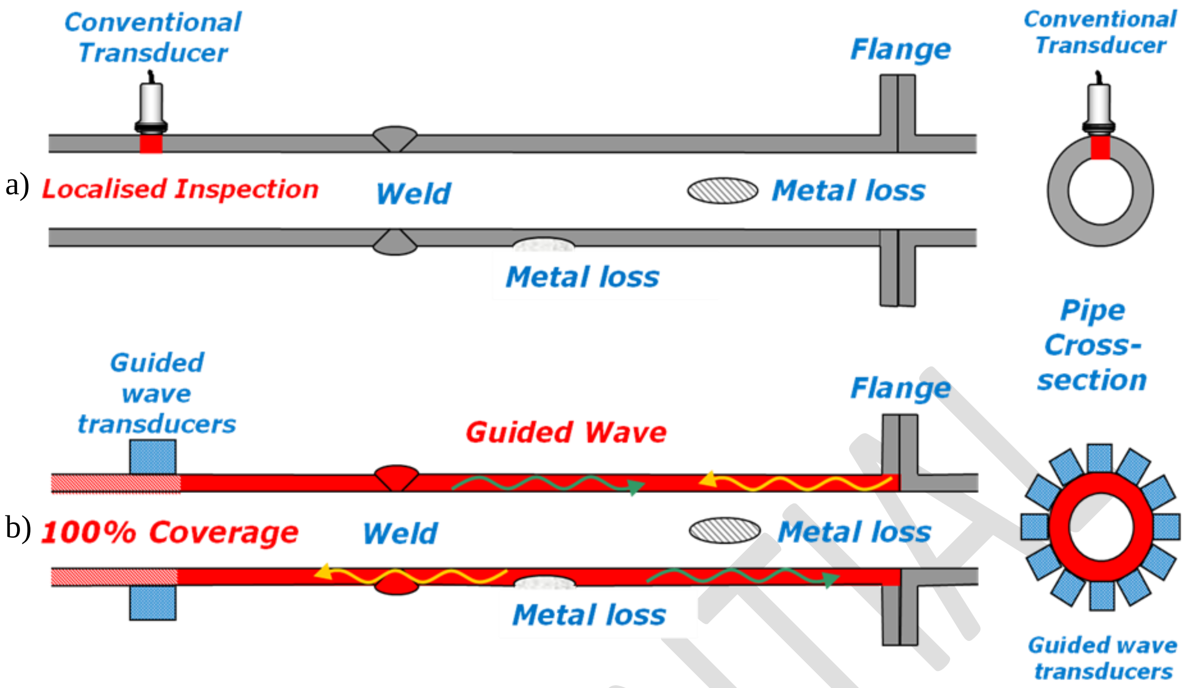


Figure 1-6. Comparison between conventional NDT and TeletestFocus™ LRUT inspection of pipe.

a) Conventional techniques inspect a few cm^2 under the device
b) TeletestFocus™ inspects 100% of the pipe wall for tens of metres in each

Figure 1-6b) shows how in a long range ultrasonic system a ring of transducers are coupled circumferentially around a pipe undergoing inspection. This arrangement allows for 100% coverage from a single location and can detect anomalies both internally and externally to the pipe and inaccessible locations such as road crossings where a pipe would be buried.

1.2.3 Principles of long range guided wave ultrasonics

Conventional ultrasonic testing makes use of bulk waves that propagate through the middle of a material and can either take the form of a longitudinal or shear vibration (Krautkramer and Krautkramer 1969). As these waves propagate they are subject to spreading and this divergence leads to a loss of intensity which limits their range. However, some waves can propagate parallel to a structure's outer surfaces and are constrained by these boundaries. These are the so called guided waves and can propagate over relatively long distances because they experience little or no divergence.

Structures that have boundaries that enable waves to propagate over relatively long distances are known as waveguides. Inspection techniques that use guided waves can achieve inspection over these relatively long distances, which makes them useful for the screening of large structures that are so vast that their scale makes the use of the localised inspection techniques (such as those discussed in the previous sections) cost prohibitive.

Waveguides can be structures with one or more planar surfaces, such as a plate, or can be prismatic, such as a pipe. In plates the parallel surfaces that constrain the waves only allow propagation in two axes. In prisms the waves can only propagate in one axis.

The constraint by the structure's boundaries leads to the ultrasonic vibration within the waveguide forming a harmonious pattern of vibration. For a given waveguide there are many possible patterns of vibration that a propagating wave may take and these are known as wave modes. The nature of the pattern of vibration for each mode depends on frequency which leads to the mode having a frequency dependent velocity. Wave modes can have vibration in combination of up to all three axes. In plates wave modes are separated into waves that predominately vibrate in the in-plain direction perpendicular to propagation (horizontal shear waves) and waves that vibrate in the out of plan axes and the axes of propagation (Lamb waves) (Lamb 1917). In pipes, wave modes are separated into waves that have a pattern of vibration that is axisymmetric and those which are not (flexural modes) (Figure 1-7). Axisymmetric modes like plate modes can be divided into horizontal shear modes (torsional modes) and modes with vibration out-of-plane and in the axes of propagation (longitudinal modes) (Silk and Bainton 1979). In other structures similar distinctions can be made although for many structures there are no conventional naming schemes.

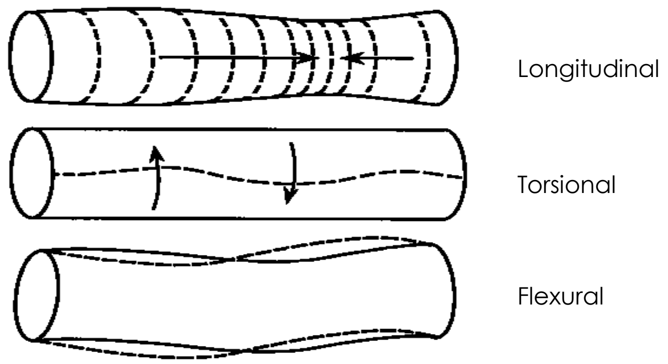


Figure 1-7. Pipe wave mode naming scheme.

As each wave mode has a velocity which is dependent on frequency, it will experience distortion as it propagates. Since pulses of sound have a bandwidth, this leads to the pulses elongating over time. The rate of dispersion varies with wave mode and frequency. It is common to depict the velocity dependent characteristics in graphs showing the velocity of each wave mode for a given waveguide over a range of frequencies and these graphs are known as dispersion curves. Figure 1-8 gives a typical example of dispersion curves for wave modes for a pipe. This distortion can be detrimental to inspection techniques. It is important to select a wave mode and bandwidth for inspection that reduces the amount of dispersion. In Figure 1-8, for example, it can be seen that the wave mode "L(0,2)" is non-dispersive above 40kHz and is desirable for use in testing. It is also noteworthy that for many waveguides there exists an exceptional shear mode whose velocity is independent of frequency. The "T(0.1)" mode can be seen in Figure 1-8.

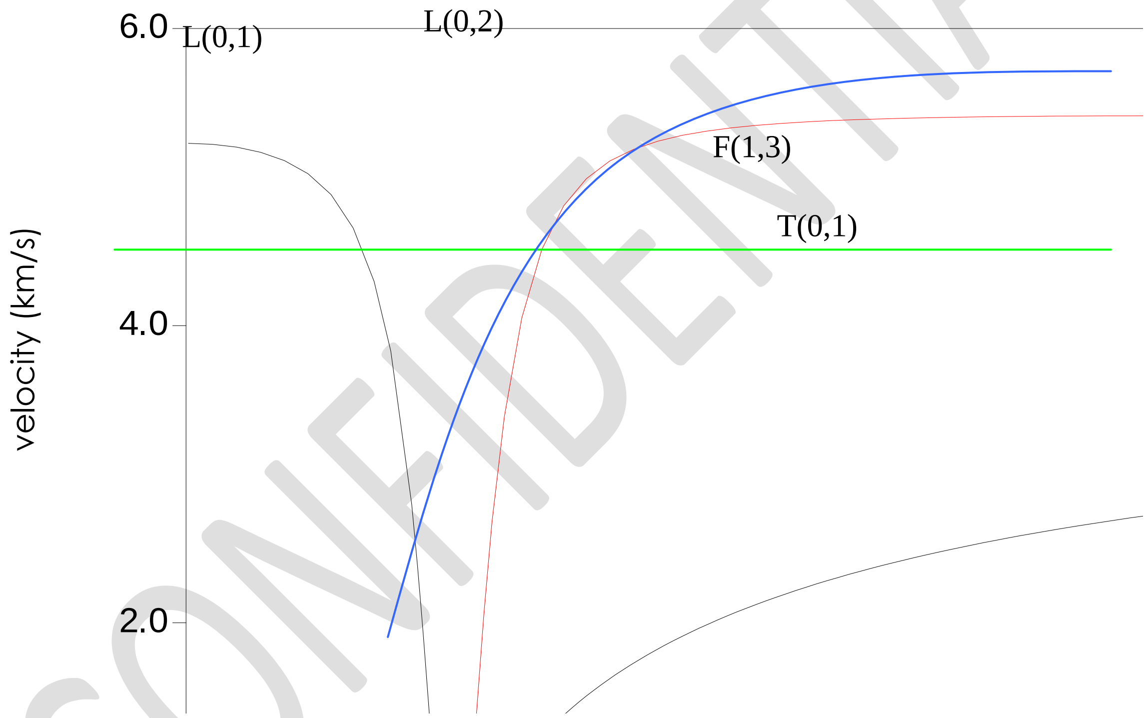


Figure 1-8. Typical example of dispersion curves for a typical pipe.

Waves propagating in a structure will continue to propagate undisturbed whilst the cross-section of the wave does not change. Changes in the thickness or materials will cause the sound to scatter or reflect (Figure 1-9). If the velocity of a wave is known propriety software developed by TWI can use sophisticated algorithms and calculate the time of arrival of reflections to determine the range of reflecting features. The amplitude of reflections can also indicate the extent to which the cross-section has changed. Inspection techniques make use of both time of arrival and amplitude of reflected waves to determine the presence and severity of any defects.

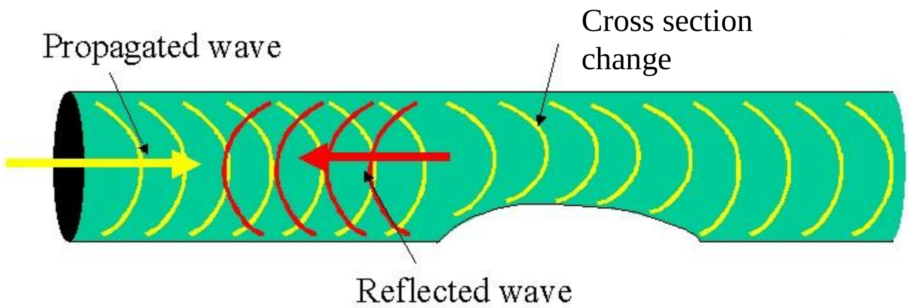


Figure 1-9. Wave reflection form defect in a typical pipe.

Waves can be excited in a structure by devices that cause vibration. Transducers are devices that convert an electrical signal into a vibration and vice versa. Transducers can be designed to create vibrations in different axes. The selection of frequency and vibration direction significantly influences the proportion of wave modes excited. However, this alone is often not enough to transmit a single wave mode in isolation. To achieve the transmission of one wave mode, transducers are often used in sets so that the desired wave mode is reinforced and unwanted modes are suppressed. This is achieved using transducer arrays.

The process of inspection generally involves an operator who couples a transducer array onto a waveguide, such as a pipe, requiring inspection and uses an inspection system, such as TeletestFocus™ to transmit a signal and record reflections received by the array. The received signal is displayed to the operator as amplitude against distance. This can be done for multiple wave modes. The operator analyses these signals to determine which reflections have come from known features of the waveguide, such as pipe supports or welds, and which are due to defects.

1.3 The Teletest system

Throughout the evolution of the Teletest LRUT system each generation of equipment has essentially operated using the same principles of configuration. This section gives a brief introduction to each component used within the system to conduct an LRUT inspection. The most frequently used application for this type of equipment is the inspection of industrial pipelines (Mudge, 2004).

1.3.1 System components

The LRUT system manufactured by TWI (see Figure 1-10) comprises of five components. A brief introduction to the system follows:

- A embedded electronic unit
- Modules to house the transducers in situ while an inspection is in progress
- Transducers for generating ultrasonic sound waves
- Inflatable collars that hold the transducer array
- Laptop or PC for executing the controlling software and displaying results obtained from the data acquisition cycle

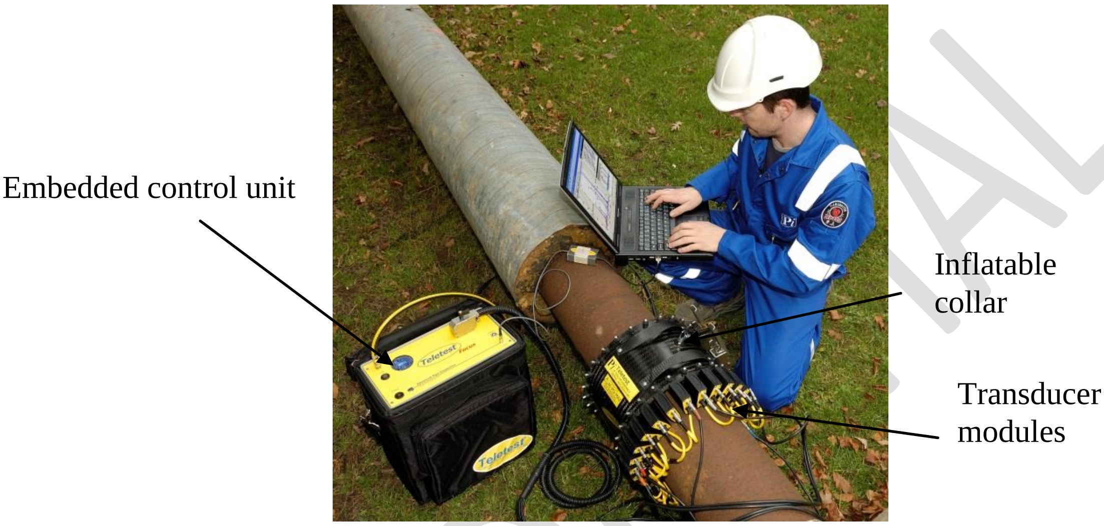


Figure 1-10. Teletest system in use on 8 inch above ground lagged pipe.

The details of the pipe dimensions, such as wall thickness, diameter and material are first entered into the user interface software running on a standard laptop or PC. The software then calculates the required frequencies to be used during an inspection based on information entered by the operator. The data collection routines, for signal generation and reception, are then passed to the embedded control unit which generates the analogue waveforms used to excite the array of transducers. Thickness shear mode transducers are held in an inflatable collar that couples them to the pipe under inspection. The generated sound waves from the array of transducers propagate along the pipe and any anomalies, such as corrosion or weld defects, will reflect a percentage of the transmitted waveform back to the embedded control unit so that the operator can analyse the results.

1.3.1.1 Teletest embedded control unit

The embedded electronics unit, TeletestFocus™ shown in Figure 1-11, is responsible for generating and collecting analogue signals used during an inspection. The unit will generate a tone burst signal normally in the range of 10kHz to 100kHz to excite the array of transducers situated circumferentially around a pipe under inspection.

Figure 1-11. Teletest Mk3 LRUT embedded electronics system

The unit then collects responses reflected back from the array of transducers and stores the data ready for processing. In this research a new TeletestFocus™ Mk4 was developed, see section 4.4.

1.3.1.2 Transducer module

Each transducer used for inspection in housed in a carrier module that will allow it to be positioned around the circumference of a pipe.

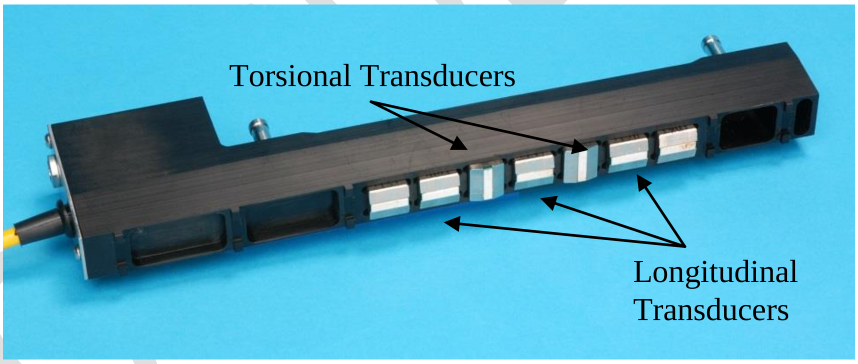


Figure 1-12. Multi mode transducer module holds transducer in position while coupled to a pipe

Transducers can be positioned in a module to either generate longitudinal or torsional wave modes within the pipe (see Figure 1-12). Transducers located within the module are the same type but orientated differently so that the in-plane vibration direction is changed and the correct wave mode will be produced. The number of modules used at any given time depends on the pipe size being inspected, for example, a nominal 8” diameter pipe will require 24 modules to be equally spaced around it.

1.3.1.3 Transducer

All transducers in the TWI LRUT system are manufacture in an identical configuration and are specifically designed to operate between 10kHz and 100kHz. They use Lead Zirconate Titanate (PZT) ceramic crystals polarised to produce a shear deformation.

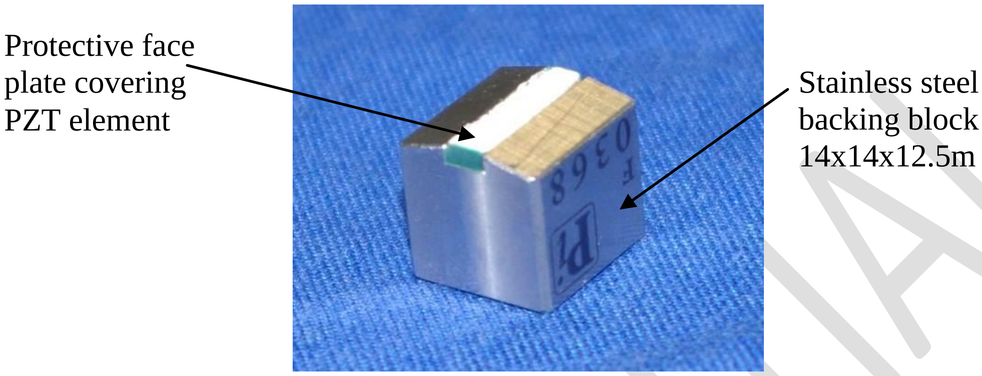


Figure 1-13. LRUT Transducer designed to generate shear ultrasonic wave modes in the Teletest LRUT system

Figure 1-13 shows a typical example of a thickness shear mode transducer used in the system manufactured and commercially exploited by TWI. The figure shows the backing block, PZT component and protecting face plate. As part of this research a higher performance version of this transducer was designed and manufactured.

1.3.1.4 Inflatable collars

A variety of different collar sizes are available to accommodate each pipe size that is in standard use within the oil and gas production industries. These can range from 2” up to 24” and are based on ASME pipe size schedules. Collars are manufactured from two different materials, a carbon composite outer band for rigidity and a polyurethane inner inflatable bladder. The collar allows the transducer modules to be positioned around a pipe and pressure applied to couple the transducers onto the pipe. The pressure applied to the modules is via a pneumatic system located and controlled within the electronic unit.

Figure 1-14. A selection of inflatable collar sizes used to hold transducer modules onto a pipe. A 2" 4" and 24" diameter collars are shown.

Figure 1-14 shows a small selection of carbon composite outer reinforcing bands with an inflatable polyurethane bladder. An air pressure force of 60PSI is used to pressurise the collar to achieve transducer coupling with the pipe surface, this equates to a load force of 200N on each individual transducer in the array.

1.4 Motivation for research

With the ever demanding increase for the use of ultrasonic guided waves techniques and the associated equipment for NDT and in particular the LRUT of industrial pipelines throughout the world service and inspection companies, who carry out screening techniques, are relying on more accurate data on which to base their finding. The construction of an ultrasonic transducer is a key component, decisive for the quality and reliability of inspection results.

With the majority of the world’s pipelines carrying hazardous substances, if compromised, could lead to catastrophic consequences to both human life and the environment, or to a lesser extent a reduction in production output, many pipe line operators and their respective support organisations, especially, petro chemical industries, now have in place rigorous screening programs relying on LRUT for monitoring the structural integrity of their infrastructure.

Throughout the world, many of today’s major suppliers of safety critical structures, or pipeline disruption facilities, rely heavily on screening processes to ensure structural integrity is maintained throughout the products lifecycle. Either at the point of manufacture, or as a scheduled maintenance programme, companies are increasingly employing ultrasound techniques as one such screening process. As many components, or structures, will naturally degrade over time to a point where a safety or an environmental concern may arise it is important to have an inspection regime in place whereby the integrity of these structure and components can be periodically tested in a cost effective manner. If an inspection process is prohibitively expensive then it's more likely than not to be included into any schedule on a regular basis. For pipelines, in particular, cost of inspection is a major issue as many of today's petrol chemical infrastructure run for hundreds, if not thousands, of miles across some of the world's most inhospitable environments. Speed of inspection, distance covered by a particular technique, quality and reliability of data collected and cost all play a decisive role in determining the type of technique employed.

Subsequently, inspection companies are increasingly looking for higher performance instruments that will ultimately deliver more detailed information relating to any defects that may be present in the test sample, and ultimately improved productivity.

1.5 Research aims

To support the delivery of improved inspection systems research has been carried out to target two main areas:

- **Transducers** - Design changes to the ultrasonic transducer and its manufacturing process to improve efficiency and reduce costs incurred during the assembly process, which has included the development of a characterisation process and the characterisation of the new transducer design.
- **Electronics unit** – The design of a new embedded control unit to improve the inspection process by delivering greater speed of data collection, more user functionality, reduced power consumption, a reduction in system weights and to lower cost incurred to manufacture the system.

1.6 Research methodology

Of the entire Teletest system two areas to improve were identified: the individual transducers and the electronics that control them. With an improved design of transducer, in terms of output amplitude and consistency between individual transducers, greater inspection lengths could be possible. This could lead to better defect detection especially where attenuating materials are in contact with the pipe, such as buried pipelines that cross under roads or have thick protective coatings to protect the structure from environmental conditions. Also, a new improved and cost effective electronics system will speed up inspection times and enable the system to be made more affordable to inspection companies and service providers. These changes together will lead to a greater adoption of guided wave inspection techniques and will ultimately reduce the risk of structural failures.

The research methodology has been a process of identifying areas of improvement, producing specifications for these improvements, designing to meet the specifications, designing for manufacture, and implementing the manufacturing processes to facilitate industrial production.

Firstly, the current commercially available guided wave shear mode transducer design was evaluated for performance and consistency over a given frequency range, randomly selected transducer samples were selected and characterised. These initial results would facilitate the way forward for any future modifications, or recommendations, to further enhance the design. Various design parameters were considered in respect to the type of piezoelectric material used, the backing material selection, for damping purposes, along with bond line thickness of adhesives used. A test bench procedure was produced that can simulate, in terms of the load applied, the conditions for which the transducer would need to operate reliably within the specified specification. Current system operating procedures require a working load of 200N per transducer and a typical frequency bandwidth of 20kHz-100kHz operating up to temperatures of 80^{o}C.

Secondly, the durability of existing designs, and any future new designs, was determined and this was achieved by designing a pressure loading test bench where transducers could be pressure cycled under working conditions and monitored. Reliability was also monitored in the field under real working conditions. Further to this, heat cycling testing and measurements was conducted, up to the new specified working temperature of 120^{o}C.

Thirdly, the manufacturing process, and the components count, of the exciting transducer design was evaluated, and new procedures were introduced to facilitate process control and reduce overall costs during the assembly phase.

Research into current design concluded that the assembly process for most, if not all, transducer arrays were very much labour intensive and the performance varied considerably from one assembly operator to another. By reducing the component count and the difficulties associated with the transducer assembly, more performance consistency was achieved.

Finally, the existing TeletestFocus™ electronic system components were evaluated and improvements to the design implemented. Areas to improve included speed of data acquisition cycles, power consumption, unit size and weight, greater user functionality and reduced system costs.

New components were specified, new circuit layouts were introduced, and new manufacturing techniques were implemented along with new techniques for controlling the analogue hardware designs.

1.7 Organization of thesis

This chapter has introduced the research carried out for this thesis and gave a brief background into the techniques employed for the inspection of structures using long range ultrasonic sound waves. Chapter 2 discusses the design of a new transducer and introduces new manufacturing methods to improve the performance and output consistency between devices. Chapter 3 details new methods for the characterisation of the new design. Chapter 4 evaluates the current commercially available embedded electronics unit used for LRUT and introduces a new improved embedded electronics unit culminating in the design and manufacture of the TeletestFocus™ Mk4 system. Chapter 5 give conclusions to the research conducted and looks at future recommendations.

Chapter 2 Transducer Design

2.1 Introduction

This chapter discusses one technique used for introducing sound into a structure. It focuses on one particular method used for the generation of ultrasonic guided sound waves with the use of Piezo electric crystals, and their application for long range ultrasonic testing (LRUT) of structures. The following sections look at the basic principles of piezoelectric behaviour and how they are used in the Teletest system. Review of the current piezoelectric transducers used with the Teletest system was evaluated and changes in the manufacturing process implemented to show how improvements to their efficiency can be made. The new transducer design was developed and characterised. A new assembly technique was developed and discussed that resulted in a reduced manufacturing time for the transducer, improved performance, reduced component count and lowered manufacturing costs.

2.2 Sound and its use for NDT

Ultrasound can be used as a means of testing materials for structural integrity without the need to dismantle or affect the object in anyway. This form of testing is known as Non-destructive testing (NDT) and is commonly used throughout industry as a means of ensuring the integrity of a test sample, albeit a pipe, bridge, aircraft, or virtually any component that is capable of supporting the distribution of sound waves within its boundaries. Sound is transferred to the human ear, or any receiving device, by means of particle movement. Sound is a pressure disturbance that travels through a medium as mechanical waves. When an external force is applied to a particle, it will move from its state of equilibrium and exert force onto adjacent particles. Adjacent particles will then move from their resting state and move their neighbouring particles, this process will continue until the initial energy from the source has abated, or attenuation of the energy has occurred over the distance of travel. This disruption of movement in a medium is commonly referred to as a mechanical wave (elastic wave).

2.2.1 Ultrasonic guided waves for inspection

As early as the nineteenth century work was being carried out by Rayleigh into the theory of mechanical waves travelling across a plane, these waves today are described as *Rayleigh* *waves*. Later in the twentieth century *Horace Lamb* followed *Rayleigh's* work and established the theoretical rudiments of such waves in his publication, O*n waves in an elastic plate*, Lamb (1917).

Over the last 60 years research and development of new techniques has been centred on the use of Ultrasonic waves. In the early fifties Worlton (1951) recognised that Lamb waves could possibly be used for non-destructive testing procedures within plates. He then conducted experiments using the theory presented by Lamb at MHz frequencies and developed equations relating phase velocity to frequency and plate thickness in terms of longitudinal and shear wave velocity Worlton (1961). Then in the mid sixties Viktorov (1967) studied previous research carried out by Rayleigh and Lamb and concluded that these wave modes could potentially be used on other structures such as pipes.

2.2.2 Transducers for guided waves

As previously discussed in Chapter 1, the selection of a particular wave mode is critical for the successful application of guided waves used in LRUT inspections. In conventional ultrasonic testing it is common to use a compression mode transducer. These types of transducer produce compression waves into the structure under test and use a coupling fluid to aid the transfer of sound energy. In this case, a single wave mode is excited because only the bulk compression mode exists in the frequency ranges used (typically in the range of 10MHz). At relatively low frequencies, typically less than 1MHz, this out-of-plane vibration will excite a number of ultrasonic guided waves. For inspection techniques using guided wave ultrasound it is important to be able to control what is transmitted to prevent unwanted wave modes. It is often desirable to transmit just one wave mode. Using just one transducer as a single transmitter will generate unwanted modes. If however, an array of transducers is circumferentially equally spaced around a pipe, in a ring configuration, these unwanted modes will be suppressed. Using more than one ring of transducers can suppress the L(0,1) mode and can reduce sound in the unwanted direction along the pipe (Cawley and Alleyne , 1995; Li and Rose, 2001).

A compression transducer will generate an out-of-plane vibration which can be optimised to bias a particular mode if that mode has a high out-of-plane component (Clarke et al, 2009).

An alternative way of achieving biasing a particular wave mode is to use an angle probe to target a particular wave length however; this approach requires a large transducer with respect to wavelength, which at low frequencies is not feasible (Wilcox, Lowe and Cawley 2001).

Another method is to use an in-plane extending transducer that will produce Lamb waves in a structure (Cawley, Alleyne and Chan, 1995). Alleyne and Cawley (1996) developed such a transducer that biased longitudinal wave modes, specifically the L(0,2) mode in pipes. This transducer used a length-expander piezoelectric element commonly found in strain gauges, the length of which was 12.5mm and produced both L(0,1) and L(0,2) wave modes when excited with a 140V peak to peak voltage. It is desired that only the L(0,2) mode is transmitted and it was shown that this could be suppressed by making the element equal to the wavelength of the undesired wave mode. For a transducer acting in-plane liquid coupling cannot be used because to transfer the energy produced by the transducer the coupling media would have to allow a shear vibration to exist and this is not possible in fluids. An alternative is to use force to couple the surface plate of the transducer onto the test sample. It has been shown that a coupling force of less than 40N was sufficient to achieve stable sound transfer in this particular experiment.

For many inspection techniques the most appropriate wave mode to use is an in-plane shear wave, such as T(0,1) in pipes (Alleyne D and Cawley P, 2009). Unfortunately, a in-plane extensional transducer is known to be a poor transmitter of shear plate waves as wave modes will emanate from the transducer on both sides of the area of contact and will be out of phase with each other at any point time therefore, cancelling out shear waves (Haig et al 2011)

However, it is possible to generate shear mode propagating waves with an in-plane extender type piezoelectric transducer by means of a asymmetric type clamping mechanism as detailed by Cawley, Alleyne and Chan (1995).

A more practical approach is with the use of a piezoelectric element polarized to produce a shear deformation when a voltage is placed across its electrical terminations (Figure 2-1)

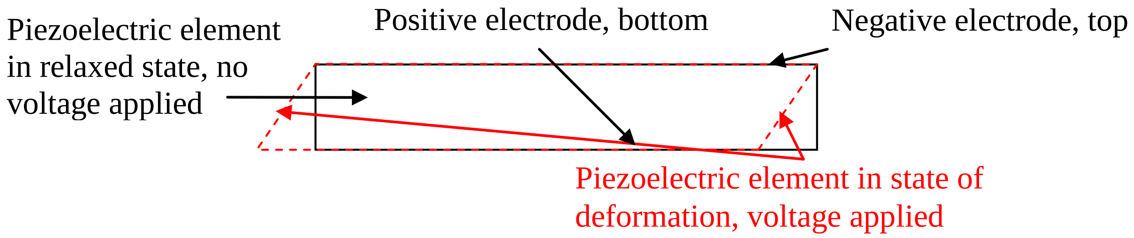


Figure 2-1. Thickness shear polarized piezoelectric PZT element

The transducer being enhanced in this research uses a thickness shear polarized PZT element and requires forced coupling.

2.3 Principles of piezoelectric technology

In 1880, Jacques and Pierre discovered that certain mineral materials became electrically polarized when subject to a force being applied across them producing a small voltage. Tension and compression generated voltages of opposite polarity and the voltage was proportional to the applied force. Later on it was discovered that the same crystal minerals would experience an elastic strain and shortened or lengthened according to the polarity and strength of the applied electric field. This phenomenon was described as the Piezoelectric and the inverse piezoelectric effect after the Greek word *piezein* meaning to press or squeeze.

In the past natural occurring crystals were used to manufacture piezoelectric devices such as quartz, sodium potassium tartrate and tourmaline and these have been used for many years. These natural crystals however exhibit a relatively small piezoelectric effect proportional to their size.

From the early sixties manmade materials were starting to be used as an alternative to the natural crystals. These ceramics are prepared from metallic oxides such as barium titanate ($B_aT_iO_3$) or lead zirconate titanate $Pb(Z_{rx}Ti_{1-x})03$ (PZT) and they exhibit much larger displacements or induce larger electric voltages than the early naturally occurring materials. Subsequent research carried out over resent years showed that lead zirconate titanate (PZT) materials facilitated greater sensitivity and higher operating temperature than $B_aT_iO_3$ so has replaced this ceramic in many applications.

To manufacture a ceramic piezoelectric structure metal oxides are mixed together, in the case of a PZT element, these are Lead, Zirconium and Titanate. These three oxides are usually available as fine powders before the process of manufacturing the ceramic begins. They are first mixed in specific quantities before heating (calcined) to produce a uniform powder. A bonding agent is then added to this powder before being pressed into the desired shape, this can be in form of a disk, rod or plate. A heating process is then used to sinter the material which then forms a crystalline structure as shown in Figure 2-2.

At temperatures above a certain point, known as the Curie temperature, the crystals within each grain of the material exhibits a common cubic symmetry with no dipole movement, as shown in Figure 2-2a. However, at lower temperatures than the Curie temperature the crystals take a tetragonal or rhombohedral shape as shown in Figure 2-2b.

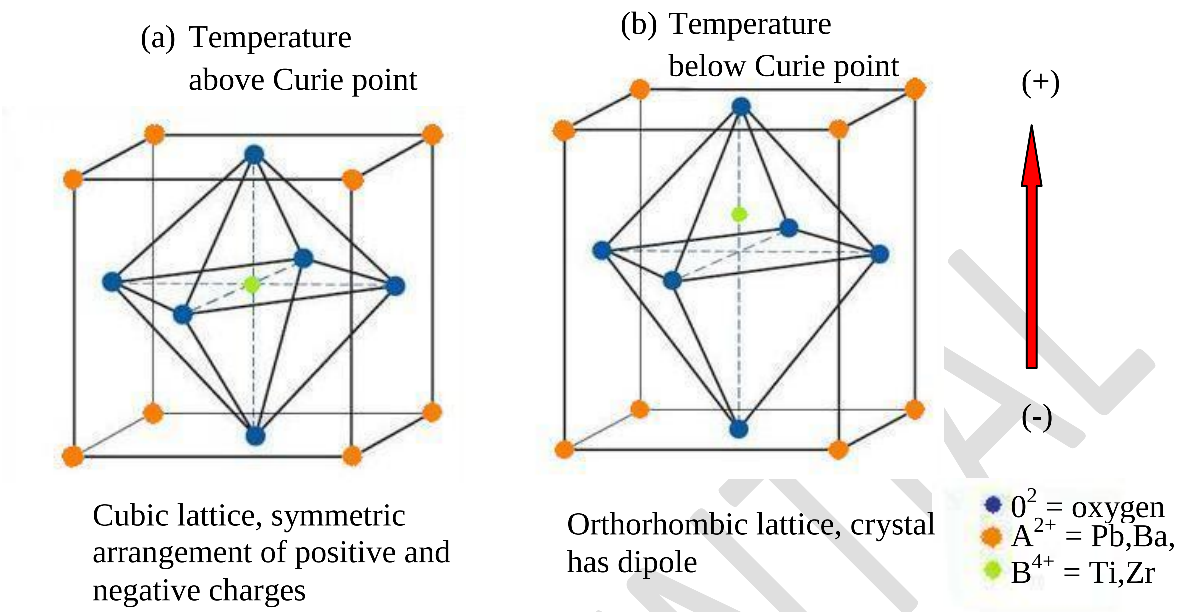


Figure 2-2. Crystal Structure of a traditional piezoelectric ceramic.

After the initial stage of consolidation the individual oxides and bonding the dipole movement are randomly disfigured within the crystal structure and have no polarization as shown in Figure 2-3a. To align these dipoles a strong electrical DC field is applied to the crystal structure which forces the dipoles to align in the direction of the applied electric field, as shown in Figure 2-3b. After removing the polarization voltage the dipoles remain in this fixed state, Figure 2-3c at which point the ceramic exhibits the characteristics of a piezoelectric element.

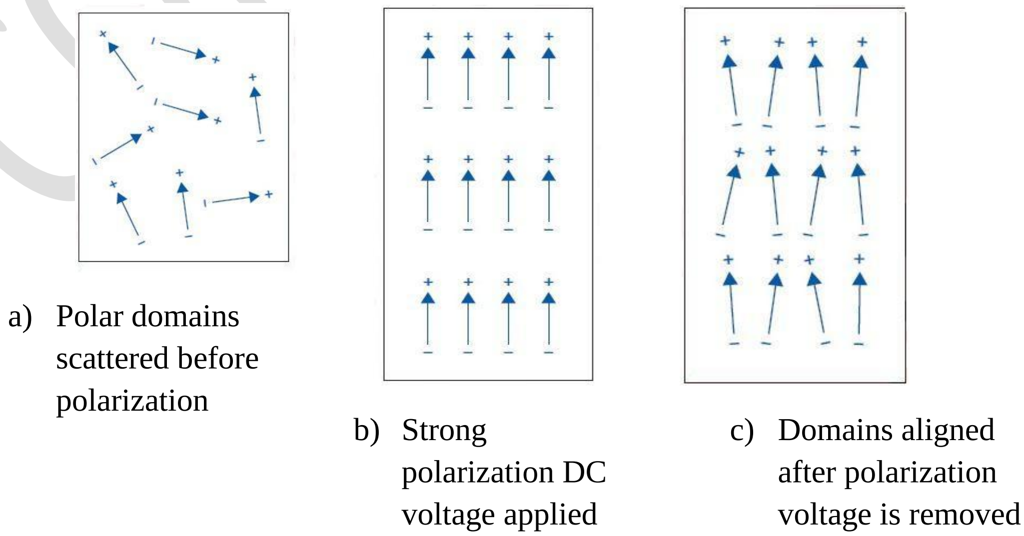


Figure 2-3. Process of alligning domains with a ceramic crytal using a high DC voltage >10KV

After the ceramic compound has been polarized any final detailing operations can be performed. This involves the application of electrodes onto the surface of the ceramic to allow electrical connections to be made during the installation into the final product. This process usually involves a technique known as sputter coating (Emsduiasum 2011). Final machining of the element can also be undertaken at this stage to remove any unwanted material to produce the finished component. Piezoelectric ceramics are physically strong and are resistant to chemicals and humidity. They can be manufactured relatively cheaply and formed into many different shapes and sizes depending upon the application. Figure 2-4 shows a selection of Piezo ceramic products manufactured in a variety of different shapes and sizes

Figure 2-4. A typical selection of Piezo ceramic crystals produced by PI (Physik Instumente) ltd

2.4 Existing transducer design

The current design of transducer used in conjunction with the Teletest system has been in circulation for over 8 years without its performance being evaluated in any great detail, apart from having a minimum output amplitude of 50mV being specified, when the transducer was subjected to a 285V peak to peak tone burst, as an acceptable threshold level. This requirement was measured using the 1.2 meter length of bar used in pre-modified test rig, as detailed in Chapter 3. The transducer was manufactured by a third party company not directly involved in long range ultrasonic testing and no tests were conducted into the performance of the device once assembled. Only capacitive checks and voltage isolation tests between the PZT element and grounded outer casing were performed after the transducer had been manufactured. Subsequent testing was undertaken by TWI on receipt from the manufacturer of newly assembled transducer to check that the minimum specified output level of 50mV was achieved. The design of the transducer was also in question, and it’s suitability for maintaining a consistent and reliable manufacturing process. As a result of this, high levels of failures were experienced, more than 60% in some batches, and output levels were poor. Although experienced personnel were involved in their construction the manufacturing process and design proved to be cumbersome to repeatability reproduce a consistent product.

2.4.1 Components and assembly process

The previous transducer design required eleven separate components within its assembly, see Figure 2-5.

These components are

- Electrical connection – connectivity for transducer element signal
- Stainless steel backing block – used for damping and housing
- First insulation adhesive layer – insulation layer to prevent PZT element from shorting to backing block
- Alumina guide rails – creates cavity for conductive adhesive
- PZT element – The piezoelectric element exciting and sensing vibration
- Adhesive layer – bonds PZT element to the protective face plate
- Alumina protective face plate – used for protection of PZT element against external environmental damage
- Nickel plated 50 micro connecting wire – connects PZT element to electrical connection
- Silicon insulation sleeving
- Solder
- Conductive adhesive

To assemble each transducer, 7 different operations were carried out without the aid of fixtures and entirely fabricated by hand.

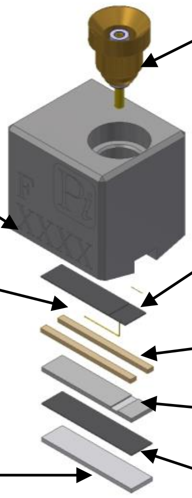


Figure 2-5. Individual component used in the existing design of transducer.

Figure 2-6 shows a typical example of the PZT element used in the design of the Teletest system transducer. The element measures 13mm x 3mm x 0.5mm. The negative electrode, although not shown, is wrapped around the far end of the element and extends along its length. This wrapping of the negative electrode creates a small dead zone where no potential differential will exist when an applied voltage is present. Subsequently, this affected the active area of the active element and reduced its operation length.

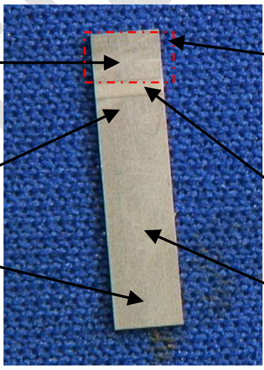


Figure 2-6. Single PZT element showing separation between positive and negative electrodes

As the piezoelectric component within the transducer can be classed as a electrical item this requires some form of electrical insulation from the metal backing material used as the damping mass. To achieve this, a thin layer of adhesive was laid at the base of the grove where the Piezo element was located. On top of this adhesive layer two alumina guide rails were positioned along the length of the grove to create a void, these two rails act to create a void that was later be filled with conductive adhesive. A connector was inserted into the backing block; this forms part of the main electrical contact for the electrical signal to the Piezo element and the ground connection, the backing block. A single 50 micron length of nickel plated wire was attached to the main connector and then run through an insulation sleeve, to prevent a short circuit to the backing block forming. The wire was channelled between the two alumina rails that form the void. The void was then filled with a conductive adhesive and the Piezo element positioned on top. The part assembly is then cured in an oven for 1.5 hours at a temperature of 150^{oC}. Once this process was completed another adhesive layer was positioned directly above the Piezo element and an alumina protective face plate was attached and the assembly was again cured for a second time for 1.5 hours at a temperature of 150^{oC}.

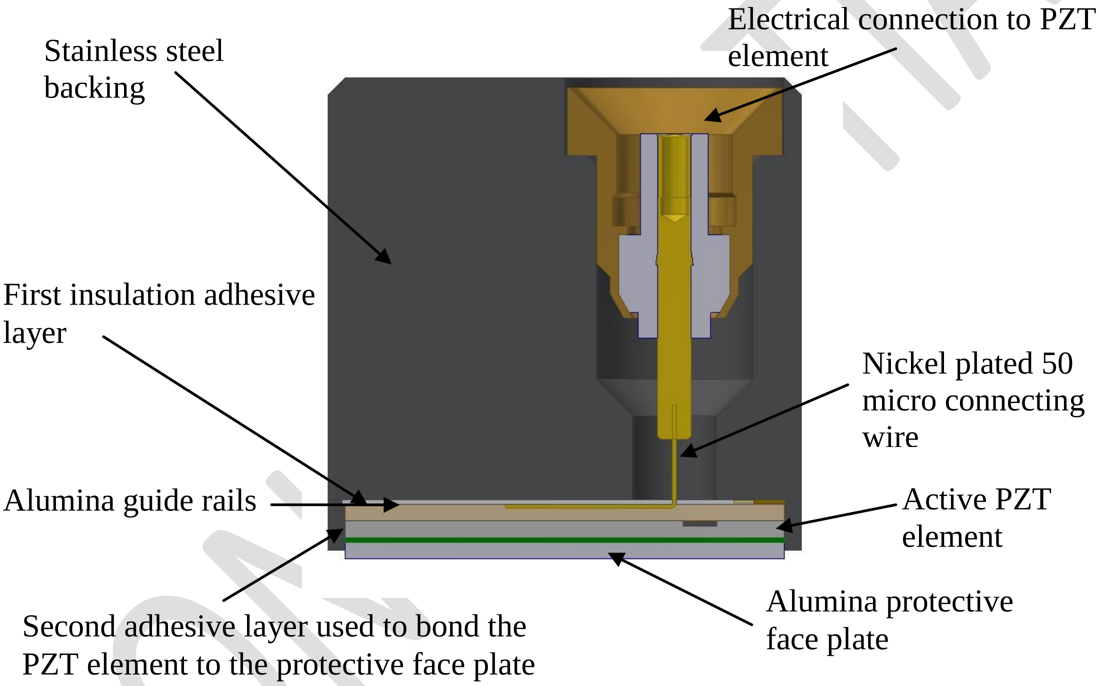


Figure 2-7. Cut away section showing construction of previous design of transducer.

In Figure 2-7 the various component layers are shown for clarity of the manufacturing process. To simplify the figure, the conductive adhesive has not been show but would be applied in the void between the two alumina rails. This conductive adhesive will make the electrical connection from the positive terminal of the PZT element to the nickel wire and the connector, and also the negative terminal of the PZT element to the Stainless steel backing block.

The whole assembly process is very labour intensive and time consuming. With the various operations involved, and the relatively small dimensions for each component, errors in consistency during the manufacturing process are non avoidable.

It can be seen from Figure 2-8 that due to the design of this early transducer, and the amount of separate components and assembly process involved, the completed transducer was prone to poor manufacturing quality. Due to the relatively large distance, 0.5mm, occupied by the alumina guide rails that formed the void for the conductive adhesive problems arose with the introduction of air pockets. These air pockets were caused as a result of the curing process for the electrically conductive adhesive becoming less viscous at the elevated curing temperatures and therefore, a settling motion was induced. As the adhesive settles into the void between the guide rails a vacated area was formed that contained no support once the adhesive curing process had been completed. This lack of support for the PZT element and protecting face plate caused the assembly to fail when subjected to coupling under pressure in the collar as inflation was taking place. Noticeable failures were observed in the form of severe cracking of the protective face plate and PZT element.

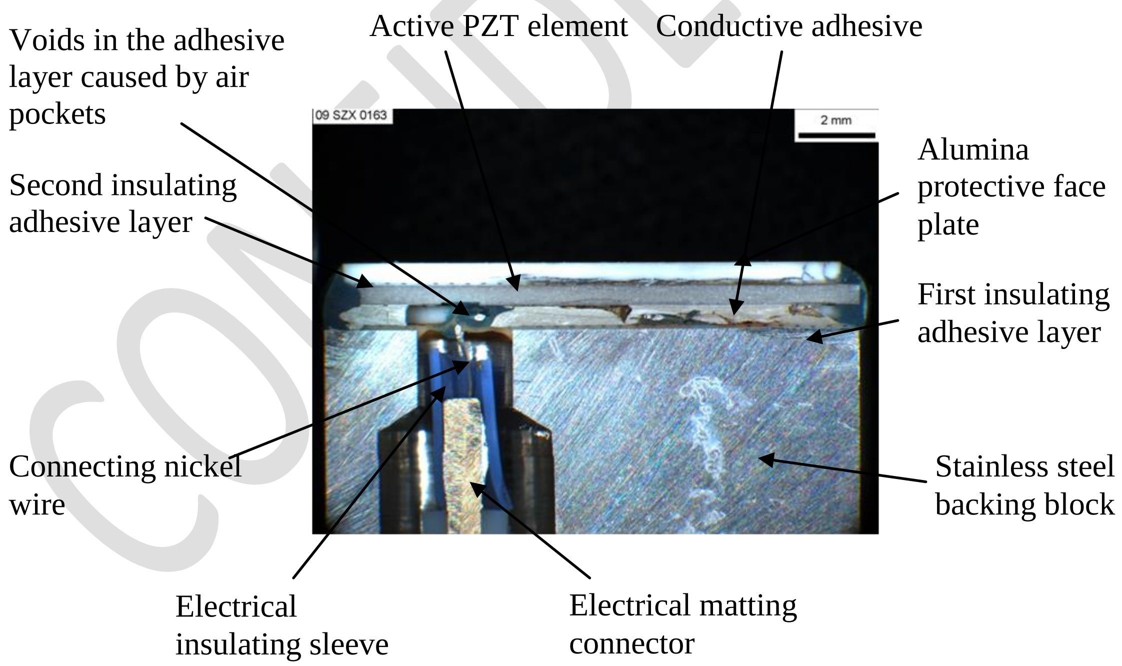


Figure 2-8. Cut away section of old transducer design showing different construction layers and flaws in the construction caused by the low viscosity of the adhesive at curing temperature.

Also, as a result of these pockets in the layer between the active PZT element and backing material an unsatisfactory anchorage resulted. This lack of support potentially result in a large percentage of the energy transfer from the active PZT element being dissipated inside the construction and not transferred to the material being inspected.

2.5 New transducer design

Having identified problems with the original transducer design a new concept for the assembly process was introduced that would address these deficiencies. Firstly a new design for a transducer was visualised that would reduce the total number of components required. A reduction in the component count would facilitate the assembly process and lead to tighter process control during the assembly phase. The new design solution would incorporate the same active PZT element, backing block, and connector. The same backing block dimensions had to be maintained as backward compatibility with the Teletest transducer mounting arrangement was specified as being a requirement during this research. However, research carried out by Engineer (2014) introduced alternative discussions for the use of different backing block dimensions and materials, but are not included in this research. A new electrical connection scheme was introduced into the new transducer design along with an improved scheme of electrically isolating the active element from the backing block. These improvements would reduce assembly times, improve the efficiency of the transducer and ultimately reduce costs.

Figure 2-9 shows the different components used to make the new design of transducer.

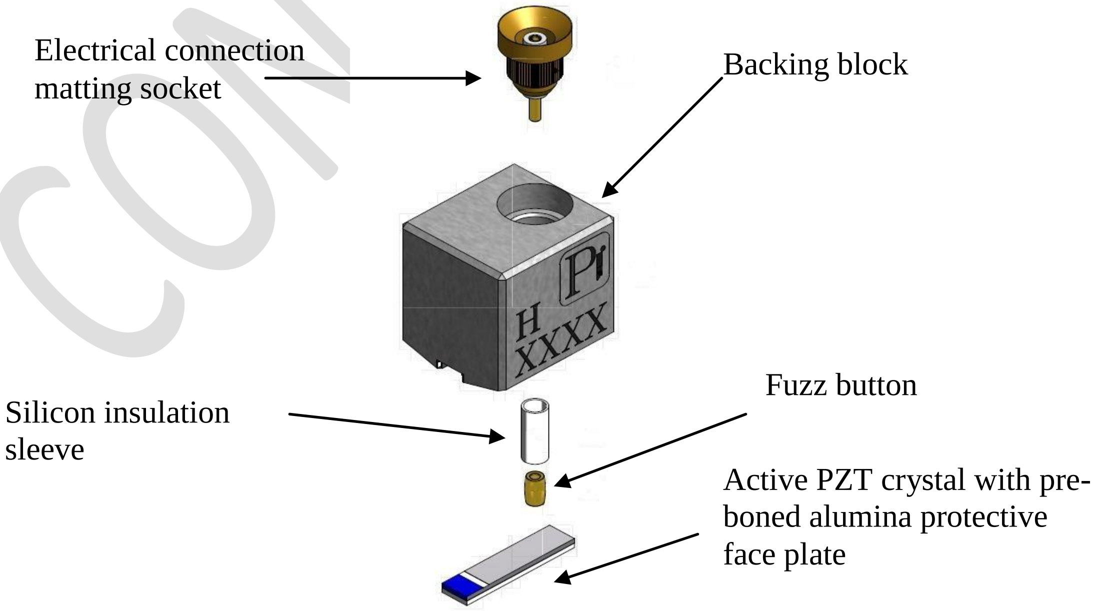


Figure 2-9. Exploded view of component layout for a new transducer design.

2.5.1 Backing block and bond line thickness

The backing block not only serves as housing for the rest of the components but also serves as a damping mass for the piezoelectric element. The transducers are designed to be non-resonant because they will be used at various frequencies controlled by the tone burst used during an inspection. The frequencies typically used in a guided wave inspection system are well below the natural resonance frequency of the piezoelectric crystal. The damping effect of the backing block is governed by the density and elasticity of the material being used, in this case stainless steel which is 7750-8050 kg/m^3. For a transducer used in a LRUT system its output characteristics need to closely follow the input electrical wave form, i.e. it is desirable that any resonance behaviour from the piezoelectric element is damped. The consistency of the thickness of the alumina coating and the supporting adhesive layer (bond line) significantly influences the damping and so affects the consistency of the transducers' performance. A thick material between the piezoelectric element and the backing block will decouple the backing block and reduce its effect on damping, so a thin bond line is desired. To improve the distance between the active PZT element and backing block a new scheme was introduced that would reduce this distance to 100 microns (from 700 microns) but still maintain the isolation requirements required to insulate the active PZT element from its surrounding components.. As previously discussed, the old design used a number of different components to achieve a bond insulation barrier, culminating in a far from ideal bond line. To achieve a more accurate and consistent bond line a process of coating the channel that supports the PZT element with an alumina oxide barrier was introduced into the design.

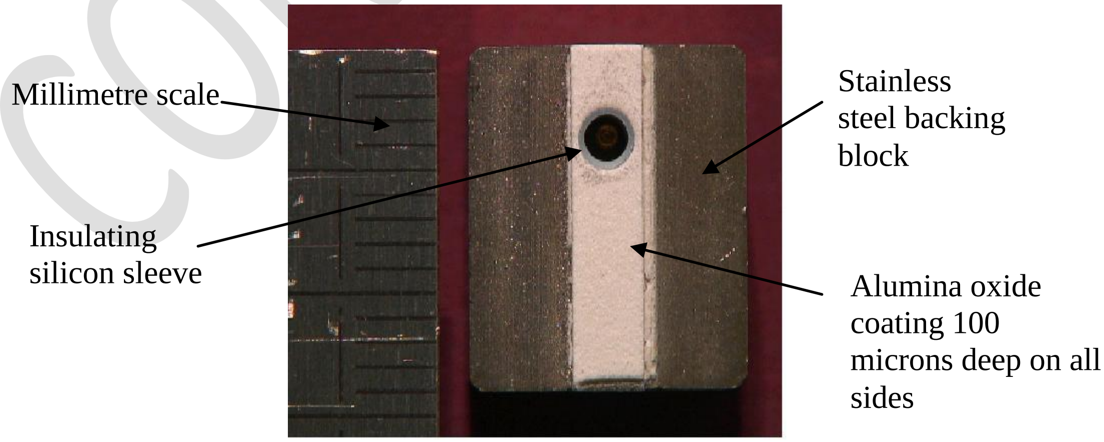


Figure 2-10. Transducer block showing 100 micron coating of Alumina on each face of the channel ready for the active PZT element to be bonded.

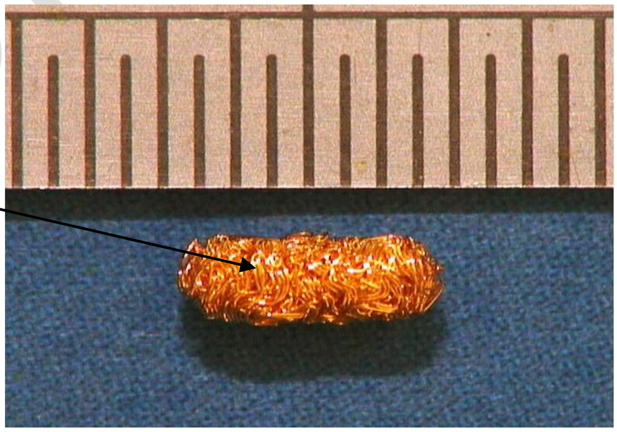
Alumina oxide is a hard chemical compound resulting from a mixture of aluminium and oxygen with the formula Al_2O_3 (Makeitfrom 2013) It has a high electrical resistivity and is applied using a process of Plasma spraying (Bodycote 2013) Using this manufacturing process would allow for a small, but even layer, of alumina to be applied to each side of the backing block in the area where the active PZT device would be mounted.

The alumina would serve as an electrical insulation barrier to prevent the active PZT element from short circuiting to the stainless steel backing material. Figure 2-10 shows backing block after the plasma spray process is complete. To achieve a uniform coverage without large amounts of over spray special fixtures were design and used during the process.

2.5.2 Electrode connections

The electrical connection for a transducer provides a signal path for both the active element (PZT crystal) drive voltage and current and the return path. In the previous design this was accomplished by the use of a single strand of nickel plated wire with a diameter of 50 microns. Adhesive was then applied to the wire to bond it to the element. This wire first had to be soldered on the mating connecter that is housed in the backing block and then routed to the positive terminal on the PZT element. This process was time consuming and involved several processes of soldering and cleaning and involved adhesives that need careful application and storage. The new design of transducer would incorporated a much simpler approach that negated the need for any soldering, bonding or cleaning process to be involved. Again, consistency between assemblies could be achieved due to the minimal assembly processes involved and subsequent quality can be more easily monitored.

Custom Interconnect Fuzz Button[R] measuring 3.5mm x 1.6mm made from Beryllium copper



Millimetre scale

Figure 2-11. Custom Interconnects Fuzz Button[R]

The use of small connecting component manufactured and supplied by Custom Interconnects (Custom Interconnects 2012) would greatly simplify the process of making an electrical connection for the PZT element. This new component in the design is marketed as Fuzz Button^{R} and was initially introduced into the market back in 1959 and was mainly used in grounding applications. These components were originally large items but with the growing semiconductor markets in the early 90's they were miniaturised for use in production testing, such as automated test equipment (ATE). Fuzz buttons are now found in many commercial products, anything from test dummies, satellites, to military weapons.

A fuzz button can be classed as two sampling requirements in one structure. First is acts as the signal element and secondly a spring. They are manufactured from a signal piece of wire, usually gold plated Beryllium copper, but other materials can be specified.

2.5.3 Protective faceplate

The face plates acts as a protective barrier for the active element to prevent damage when coupled to a test sample. The face plate used on the transducer was made from Alumina Oxide. Alumina is well suited for use as a protective material to prevent damage to the relatively soft PZT element. It is water, gas and chemical resistant so is ideally suited to be exposed to these substances during operation of the Teletest equipment. As the face of the transducer is in contact with many variable conditions of surface that may be present on a structure undergoing an inspection the hardness of the protective face is of paramount importance. The type used for this application is rated by the Rockwell 45N procedure as having a hardness value of 78. Alumina is used in many applications where durability of a non warring material is required, such as abrasives, and has a high electrical resistivity value greater than 10^{12} ohm (Ω) @25^{o}C.

For the new design of transducer the protective face plate was pre-boned to the PZT element during its fabrication. This reduced the transducer assembly process as the operation of bonding the alumina and PZT element together could now be carried out before the elements were cut to the required size. Using this approach meant there was no misalignment in the finished component. Also, the bond line thickness could be more easily controlled as a larger slice of PZT material and Alumina was bonded together and the adhesives cured before slicing.

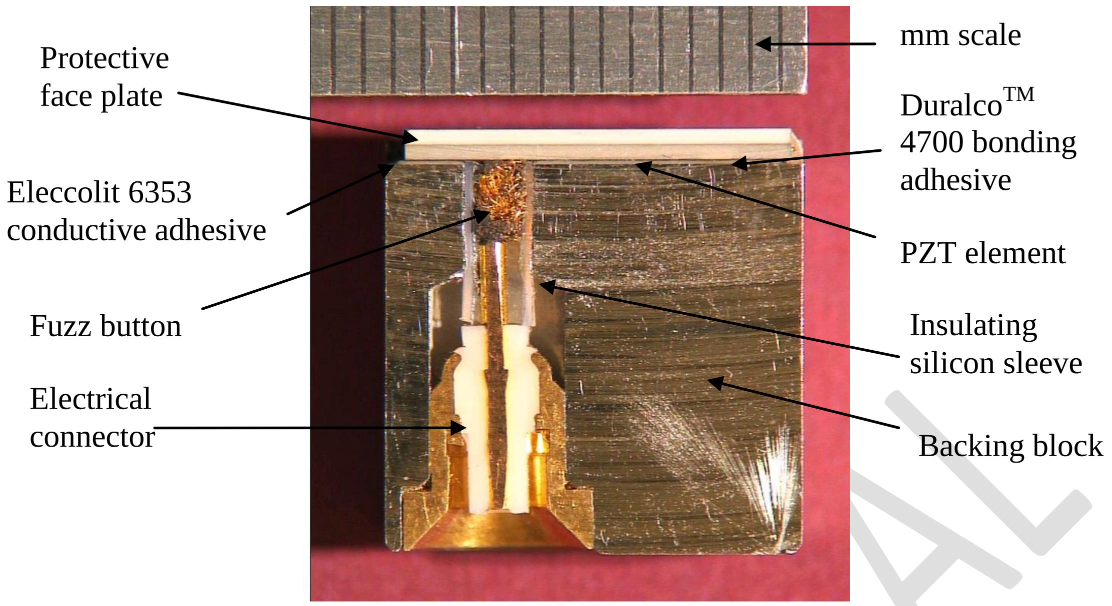


Figure 2-12. Cut away section of the new design of transducer

Figure 2-12 shows the component make up for the new design of transducer. It consists of only eight components. These are:

- Backing block
- Connector
- Insulation tube
- Fuzz button
- Active PZT element
- Protective face plate
- Conductive adhesive (Elecolit 6353)
- Bonding adhesive (Duralco 4700)

The manufacturing process has been simplified along with the assembly activities. First of all, an electrical connector is inserted into the backing block. Bonding adhesive Duralco™ 4700 is then applied to the bottom of the channel where the active PZT element will be seated. A silicon insulation sleeve is placed into the backing block to form a barrier against the fuzz button shorting onto the metal block. A fuzz button is then placed into this insulation tube, the fuzz button will seat onto the electrical connector and then sit proud, by a 0.2mm into the channel where the active PZT element will be bonded. The active PZT element is then placed into the channel, within the backing block, and pressed down forcing the fuzz button to compress and make a low resistive and reliable connection. The assembly is then placed into an oven to cure the adhesives.

2.6 Summary

Research has been conducted into one particular guided wave inspection system manufactured by Plant Integrity Ltd, a subsidiary of TWI Ltd. This company uses shear wave mode transducers for ultrasonic testing within its Teletest LRU system. The existing design of transducer had been in production for more than 8 years and the original production and characterisation techniques that were first developed for the assembly process were still being implemented. In this research these processes and the design of the transducer were reviewed and recommendations were made to improve both the output performance and assembly techniques.

The existing design of transducer consisted of eleven separate components (including any solder operations). The size and shape of the components made it very difficult for an operator to assemble the transducer by hand and no automated assembly processes were used in its construction. This resulted in variations with the alignment of the components and inconsistencies with the application of the adhesive layers being introduced during the manufacturing stages, which led to variation and poor quality of the finished product.

Development was carried out to improve the transducer design, optimise the assembly process, reduce the component count and ultimately improve transducer performance and achieve more consistent quality.

The component count was reduced from eleven to eight. This was achieved firstly by eliminating the need for the two alumina guide rails by introducing an insulative alumina coating onto the backing block where the piezoelectric element is seated. Secondly, with the introduction of a new electrical connection scheme the solder operation to connect a 50 micron wire to the mating connector was also removed. Reducing the component count has made the process of assembly much easier and limited the amount of errors that could potentially be introduced.

Previously, the fabrication of the transducer involved the use of two layers of pre-impregnated adhesive mesh layers and a conductive adhesive. The conductive adhesive was applied in liquid form between the piezo element and the backing block and then cured for 1.5 hours at a temperature of 150^{o}C. As the temperature of the adhesive was raised and before curing occurred it would become less viscous. It was shown that the adhesive would displace because the volume it occupied between the guide rails was substantial and not always fully filled to obtain a solid base. This could have the effect of causing air voids between the piezo element and the two alumina guide rails resulting in the piezo element not being sufficiently supported by the backing mass. The removal of the guide rails overcame this problem by reducing the amount of space the adhesive was required to fill. Investigations into transducers of both designs after fabrication found that the old design contained voids in the adhesive, while the layer of adhesive in the new design was null of any voids. Also, with the removal of the two alumina guide rails, the bond line thickness between the piezo and the backing block is reduced resulting in better attachment between these two components.

The electrical connecting wire was replaced by the introduction of a component known as a "Fuzz Button™", which is manufactured as a compressible, cylindrical shaped, thin wire mesh that can be used to electrically connect components in close proximity. In the new design, the Fuzz Button™ joined the electrical mating connecter, in the backing block, to the underside of the piezo element and was held in place by mechanical pressure. In the previous design, a solder operation was required to connect the mating connection to the piezo element. This process was time consuming, relied on the skill of the operator and introduced variations in the construction of the transducer. Using the new approach of a Fuzz Button™ eliminated the need for a solder joint, allowed for much greater consistency and reduced the assembly time.

To further reduce the transducer assembly time the protective alumina face plate, previously bonded to the piezo element during the assembly process, was now introduced at the piezo element manufacturing stage. Before this introduction, the protective face plate and piezo element had to be aligned by eye and bonded together. The new assembly method of pre-bonding the face plate and element at the piezo manufacturing stage meant that the two components could be joined before the parts were machined to their finished size. This resulted in a much finer finish to the edges of the bonded assembly and made the final process of positioning and aligning the component into the backing block more consistent.

Implementing the new transducer design, and the new assembly techniques, have significantly reduced the manufacturing cost price and greatly improved the overall performance of each transducer. The characterisation and comparison of performance for the old and new designs are discussed in Chapter 3.

Chapter 3 Transducer Element Characterisation

3.1 Introduction

As disused in Chapter 1, the requirement for a high ultrasonic output array of transducers coupled to the test sample is paramount for the successful detection of a flaw in a given structure. To this end, transducers that constitute the array configuration ideally need to be identical in their individual characterisation, with relationship to the overall system performance.

To successfully evaluate the performance of each transducer some form of repeatable test setup is required that would facilitate characterization of the individually assembled transducers. The test rig and associated electronic equipment are needed to produce consistent reliable and accurate results in terms of the load force applied to the transducer under test, the transducers measured capacitance value, and the actual ultrasonic measurements taken during testing. All of these parameters need to be obtained and recorded in one easy to use setup, and without the need to remove, or physically adjust, the transducer from the rig until characterisation was complete.

To characterise the performance of each transducer it is subject to a series of tests, which would ultimately determine its overall performance, and subsequently its suitability, for use in the LRUT Mk4 TeletestFocus™ system.

The series of tests would comprise of:-

3.1.1 Output performance

This is a measurement of the maximum amplitude ultrasonic wave that the transducer will produce into the wave guide medium, for a given excitation signal. This will indicate the transducers ability to convert the applied electrical signal into the desired acoustic signal. In this test the Mk4 TeletestFocus™ (see Chapter 4) voltage amplifier output circuits generated an excitation signal to excite the transducer resulting in an ultrasonic shear mode wave form being produced. This transmitted shear mode wave form is subsequently received via a second permanently fixed PZT element placed on the wave guide medium a short distance from the transmitting transducer. The mechanical to electrical response obtained from this second fixed PZT element is recorded and made available for immediate analysis, or can be recalled at a later date. Fixed PZT elements are bonded directly onto the steel bar using a suitable adhesive. In these tests, the use of Loctite SuperGlue® was implemented as the bonding agent and was found to be appropriate to secure the fixed PZT elements to the steel bar. No loading mechanical force is applied to these bonded PZT elements.

3.1.2 Transducer receiver sensitivity

This determines the transducers ability to convert mechanical motion into an electrical signal. Again, the fixed PZT elements placed on the medium act as the ultrasonic shear mode wave form generator. The transducer under test receives this transmitted wave form and converts the mechanical response back into an electrical signal where upon the electronic circuits digitize this received electrical response. The results collected from this transducer are recorded for analysis.

3.1.3 Transducer capacitance value

The transducer should have a capacitance within the expected tolerance of 1nF. The TeletestFocus™ equipment electronics has been designed such that large voltages may be applied to a number of transducers simultaneously. Therefore, the total capacitive load seen on any single channel output must be within the target design limits of 16nF. The number of transducers required increases with pipe size, so the electronics are able to cope with a large range of total capacitance. As the module count increases, to accommodate larger pipe diameters, so the load on the output also increases. Since modules that house the transducers are wired in parallel and their total capacitances equates to C1+C2+C3…. the total number of modules are limited to 16. See Chapter 1for more details of tool configuration.

As capacitive impedance is expressed as $X_c = \frac{1}{2\pi f c}$, the greater the amount of transducers acting as the load results in a decrease of impedance. This decrease in apparent load will demand more current from the output drivers, which are set to 2.3A, to prevent electronic component failure, before an over-current situation occurs and the system will abort the waveform generation and flag a system error.

However, the principal reason that there should be a tight tolerance on the capacitance of individual transducers is such that when they are wired in parallel on a pipe, the total capacitance may be measured and a check made that all the transducers are functioning as specified (from a capacitance point of view).

The expected value is obtained from the assembled transducer and is based on the PZT material used in the manufacture. The PZT manufacturer specifies a nominal value of 1nF with a tolerance of ±20% for the configuration of the crystal used in the construction of the assembled transducer. Although other components are used in the assembly of the transducer, connector, fuzz button, the effect on the total capacitance reading is negligible and can be disregarded.

3.1.4 Transducer output phase

It is important to ascertain that the PZT has either been correctly polarized for the correct wave mode generation, in this case shear mode, or assembled into the backing block correctly orientated. If either of these two scenarios exists then the transducer will be out of phase with neighbouring transducers then unexpected cancellation can occur, and wave modes could be cancelled or an axisymetric propagation will not be formed in the test bar.

3.2 Characterisation method

Although previous methods for testing transducers were employed those procedures proved far from ideal in respect to results collected, and ease of use for a technician. Information collected relating to the performance of each transducer under test was manually recorded on paper, with no data files being stored electronically. This resulted in the analysis of batch performance difficult and not easily to access, and very time consuming.

Previously, the force applied to the transducer, to make contact with the wave guide medium during testing consisted of a large heavy weight being placed directly above the transducer under test forcing it onto a specimen steel bar used as the wave guide medium. No measurement of the force applied to the transducer in contact with the bar was recorded. This was not an ideal solution for reliable and repeatable characterisation of a transducer, let alone the health and safety implications for the operator when repeatedly removing and replacing a large heavy weight from the test rig.

The software originally developed to carry out testing was far from adequate with only transducer output and receiver performance being available for analysis. The software user interface was very complicated to configure and more importantly, in terms of analysis, no previous records were stored on file.

Only three parameters were recorded on paper during each test, the transducers' serial, output performance and receiver sensitivity would all be manually recorded on paper. No Phase angle criteria or noise sensitivity of the transducer under test was investigated and the capacitance of each transducer was obtained manually by the operator using a hand held capacitance meter purchased from Fluke instruments .

These deficiencies all lead to the design and manufacture of a new test rig during this research. This equipment was made available to the manufacturing test departments for use in the production process of LRUT transducer used for guided wave applications centred on the equipment manufactured, and marketed as TeletestFocus™, by Plant Integrity Ltd (Commercial arm of TWI Ltd).

3.2.1 Proposed method

A new method was required that could reliably and repeatedly characterize the performance of a transducer. A new method was required to load and monitor the forces applied to a transducer during characterizing. More advanced software was introduced to record digital data collected from each test to eliminate any human errors while testing was in process. This new method is divided into experiment and analysis which are documented in detail in the following two sections.

3.3 Experimental setup

In order to efficiently test and measure the performance characteristics of each single transducer under test some means of an automated test rig and procedure was required. To achieve a consistent and reliable method for testing a dedicated test rig was designed and manufactured. The test rig provided a means of pneumatically clamping the transducer under test to an ultrasonic wave guide medium, in this case a carbon steel bar. The test rig was also required to automatically take measurements for the transducers output and receiver characteristics, capacitance, ringing and then recording these parameters on file for immediate, or future, analysis.

3.3.1 Configuration

The schematic diagram of the test rig is shown in Figure 3-1. A photograph of the new test jig is shown in Figure 3-2. The Teletest Mk4 was used as the pulse signal generator and receiver along with the following pieces of equipment:-

- Standard laptop or PC used for data analysis and storage of collected signals.
- Fluke 287 Capacitance meter used for recording capacitance of each transducer UT.
- Switch box enables switching between the transducer under test and the Capacitance meter. This is controlled via a Parallel port on the laptop.
- Mecmesins advanced force gauge used to measure the load applied to each transducer UT.
- Load actuator applies predetermined force to be applied to each transducer UT.
- Load cell output is attached to the Mecmesins advanced force gauge.

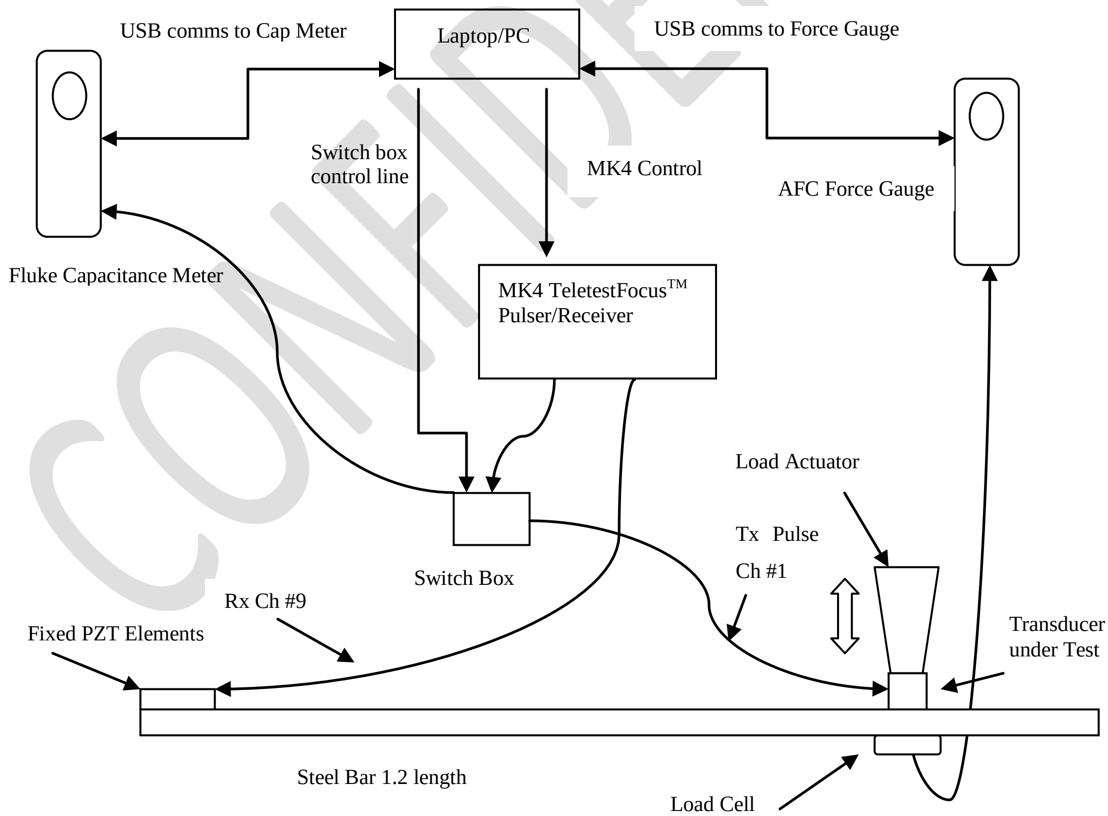


Figure 3-1. Schematic view of transducer test rig.

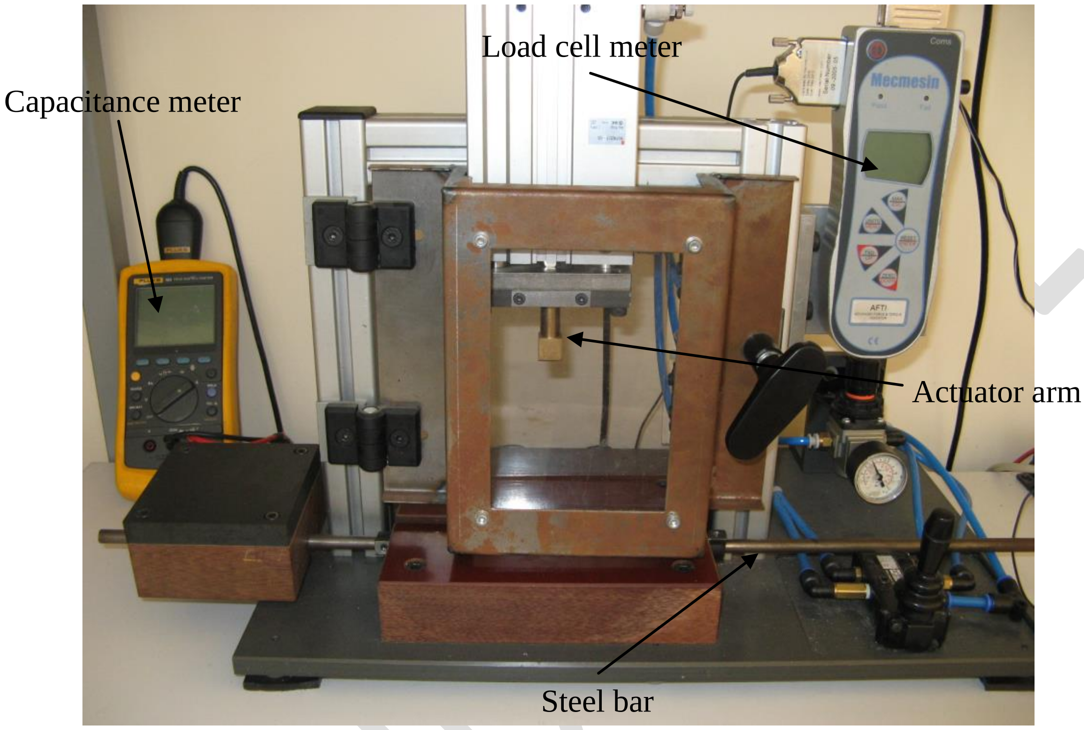


Figure 3-2. Transducer Test Rig Set-up (laptop not shown).

3.3.2 Test Rig design considerations

Each component of the test rig was chosen to facilitate a user friendly test environment that could be capable of measuring and recording all the parameters of interest of a transducer. Manual intervention during testing should be kept to a minimum, with the majority of signal capture and interpretation of results made as automatic as possible. Portability was also considered as a design constraint. Also, any externally procured items, just as peripheral measuring devices, are required to be compatible with the controlling software being executed to perform the ultrasonic characterisation.

Force Gauge – load cell

For the purposes of monitoring and recording the force applied to the transducer under test a Mecmesin advanced force gauge (see Figure 3-3) was integrated into the rig. This instrument was selected for two key operating features. First of all, its design was specific for monitoring and recording forces applied to an object under inspection. It consisted of a free standing load cell that, for this application, could be easily positioned directly under the transducer under test (see Figure 3-5). This meant its position, relative to the transducer, could be predetermined and integrated into the rig ultimately eliminating any variation in applied force due to misplacement of the cell during testing. The second requirement was the ability of the instrument to communicate with the PC/Laptop via some interface; in this case it used the industry standard RS232 protocol and interface. Also, using an off the self instrument meant it could be calibrated by the equipment manufacturer to recognised industry standards so that a controlled transducer evaluation test setup could be maintained and monitored. During testing, and after the pneumatic arm had been lowered applying a known force to the transducer, the controlling software interrogates the force gauge instrument to generate a reading. The results are stored on a PC/Laptop for future analysis.

Research carried out by Plant Integrity Ltd both in the laboratory and in situ on site, and then later by Engineer (2014), described how dry coupled ultrasonic transducers designed for the purpose of LRUT varied in sound transfer into the test sample under variations in force applied. A load applied to each transducer onto the test sample of 200N gave the most efficient transfer of energy.

Figure 3-3. Mecmesins advanced force gauge.

Pneumatic actuator arm

The pneumatics was assembled from a standard off the self actuator arm and was controlled via a hand lever to allow the operator to either lower or raise the transducer from the guide wave medium, in this instance a steel bar, (see Figure 3-6). The remainder of the rig is made up of standard Aluminium pre-formed trunking to support the pneumatic actuator and control mechanism. A formica housing that holds load cell and aligns the Steel bar in position while the transducer is raised or lowered. Formica was chosen to house the load cell and support the Steel bar because of its non-interference with any of the ultrasound signatures that pass along the Steel bar during testing. All of these sub-assemblies then located onto an Aluminium base plate for ease of moving the rig without the need to dismantle.

From a safety aspect, a clear perspex window was designed into the rig to prevent any obstruction in the travel path of the actuator arm and must be in the closed position before the actuator arm can be operated.

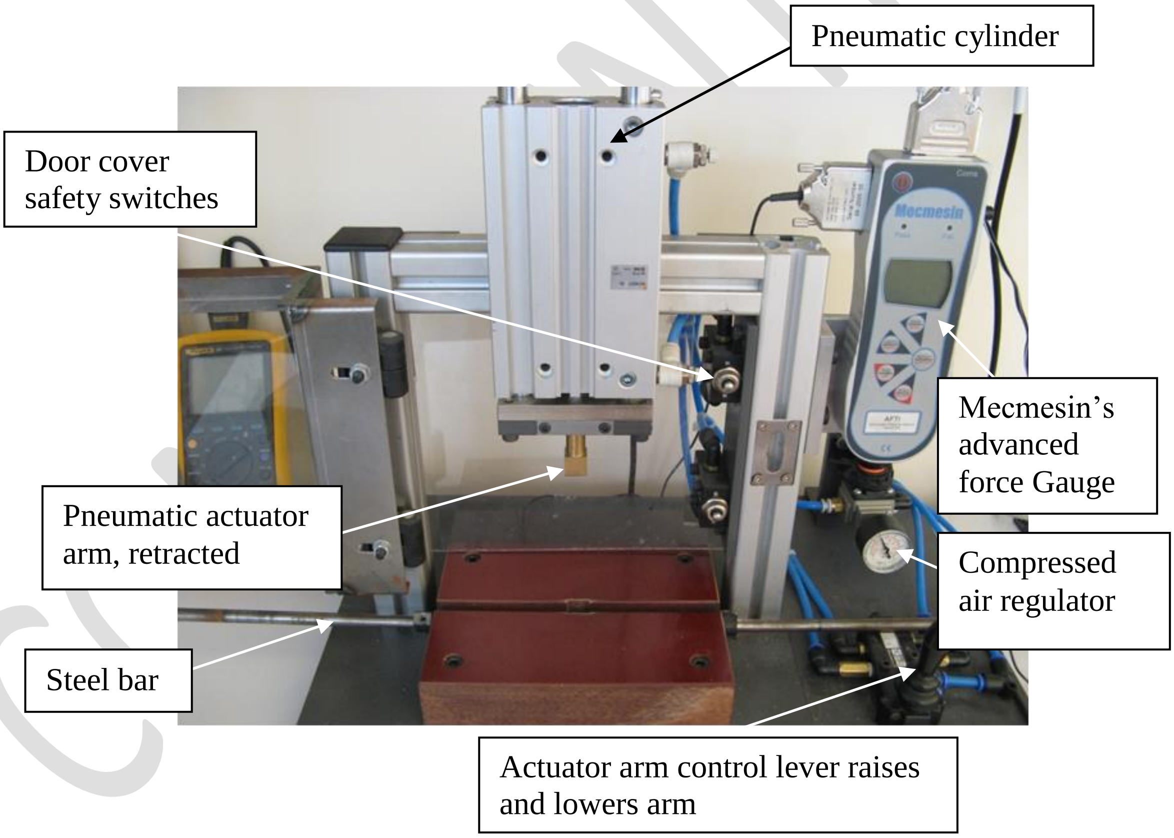


Figure 3-4. Pneumatic actuator arm, raised position.

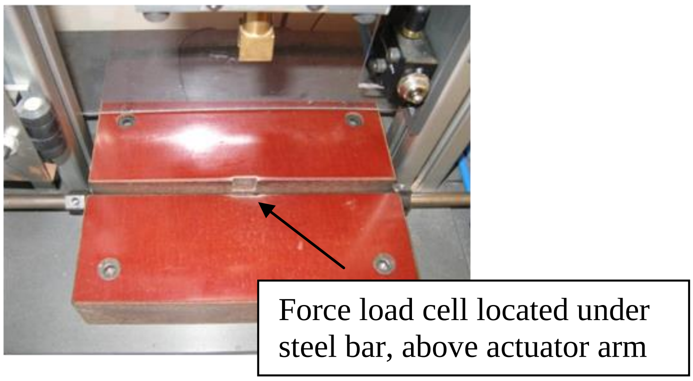


Figure 3-5. Position of Load cell .

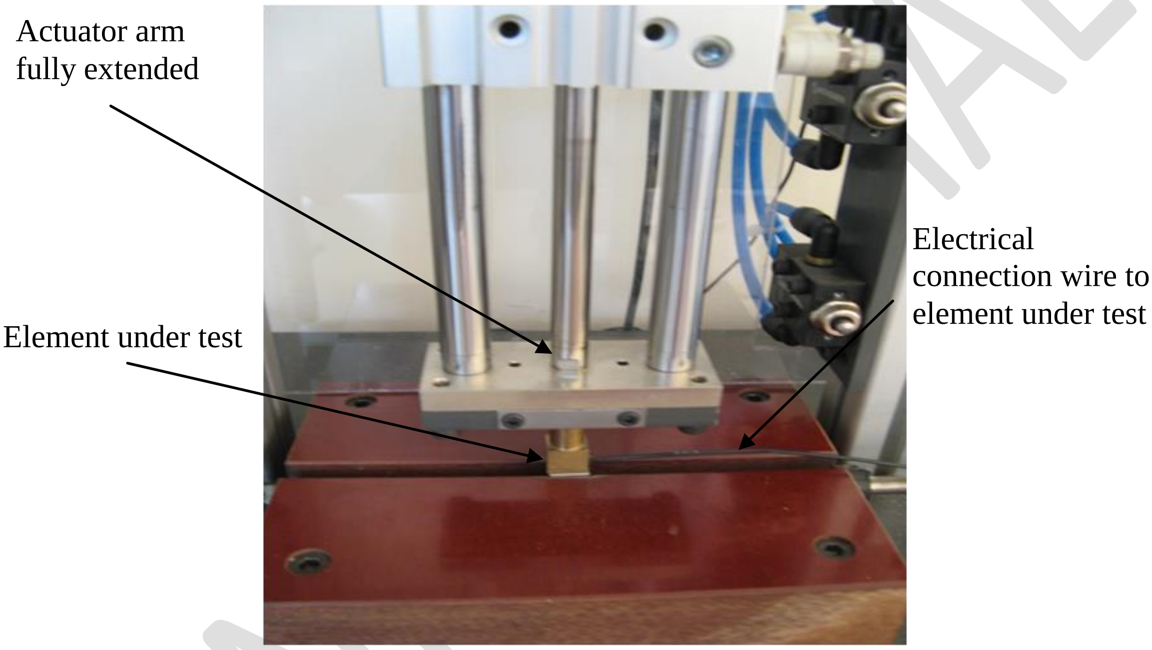


Figure 3-6. Actuator arm extended forcing load onto transducer under test.

Capacitance meter

In order to monitor and record the capacitance of each transducer under test a Fluke 287 Capacitance meter was also integrated into the test rig. For the selection for this instrument, again two operating parameters were essential. Firstly the device needed to accurately be capable of measuring capacitance values of 1nF and also have a communication interface that was compatible with a standard PC/Laptop. Again, using an off the self instrument meant it could be calibrated by the manufacture to recognised industry standards.

Switch box

To enable the transducers capacitance value to be taken while in situ within the test rig, and without the need to remove any cabling, a simple switch box was incorporated into the rig to electrically isolate the transducer from the circuits contained in the Mk4 TeletestFocus ™ unit. Without the switch box, effectively both the capacitance meter and electronic circuits would have been in parallel and could cause damage to the capacitance meter resulting from high voltage excitation signals used to drive the transducer. The switch box would simply, from an electrical path prospective, directly connect either the transducer to the capacitance meter, or the Mk4 TeletestFocus™ unit. Directional control of the switching was achieved by using one of the PC/Laptops user programmable parallel printer port outputs.

The presence of the switch box in line with the Mk4 TeletestFocus™ reduced measured amplitudes by 2.5%, (see Figure 3-7). This is compensated for when comparing amplitudes against thresholds and is discussed further on in this chapter.

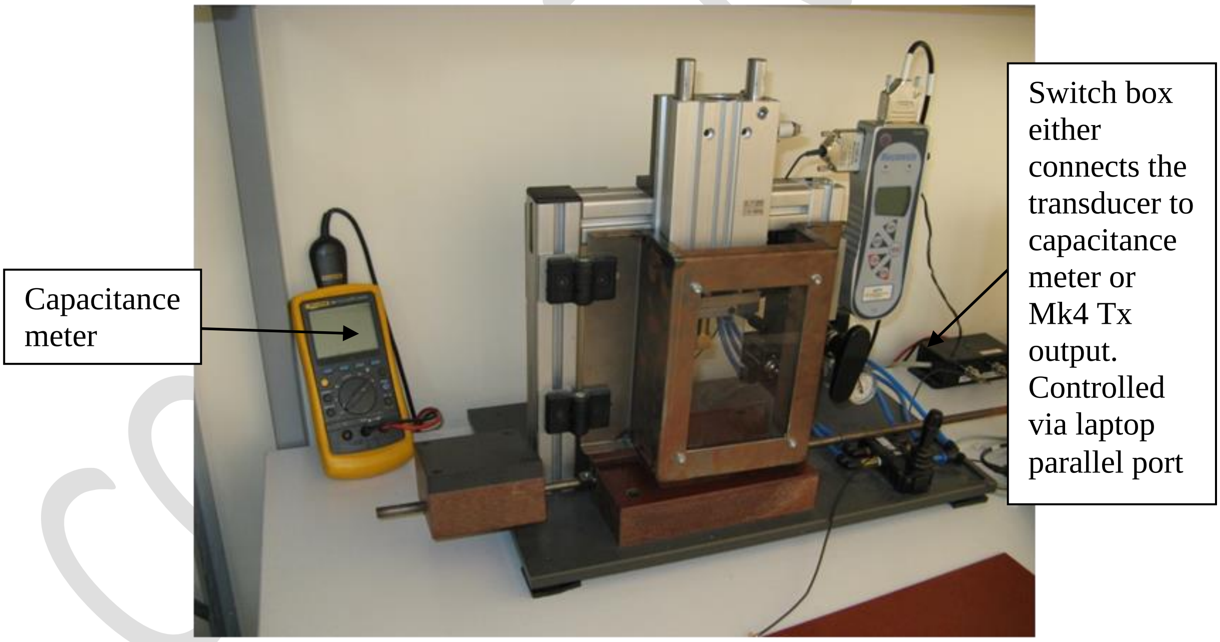


Figure 3-7. Capacitance meter and switch box.

3.3.3 Pulser-receiver Mk4 TeletestFocus™

The electronic circuits required to generate and receive the test waveforms used to excite both the fixed PZT element and the transducer under test were obtained using a Teletest focus Mk4™ focus system, (see Figure 3-8). This instrument was also designed and manufactured along with the new concept for a transducer. Details can be found in Chapter 4

Figure 3-8. New MK4 TeletestFocus^{TM} LRUT system.

3.3.4 Waveguide medium selection (steel bar length)

For the purposes of testing each Transducer a sample length of steel bar was used as a conduit for the ultrasonic signal path. When an ultrasonic signal was injected into the steel bar, via the transmitting transducer, this sound wave will propagate along the bar at a constant speed. Longitudinal modes on a solid bar are more reminiscent of Lamb Waves in a plate, rather than guided waves in a pipe. The group wave velocity of the mode (the non-dispersive one) is approximately 5000m/s.

Ideally, the test bar should be as long as possible to avoid situations where the transmitted signal doesn't overlap with any reflected signals that would be caused by the end of the steel bar, making interpretation of the signal of interest difficult. If flexural signals (reflections) are present, propagation of the sound wave over a longer distance of bar would allow them to separate out from the symmetric signal. However, this would be difficult to achieve, since it would involve having a steel bar length of many meters long, which would be impractical to implement in a test environment. Consequently, a bar length was chosen to avoid flexural signal interfering with the signal of interest and to make testing practical in a limited space, such as a production environment.

To aid interpretation of any received signal a featureless length of steel bar was used as the test specimen. Any defects or flaws in the sample could introduce flexural wave modes which would be undesirable for these tests. For testing purposes, the feature of interest within the received signal is the peak value of the reconstructed excitation pulse.

For the purposes of testing newly assembled transducers, a set of fixed PZT crystals elements, of the type used in the construction, are used for either generating or receiving ultrasonic signals. These individual crystals were arranged circumferentially around one end the steel bar at 0^o, 90^o, 180^o and 270^o apart, and wired in parallel to each other. This arrangement allowed for the transducer undergoing tests to be independently assessed for transmission and reception characteristics (see Figure 3-9).

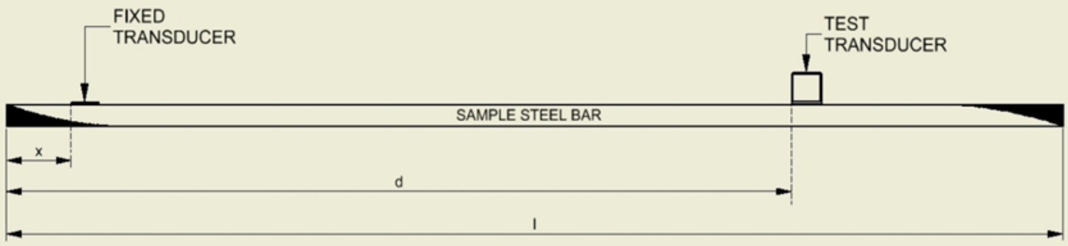


Figure 3-9. 1.2m Steel bar showing fixed PZT crystals element and transducer under test.

3.3.5 Software considerations

Special proprietary software was developed to aid the characterisation of individual transducers after the manufacturing process was completed. The transducer testing software (testbar.exe) was developed using National Instruments LabView. This provides a standard C compiler together with various libraries which may be used for Instrument control. A graphics-based library is also provided which allows a user interface to be created such that a virtual instrument may be created and results analysed. The software provided a means of assessing the performance of a transducer in order to verify its suitability for use in ring array configurations in the guided wave inspection of pipes using the TeletestFocus™ technique.

The fundamental requirements of the transducer are as follows:

(i) It should be polarised correctly. The TeletestFocus™ technique involves summing the contributions from multiple transducers and it is essential that signals have the correct polarisation such that unexpected cancellation is avoided.

(ii) It should have a capacitance within the expected tolerance. The TeletestFocus™ equipment electronics have been designed such that large voltages may be presented to a number of transducers simultaneously. Therefore, the total capacitive load must be within the target design limits. The number of transducers required increases with pipe size, so the electronics are able to cope with a large range of total capacitance. However, the principle reason that there should be a tight tolerance on the capacitance of individual transducers is so that when they are wired up in parallel on a pipe, the total capacitance may be measured and a check made that all the transducers are behaving correctly (from a capacitance point of view).

(iii) It should output an ultrasonic signal of sufficient amplitude when loaded on to a surface with a given load.

Requirements

The following describes how the software verifies that these three criteria are satisfied.

Testing was carried out on a 1.2m long 10mm diameter circular section bar. Four fixed elements were bonded to one end of the bar around the circumference. The transducer under test was positioned on the bar 0.9m from the fixed PZT elements, with its long axis (the direction in which the shearing occurs when a tone burst Hanning window of 230V was applied to the crystal) aligned with the bar.

A load of 200N was applied to the transducer forcing it into contact with the bar. 200N was used since this is the load at which it has been determined that no appreciable increase in amplitude is achieved if the load is increased further. This is the load used when the transducers are used in their ring configuration for pipe testing. A force gauge has been incorporated into the load delivery mechanism to ensure that the correct load is being applied. The software reads and verifies this load before any further tests are done on the transducer.

The lead which is plugged into the transducer connects to a software controllable switch which connects it either to a capacitance meter or to the TeletestFocus™ ultrasonic equipment. First, the software instructs the capacitance meter to read the capacitance (allowing a short period beforehand so that switch bounce from the relay embedded in the switch box has no effect). The capacitance of the transducer is measured while under load, since these are the standard operating conditions the array of transducers will experience while in service during an inspection. The software then changes the switch so that the transducer is connected to the TeletestFocus™ unit and four ultrasonic tests are carried out.

(a) Pulse-echo on fixed PZT elements.
(b) Pulse-echo test on transducer under test.
(c) Transmit on fixed PZT elements, receive on transducer under test.

(d) Transmit on transducer under test, receive on fixed PZT elements.

The purpose of these tests is as follows.

(a): This establishes that the fixed PZT elements are working and are able to measure a received signal.

(b): This establishes that the transducer under test is working as it should in practice.

(c) and (d) establish that the transducer under test can operate just as a transmitter and a receiver. Furthermore, the signal obtained in test (d) is examined in detail to check that the phase is correct.

Display window

Figure 3-10 shows an end of test output display from the test bar software. The operator testing individual transducers uses this screen as an indication to whether a transducer has passed or failed the capacitance tolerance value, the minimum amplitude of 100mV on transmission or the correct phase angle.

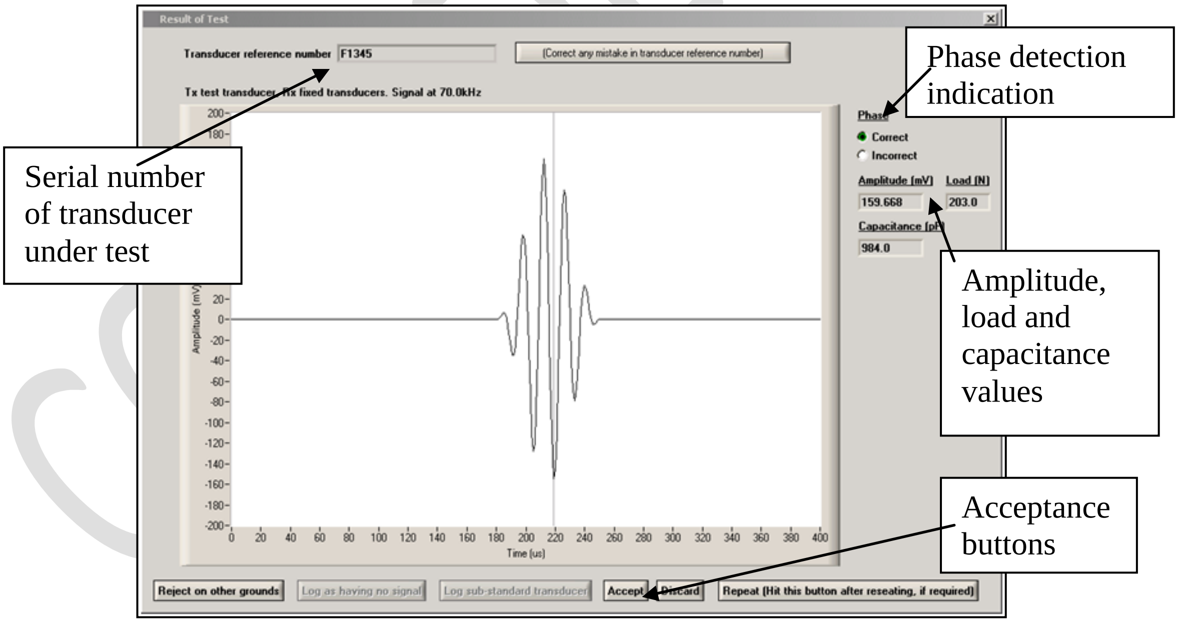


Figure 3-10. End of test output display.

All results are written to a file and when a batch is completed, an Excel readable file is produced showing all the measurements which have been made on all of the transducers in that batch. Another file is created which stores all the signals which have been collected. This may be recalled in an analysis mode of operation of the software to review the batch in detail.

Analyse window

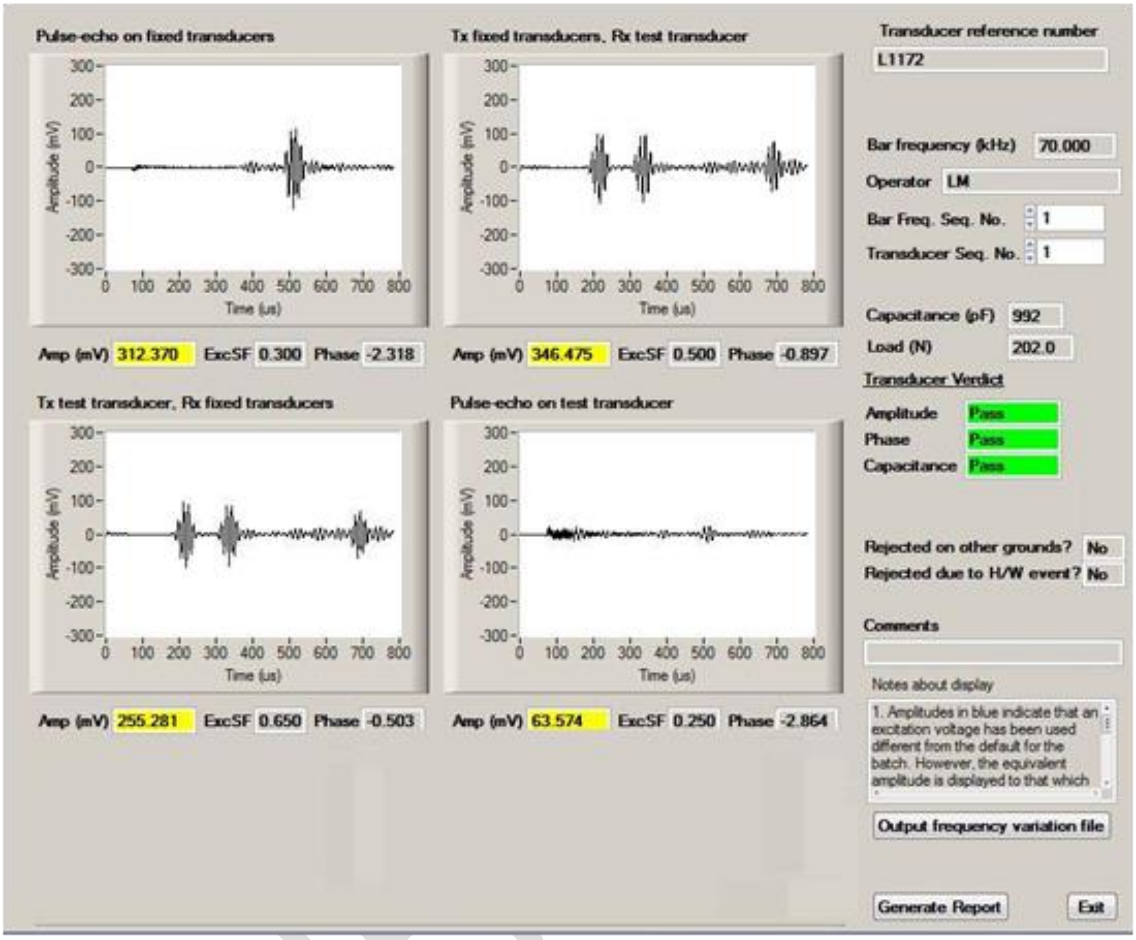


Figure 3-11. Typical analyse window display.

Figure 3-11 shows a typical analyse window which is available any time for future examination of a particular transducers performance when subject to the tests. Individual transducers tested within a batch can be re-examined for the initial results obtained at the time of manufacture, and compared at a later date.

Implementation of transducer tests

The following sections describe how each test was conducted and the procedures used for determining the excitation signals used, group velocity, amplitude detection for the signal of interest, receive sensitivity, phase angel and capacitance check. The force applied during each test will also be monitored and recorded.

Transducer excitation signal

Four different ultrasonic signals are collected, each at 50kHz, 60kHz, 70kHz and 80kHz in the course of the tests carried out. These frequencies are used as they represent the more regular units used during the operation of the TeletestFocus™ Mk4 system for inspections on site. Also for signal clarity on a relatively short wave guide medium, steel bar, these frequencies are ideal for preventing signal interference from reflections caused by either end of the bar if lower than 50kHz is applied.

Hanning window

A Hanning window is applied to the excitation signal to drive the transducer under test, or the fixed PZT elements. If a plain tone burst type signal were to be used, the large transition from no signal to sinusoid at the start of the pulse and at the end of the pulse would lead to high frequency components (large frequency sidelobes), which would generate signals at frequencies other than the desired centre frequency. The amplitude of these sidelobes is reduced by using a smoothing window. The best sidelobe reduction window is Gaussian; however, mathematically this causes problems since it never actually decays to zero. The problem of deciding which decay factor to use for a given pulse length would arise. Hence, the use of a Hanning window which has good sidelobe reduction and a defined window length can be chosen to be the same as the fundamental tone burst. Figure 3-12 shows a typical example of a Hanning window used for pulse excitation signals.

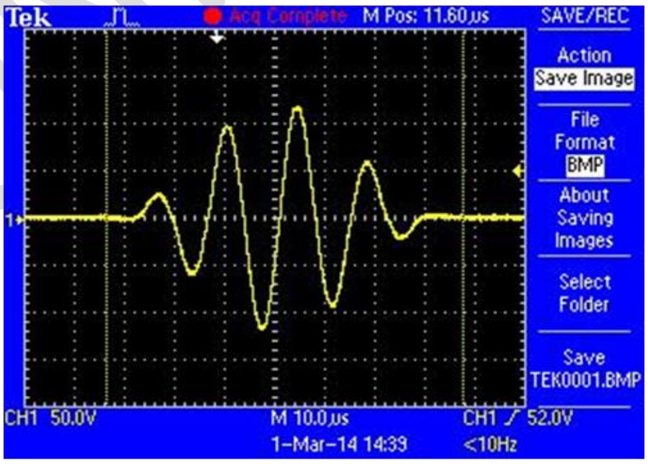


Figure 3-12. Typical Hanning window of 70kHz 5 cycles used for excitation pulse wave.

Excitation scale factors

Before an iteration of a particular test, the signal output drive voltage from the Mk4 TeletestFocus™ pulser-receiver unit is subjected to some excitation scale factors. These scale factors are chosen such that the feature of interest in the respective received signal does not distort or “clip” at a given test frequency. Clipping is defined, in this case, as the received pulse exceeding 95% of full-scale deflection of the A/D converter at the gain at which the test is carried out. A default gain value of 20dB is used as this is the minimum selectable gain that any one receiver chain, on the Mk4 TeletestFocus™, can accommodate. The gain for each 24 receiver channels is selectable from 20dB to 100dB in increments of 1dB.

The ADC’s used in the receiver design are referenced from a stable +5Vdc source, and their inputs biased at +2.5Vdc giving a maximum ± 2.5V allowable input voltage swing. Given that clipping of the input signal is defined as 95% full scale of the ADC, this allows for a maximum of 237mV before clipping is detected.

As clipping would only apply to a transducer undergoing a reception signal sensitivity test the possibility of this occurrence could result from the drive signal applied to the fixed PZT element, or the receiving transducer having a much greater sensitivity. As variations in the transducers sensitivity cannot be changed as these variations are due to component tolerances and manufacturing process conditions alternative procedures need to be employed. Also, it should be noted, the use of a longer steel bar would alleviate the need to compensate for variations in transducer receiver performance as this would result in more signal attenuation over a longer bar length, but as previously discussed, the introduction of a longer test bar would be impractical.

To accommodate variations in the efficiency of a transducer undergoing a receiver sensitivity test the output drive voltage from the fixed transducer is modified in amplitude. Under normal operation of the TeletestFocus™ Mk4 unit the excitation signals used to drive each channel are derived from a digital value passed to the Digital to Analogue convertor, more details can be found in Chapter 4, the voltage output from this DAC is then amplified using a fixed 34db voltage gain operational amplifier and then routed to the associated channel transducer. To control the amplitude of this excitation signal the digital values passed to the transmission DAC can be adjusted to produce the desired higher or lower voltage waveform.

For the purpose of this document, this technique is termed ‘Scale factor’ and is represented using a percentage of the maximum allowable output voltage from the DAC’s. Using a scale factor of 0.85 applied to the digital value presented to the transmitter DAC’s would generate an output voltage of ±3.00V culminating in excitation voltage peak to peak amplitude of ≈300V when a reduced load is present on the output of the voltage drivers. As the load on the voltage drivers increases, due to more transducers arranged in the array, so this scale factor can be adjusted to compensate for this increase in load, to a maximum of 1.0. The higher the scale factor used the higher the resulting excitation signal will be presented to the transducer ultimately generating a larger sound waveform. Furthermore, the same scale factor is used for all the frequencies at which this signal is collected and must not clip at any of these frequencies.

Estimating group velocity

Since the length of the bar and the position of the fixed and test transducers can be changed, if a new bar is required, or a second fixture produced, a dynamic procedure is used to ascertain a point at which to calculate a time base for measuring received signal responses.

The first stage is to measure the group velocity of the wave mode at the frequency being used, 50kHz-80kHz. The pulse-echo test on the fixed PZT elements is used for this, since the only significant feature in the trace will be that corresponding to path ‘A’ in Figure 3-13. For this reason this is the first test carried out at each of the required frequencies that will be used during testing.

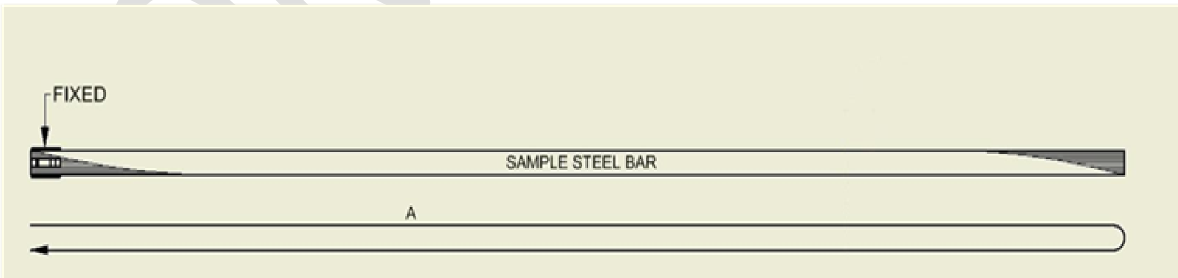


Figure 3-13. Round trip of wave mode to determine group velocity.

To find the group velocity at each frequency used an estimated time envelope around the rectified received trace is first constructed. As the group velocity is the main point of interest, so consequently a single point in time will be observed, a rectified received signal is used for ease of calculation. Rectification is achieved via a software process of eliminating either the positive or negative values in the received wave form; in this case negative values are discarded.

Next, a time period for the received signal is estimated, this will be a time in which the point of interest in the received signal will be interrogated. In this case the maximum peak value of the round trip pulse echo signal corresponding to a propagation distance of twice the steel bar length.

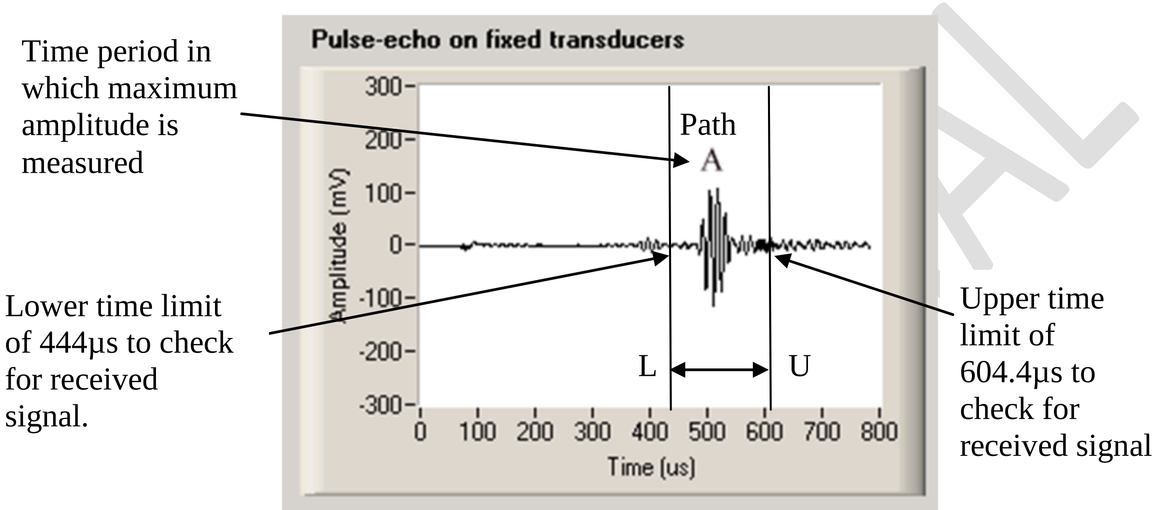


Figure 3-14. Received signal from a transmission and reception on the fixed PZT elements.

Figure 3-14 shows estimates for the upper and lower time limits which should encompass the pulse corresponding to the round trip pulse-echo signal (i.e. a propagation distance of twice the length of the bar). For the lower time limit, i.e. the fastest time the received signal could appear, a high estimate of what the group velocity might be: 5200m/s.

Therefore, a round trip of 2.4 meter over the twice the bar length equates too:-

2.4/5200m/s ≈ 444µs for L

For the upper time limit, i.e. the slowest time the signal could appear, a low estimate: 4500m/s is used. An allowance for the pulse length (at the appropriate frequency) is also added to the upper time limit.

2.4/4500m/s = 533µs
Plus 5 cycles of 70kHz ≈71.4µs

Giving a total time ≈ 604.4µs for U

The time corresponding to the maximum envelope amplitude within these time limits is found, which will be the time at which the peak in the reflected signal corresponding to path 'A' in Figure 3-14 occurs.

The group velocity, v_g is calculated as being the propagation distance (two bar lengths) divided by the time difference between the peak of the excitation pulse and the peak of the reflection.

$$V_g = d/t$$

Where V_g = Group velocity
d = distance
t = time

Measuring signal amplitude

Having a better estimate of the group velocity from the pulse-echo test on the fixed PZT elements the amplitude and time base for each signal corresponding to paths A, B, C and D in Figure 3-16 at their test frequency can now be found, each test was conducted in the frequency range from 50kHz to 80kHz.

The same technique is used for each of the four signal paths A-D. First a time period which will capture the signal of interest is calculated. This time period is different for each of the required signal paths owing to the differing lengths the wave form has to travel.

- For path A, a propagation distance of twice the length of the bar
- For paths B and C, the propagation distance between the fixed PZT elements and the transducer under test
- For path D, a propagation distance of twice the length of the bar

As in the technique for wave group velocity estimation a time frame envelope is constructed around the whole rectified input signal trace, although this time the signal path distance of the waveform is taken into account. The time corresponding to the maximum envelope amplitude within these time limits are found, which will be the time at which the peak of the feature of interest occurs.

The group velocity, v_g, is calculated as being the propagation distance divided by the time difference between the peak of the excitation pulse and the peak of the reflection. The time to the start of the pulse, t_s, is thus propagation distance/v_g.

So that a time frame window can encompass the signal of interest ± 5% is applied to the t_s value. For the lower time limit, a $1.05t_s$, is used. For the upper time limit, a low estimate of $0.95t_s$ is used. An allowance for the pulse length (at the appropriate frequency) is added to the upper time limit, this allows for the whole pulse length to be encompassed within the time window

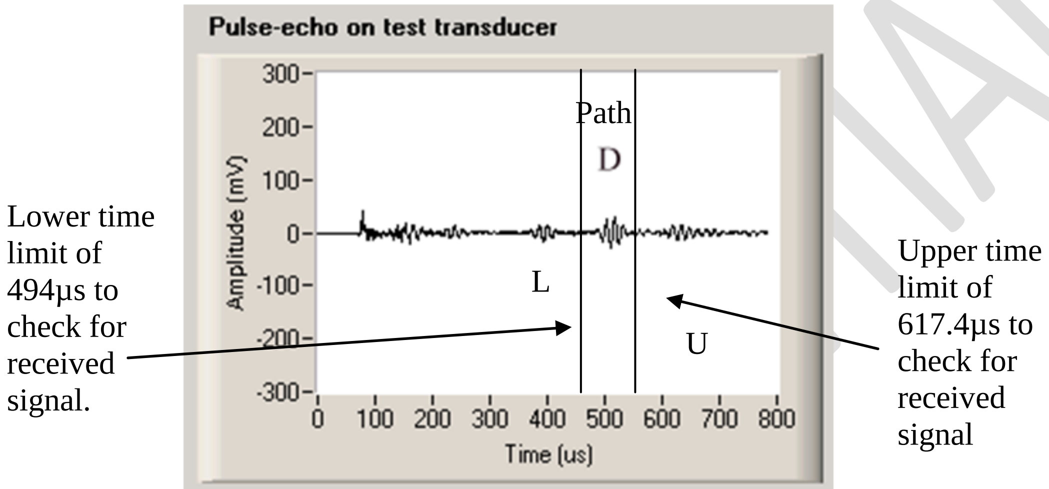


Figure 3-15. Received signal from a transmission and reception on the transducer under test.

This time, using the round trip of 'D' in Figure 3-16 for the transducer under test, the time frame window is calculated as follows.

From the group velocity test previously carried out it can be seen that V_g is ≈5000m/s. Therefore a round trip of 2.4 meter over the twice the bar length equates too:-

$2.4/V_g \approx 480\mu s$
Appling -5% = 456μs for L

For the upper time limit, i.e. the slowest time the signal could appear, an allowance for the pulse length (at the appropriate frequency) is also added.

$2.4/V_g \approx 480\mu s$
Appling +5% = 504μs

Plus 5 cycles of 70kHz ≈71.4μs

Giving a total time ≈ 575.4μs for U

Having established a time window for which the signal of interest is encompassed the maximum digitised value is recorded to represent the amplitude value for a given signal.

3.3.6 Evaluating individual transducer characterisation

Once a procedure for establishing wave mode velocity, and signal amplitude, has been ratified, testing of individual transducer characterisation can commence.

The signals of interest, resulting from the excitation signal used, relate to the paths shown in Figure 3-16.

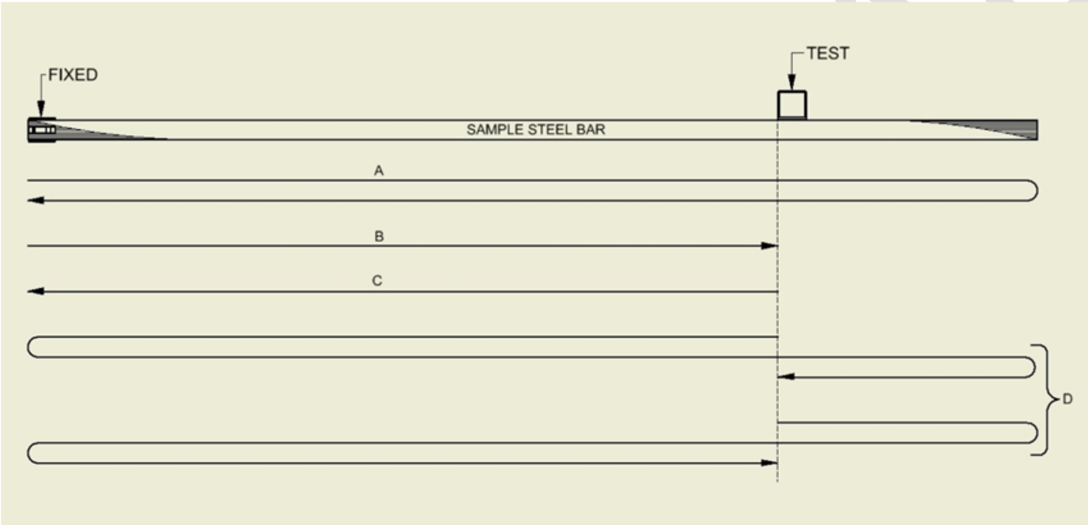


Figure 3-16. Signals of interest during transducer characterisation

- Path A. Pulse transmission from fixed PZT elements, received echo on fixed PZT elements
- Path B. Pulse transmission from fixed PZT elements, received on transducer UT (no echo)
- Path C. Pulse transmission from transducer under test, received on fixed PZT elements (no echo)
- Path D. Pulse transmission from transducer under test, received on transducer UT (double echo)

3.3.7 Pulse echo test on fixed transducers

The purpose of this test is to establish the correct operation of the fixed PZT elements bonded at one of the bar, as these will be used as a reference source for all other tests carried out on the transducers undergoing characterization, in particular, the sensitivity of the transducer under test. An excitation pulse is sent to the fixed PZT elements, the same fixed PZT elements are switched to receive mode once the excitation signal has relapsed. As a 70kHz 5 cycle waveform is generated from the fixed PZT elements the receiver on this same output-input channel is not switched to receive until 71.4 µs after the initial pulse has expired. The sound wave produced by the fixed PZT elements will travel along the steel bar until it reaches the far end where it will be reflected back towards the fixed PZT elements, at which point the signal will be received digitised by the receiver circuits and the data recorded.

Due to the relatively long signal travel length, in this case a round trip of circa 2.4 meters, a much smaller output drive excitation scale factor can be used when these signals are collected.

The feature in the signal obtained from the pulse-echo test on the fixed transducers corresponding to path ‘A’ in Figure 3-16 is shown below in Figure 3-17

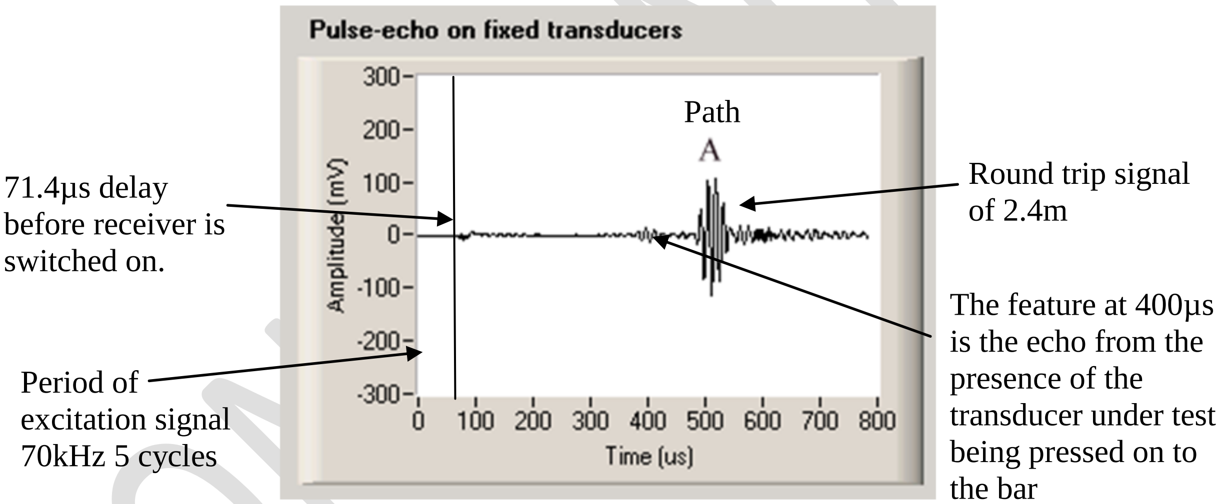


Figure 3-17. Pulse-echo on fixed transducers following path ‘A’ of Figure 3-16 .

3.3.8 Tx fixed transducers/Rx test transducer

This test will enable the receiver characteristics of the transducer under to be ascertained. This time, the fixed PZT elements at the end of the bar are used as the signal originator and the transducer under test is the receiver. Again an excitation pulse is sent to the fixed PZT elements. The transducer under test receives this waveform and the receiver circuits digitise the response and results are stored. As the source of the waveform is generated from the fixed PZT elements any backward going signal are virtually nonexistent as a result the fixed PZT element being placed as near to the end of the bar as possible.

The feature in the signal obtained from the Tx fixed transducers/Rx test transducer corresponding to path B in Figure 3-16 is shown in Figure 3-18

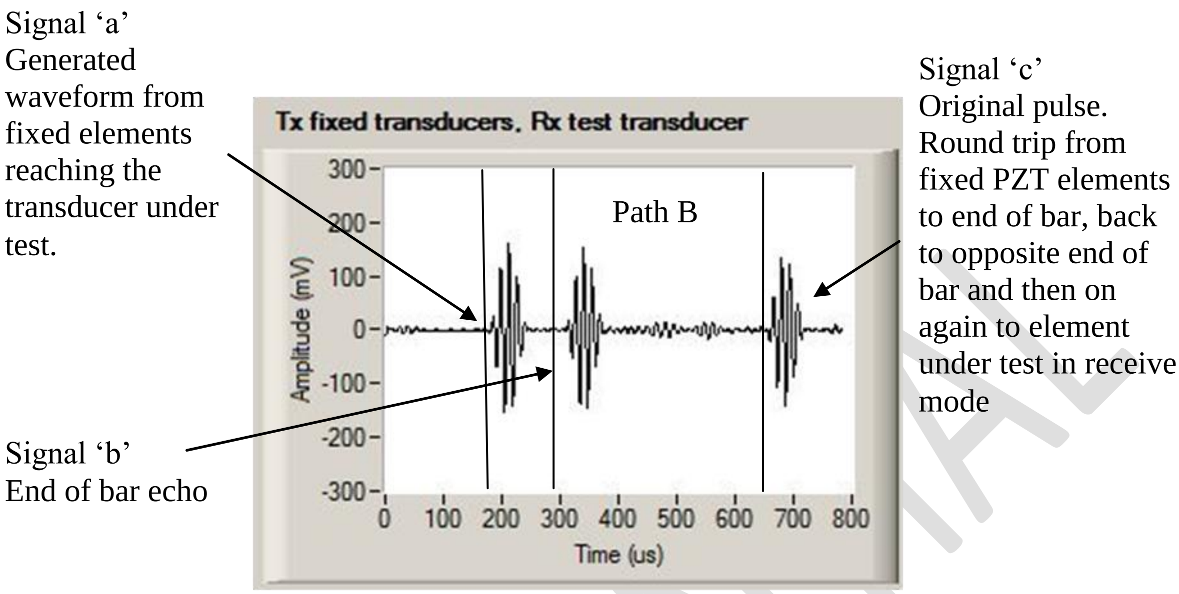


Figure 3-18. Generated waveform originates from fixed PZT element whilst transducer under test acts as receiver

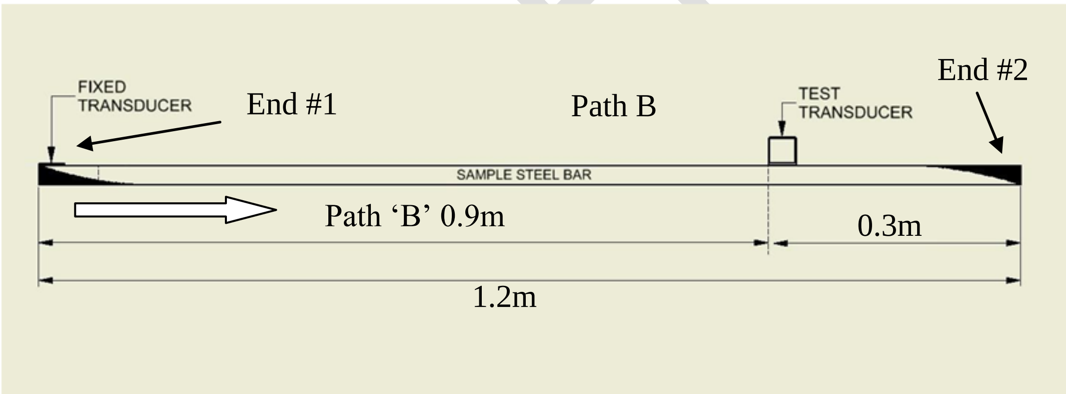


Figure 3-19. Path 'B' signal route

Figure 3-19 shows the signal path for route ‘B’. As the fixed PZT elements, in this case, are used to generate the waveform the distance for the sound to travel is from the source of the waveform, ≈0.0m, to the location of the transducer under test ≈0.9m the total time of flight can be calculated as:

Signal ‘a’ propagation time T= distance/velocity

$= 0.9/V_g$

$= 180\mu s$

Once the waveform reaches the transducer under test it will continue past until reflecting from the end of the steel bar, another 0.6m round trip, until it reaches the transducer under test once again.

Signal ‘b’ time equates to:

Propagation time = the length of the steel bar, 1.2m, plus another 0.3m/velocity

$$= 1.5/V_g$$

$$= 300\mu s$$

And, signal ‘c’ time equates to:

Propagation time = 2 x bar length plus 0.9m/velocity

$$= 3.3/V_g$$

$$= 660\mu s$$

Due to the relatively short signal propagation time before reaching the receiver, in this case 0.9 meters, a much smaller output drive excitation scale factor is used to reduce the amplitude of the excitation signal generated from the fixed PZT elements down to prevent clipping when these signals are collected by the transducer under test.

3.3.9 Signal separation

The separation between the start of echo B and the following signal, end of bar echo, is just over 100µs. This corresponds to a propagation distance of 600mm, twice the length, round trip, from the transducer under test to end of the bar. 100µs is thus the maximum duration of excitation pulse that can use without these two pulses overlapping. The period of a 50kHz signal is 20µs hence if a 5 cycle excitation pulse signal is used it is possible to test down to a frequency of about 50kHz with no overlap occurring. If a lower frequency was used then the pulse length would increase proportionately to that frequency.

3.3.10 Tx test transducer/Rx fixed transducers

To check the output performance characteristics of a transducer under test an excitation pulse is used to generate a waveform from this transducer. The induced sound wave will travel along the steel bar until it reaches by the fixed PZT elements. There, the fixed PZT elements will convert the sound wave back into an electrical signal which will allow the receiver circuits to measure and record. Also, as there is only one source of excitation waveform generation, and its positional relationship to the end of the bar, backward going signals will feature more in the displayed results. The feature in the signal obtained from the Tx test transducer/Rx fixed transducers corresponding to path C is shown in Figure 3-20

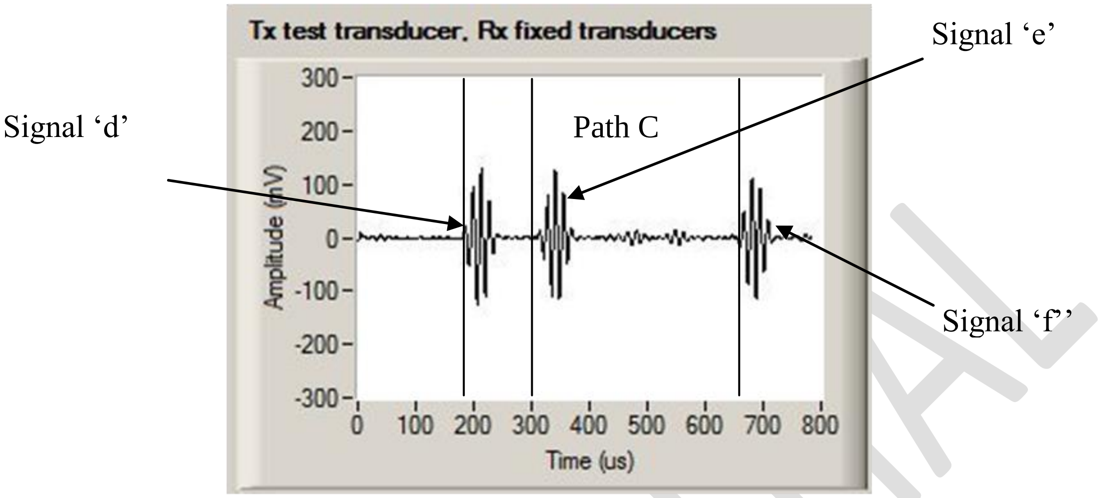


Figure 3-20. Transducer under test generates sound wave, fixed PZT elements act as receiver.

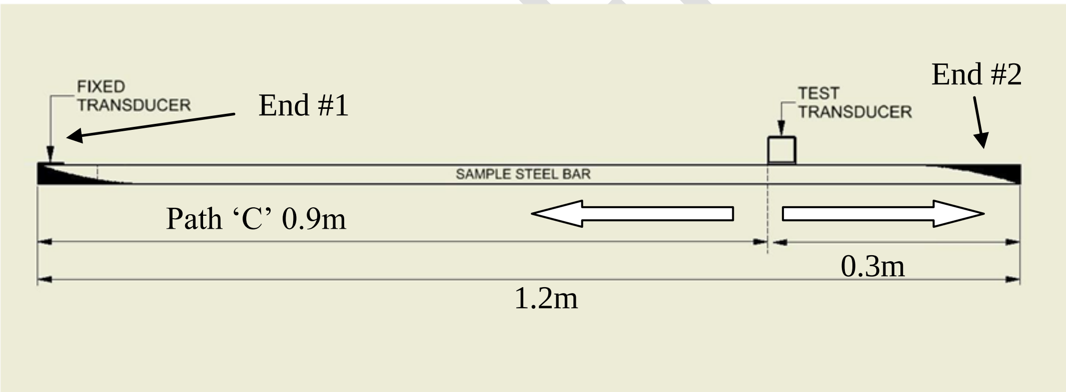


Figure 3-21. Path 'C' signal route

Figure 3-21 shows the propagation for signal path 'C' which originates from the transducer under test. Sound waves emitted from this transducer, into the bar, will radiate in both directions, due to the absence of any cancellation. Sound in direction, path 'C' will, at a finite point in time reach the fixed PZT element receivers at end #1. Although sound waves have also travelled in the opposite direction to path 'C', from their point of origin, will, at a finite point in time, reflect at end #2 and travel in the direction of end #1.

The propagation time for signal 'd', along path 'C' can be expressed as:-

$$0.9/V_g = 180\mu s$$

Signal ‘e’ could be considered as backward going sound waves as their direction is not originally along path ‘C’, and therefore are not the signal of interest in this test. However, for clarity of displayed received data from the fixed PZT element receivers their position in time can be expressed as

The distance travelled from point of origin to end #2, and reflected back to end #1

$= (0.3m + 1.2m)/V_g$

$= 300\mu s$

Signal ‘f’ is the original signal ‘d’ after travelling twice the length of the bar. Signal ‘d’ first reached end #1 at 180µs. It is reflected towards end #2 eventually being reflected back to end #1 by the presence of end #2.

The total excursion period is therefore:-

The distance travelled from (end #1 to end #2 and back to end #1)/v_g

$= 2.4/V_g$

$= 480\mu s$

For clarity in Figure 3-20. Total excursion time, for signal ‘f’, from the start of the pulse would be

180µs + 480µs = 660µs

3.3.11 Test transducer pulse-echo test

This test at 70kHz 5 cycles is used to characterise the transducer under test performance to generate a sound wave, and receive one. The feature in the signal obtained from the pulse-echo test on the transducer under test corresponding to the two equidistant paths D is shown in Figure 3-22

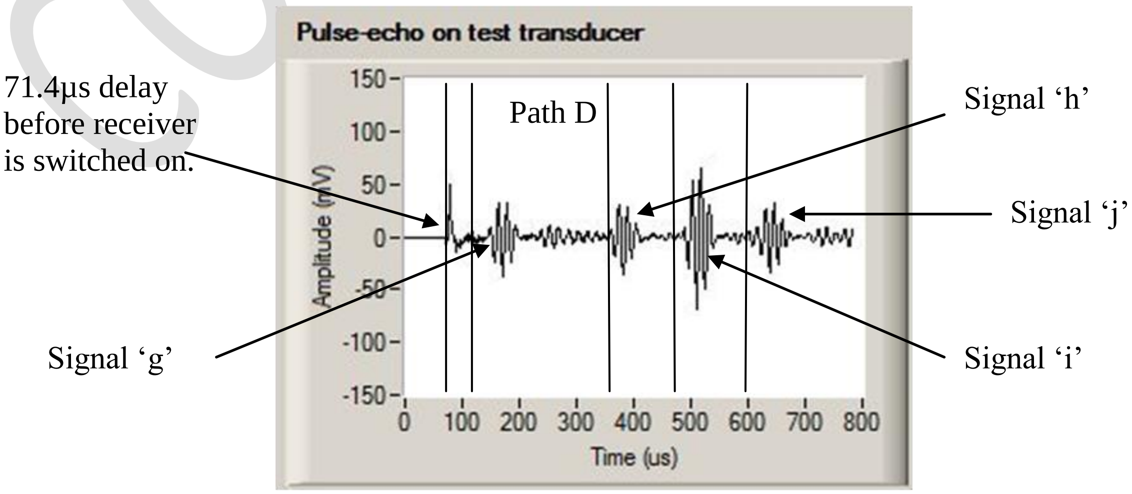


Figure 3-22. Pulse-echo test on the transducer under test corresponding to the two equidistant paths D.

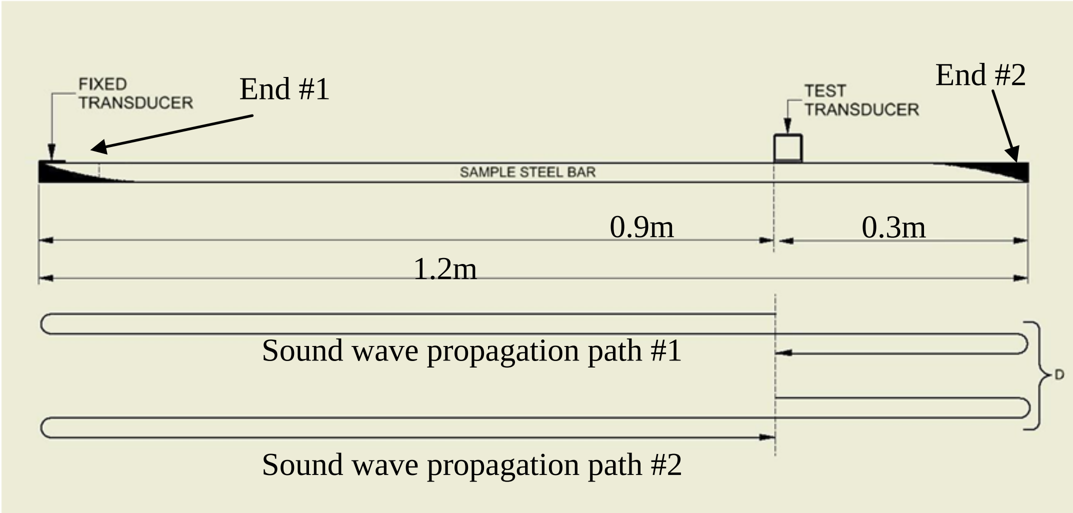


Figure 3-23. Route taken for sound wave generation and reception using transducer under test.

Figure 3-23 shows the route taken for path 'D'. The most expedient path back to the origin for the sound wave is via the end #2 reflection. However, as this travel distance is relatively short, the time of arrival is 120µs, (d/V_g), and as this reflected signal, signal 'g', arrives back to the transducer shortly after the receivers have turned on a more defined signal response is available from signal 'I'.

Signal 'g' is the first reflection from end#2 after the initial excitation pulse, its path has a round trip time of $0.6m/V_g$ = 120µs

Signal 'h' is the first reflection form end#1 after the initial excitation pulse, it's path has a round trip time of $1.8/V_g$ = 360µs

Signal 'I' is the accumulation of both paths taken from the transducer under test, as shown in Figure 3-22 path D. As both signals will travel the same distance of two bar lengths their propagation time is $2.4m/V_g$ = 480µs

Signal 'j' is the start of the reflection again form end#2. It path of travel would have been twice the length of the bar plus another 0.6m giving a time of flight of $3.0m/V_g$ = 600µs

3.3.12 Phase checking

It is important to ascertain that the PZT has either been correctly polarized for the correct wave mode generation, in this case shear mode, or assembled into the backing block correctly orientated. If either of these two scenarios exists then the transducer will be out of phase with neighbouring transducers and wave modes could be cancelled or an axisymmetric propagation will not be formed.

Although the phase of the transducer under test is checked automatically (using feature C at 70kHz), it is also possible to verify this and make a visual assessment of the signal by checking for a particular feature at a given time period. When examining the result for the transducer under test a vertical line is drawn at this position on the time base for the Tx test transducer/Rx fixed transducers signal. By default, 219µs is specified, which corresponds to the centre of the negative going peak with the greatest deflection (when the transducer is at its default position on the bar), as shown below in Figure 3-24.

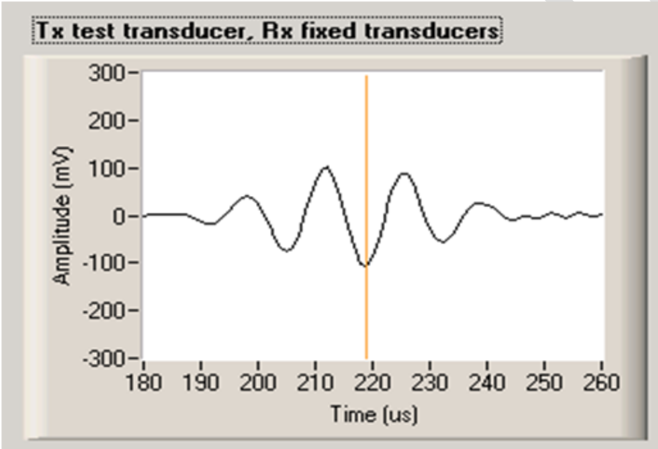


Figure 3-24. Point of detection for correct phase relationship at 219µs.

3.3.13 Load monitoring

For consistence transducer loading a pressure sensor and pneumatic actuator was designed into the test fixture. The load pressure sensor was positioned directly under the transducer under test. A load of 200N force is applied to the transducer under test and the load is recorded by the pressure sensor which was place directly beneath the steel bar in the vicinity of the transducer. The output from the load sensor is visually presented and also recorded for future reference.

Before the commencement of any ultrasonic tests, and after the pneumatic arm has been lowered into position onto the transducer the test bar software will automatically check the load applied by reading the value obtained from the force gauge. This is simply achieved via a USB connection from the controlling laptop/PC to the force gauge. The measured value is then recorded against the serial number of the transducer undergoing the series of tests.

3.3.14 Capacitance check

As the capacitance of each transducer can affect the Mk4 TeletestFocus™ output voltage drive circuits is it important to measure this. The Mk4 TeletestFocus™ is designed to accept an output load of 16nF capacitance, any more load will cause an over current error to be reported and the drive circuits will shut down as a percussion. As the impedance of the transducer is mostly capacitive this value is measure and recorded against each transducer under test. To obtain this value a capacitance meter is connect in series with the transducer under test. The capacitance measurement is automated with the meter being connected in circuit via the switch box, controlled via a convenient output port on a PC/Laptop. All measurements are recorded against the transducers serial number and the results stored for future reference. The capacitance value of the PZT material is defined by the ceramic manufacture and is quoted as 1nF ± 20%

3.4 Characterisation results

Table 1shows a typical results field generated via the test bar characterisation software as detailed in this chapter. Transducers are individually tested and their performance recorded. During manufacture each transducer is given a unique serial number for later identification, this can be seen in the figure below as the '*Ref.no.*' field. As the series of tests are conducted, as previously discussed, each result will be entered in the appropriate fields. The main result of interest are the transmit and receive values for each transducer, labelled Tx(mV) and Rx(mV), these will be discussed in the following section.

Ref.no.	Tx (mV)	Rx (mV)	Cap.(pF)	PE (mV)	Operator	Grading	Load (N)	Pass/Fail	PE Fixed SF	Tx Fixed SF	Rx Fixed SF	Test PE SF	Comment
L1056	178.66	243.05	921	37.32	LM	B	201	PASS	0.3	0.5	0.65	0.25	
L1305	186.58	253.67	925	41.84	LM	B	204.9	PASS	0.3	0.5	0.65	0.25	
L0650	189.26	257.16	930	41.02	LM	B	203.4	PASS	0.3	0.5	0.65	0.25	
L0929	195.52	263.96	905	43.89	LM	A	206.4	PASS	0.3	0.5	0.65	0.25	
L0503	205.22	276.91	920	49.77	LM	A	201.2	PASS	0.3	0.5	0.65	0.25	
L0521	209.56	286.88	918	52.23	LM	A	204.3	PASS	0.3	0.5	0.65	0.25	
L0712	210.58	287.21	911	49.9	LM	A	200.7	PASS	0.3	0.5	0.65	0.25	
L1226	226.04	306.13	913	57.29	LM	A	204.9	PASS	0.3	0.5	0.65	0.25	
L1110	230	312.44	912	61.66	LM	A	200.8	PASS	0.3	0.5	0.65	0.25	
L1176	230	312.11	916	62.07	LM	A	200.1	PASS	0.3	0.5	0.65	0.25	
L1094	235.36	315.76	933	63.3	LM	A	203.9	PASS	0.3	0.5	0.65	0.25	
L0817	239.7	329.71	904	67.81	LM	A	207.3	PASS	0.3	0.5	0.65	0.25	
L1034	240.59	325.39	920	66.58	LM	A	201.6	PASS	0.3	0.5	0.65	0.25	
L0845	245.7	337.51	900	71.09	LM	A	209.9	PASS	0.3	0.5	0.65	0.25	
L0553	248.9	337.34	923	71.78	LM	A	200.9	PASS	0.3	0.5	0.65	0.25	
L1203	248.9	340.5	919	73.96	LM	A	207.2	PASS	0.3	0.5	0.65	0.25	
L1145	252.73	342.99	909	73.55	LM	A	203.5	PASS	0.3	0.5	0.65	0.25	
L0989	259.75	355.77	912	79.71	LM	A	204.3	PASS	0.3	0.5	0.65	0.25	
L0577	260.39	354.78	920	79.84	LM	A	204.4	PASS	0.3	0.5	0.65	0.25	
L1105	266.26	360.42	935	81.62	LM	A	205.1	PASS	0.3	0.5	0.65	0.25	
L1007	266.77	359.76	931	84.9	LM	A	206.5	PASS	0.3	0.5	0.65	0.25	
L0834	267.67	365.4	920	86.13	LM	A	207.8	PASS	0.3	0.5	0.65	0.25	
L0637	278.4	378.18	914	92.42	LM	A	206.9	PASS	0.3	0.5	0.65	0.25	
L1048	284.01	388.97	920	101.17	LM	A	205.8	PASS	0.3	0.5	0.65	0.25	
L1397	285.8	388.14	916	98.85	LM	A	206.1	PASS	0.3	0.5	0.65	0.25	
L1416	287.46	386.98	921	96.39	LM	A	204.1	PASS	0.3	0.5	0.65	0.25	
L0603	288.87	393.29	907	97.48	LM	A	200.6	PASS	0.3	0.5	0.65	0.25	
L0952	303.55	412.71	905	107.32	LM	A	204.9	PASS	0.3	0.5	0.65	0.25	
L0931	325.26	445.75	917	131.39	LM	A	203.4	PASS	0.3	0.5	0.65	0.25	

Table 1. Sample report after completion of a batch of transducer. Report is generated by the test bar software.

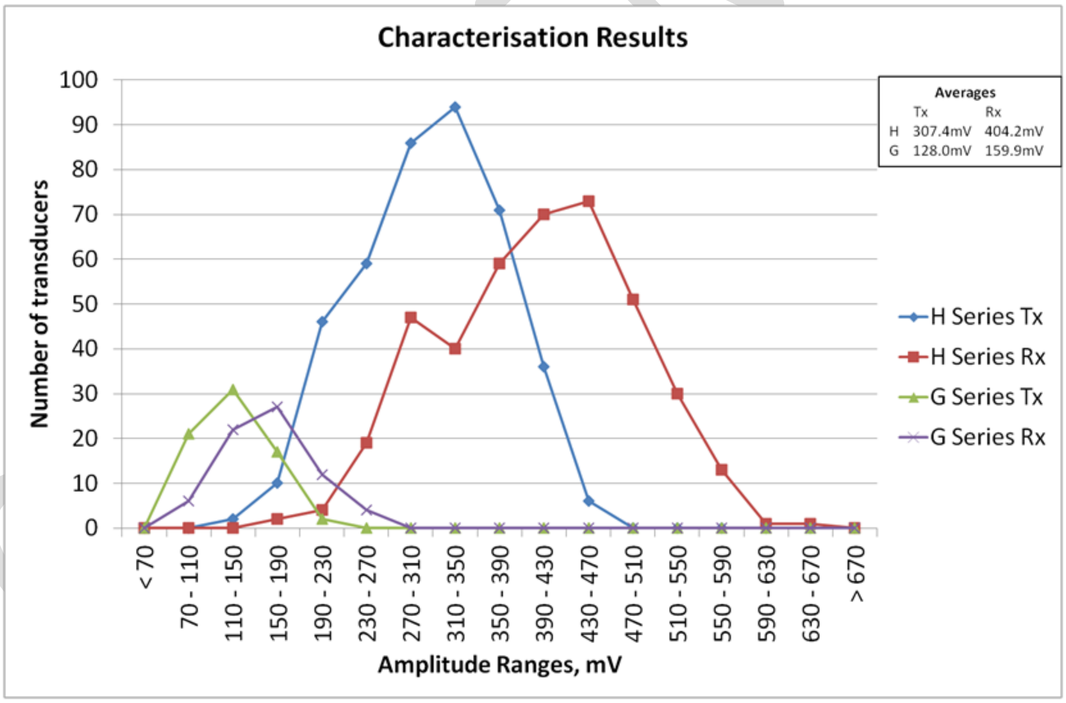


Figure 3-25. Values plotted for Tx, Rx for 410 new design transducers against 71 old design.

Figure 3-25 shows the results plotted against a batch of 410 new design transducers in comparison to 71 of the old design. It should be pointed out that during the characterisation for the new transducer only a small batch of the original design of transducer could be evaluated for comparison. This was due to the lack of older transducers being available at this time. Although only a small percentage of older transducers were evaluated it is believed that the results collected with this smaller batch represented the average performance levels for the old design.

It can be seen in Figure 3-25 that although the relationship between the transmitted and received signal for the new design of transducer is significantly greater than that of the old design there appears to still be a large variation between individual transducers, which is not ideal for a LRUT system. The lowest value for a transducer output transmission for a new design of transducer is ≈145.07mV compared to the highest transmission of ≈408.14mV, and ≈186.66mV and ≈540.21mV for the same transducer on reception.

Although there is still some variation in the results obtained whilst conducting these tests higher amplitudes can be achieved over the previous design. The acceptance criteria for amplitudes recorded during the PZT fixed element pulse transmission and transducer under test receive condition for the previous design of transducer was set at 50mV peak. Because of the improvements made in the new design a higher value of acceptance threshold has been set at 100mV peak reception for a transducer under test. Tests conducted so far on a sample batch of 410 transducers clearly shows an improvement in output amplitude of over 240% compared to the original values specified for the older design of transducer. The characterization process can now be reliably reproduced for any new designs produced in the future and results compared against any future design changes and quantified.

3.5 Summary

Transducer performance is an important component for the successful detection of anomalies while conducting LRUT. The design and manufacture of the transducer both play important roles in the overall system performance. Before this research, transducer characterisation consisted of a just a capacitance and insulation check to determine the electrical integrity of the transducer, followed by an ultrasonic test at a single frequency of 70kHz on a steel bar with the final results from these tests being manually recorded on paper.

Several problems existed with this approach. The procedure was very labour intensive as the software configuration for conducting the test had to be manually configured each time. Also, using just one frequency didn't give a clear understanding of how the transducer performed at other frequencies that are commonly used in a LRUT system. The load applied onto the transducer to couple it to the test bar consisted of a large metal block weighing 10kg that had to be manually removed from the test set-up each time a transducer was tested. The mechanical mechanism for coupling the load to the transducer could experience friction which would have resulted in the load not being applied correctly as no measurement of applied force was monitored. No electronic records were obtained from the procedure which meant no analysis of batch performance was undertaken to ensure consistent quality was achieved (despite several years of transducer testing having already been undertaken). To understand the transducers' performance history would have meant manually inspecting all the results obtained in paper form and entering this information into a computer database for processing which would have been prohibitively labour intensive.

Once these deficiencies were identified, a new method in which to characterize current and future designs of transducer in a more repeatable and reliable method than previous generations of transducer was established. Characterization for individual transducers can now be quantified and results recorded for analysis for both process control monitoring, which will allow for comparison of different batch runs to ensure quality is maintained, and for comparing any new designs to measure the performance changes. In future, data that has been recorded against individual batches of newly manufactured transducer will enable analysis and performance quantification using standard computing tools, such as Matlab™.

Proprietary software was specified and developed that allowed the automation of test frequencies, transducer coupling force and capacitance readings to be recorded, along with the ultrasonic results of the individual characterisation of each transducer tested. This automation, and the implementation of a new test rig, resulted in a reduction of the test time for large batches of transducers and eliminated the chances of human error that were previously possible using a manual method of recording transducer characterisation results.

The new method of characterisation as described in this chapter was applied to the new and old transducer designs as discussed in the last chapter (Chapter 2). This has shown major improvements have been achieved with the new design. The amplitudes measured demonstrated improvements to the average output amplitude of 240% compared with the previous design of transducer. Any performance enhancements achieved through design changes in the future can now be quantified and recorded against any design change history.

Chapter 4 Enhancements to the Teletest Acquisition Embedded System

4.1 Introduction

This chapter looks at previous generations of Teletest electronic equipment and introduces a new embedded system for better facilitating LRUT techniques and procedures. Previous designs of embedded electronic control units used for the LRUT system is discussed and evaluated along with a detailed description of a new TeletestFocus™ Mk4 embedded control unit, which was developed as part of this research. The research covered within this thesis has included improvements to the electronics systems. Specifically, this has covered improved developments of the analogue transmitter and receiver circuits, main system controller design, front panel display circuits and pneumatic collar inflation control along with the enclosure design and PCB configurations. All this has contributed to a faster data acquisition system that is smaller, lighter, more user friendly to operate, more power efficient, and has a lower cost to produce than previous generations of Teletest.

The introduction of a new Teletest system was introduced to compliment the new higher amplitude transducer (Chapter 2) so that a new LRUT system could be offered to companies and operators in the NDT sector. Market forces dictated a release of a new system that could be more cost effective in terms of inspection times and operator ease of use.

To facilitate this new requirement various new approaches to the electronics and the packaging of the system were evaluated and implemented into the overall design. A new faster FPGA was introduced as the main function controller, which offered new levels of flexibility and performance. Increased functionality was added to the transmitter and receiver circuits by the inclusion of independently addressable gain and filter settings. Data communication between the embedded electronic system and the controlling remote laptop was upgraded to a newer technology. New materials and manufacturing process were utilised so save weight and costs in the unit enclosure. A more efficient power supply unit and the use of newer technology components resulted in reduced power consumption and also contributed to weight savings. Details of these improvements are discussed in this chapter.

In parallel to this work, two other researchers gained PhD's in the development of other electronic functions associated with the design of the TeletestFocus™ Mk4. These were awarded to Partipan (2013) for work carried out on an improved power supply design, and

Zhang (2012) for research into new techniques for optimisation of the acquisition logic used in the FGPA (field programmable gate array) for controlling the embedded system.

4.2 Industrial inspection systems

In 2008, along with research carried out into a new design and manufacturing process for the transducers used in conjunction with equipment operated by Plant Integrity Ltd for LRUT, a new TeletestFocus™ Mk4 system was introduced by TWI. This new system would take advantage of new technologies currently available at the time to produce a much improved system in terms of weight, speed of data collection, power consumption and reduced size compared to previous generations of LRUT equipment.

To utilise the properties of ultrasonic guided waves as a form of NDT procedure some form of electrical equipment is required to generate the required signal to drive the active material within a PZT based transducer. Any received ultrasonic responses back from the component, or structure being examined, require collecting the return signals from the same equipment and then presenting in a format that can be interpreted by an operator.

At the time of conducting this research, the author was only aware of three other electronic systems that were commercially available for use on LRUT techniques, which utilised PZT crystal technologies as a means of generating ultrasonic guided waves. The Teletest system was designed and manufactured by a subsidiary of TWI namely Plant Integrity Ltd and was marketed as “Teletest”. The second system is manufactured by Guided Ultrasonics Ltd and marketed as the “Wavemaker G4” and most recently the Olympus “UltraWave LRT”.

All three systems use dry coupled PZT transducer technology mounted in an inflatable collar arrangement for attaching the transducers onto the medium under test, most frequently industrial pipelines, but other structure such as railway tracks, bridge supports, oil rig risers can be inspected using these systems. Although, TWI primarily uses its system for the inspection of industrial pipe lines it is currently investigating the use of their new Mk4 equipment to inspect large storage vessels, with diameters in excess of 30 meters, and bridge crossings. Each system is primarily designed for utilizing long range ultrasonic guided waves for the detection of anomalies, such as corrosion, erosion or weld defects in pipes ranging in size from 2 inch to 24 inch. Larger diameter pipes up to 72 inch can be accommodated using both the Teletest system and Wavemaker G4 by the introduction of special joining clamps which enable the standard collar sizes (2” to 24”) to be linked together to form larger diameter collars.

Each system is designed to be lightweight, portable and function as an instrument for the generation and collection of low frequency ultrasound, 10kHz to 100kHz, communally used in the technique of LRUT. Each system adopted the same principles of operation whereby some form of embedded electronics unit would principally control the generation and reception initiated from an acquisition cycle. The embedded controller unit would then send data back to a controlling remote laptop or PC running proprietary software.

4.3 Previous generations of Teletest

All previous generations of TWI’s Teletest system used the same principle of coupling ultrasonic PZT based thickness shear mode transducers to a pipe by means of an inflatable collar arrangement as discussed in Chapter 1. Each system had the means to collect data and present results back to a controlling remote PC. The following sections give a brief overview of each system.

4.3.1 Teletest Mk1 LRUT System

TWI, along with Plant integrity Ltd, who manufactured the system, launched its first LRUT system back in 1989 with the introduction of the Teletest Mk1 (see Figure 4-1). This system was the first truly portable embedded system on the market of its kind.

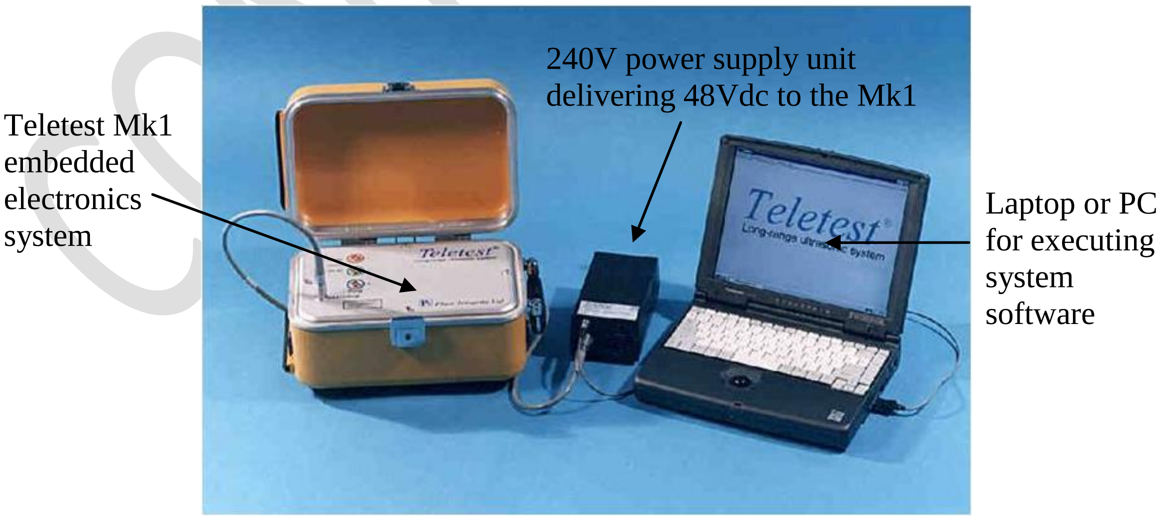


Figure 4-1. TWI’s first commercially available LRUT Teletest Mk1 system.

The Teletest Mk1 unit consisted of an embedded electronics unit used for the physical data collection. It comprised of 12 transmitter, 4 receiver circuits and is operated from a single 48V external power source, which gave it an operating window of roughly 6 hours (see Figure 4-1).

Operation of the electronics unit was controlled via remote PC with executable proprietary software developed by TWI using an Arcnet networking protocol. No user interface or direct control existed via the instrument for configuration purposes. Pressurisation of the inflatable collar coupling the transducers to the test sample was manually achieved using a standard foot operated air pump. Although this original concept proved effective in successfully locating anomalies and defects in test samples, its use was limited by the inclusion of only of 12 transmitter and 4 receiver circuits resulting in slow data acquisition cycles with limited defect resolution. The author was unable to quantify the operation of the Mk1 unit due to lack of availability of the equipment.

4.3.2 Teletest MK2 LRUT system

Then in 2003 TWI released its second generation the Teletest Mk2 system (see Figure 4-2). This new and improved system had much more functionality in terms of more transmitter and receiver circuits, but still used a relatively slow hardware configuration and communications protocol. Along with the Mk1, system operation via the embedded electronics unit was still controlled via remote PC executing proprietary software developed by TWI. The Mk2 still required an operator to carry out all unit configuration functions via remote PC. The pneumatics for the collar inflation mechanism still required the manual intervention of a standard foot operated pump. Although test data resolution were greatly improved with the introduction of 24 transmitter circuits, which meant a total of 384 transducers, each with a capacitance not exceeding 1nF, could be accommodated within the collar. Inspection times were still hampered by only having 8 receiver circuits in the unit, which meant that three data acquisition cycles would need to be performed to collect data from all three transducer rings located within a collar. Power for the Mk2 was still derived by a 48V external supply use with the Mk1. The Mk2 embedded electronic unit measured 350mm x 240mm x 200mm and weighed 10Kg.

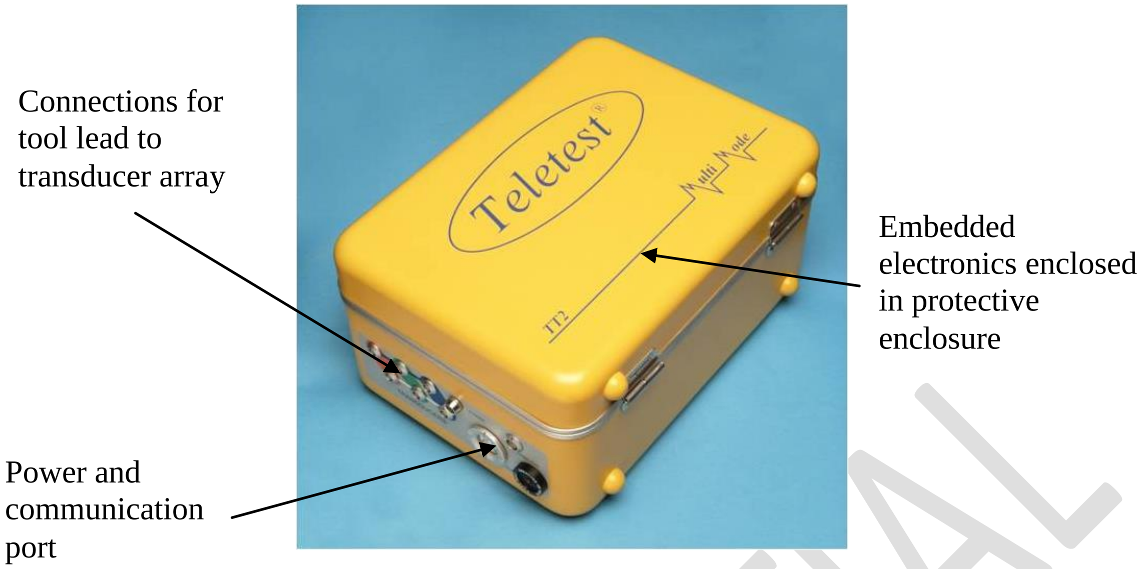


Figure 4-2. The second generation LRTU Teletest Mk2 system.

4.3.2.1 Teletest Mk2 embedded control system

Most embedded systems designed to undertake simple data acquisition tasks such as process control in automated environments, which don't necessitate the requirement to carry out large data computations or time critical operations such as employing critical safety systems, usually adopt a simple central processing unit to help reduce complexity and lower system costs.

The embedded control system in the Mk2 (see Figure 4-3) was based on a derivative of the 8 bit 8051(Atmel 2008) microprocessor running at 14MHz. This variant and speed of this processor was acceptable for the intended application of overall system control and data transfer between the acquisition system and controlling remote PC as the main functions of analogue signal generation and the receiver functions used to collect data from a particular test sequence would be performed by an on board FPGA (field programmable gate array)

The FPGA used in the Mk2 system was designed and manufactured by Xilinx®-XCS30XL. At the time of developing the Mk2 this device was considered state of the art and selected for this application for being a cost effective solution to implementing the necessary control functions for a data collection sequence. The FPGA effectively acted as glue logic between the processing unit and the functions required to control the transmitter and receiver circuits. FPGS's are ideally suited for this type of application as they are configurable enabling the logic within the device to be modified and updated to continue development of the system if other functions of operation are required to be implemented at a later date. Using a FPGA in this manner is more cost effective than designing individual circuits to carry out certain functions and dramatically reduce the amount of PCB space required.

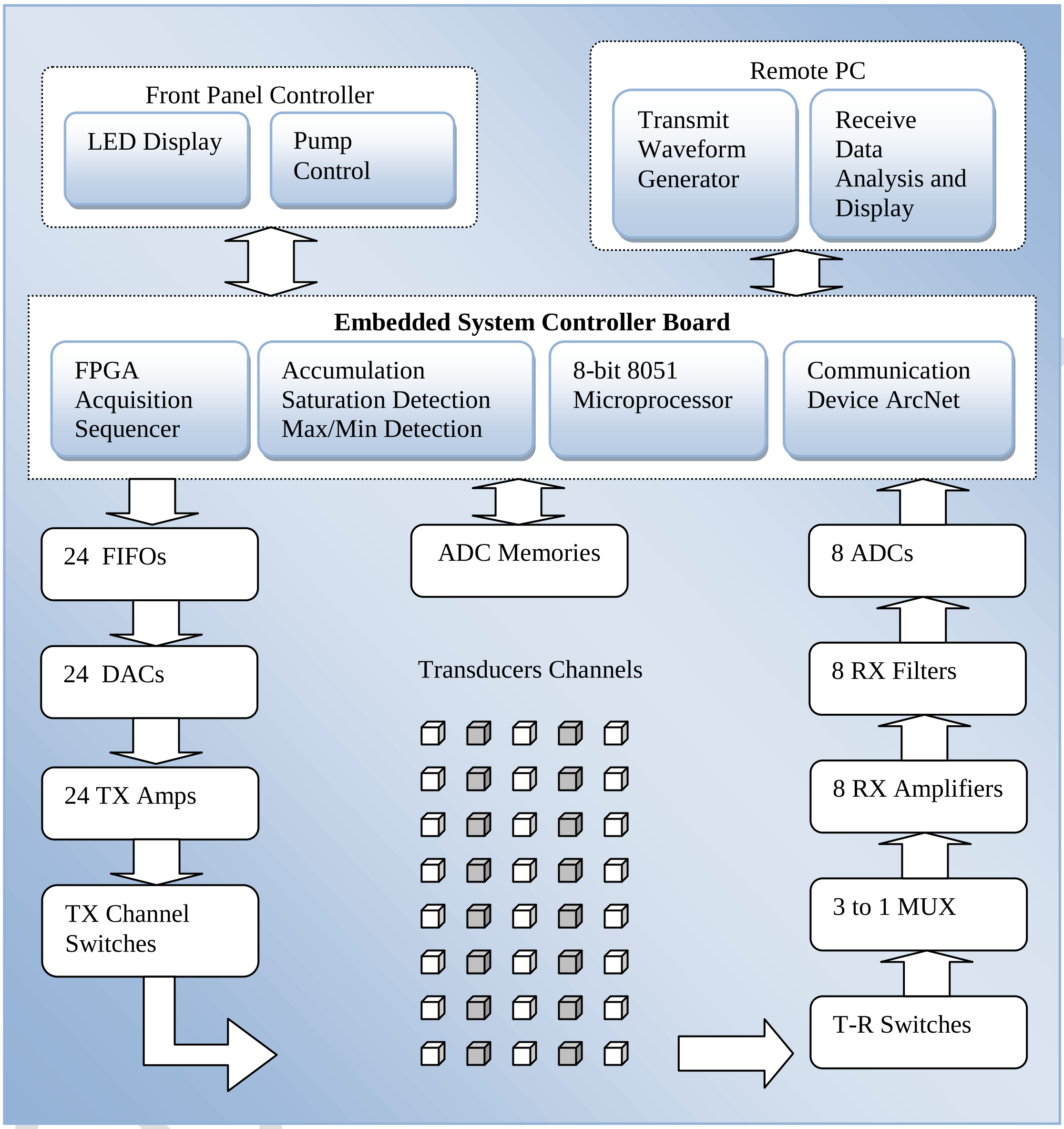


Figure 4-3. Outline of the basic functional elements of the Teletest™ Mk2 system.

4.3.2.2 Teletest Mk2 transmitter

The 24 transmitter circuits were capable of independently delivering a peak to peak output waveform of 280V at frequencies between 20kHz and 100kHz for a duration of 10ms. Each transmitter circuit was able to supply a maximum current of 2.8A to a capacitive load; this was limited to protect over current situations if the load was reduced below a certain impedance value due to a fault or short circuit condition in the transducer array. The maximum capacitive load condition specified for each transmitter circuit was 16nF and is based on the maximum number of transducers permitted per channel.

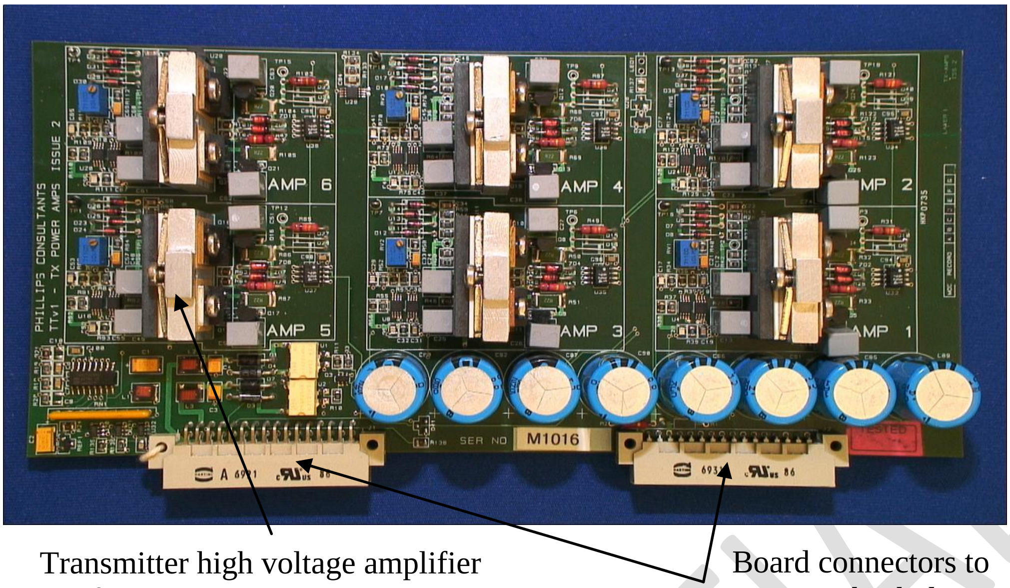


Figure 4-4. High voltage amplifier board showing a single channel, one of six per board, each board measure's 220mm x 110mm

Figure 4-4 shows the high voltage amplifier board as used in the Mk2 system. A total of 4 transmitter boards are required to give 24 channels in total. Each board is located into a common backplane as shown in Figure 4-5.

4.3.2.3 Teletest Mk2 receivers

The eight receiver channels each had a gain setting of between 20dB to 100dB and were configurable in increments of 1dB. A set of five selectable analogue filters were present for each channel with cut off frequencies of 15kHz, 32kHz, 75kHz,150kHz and 300kHz. Both the receiver gain and filters settings for each channel were common to all 24 channels and could not be independently controlled. To digitalize the analogue waveforms received back from the array of transducers eight 12 bit ADC's are incorporated.

4.3.2.4 Teletest Mk2 memory

To store the results from a single receiver channel a memory area of 64K x 24 bit is used. Twelve bits are used for the actual digitise data from the 12 bit ADC's and the remaining twelve bits are used for the accumulation of the received data to average out any noise that may be present in the original analogue signal. The total memory configuration consisted of 12 memory devices, each device being 64K by 16 bit, but arranged to give the required 64K x 24 bit for eight receiver channels.

4.3.2.5 Teletest Mk2 power supplies

Power required to operate the system was provided by an external 48VDC supply which required a mains voltage of between 110 and 240 volts AC. This converted lower DC voltage is then converted down once more to produce an internal operating voltage of 12V, which was reduced down further to +5V and +3.3V to power the logic circuits. This approach was not very efficient in terms of power consumption and flexibility as firstly, a 240 V AC mains outlet was required and secondly external cables were required to link the embedded unit to the power source. Later, an external battery pack was included but although the requirement for a 240V AC mains outlet was negated, the need for a power cable umbilical from the new battery pack to the electronics units still remained.

4.3.2.6 Teletest Mk2 PCB topology

Board layout and space requirements were not considered to be a major factor when designing and packaging the Mk2 system. Printed circuit boards were arranged in a vertical configuration from as shown in shown in Figure 4-5. A common backplane used as a signal path to join individual sub-assemblies together. This required a large area in the final enclosure just to house the embedded electronics unit. The space required for this unit measured 250mm x 250mm x 120mm. Once assembled into the final system enclosure, the overall dimensions for the Mk2 increased to 360mm x 360mm x 190mm.

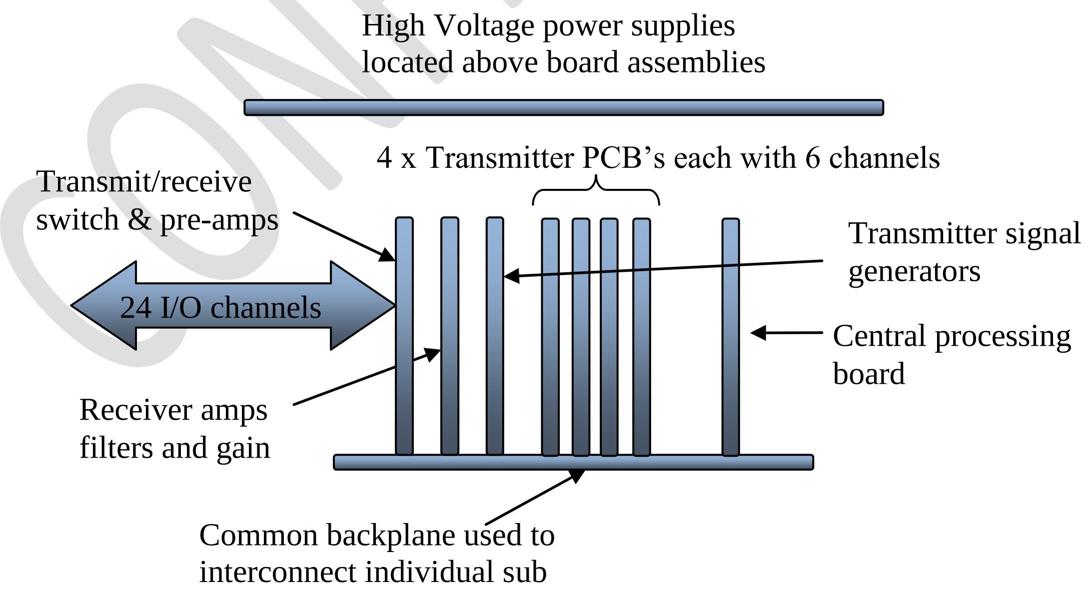


Figure 4-5. Mk3 PCB sub-assembly configuration

The resulting configuration required ten separate printed circuit boards.

- 1 x common backplane to interconnect individual sub-assemblies
- 1 x control board implementing the main processor and FPGA
- 1 x 8 channel receiver filter and gain
- 4 x transmitter board each with six high voltage waveform generators
- 1 x transmitter signal generator board converting DAC values for transmitter boards
- 1 x transmitter-receiver and pre-amp switch board to route 8 receiver inputs from transducers into the amplifier gain and filter board
- 1 x power supply board

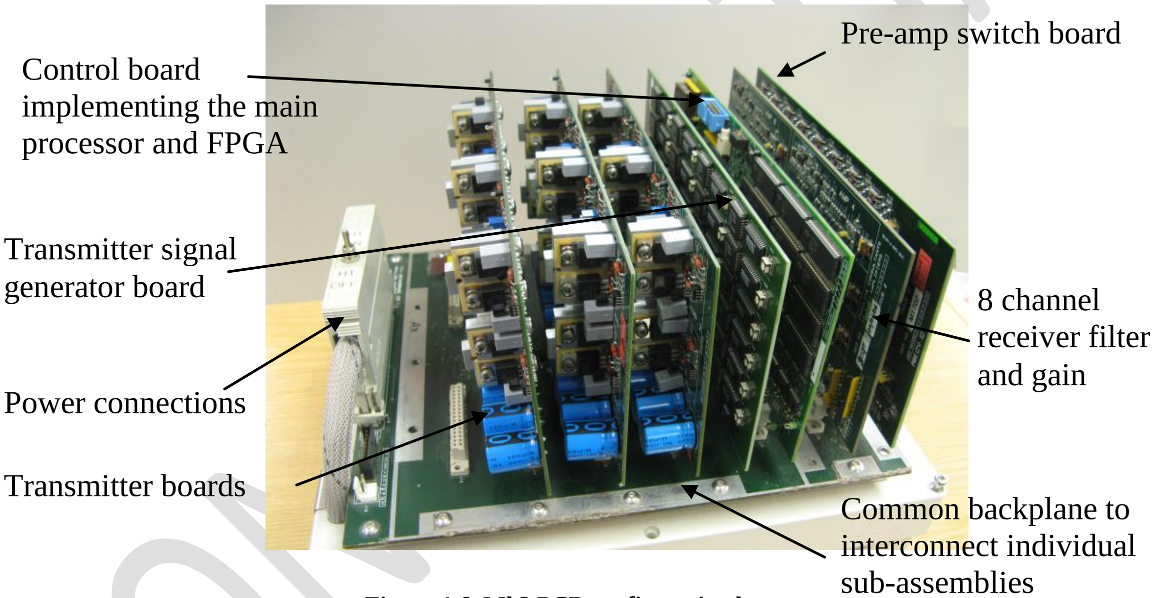


Figure 4-6. Mk2 PCB configuration layout

Figure 4-6 shows a picture of the MK2 board layout. Although, once assembled into the outer enclosure, the individual component boards were held rigid by the use of guild rails the boards had a tendency to become dislodged during transport. This was especially the case with the transmitter boards which used large aluminium heat sinks on the high voltage amplifies which made the board assemblies top heavy. If any single component board became dislodged in transit it resulted in the unit being returned to base for repair.

4.3.3 TeletestFocus™ Mk3 LRUT system

Again in 2007, TWI released its third generation system, the TeletestFocus™ Mk3 (see Figure 4-7), the marketing term Focus was included after 2008. The new Mk3 system was effectively a repackaging exercise, which adopted the same embedded control features available in the Mk2 system but refined the overall operation of the unit as a whole. The decision to remain with the existing data acquisition components carried over from the Mk2 was based on proven technologies previously used to good effect in that design. Enhancements to the Mk3 included the introduction of a simple user interface screen integrated into the unit. Although, overall system control was limited via the new interface, it proved popular with system operators as some initialisation sequences could be performed while the engineer was still configuring the transducer array, therefore, the requirement to access a remote laptop or PC was now redundant during the initial system installation procedure.

The second enhancement, over the Mk2, introduced a pneumatic pump integrated into the system. On previous Teletest systems the operator was required to pressurise the collar manually either by operating a hand or foot pumps. Inflation of the collar was now automated and pressure readings could be monitored and adjusted for optimum pressure during a data collection period without the intervention by the operator. This new feature proved very successful amongst system operators as some test environments had minimal space in which to comfortably use a manual inflation device. There also existed the added advantage to the system operator; it was less physically demanding to operate hence reducing the risk of injury.

The third enhancement included GPS functionality. This feature enabled the controlling software executing on a remote PC or PC to request information on the location of the test site. The co-ordinances of latitude and longitude could be retrieved and made available to the system operator, if requested. Such data can be included in any reports that an end client has requested as part of the inspection contract.

Each of these new features, along with the existing embedded control electronics, were re-housed in a off the shelf enclosure and re-branded. The Mk3 also became popular as a research tool for the continuing development into ultrasonic guided wave techniques used in long range ultrasonics, and to investigate potential new markets were LRU could enhance structural monitoring and defect quantification.

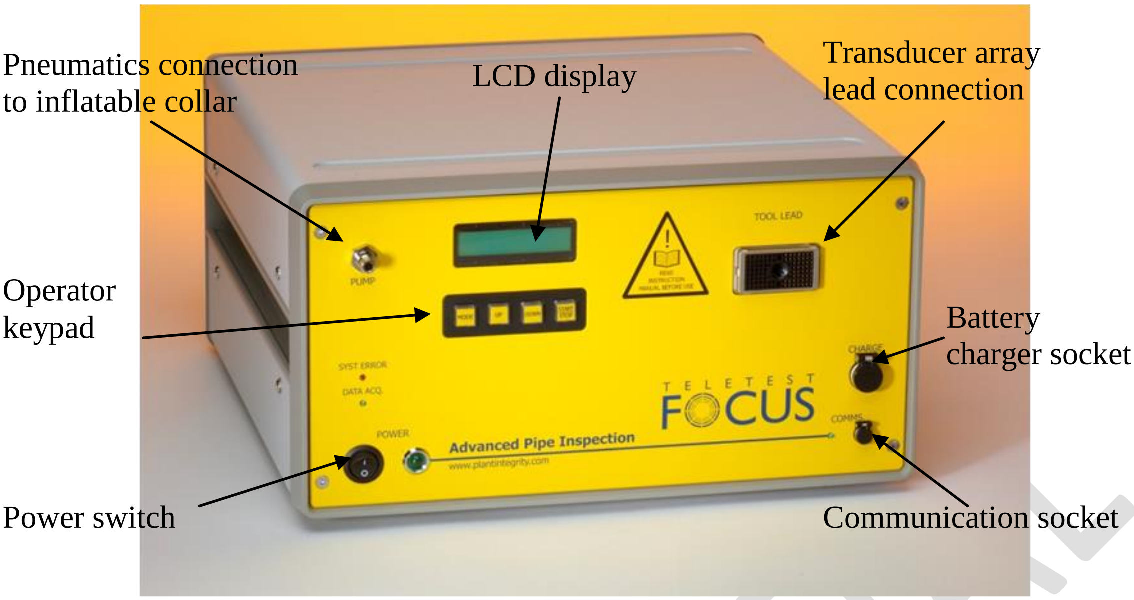


Figure 4-7. Plant Integrity TeletestFocus™ Mk3 electronics unit

4.3.3.1 Limitations of Mk3

Although the TeletestFocus™ Mk3 system was commercially successful, it did however, have some limitations to it operating performance.

The Mk3 system was designed with twenty-four high voltage output circuits that were used to excite the transducer in the tool coupled to a pipe. To receive any response back from these transducers, only eight input receiver circuits were implemented to signal condition and record data. The eight receivers could only be configured to collect data from only a single array of transducers at any one time. This set of eight receivers equated to one ring of transducers when connected to a tool head collar. During a data acquisition cycle, all twenty-four transmitters would be initialised and transmit the required output pulse, see Chapter 3 for details of excitation waveforms. On reception, the eight receivers could only collect data from one of the three rings during the current acquisition cycle. This limitation to the number of input receiver circuits necessitated the need to repeat the acquisition cycle three times to fully capture data from all three rings used in the Teletest LRU system.

Received signals from the transducer in the tool head could be amplified within a range from 20dB to 100 dB but was restricted to all eight channels simultaneously; no individual receiver gain could be altered. Although not critical for pipe line inspection techniques, this proved to be a limitation for research purposes.

4.3.3.2 Mk3 System costs

As the Mk3 became increasingly older then components availability became more of a problem. Many components were becoming obsolete and costs were rising due to increased demand for these components. Many of these components used through-hole technologies that resulted in higher assembly costs compared to surface mount technologies. Reliability was also becoming an issue with the Mk3. Using the backplane approach to locate the sub-assemblies meant that any misuse while shipping the equipment around the world resulted in some of the sub-assemblies becoming dislodged from the backplane, this caused the unit to fail and had to be returned to base for repair, which incurred downtime of the operators and additional expense in returning the equipment to base.

4.3.3.3 Mk3 System weight

The Mk3 weighed circa 12.2 kg and although still portable, was deemed to be too heavy for certain site inspection work where limited access or working at heights was required. The majority of this weight came from the heavy battery pack used in the equipment and the amount of external metal work incorporated in the design of the enclosure.

These limitations were addressed in the next generation of Teletest.

4.4 Development of the TeletestFocus™ Mk4 Embedded system

In the last section the previously developed systems were reviewed and a set of factors to be improved were indentified. Namely these are:

- Power consumption
- Speed of data acquisition
- Weight
- Size
- Data connectivity
- Cost
- Aesthetics
- Usability

The TeletestFocus™ Mk4 system was developed to address these requirements.

The Mk4 system (see Figure 4-8) electronics was specifically designed to be more efficient in operation over the previous Mk3 model. These improvements included faster data acquisition cycles, improved data throughput from the embedded electronics unit to the controlling Remote Laptop or PC, and lighter and more manoeuvrable when working in tighter working environments such as off shore oil installation platforms and pipe farms. Power consumption would also be greatly reduced compared to the Mk3 by using more energy efficient components.

Figure 4-8. TWI Ltd TeletestFocus™ Mk4 LRUT control system.

Functionality on the Mk4 was extended to include Wi-Fi capability. This allowed for more flexibility for operation in the field compared to using a hard Ethernet link which required a cable to be extended between the embedded control unit and controlling Remote Laptop or PC.

A new user interface was designed into the Mk4 that gave the operator greater flexibility when configuring the unit for operation. Simple commands such as pump control, Wi-Fi configuration, Ethernet IP address changes could now be accessed through this new user interface.

The TeletestFocus™ Mk4 is operated by a separate remote Laptop or PC connected via an Ethernet cable to the embedded control unit. As shown in Figure 4-9 the embedded control unit governs the transmission and reception of waveforms alongside the operation of auxiliary sub assemblies (such as pump control, GPS, front panel controller and temperature monitoring)

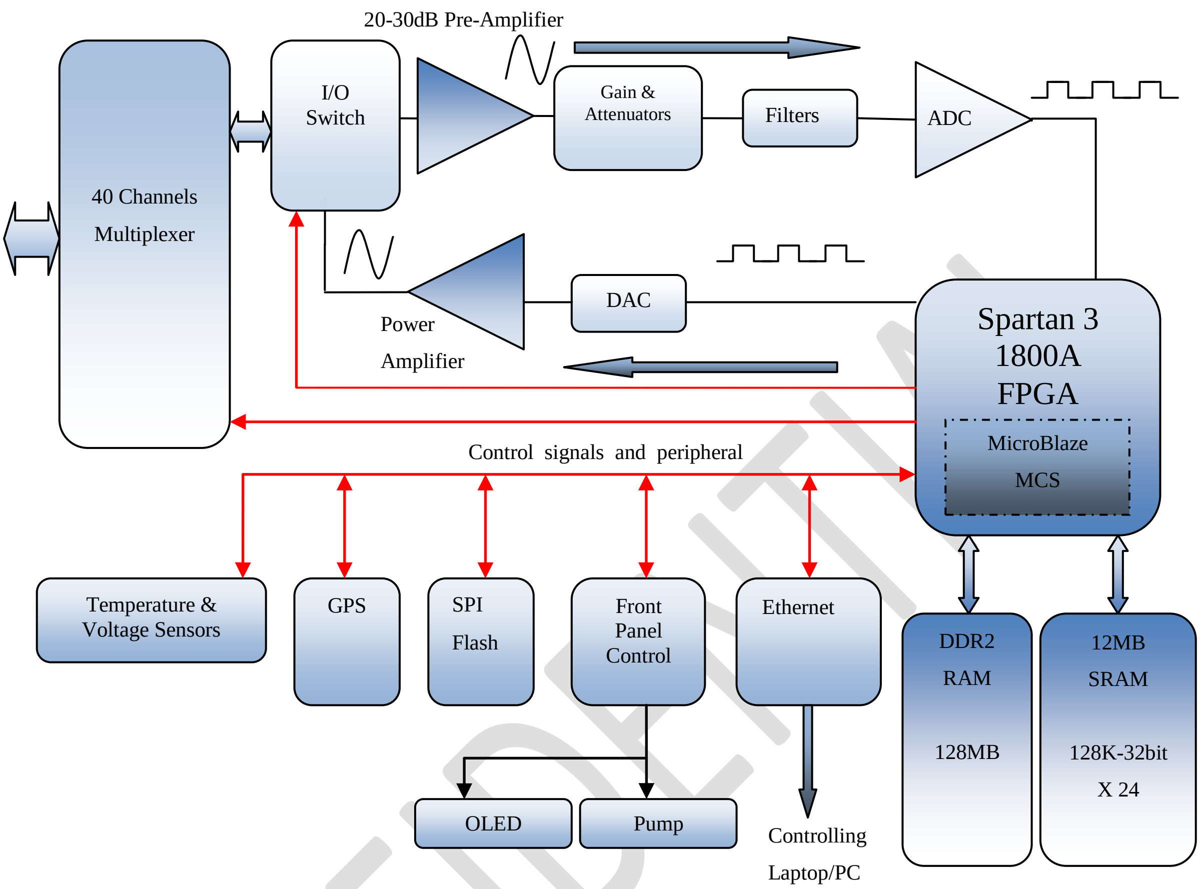


Figure 4-9. Schematic showing the basic layout of the new TeletestFocus™ Mk4

The developments for meeting the requirements can be considered as being split between design changes to the physical configuration and the electronics configuration, which are discussed in the following two sections. Full details of the electronics circuits are shown in schematic form in Appendix A

4.5 Mk4 unit physical considerations

Careful component selection is required if a reduction of any piece of equipment is to be visualized. To reduce overall size of the Mk4 system a new approach was adopted. With the use of state of the art technology components, than previously use in the Mk3 design, PCB space could be more efficiently utilised by using smaller devices, organising individual sub-systems onto single PCB's and by using a board stacking arrangement. Rather than using a single backplane approach, the new PCB sub-assemblies could be staked one on top of each other using interconnect components. The new PCB layout concept is shown in Figure 4-10, which demonstrates significantly more optimal use of space than the previous design (as was shown in Figure 4-5). This has lead to the achievement of a 46% reduction in volume for the electronics within the embedded sub-system.

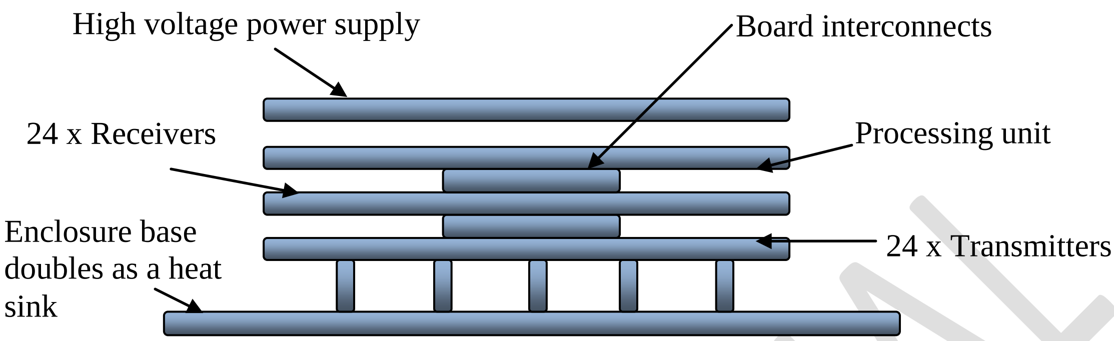


Figure 4-10. Mk4 PCB Arrangement based on board stacking.

This approach was commonly used in the PC104 form factor first released in 1992. Although signal integrity doesn't conform to this standard in the Mk4, the concept of stacking PCB's has been implemented. Interconnections between the stack consisted of 80 way 309AE-80-SG-1W-1555 type connectors. These type of connectors have been used extensively for PC104 applications and are ideally suited for this application where low resistance mating contact is imperative, as high speed digital signals are present, and are available in relatively large pin counts are beneficial. This means that signals required to pass thought to a different layer in the stack can be routed on the PCB to one location without the need to use multiply connectors. Electrical connections in any system can lead to premature system failure so reducing the quantity required in any design is preferable Mroczkowski R (2003).

4.6 Mk4 unit electronics configuration

New components were used to enable a new design topology, to replace obsolete components and take advantage of new technologies. The use of these new components required a schematics redesign of each sub-assembly. The transmitter circuits were redesigned to include all 24 channels and the associated isolation switching between out transmit and receive signals.

A new receiver circuit board was designed that would hold all 24 input channels plus individual gain and filter components and associated control signals for these functions.

The main system control board was redesigned to use new components including a more advanced FPGA, DDR2 and SRAM system memory, on board voltage regulators, Ethernet PHY, flash memory and voltage and temperature monitoring.

Design changes to the front panel display used in the earlier Mk3 were also carried out to include a new OLED display and GPS functionality. Changes to the side panel connection board that carries analogue signals between the electronics unit and collar transducer array was updated to include mating sockets for a battery charger, Ethernet cable, pneumatic air hose and external trigger functions that would be implemented at a later date.

Each new PCB schematic were created using the 'Cadance Orcad' schematic capture program version 16.1, which is an industry standard tool used for visualizing circuit diagrams. The benefits of using such a package enable the designer to layout a schematic circuit in electronic formant then pass this information into PCB routing software for the generation of Geber files used in the manufacturing process of producing printed circuit boards.

4.6.1 Mk4 new FGPA

The following sections describe the various sub-assemblies used in the design of the TeletestFocus™ Mk4 embedded system.

Research carried out by Zhang (2012) implemented a new Xilinx® Spartan 3 1800A FGPA into the design.

Designed and manufactured by the Xilinx® Corporation, this device was well suited for embedded process control Xilinx (2011). Many of the functions that were previously adopted in the Mk3 design as discrete components could now be incorporated within one single integrated circuit. This, along with other new technologies used had the added advantage of reducing further total power consumption with the TeletestFocus™ Mk4 electronics system. Figure 4-11 shows the simplified layout for the Mk4 peripherals and illustrates their direct relationship to the FPGA.

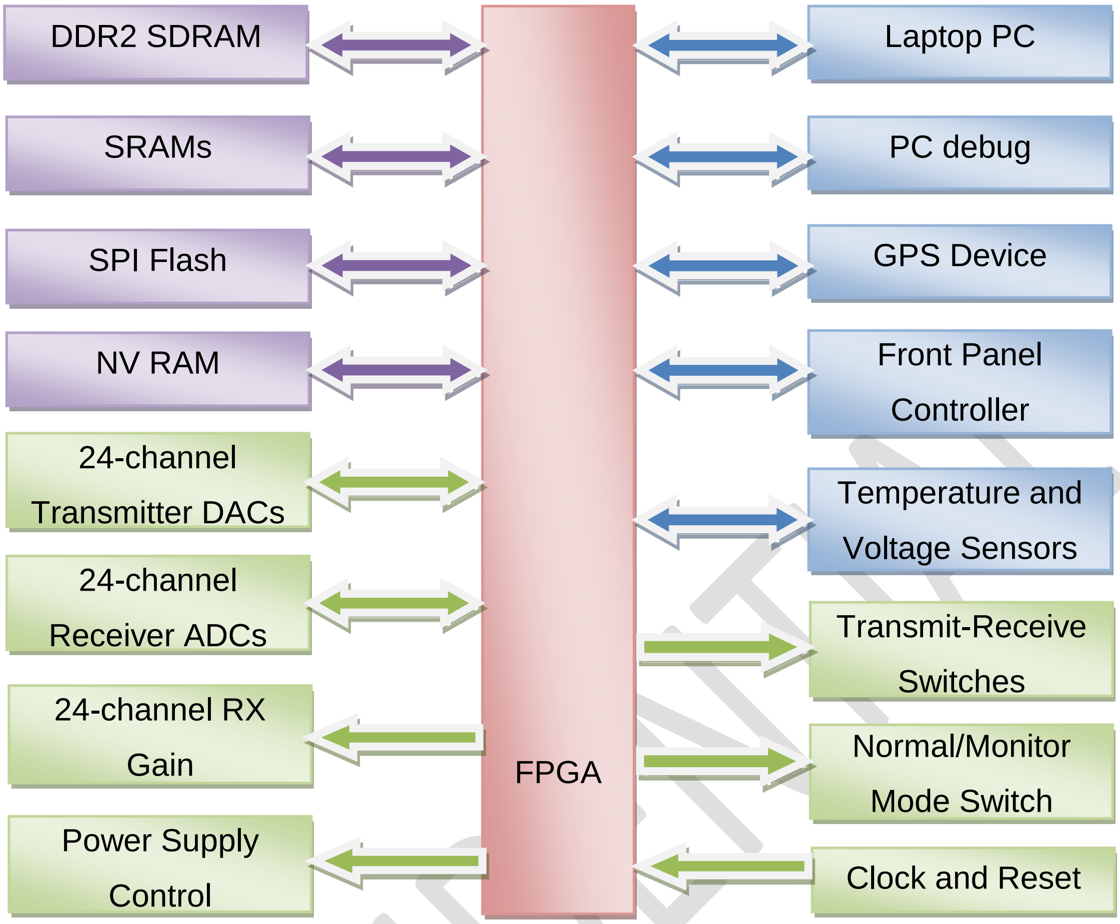


Figure 4-11. TeletestFocus™ Mk4 FPGA functional system block diagram.

Many of the peripheral operations such as SPI (Serial Peripheral Interface), DDR2, and Ethernet functionality can easily be included into the design using Xilinx® generated IP cores. These are pre-written VHDL codes which are implemented into the FPGA design at the development stage. This approach reduces the time for the design engineer to write specific application code, which ultimately reduces development costs, potential code debugging and reduces the time to market. Simple IP cores, as mentioned, are free to download from Xilinx® but more sophisticated IP cores can carry a licence fee for use. One such type that carries a fee is a Giga byte transfer speed IP core for an Ethernet implementation.

One important IP core available for the Spartan 1800A is a soft processor marketed as MicroBlaze™ Xilinx (2012) and is an industry leader in FPGA based soft processors. Using a soft core processor included in the FPGA design reduces component count and negates the need for external PCB space.

4.6.2 Transmitter circuits

The TeletestFocus™ Mk4 system uses 24 independently addressable transmitter circuits. Each output can achieve a possible excitation voltage of 280Vpp at 20kHz to 100kHz. High voltage power supplies designed by Partipan (2013) are used to supply load voltage and current into a maximum of load of 16nF per output channel. This equates to 16 individual transducers, the maximum used in any one configuration of the tool array coupled to the sample pipe undergoing inspection. The power supply unit was designed to deliver ±150Vdc to power the high voltage amplifies and drive current circuits but in practical use, 300V p-p is not possible due to losses in the supporting components.

Many of the components used for the transmitter circuits within the Mk3 system were carried over into the design of the Mk4. This approach was taken to reduce the overall development time but more importantly, from a reliability stand point, the exciting Mk3 transmitter circuit design had proved extremely reliable thought-out its lifetime. However, improvements to the design on the Mk4 were implemented using newer technology DAC's.

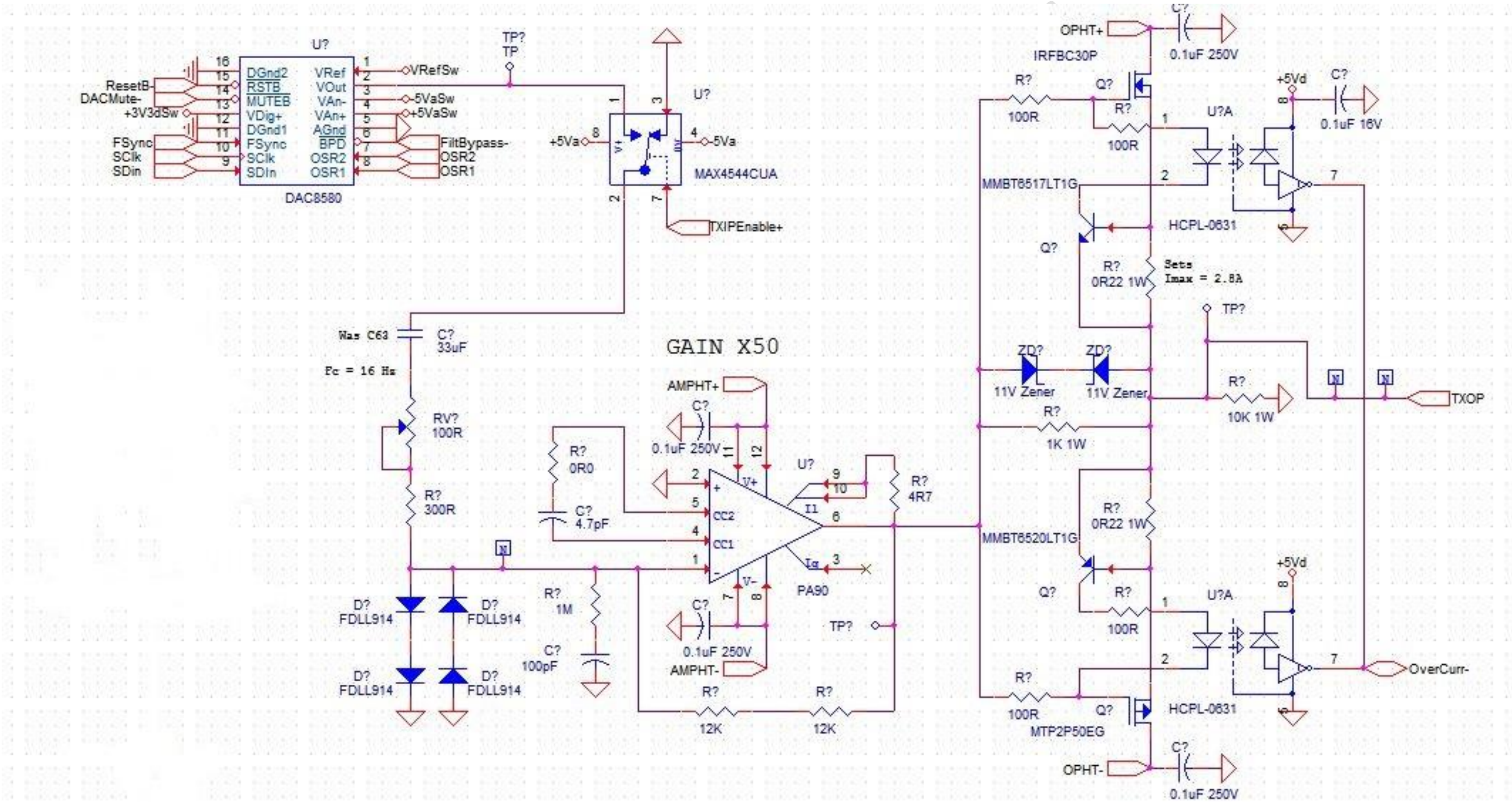


Figure 4-12. Single channel transmitter schematic used on TeletestFocus™ Mk4 system.

The circuit shown in Figure 4-12 comprises of a single DAC, which generates the desired analogue waveform required for a particular frequency based on data controlling software supplies to the DAC, these frequencies are briefly discussed in Chapter 1.

The output waveform amplitude from these DAC's, 24 in total, is small compared with the voltage amplitude required to drive a PZT crystal transducer used in the LRUT system operated by TWI. The output drive voltage amplitude used in the TeletestFocus™ system is specified as being able to produce a minimum of 285Vp-p. This requirement was based on practical tests conducted using previous generations of LRUT equipment used by TWI Ltd and was deemed unnecessary to carry out research into lower excitation amplitudes as part of this current research program. Amplification of the voltage produced by the DAC before reaching the load is via a high voltage operational amplifier, this output in turn drives a push-pull MOSFET arrangement that increase the available current.

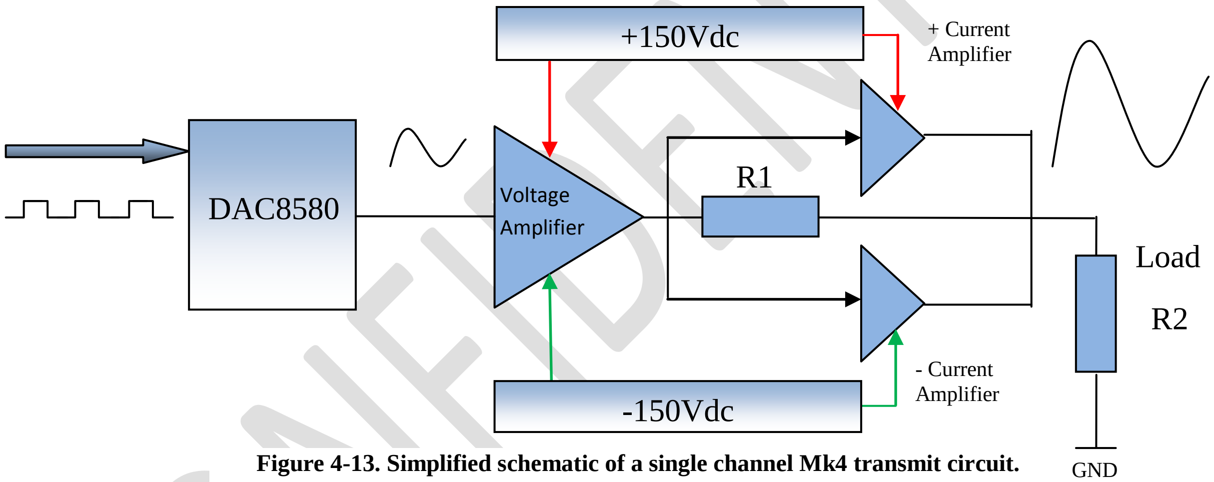


Figure 4-13. Simplified schematic of a single channel Mk4 transmit circuit.

To amplify the relatively small voltage produced from the DAC, ±3V, a high voltage single package operational amplifier was used. This device is manufactured by Apex Micro technology and is branded as PA90. The PA90 Apex (2010) is a high voltage low quiescent current (10mA) MOSFET operational amplifier designed as a low cost solution for driving piezoelectric transducers. Voltage amplification of an input signal can be as high as ±200V @ 200mA, with a high slew rate of 300V/µs. The device is packaged in a SIP configuration that allows for minimum board space, therefore, is ideally suited for this application where board space is a vital consideration. Also, the PA90 proved robust in its reliability in previous Teletest systems so a decision to keep this technology was adopted during the design specification phase. Figure 4-13 shows a simplified schematic representation for the single amplifier stage.

4.6.3 Digital to analogue convertor DAC8580

The DACs used for the analogue waveform generation were upgraded to a more sophisticated device. Whereas the Mk3 system used 24 x 9 bit devices, all of which required an independent data bus of 9 bit width, and subsequently required PCB trace allocation and routing, this had the detrimental effect of increasing the overall board footprint. The previous generation required a PCB footprint of 18.10mm by 10.65mm per device and in total consumed a combined power of 28.4W.

The Mk4 however used a much more conservative approach by exploiting the features available in the Texas Instruments DAC8580, Texas Instruments (2005). This relatively new IC, at the time of design of the Mk4, operated from a dual ±5Vdc supply and took only 6.6mm by 5.1mm of board space per device. This resulted in a board space saving of 82% over the Mk3, although total power consumption remained the same for both designs.

Another useful feature of the DAC8580 is its serial communication port. Unlike the devices used on the Mk3, which required 9 signal traces to be routed on a PCB, the DAC8580 device only required one PCB trace to enable data transfer from the controlling hardware, in this design the Xilinx® FPGA.

One of the most important considerations when choosing this device was its ability of carry out digital interpolation within the device itself. This meant that data strings sent to the device can be reduced in quantity without losing any of the resolution to the output waveform. Work carried out by Zhang (2012) showed that by using this integral interpolation function within the DAC8580 memory allocation for the sample data that reconstitutes the output waveform could be reduced by a factor of 16. By utilising the interpolation function within the DAC8580 facilitated the reduction of memory storage allocation to hold the sample data.

4.6.4 DAC8580 interpolation

The internal interpolation function of the DAC8580 is illustrated in Figure 4-14

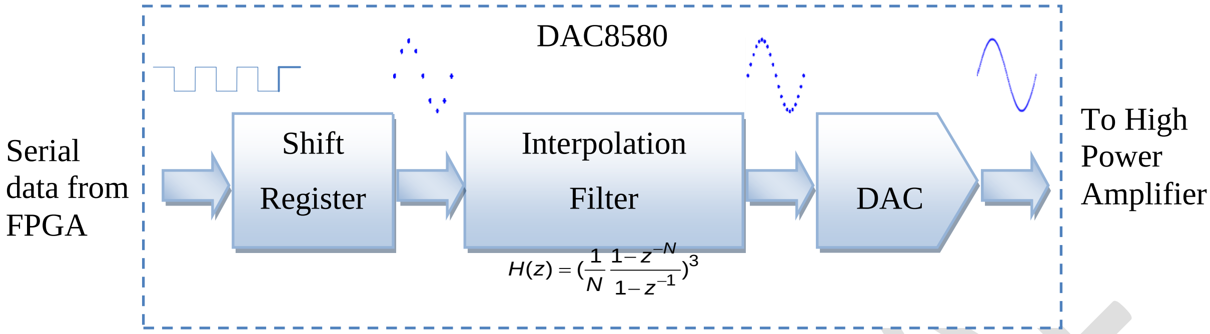


Figure 4-14. A simplified schematic representation of the internal Interpolation filter integral to the DAC8580.

Serial data is passed from the FGPA block ram to the DAC in the form of a 16-bit serial representation of the intended output analogue waveform. The interpolation function is capable of x2, x4, x8 or x16 over sampling meaning that a 1K sample can be passed to the DAC, with a setting of x16 interpolation, with the output waveform being equivalent to a 16K sample (see Figure 4-15).

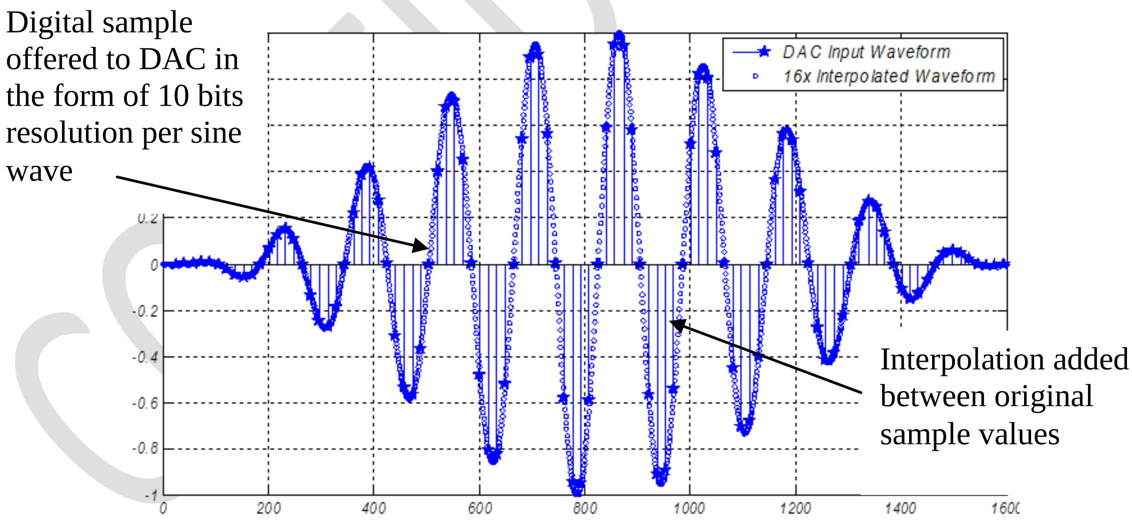


Figure 4-15. Test waveform and 16x Interpolation.

4.6.5 Transmitter to receiver switching

As a single transducer can function both as a transmitter and receiver, electrically connected on the same signal path, a method of switching is required to differentiate between a transmitted high voltage output waveform to a transducer, or a received response back from a transducer. If isolation between these two separate cycles (transmit-receive) doesn't exist then serious damage to the receiver circuits can result from the high voltage transmitted waveform pulse passing directly into the sensitive low voltage receiver circuits.

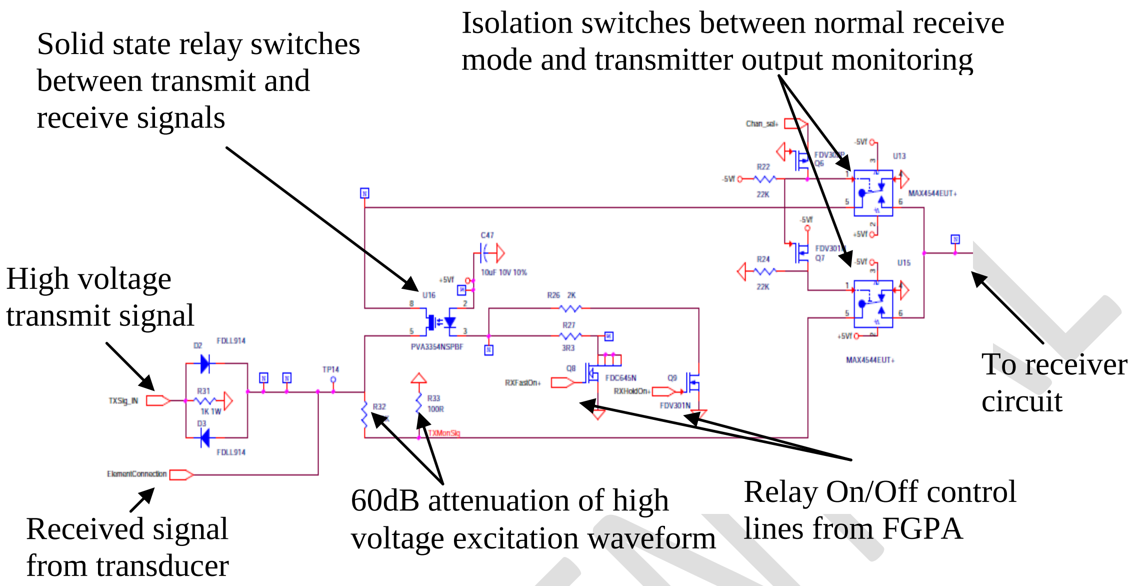


Figure 4-16. TeletestFocus™ Mk4 Input isolation and signal routing circuit.

To overcome this problem a simple solid state relay was introduced as an isolation barrier as shown in Figure 4-16. The device used is a PVA3354NSPbF as it operating parameters are well suited for high voltage isolation, low 'ON' resistance, high 'OFF' resistance of 10^{10} **Ω**, solid state reliability and bounce free operation.

Figure 4-17 shows the typical resistance characteristics of the PVA3354NSPbF. Twenty four of these devices are used in the Mk4 design and are directly controlled via the FPGA, Zhang (2012).

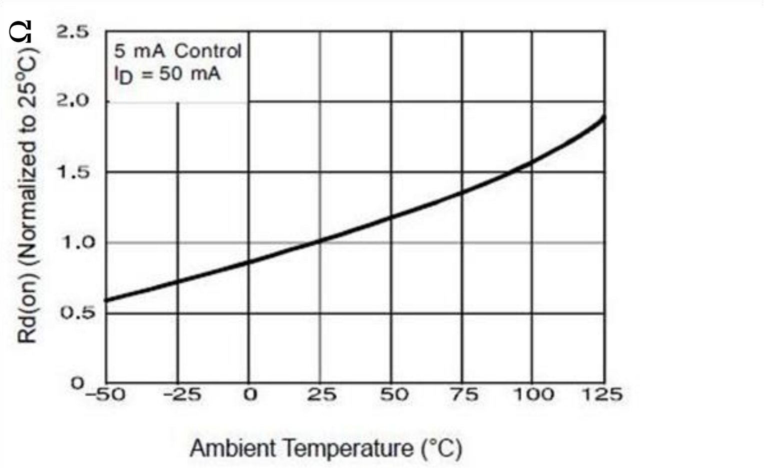


Figure 4-17. Typical On-Resistance for a PVA33N device.

When an excitation signal is initiated from the high voltage output circuits the relay, is in an open position to prevent the signal from reaching the sensitive receiver input circuits. Due to the relatively slow delay switch on time for the relay, two drive signals are used to force the device into a closed relay state in a much shorter period of time. Although the typical delay times are not shown for ‘I LED’ current above 20mA, extensive testing involving higher currents were conducted. These results showed that large increases of current were possible for short periods of time without damaging the device. Extended operation using this technique in the Mk3 system over its life time has also validated this technique as a viable means of fast switching these devices. Figure 4-18 shows typical values for the forward bias current against time.

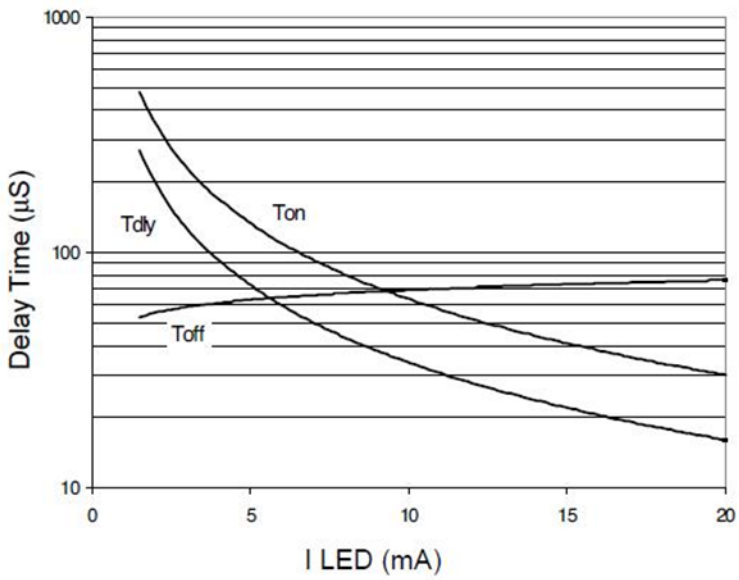


Figure 4-18. PVA3354NSPbF typical time delay graph

The first signal called ‘RXFastOn+ turns on an N channel MOSFET allowing current to flow through an integrated LED (Light Emitting Diode) in the device via a small 3R3 Ω resistor. The current flow through the LED controls the opening and closing of the solid state relay. This signal is used to rapidly turn on the device before a smaller hold on current is applied via the control signal ‘RXHoldOn+’. The RXfastOn+ signal will produce a current flow of circa 1.5A for a limited period of time, otherwise damage to the device would occur; the time period of 300ns is used for the duration of this signal.

The second signal ‘RXHoldOn+’ is also activated at the same point in time as ‘RXFastOn’ but remains active until the termination of the data receive cycle. This signal produces a current flow through the LED of 2mA and can remain safely in this state indefinitely. Also, a 2mA output flow control current allows or a maximum load current of 170mA to be achieved.

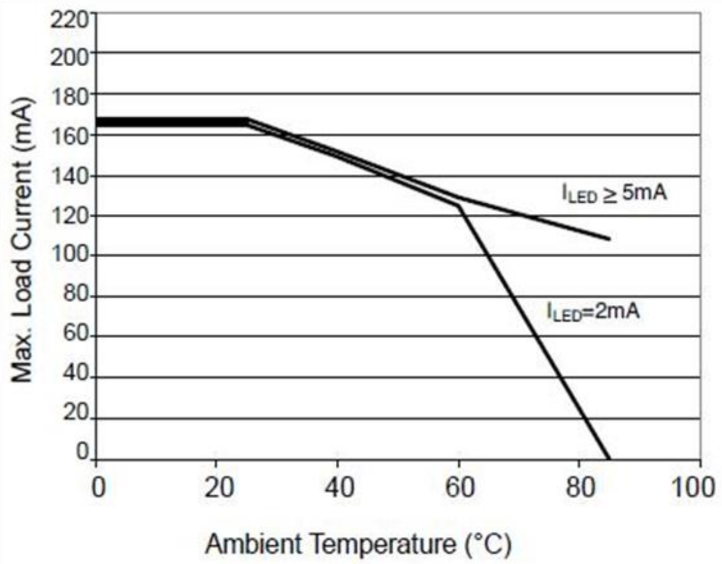


Figure 4-19. PVA3354NSPbF derating graph

From Figure 4-16 it can be seen that there are two potential pathes for the revieced signal to take. Under normal operation, when an acquisition cycle is being aquired, response signals obtained from a tranducer are routed through to the reciever circuit via the solidstate relay, and a secondry isolation switch, before passing onto the pre-amplifier stage and finally to the ADC's. See Figure 4-20 P109 for full circuit diagram showing input switching, reviever amplifiers, signlas attenuators, filters and ADC for a signal reviever channel used on the TeletestFocus™ Mk4 system.

Another feature of the input circuits is the ability to monitor the amplitude of the excitation signal that will be presented to the transducer on its prospective channel number. This feature fersilitates calibration of the TeletestFocus™ Mk4 electroincs. Under conditions of either variations in component tollerance, casued by temperature fluctuations, inherant component tollerance during manufacture or tollerance changes due to ageing the excitation output voltage amplitude can be adjusted to compensate for variations.

Monitoiring for the amplitude of the excitation pulse is achieved by routing the high voltage pulse via a 60dB attenuation circuit that reduces this signal the reciever circuits can occomodate. The signal then passes thought the reciever circuits and is digitised.

Knowing the original value that was passed to the DAC's to generate the excitation amplitude and frequency a compensation value can either be added or subtracted to this value before passing to the DAC's.

4.6.6 Receivers

To accelerate the access time for a data acquisition cycle the Mk4 is designed with 24 receiver channels as shown in Figure 4-20. As previously discussed, implementing more input channels negates the need to repeat the data collection cycle more than once. Each individual input circuit (channels 1-24) can be independently switched to receive input signals from its designated path from time zero of a collection. This means if a particular channel is set to receive signals at time zero then that channel cannot be used as a pulse wave transmission channel. Having the channel configured to both transmit and receive at the same time would result in the high voltage pulse entering the sensitive receiver and damage would result.

Therefore, a channel can be configured by the control logic to receive input signals at the start of the data acquisition cycle and digitize any response received at time zero, or wait until the end of the excitation pulse waveform, if the channel is configured as a transmitter, and then switch to receive mode and collect data.

The time period for the pulser receiver unit switching from transmit to receive is governed by the length of the excitation signal, and is contolled via the acquisition state machines running inside the FPGA. If, for example, the transmit excitation pulse length was 5 cycles at 70kHz then the time period before the unit switched to receive mode would be in the order of 71.4µs after the start of this excitation pulse.

Each receiver channel has an independently selectable gain and filter setting. Gain can be adjusted to any value from 20dB to 100dB in steps of 1dB. This allowed for small received signals to be amplified before passing to the DAC's for digitisation. To minimize component count in the design a scheme was introduced whereby Attenuators are introduced alongside the voltage amplifies within the receiver chain. Using both a combination of gain and attenuation the desired amplification of 20dB to 100dB can be achieved.

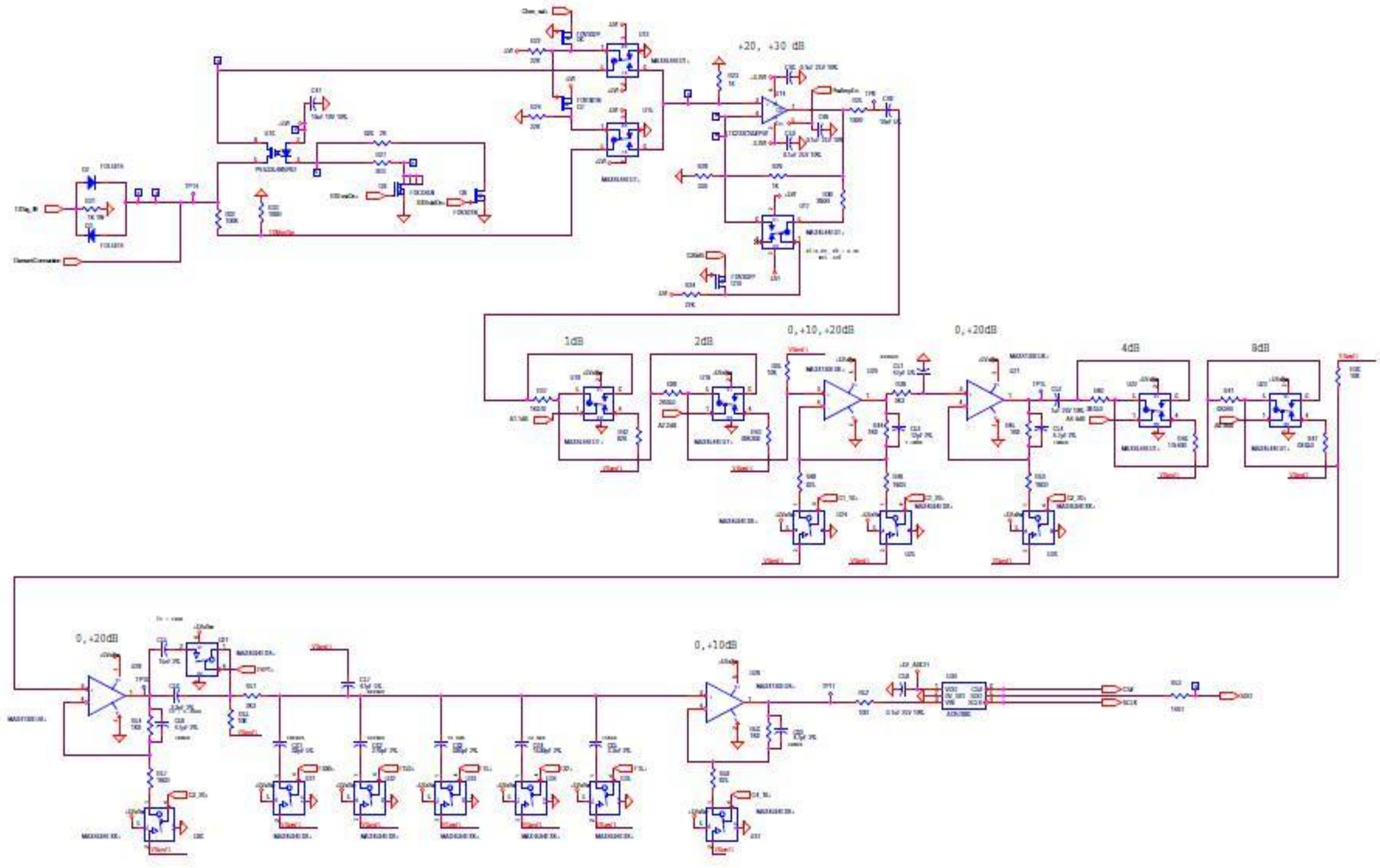


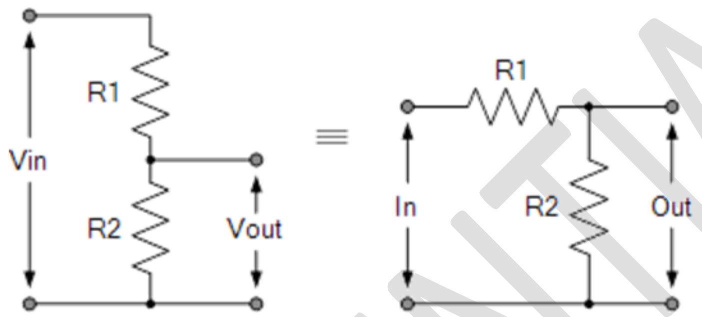
Figure 4-20. Single channel receiver circuit used on TeletestFocus™ Mk4

4.6.7 L-Pad attenuators

Each input channel implemented a simple L-Pad attenuator with values of -1dB, 2dB, 4dB and 8dB.

An L-Pad attenuator circuit is virtually identical to a simple voltage divider commonly in electronic circuits to generate a lower output voltage from a higher input voltage.

Figure 4-21 shows a typical L-pad circuit arrangement alongside a common voltage divider.



Simple Voltage divider L-Pad Attenuator

Figure 4-21. Simple voltage divider and L-Pad attenuator.

Although the circuits appear to be identical the main function of an L-Pad attenuator is to introduce attenuation into a circuit. The introduction of the attenuator into the Mk4 Teletest receiver circuits must not alter the source voltage amplitude, and therefore, the resistance seen by the source must remain the same at all times. Only the output signal from the attenuator must change depending on whether the circuit is in a on or off state. As input signals into the receivers from the transducer during an acquisition cycle can be small, any unwanted attenuation is undesirable.

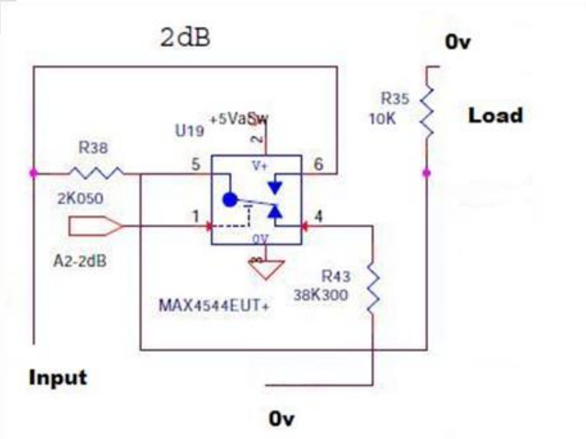


Figure 4-22. TeletestFocus™ Mk4 2dB attenuator circuit.

To calculate the value for the resisters in the attenuator circuit to generate a 2dB attenuation the above circuit can be redrawn and the following formula used. The equations are based on the maxim solid state being closed as show in Figure 4-22 When the switch is in the open position the resister network of R38 and R43, used to produce the required attenuation, are bypassed and all signals from the input are directly presented to the output load, in this instance 10K Ohms

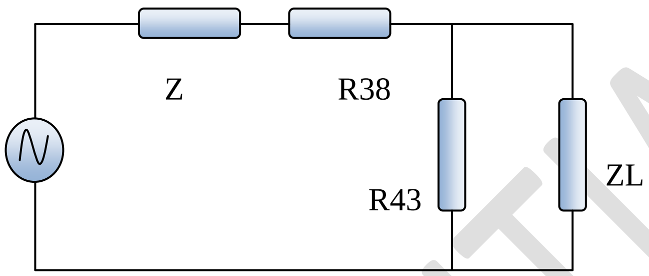


Figure 4-23. Equivalent simplified circuit layout of Figure 4-22.

Resister values for the L-Pad attenuators were calculated using the equivilant circuit shown is Figure 4-23.

For R38

$$\mathbf{R38} = \frac{\boldsymbol{Zs}}{\boldsymbol{S}}\left(\frac{\boldsymbol{KS-1}}{\boldsymbol{K}}\right) \qquad \textbf{(4-1)}$$

$$= \frac{10000}{1}\left(\frac{1.2589*1-1}{1.2589}\right) = 2057\Omega$$

For R43

$$\mathbf{R43} = \frac{\boldsymbol{Zs}}{\boldsymbol{s}}\left(\frac{\boldsymbol{1}}{\boldsymbol{K-S}}\right) \qquad \textbf{(4-2)}$$

$$= \frac{10000}{1}\left(\frac{1}{.2589}\right) = 38624\Omega$$

Where S = $\sqrt{\frac{Zs}{ZL}}$ = 1

and K= $10^{(\frac{dB}{20})}$ (where dB is the amount of attenuation required)

For 2dB, K = 1.2589

Although the calculated values are not exactly the same as used in the actual circuit as preferred values of resisters were used.

4.6.8 Analogue to digital convertors

As the response from a PZT crystal based transducer constitutes an analogue signal this requires digitizing before any computational evaluations can be performed.

In the case of the TeletestFocus™ Mk4 system there are 24 individual digitizers, one for each receive channel, implemented after the output from the gain and filter circuits (see Figure 4-20 P109).

After an output voltage excitation function has been initiated these digitizers are switched on and convert all analogue signals present at their inputs into a digital value representative of the signal amplitude at a given point in time, this time period is governed by the ADC's system clocks.

To improve overall performance compared with the older generation Mk3 a new generation ADC was designed into the receiver circuits. As a design requirement for the TeletestFocus™ Mk4 was not only to reduce system size and weight but also power consumption. An analogue to digital converter produced by Texas Instruments was chosen for the design due to three important attributes. This devise is marketed by Texas Instruments as part number ADS7886

Firstly, the ADS7886 is available in a small 6 pin SOT-23 package just 3.05mm by 3.0mm compared with the footprint of the older ADS803 analogue to digital converter used on the previous Mk3 system design; this resulted in a 90% reduction in PCB layout area.

Secondly, during operation with data throughput of 1MHz the ADS7886 only consumes a total power dissipation of 7.5mW. The older ADS803 used in the Mk3 consumed a much greater 115mW whilst running at the same sampling frequency of 1MHz. This reduction in consumed power equate to a saving of over 93% per receiver channel.

Thirdly, to continue the focus of reducing the physical PCB board space the ADC7886 uses a series data bus to output data. As a serial device only 1 output pin required, therefore reducing the overall PCB board space required to route signals back to the data processing unit, in the case of TeletestFocus™ Mk4, a Xilinx® Spartan 1800A FPGA. Table 2 shows the comparison PCB footprint and power consumption between the analogue to digital convertors used on the Mk3 and Mk4 systems.

Variant	Part No.	Footprint	Power Consumption
Teletest Mk3	ADS803E	10.5 mm x 8.2 mm	115mW @ 5 V
TeletestFocus™ Mk4	ADS7886	3.05 mm x 3.0 mm	7.5 mW @ 5 V

Table 2. Comparison footprint and power consumption between TeletestFocus™ Mk3 and Mk4.

The ADC7886 is quoted by the manufacturer as having a 1Mbit conversion rate; this equates to one digital sample being available every 1µs. The ADS7886 has a serial data output bus for transferring the digital value of the converted analogue signal to the controlling device, in this case a FPGA (Field programmable gate array). Serial bits are clocked from the device using a control line 'SCLK' which runs at a constant 20MHz (see Figure 4-24). The ADC7886 outputs a 12 bit data stream in MSB format that represents the converted input signal, but also 4 zero bits. A 20MHz SCLK is able to clock out of the device one data stream of 16 bits within 1uS. This allows the FPGA to access the data and store it in memory before having to fetch the next available data stream. The conversion of the input analogue single is instigated by the control signal #CS, negating this signal forces the ADC to start an input signal conversion.

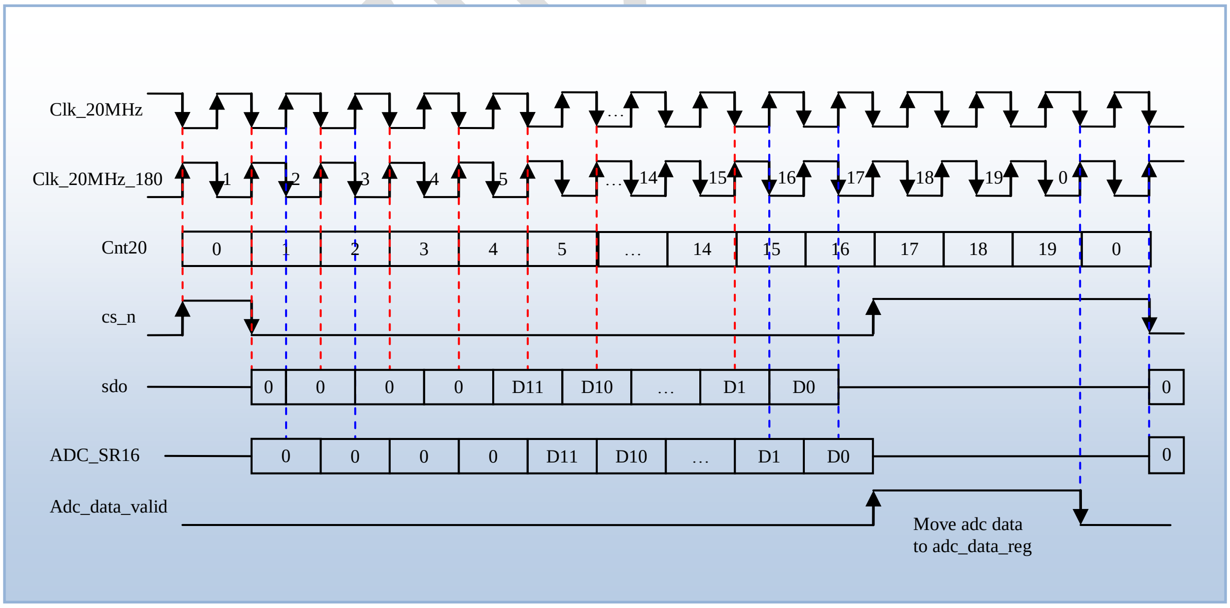


Figure 4-24. TeletestFocus™ Mk4 system ADC controller timing diagram (Zhang 2012).

4.6.9 Data storage

During a data acquisition cycle digitized values obtained from the 24 ADC’s representing the received analogue values from the transducers located at the tool head were temporarily stored within the unit’s internal memory before passing to the controlling remote PC.

Research carried out by Zhang (2012) implemented two data conditioning functions for each received data sample from the ADC’s.

Firstly, received data values were checked for saturation caused by an over voltage signal present at the input of each ADC. If saturation was detected then an error flag would be issued by the units CPU and action could be taken by the operating technician. Reducing the input gain for the particular channel would be required.

Secondly, an accumulation and averaging function is used. Averaging the data collected from each channel over a set number of acquisition cycles effectively cleans the data of any unwanted noise that may have been introduced by some external factor such as electromagnetic radiation from close proximity high voltage sources, or random intrinsic noise from the sample being tested. The value used for averaging, of the received digitised response from the transducers, is selected by the equipment operator and is modified accordingly to produce a clear and precise pictorial image on the structural condition of the sample material under test.

This accumulation function required that data from the ADC’s, collected in real time, needed to be added to data previously stored in memory from the previous cycle and returned to memory before any subsequent data collections from the ADC’s could be processed.

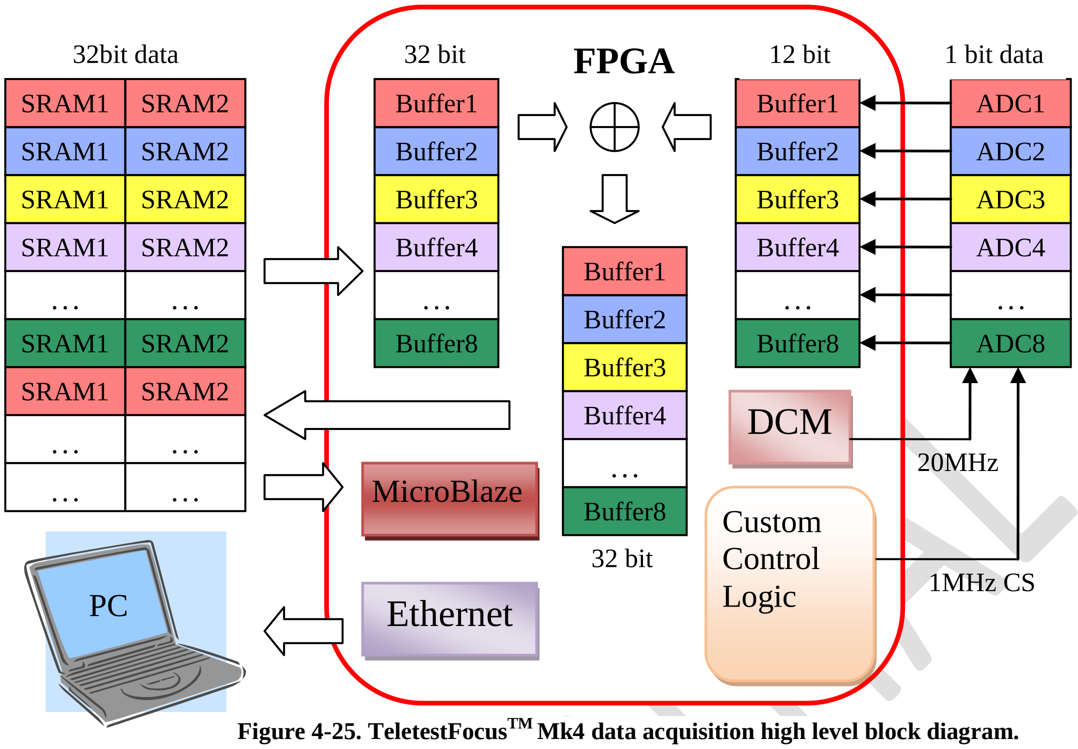


Figure 4-25. TeletestFocus™ Mk4 data acquisition high level block diagram.

The memory used for data storage is divided into three blocks with each block running in parallel. Each block representing 8 receiver channels, each allocated 128Kb of 32bit storage space. The memory area has increased on the Mk4 from 24-bit data width, on the Mk3, to 32-bit (see Figure 4-26). This increase in data width serves two purposes. The controlling CPU (FGPA Microblaze) uses a 32 bit data bus resulting in easier access to the memory banks. Also, the accumulation function can be increased using extra bits available with a 32 bit data width.

For the Mk3 system the memory allocation was 24-bit wide by 64Kb which allowed for 12 bit of data plus 12 bits for accumulation. Therefore, 2^{12} allows for 4096 accumulations to take place. This value is considered adequate for normal TeletestFocus™ operation when conducting tests on pipe lines or other structures.

With 32 bits available on the Mk4 system this averaging can be increased to 20 bit accumulation, allowing for 12 bit for ADC data, 2^{20} allows for 1million accumulation iterations. This increase in data width can facilitate the use of digital filters within the design based on Multiply-accumulation techniques as the results depends more on the resolution of the digital filter coefficients used.

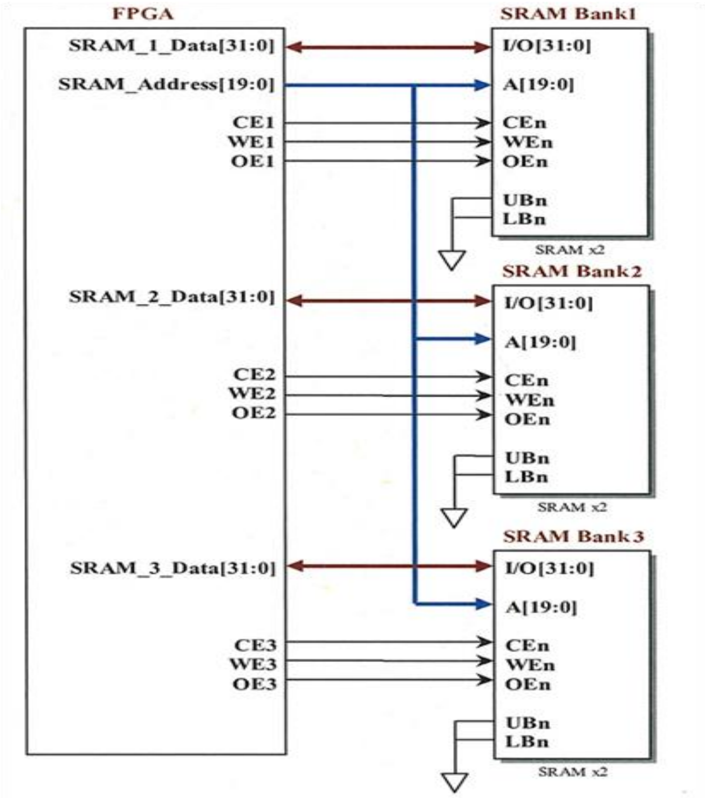


Figure 4-26. FPGA interface for three parallel SRAM banks.

The accumulation function required the control logic to access the memory of each bank of eight channels within 1µs/8 = 125ns with an access time less than 62.5ns. This requirement was placed on the design as a 1MHz ADC sampling frequency is being used to access the converted analogue data. Therefore, each successive read-accumulate-write to memory had to take place within 1µs.

To achieve the specified timing requirements, and consider PCB footprint and power reduction, SRAM devices manufactured by ISSI are used (see Figure 4-27). To accommodate all 24 receiver channels with 128Kb 32 bit storage the ISSI-61WV102416 device was used. This device is a high speed 1Mx16 asynchronous CMOS device. It can operate from a single +3.3Vdc power supply with data access times less than 8ns. For a data bus width of 32 bit two devices configured in parallel giving a total of 1Mx32bit. As each back of 8 receivers requires 128K by 32bit of storage is can be achieved using the device in parallel: ((1024*1024)/8)/1024 = 128

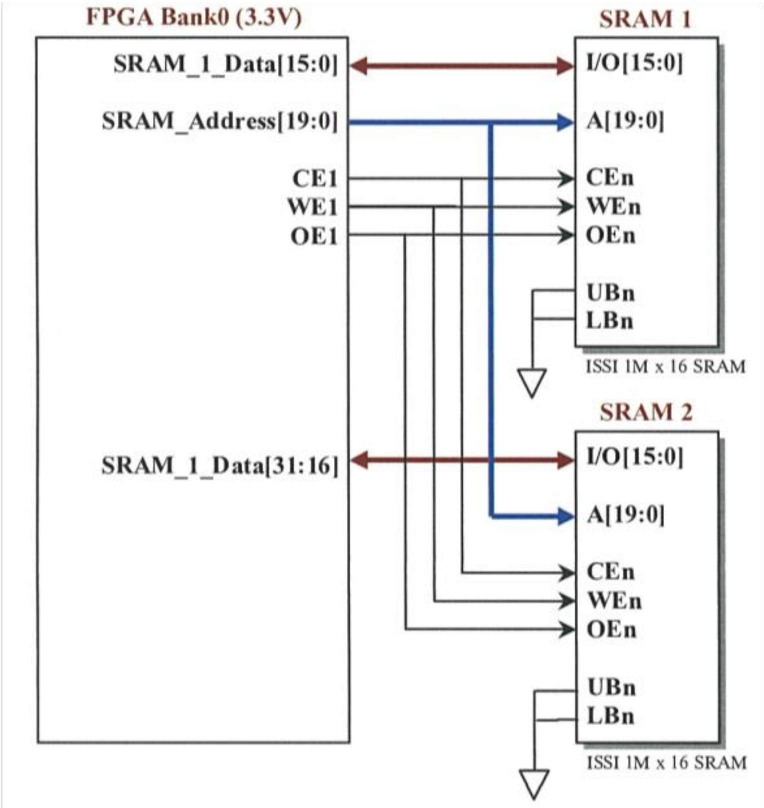


Figure 4-27. FPGA interface for one SRAM bank.

Apart from the IS61WV1024 devices satisfying timing requirements they also contributed to the total power saving and size reduction placed on the design.

The SRAM device is considerably smaller than previously used on the Mk3 system. These devices measure just 9mm by 11mm compared to the old Mk3 SRAM's measuring 26.17mm by 11.31mm. Also, the old Mk3 system used 12 devices to accommodate the memory requirements where the Mk4 and needed 6, this equates to a PCB board space saving of over 83%

Power consumption was also reduced from 15W in the Mk3 system to under 6W for the Mk4; this is a saving of over 60%

4.6.10 Mk4 controller board

A new controller PCB was designed that would accommodate all the necessary components to control the functionality of the system; this is shown in Figure 4-28. These were specifically the FPGA device for controlling a data acquisition cycle, system memory including DDR2 for the embedded firmware to reside, non-volatile flash to store the runtime code to initialise the system, ADC's for peripheral monitory such as temperature and system voltage levels, system power regulation for the FGPA and other components along with an Ethernet PHY for communication between the embedded system and remote Laptop or PC.

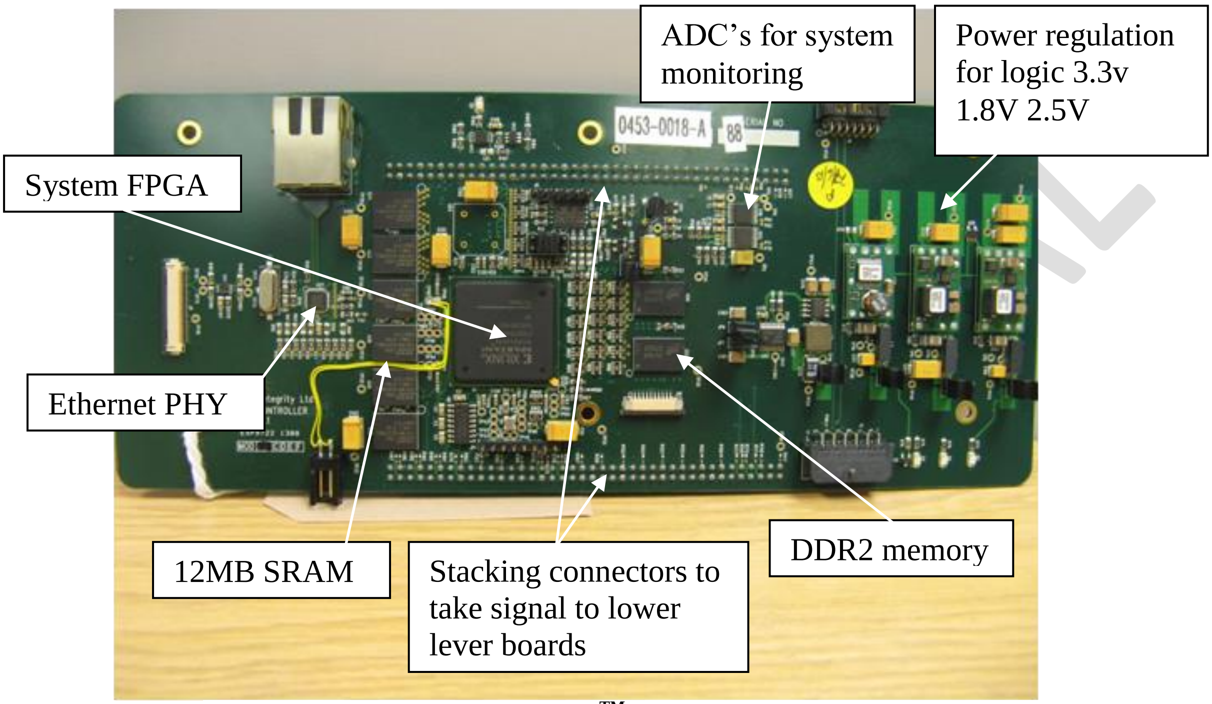


Figure 4-28. TeletestFocus™ Mk4 Main controller board

The main system board measured 240mm x 100mm and consisted of 8 layers. Unlike the previous generation Mk3 many of the supporting peripheral devices were implemented onto this board. Many of the components were surface mount which reduced overall PCB space required and aided manufacturing. In system standby mode the board consumed a total of 300mA.

4.6.11 Enclosure layout and aesthetics

To achieve a reduction in overall unit size and weight, several new techniques are employed that would facilitate this requirement.

Firstly, new materials are selected in the design for the outer enclosure. Whereas the older Mk3 used a pressed steel framework to house the electronics and supporting peripherals, such as the battery and pneumatic pump. The new Mk4 uses a manufacturing process involving Rigid Polyurethane Norse (2010). This technique involves producing a mould cavity, that represents the final component size and shape and then pouring a liquid Polyurethane compound into this mould. The cast is then cured at ambient temperature before releasing and completing any detailing work such as machining over-spills from the casting process. The end result is a product that has strength, rigidity, is lightweight, can be painted in any colour and is a cost effective solution when hard tooling costs are prohibitive due to small production runs. For the Mk4 enclosure design, hard tooling to produce injection moulded components would have been 6 times more expensive then a soft tool used for the rigid polyurethane process.

One drawback to this process is the soft tool can wear with usage more rapidly than its injection moulding counterpart. Also tolerances for a given size, ±0.3mm are not as accurate when compared to injection moulding. This approach for the manufacture of the enclosure is acceptable due to the relatively small projected production volumes of approximately 30 per annum.

Before the final design was approved an SLS (selective laser sintering) prototype enclosure was manufactured and assembled to ensure that any errors that may have been introduced during the CAD design work could be rectified. Although, this process can be quite expensive on larger items such as the Mk4 enclosure the costs involved are negligible compared to reworking of finished moulds. The use of SLS prototyping can reduce development times and some confidence can be assured that the final product will assemble correctly. Figure 4-29 shows a picture of a finished Mk4 top cover after assembly of peripheral components.

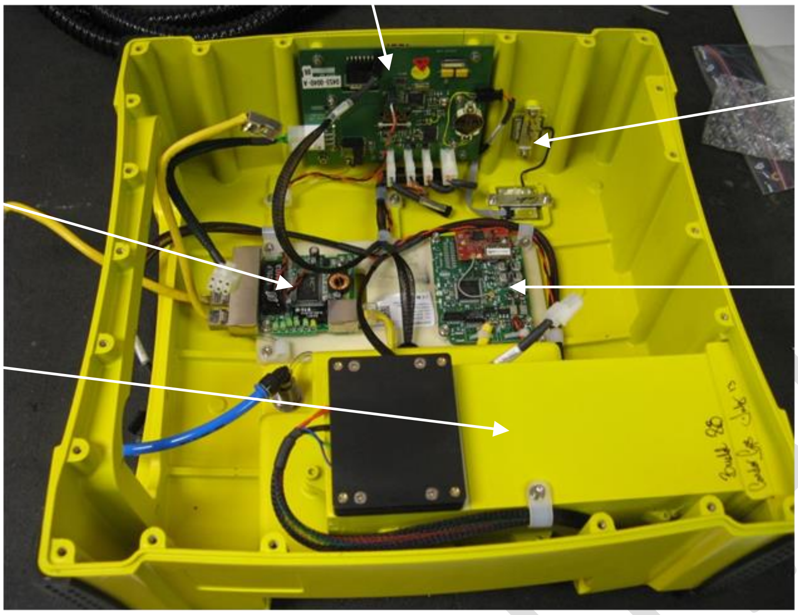


Figure 4-29. TeletestFocus™ Mk4 top enclosure with wiring harness and peripherals.

Secondly, a further reduction in weight resulted from the use of a machined aluminium component that served two purposes. First, it formed the base of the Mk4 and acted as a platform to locate a large quantity of the internal components, also, the polyurethane top enclosure cover located onto this base plate. More importantly however, it facilitated the exchange of heat from the unit. The biggest generator of heat emanated from the 24 high voltage transmitter circuits. Unlike the 24 transmitters used in the Mk3 design, which were free standing and radiated heat into its enclosure, the Mk4 uses this base plate as a heat sink and therefore acts as a passive heat exchanger. Each high voltage amplifier has direct contact with the heat sink therefore, dissipating a percentage of heat into this sink Fourier, J. B (1822).

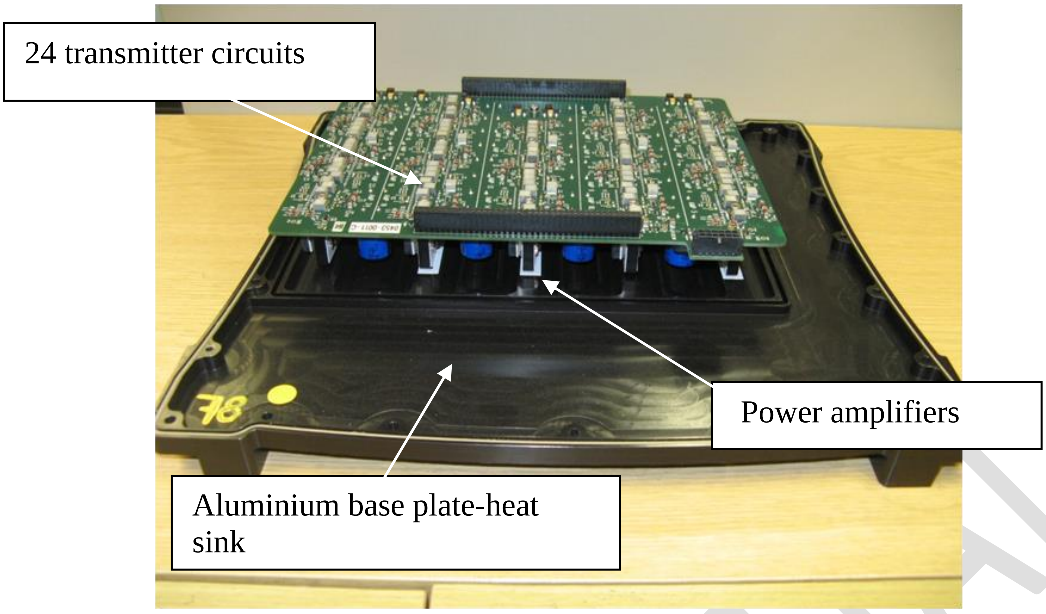


Figure 4-30. TeletestFocus™ Mk4 heat sink and power amplifier arrangement.

Extra weight saving on the Mk4 system was obtained by using a more compact battery arrangement. The previous Mk3 system used a 7 by 2 cell configuration that weighed over 2.5Kg and measured 165mm x 80mm x 60mm when packaged in its protective enclosure.

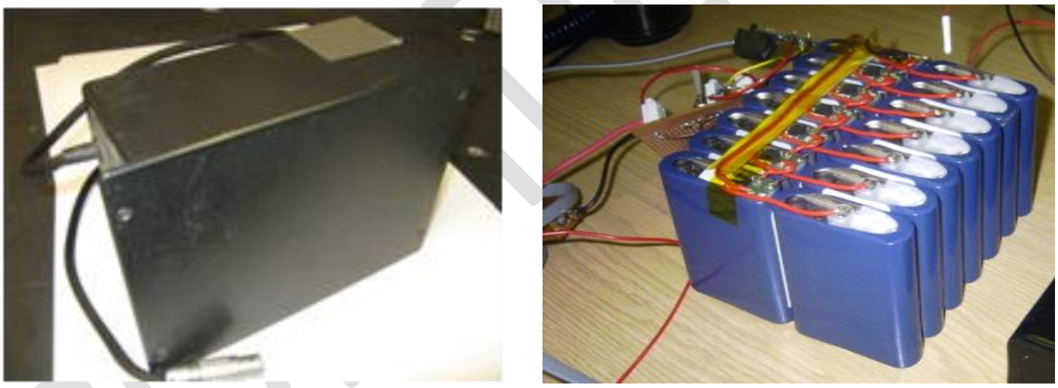


Figure 4-31. Teletest Mk3 power source cell arrangement and packaging.

The Teletest equipment was originally specified to operate for a minimum period of 12 hours. Although this figure is ambiguous as any battery operated system can only function as long as their total capacity was first of all adequate, and secondly, its load current during operation was understood as over this period. The requirement for the Teletest equipment to function over a 12 hour period was a commercial decision as this was deemed the anticipated shift working pattern for the operators during an inspection. A more realistic scenario is to consider a worst case operational requirement for power consumption. The Teletest electronic system is specified to deliver a total of 72A, when all 24 transmitter circuits are each driving a capacitive load of 16nF. This figure however doesn't take into account the power required to inflate the pneumatic transducer coupling mechanism, the volume of the air required to achieve this or the system controller's electronic circuits. If however, the specification required that the system was able to inflate the largest size 24inch transducer array with each individual transmitter circuit delivering power to a 16nF load at 100kHz, and that data was collected at no less than 10 inspection locations, a more detailed understanding of the battery performance requirements could be calculated.

The HT-Bank is the power supply bulk capacitors for the transmit circuit that drives the LRUT-transducers. In the TeletestFocus™ Mk4 pulser-receiver unit, there are 24 transmitting channels demanding approximately 72A in total for the duration of 1 ms at a pulse repartition rate (PRR) of 0.1 seconds to sufficiently excite the heaviest load. The heaviest load is when each transmitting channel supports 16 LRUT transducers connected in parallel and the excitation signal is of a frequency of 100 kHz and Vp-p amplitude 240 V.

Research carried out by Partipan (2013) into the operating characteristics of battery cells and the work undertaken to design a more efficient power supply culminated with the introduction of a new switch mode power supply and energy pack for the Mk4 consisting of a 4 x 2 cell arrangement measuring 200mm x 60mm x 50mm and weighs just 0.7Kg

Figure 4-32. TeletestFocus™ of Mk4 battery pack.

An injection moulding process was used to manufacture the external casing for the new battery pack. As tolerances for the Mk4 battery casing required tighter control, than previously implemented on the Mk3 battery enclosure, the extra tooling costs associated with hard tooling moulds these increased costs were deemed acceptable as a result of projected usage of battery pack. Figure 4-32 shows a picture of a fully assembly Mk4 battery pack.

4.7 Summary

Enhancements to the electronics are a key way of improving the Teletest LRUT inspection system to achieve gains in both performance and functionality. The work carried out on a design for an improved embedded electronics unit for use in LRUT culminated in the release of a new system branded as TeletestFocus™ Mk4. The new Mk4 system has resulted in an increased implementation of the Teletest system for the LRUT inspection of industrial pipeline, and simplified the operation of the equipment for the end user. New technologies have been incorporated into the design that improve the manufacturing and testing processes, and reduced the overall system cost. The new system has also helped to continue the advances in research and development of new techniques in the field of LRUT.

Previous versions of the Teletest system were reviewed and factors requiring improvement were identified. The previous Teletest system was becoming outdated in terms of component technologies implemented in the design, with the majority of these components now becoming obsolete. This obsolesance in components resulted in higher manufacturing costs due to supply demand. The Mk3 system was also limited in terms of speed of operation by its reduced number of receiver channels and slow data transfers rates. The unit was considered too large and heavy for ease of use in the field. A new system was designed to target these requirements. This involved improvements to the physical configuration of the components and their interconnections. It also involved a redesign of the electronics configuration.

The introduction of a new TeletestFocus™ Mk4 saw a major shift in design strategy and implementation of new technologies. Although the Mk4 still used 24 transmitter circuits, the receiver count were upgraded to 24 independently controlled channels. This allowed for much greater flexibility in system configuration compared to the previous generations of Mk2 and Mk3. Whereas the older generations of Teletest required the operator to collect a data acquisition cycle three times, due to only having eight receivers, the introduction of twenty four meant that a signal data cycle would collect all three rings of data in one iteration. A new advanced user interface was implemented that gave the operator more flexibility in overall system configuration. A new more powerful FPGA was introduced that dramatically enhanced system performance and reduced PCB real estate culminating in a greatly reduced area required for the controlling electronics. This new FPGA also implemented several customs, and pre-configured IP cores, that negated the need to design external devices to carry out functions such as Ethernet communications, DDR2 memory and SPI interfaces. A new DAC was introduced that allowed interpolation techniques to be employed that dramatically reduced the amount of system memory requirements for holding digitized data for reconstructing the required analogue waveforms. Also, this new DAC implemented a serial data interface which required only one input. This resulted in a further reduction of PCB traces required to access all 24 channels which also reduced the space required to accommodate all 24 individual devices for each channel. Another reduction in space required for system components was achieved by using a physically smaller integrated memory device used to for the overall memory configuration for the storage of received data from an acquisition cycle. These new memory IC's were not just smaller is size but contained more storage locations than previously used on each of the older systems reviewed. As a result of using new IC's and design techniques a new set of boards were required. A total redesign of the main controller, receiver and transmitter boards was produced.

The redesign of the electronic unit saw a performance increase in data collection acquisition cycle times, with the results being presented to the operator, of more than 300% compared to the Mk3 unit when executing the same data acquisition configuration. A new custom enclosure was designed that would improve the ascetics of the unit and reduce the overall size and weight of the system to 150 x 322 x 315mm and 7.5kg respectfully. A reduction is size of 46% and a saving in weight of 44% compared to the Mk3.

Chapter 5 Conclusions and Recommendations for Future Work

Inspection systems are important throughout the oil and gas exploration and distribution industry to help find flaws and prevent structural failures in pipeline infrastructures. This is an important factor when considering the economic, environmental and social implications of failing infrastructure in this sector. Using ultrasonic guided waves as a means to inspect structures has become an industry standard over the last decade with advances to equipment and procedures continually being developed. Continuous development of these systems has supported better inspection techniques and facilitated a better understanding of the principals involved when using ultrasonic guided waves as a means of inspection. This research has addressed this by developing a new system that is an improvement over the existing commercial state-of-the-art products. Development of new components used in a LRUT system, conducted during this research, has targeted inspection results, system performance, ease of equipment use, and has also taken into account some commercial considerations, such as, reduced inspection times and reduced system costs, which consequently, has lead to an increased industrial acceptance of the technology.

A review of technical developments in previous systems was conducted and deficiencies in these systems were highlighted and improvements were specified. Two parts of the system, namely the transducers and embedded unit, were evaluated and design changes implemented to create an improved system in terms of speed of operation and functionality. The design of the transducer, used in such a system, was improved for better performance characteristics, easier to manufacture, required less assembly time, had a reduced component count and significantly lowered production costs. A new form of transducer characterisation was introduced that would improve the monitoring of quality and aid future development.

Along with the design of a new transducer, an enhanced embedded control system was also designed and introduced that would have better performance in terms of speed of data collections, is physically smaller in dimensions, lighter in weight, more power efficient and is less expensive to manufacture than the previous generations of LRUT systems.

5.1 Transducer Design

A new ultrasonic transducer was designed to both improve performance and also allow for better manufacturing and characterisation of the finished assembly (as reviewed in Chapter 2)

A reduction in the number of components used in the assembly achieved a reduction in assembly time, improved process control and ultimately better transducer performance. The old design of transducer required eleven different components, the new design reduces this to eight. The previous assembly process required the alignment of two separate components before bonding, the PZT element and alumina face plate. This process was time consuming, introduced misalignment between these two components and required an extra bonding process using a two part adhesive. Inspection on the old design of transducer showed inconsistencies with the bond layer causing air voids to be present, which ultimately resulted in poor performance. This approach was abandoned with the new design as these two parts were now bonded together at the PZT element manufacturing stage by the supplier. This process ensured a uniform bonding layer between these parts and reduced the assembly time for the finished assembly.

In the old design the PZT element was electrically isolated from the stainless steel backing material by the use of alumina guide rails running along the bottom of the alignment slot in the backing block. To overcome this assembly process, the backing block was first sprayed with an alumina coating. The PZT element was then able to be placed directly into the alignment slot in the backing block and fixed using adhesives. This meant that the amount of adhesives used to secure the element to the backing block was reduced with the possibility of causing any air voids significantly reduced. Using this method resulted in less time being required to align the element and the skills required to undertake this task were minimal. A new electrical scheme was introduced that alleviated the need to use any solders in the construction. A new approach was adopted that used a Fuzz button design which took advantage of the force created once the PZT element was bonded into the slot in the backing block and the connecting face of the pressed in MCX connector. This eliminated the requirement for a solder connection between the MXC connector and the PZT element that was previously achieved using a thin 50 micron piece of wire. This concept further reduced assembly times, improved the process control, again reduced the skill levels required to carry out the assembly and meant that a smaller bond line could be achieved between the PZT element and backing block, which is known to improve ultrasonic transducer performance.

5.2 Transducer Characterisation

A new test method (including a new test jig and proprietary software) was developed that would improve the characterization and simplify the testing process (as reviewed in Chapter 3).

The old test setup used a manual method of testing. This involved the use of large heavy weights (10kg) to act as a load force to couple the transducer to the test bar. This method was unsuitable for the operator to use and represented a safety risk. The new test rig used a pneumatic arm that could be lowered, or raised, by the operator before and after each test. Previously, any ultrasonic results obtained during a transducer test, and the transducers capacitance value, had to be manually recorded on paper. The specification and design of new software was introduced that would automatically record these results. The new software would also automatically generate the required digital output values required by the embedded system to instigate tests at the required frequencies. Previously, only one frequency was used to test transducers, however, now with the new software, it is possible and more time efficient to test at all frequencies in the range of 50kHz to 80kHz (as described in section 0). In the old test rig only one frequency was used and this had to be entered manually into the controlling software, which was a potential source for human error. Each set of results obtained after testing of an individual transducer could now be electronically stored and reviewed by the operator, now or in the future. The database this will produce will aid future analysis of transducers to be reviewed and comparisons made with any design changes that may take place. A sample batch of the current design of transducer, alongside a batch of the new design, was characterised. The results showed improvement in the output amplitude typically in the order of 250%.

5.3 Mk4 System development

Alongside the transducer development, a new Teletest embedded electronics unit was also designed and manufactured to compliment the performance improvements obtained with the new transducer. This new design would impropriate new techniques for data handling and new integrated silicon device technologies were introduced to improve the functionality and efficiency of the overall system.

A new high speed FPGA was used to handle all the acquisition cycles and data storage interfaces from the system memory. Peripheral components such as Ethernet, SPI and even the embedded system processor were integrated within this new FPGA. A new design of system SRAM memory using smaller, but greater density devices, helped to reduce the overall board space and reduce power consumption. The use of serial interface ADC's and DAC's allowed for tighter packaging of these components and minimise the required number of PCB traces to bridge data and control lines. The previous generations of embedded units, namely the Mk1, Mk2 and Mk3 all used a common backplane to electrically connect individual electronic sub-assemblies (as reviewed in Chapter 4 P87). A new concept of staking individual sub-assemblies one on top of the other on a horizontal plan was introduced that culminated in a much smaller footprint; this is discussed in Chapter 4 P94. The redesign of the electronic unit, and the introduction of 24 independently selectable receiver channels saw a measured performance increase in data collection of more than 3 times compared to the Mk3 unit when executing the same data acquisition configuration. A new custom enclosure was designed that would improve the ascetics of the unit and reduce the overall size and weight of the system to 150 x 322 x 315mm and 7.5kg respectfully. A reduction is size of 46% and a saving in weight of 44% compared to the Mk3.

These design improvements significantly enhanced data collection and analysis and enables system operators to cover more test locations within a given time period therefore increasing efficiency and reducing costs. As a result of this evaluation a new embedded electronics unit (Mk4) was designed and manufactured. The two new designs covered in this thesis, the transducer and embedded system, are now in production and are commercially available.

5.4 Future work

The results obtained by the new characterisation method indicated that the performance spread of the new transducer was exhibited inconsistency between assemblies. Two areas for future research would include an investigation into the adhesives used during the construction of the transducer

The adhesives used in the present construction, mainly bonding the PZT element to the backing block, were chosen for their ability to remain stable at the required operating temperature specified as 180^{oC} but little research was conducted into their cured hardness, although this information was obtained from their respective data sheets. The adhesive used by PI ceramics to bond the protective alumina face plate to the PZT element was shown to reproduce better output and receive characteristics then the adhesive selected during the early stages of this research. However, the specification for this adhesive was not made available to the author due to intellectual property rights owned by PI ceramics of Germany. Using a denser adhesive could improve some of the inconsistency witnessed during characterisation of the transducer; this could possibly be achieved by missing a tungsten powder, or similar material, to the adhesive before the bonding process.

The PZT element currently designed into the transducer has a dead zone caused by the negative electrode wrapping around one end. This scheme was introduced to allow for matting the electrical contact from the element to the backing block.

Implementing an alternative electrical connection scheme whereby the whole length of the element was active could result in more energy being produced by the transducer, and ultimately giving greater diagnostic lengths when employed in the Teletest system.

Also, evaluation into the characteristics of individual PZT elements before assembling into finished product would benefit future designs. The new transducer characterisation test jig could be adapted to investigate this at a future date.

The new Mk4 electrics unit has been well received within the LRUT industry with over 100 units currently being used in the field. A further expansion of its functionality is currently in development with the ability to link several units together to form a larger transmitter and receiver channel count. This involves using one TeletestFocus™ Mk4 configured as a master that generates the appropriate timing requirement for a data acquisition cycle and then distributing these signals to other units classed as slave units. The work currently being carried out by the author is to design a new FPGA state machine and associated hardware to achieve this new requirement.

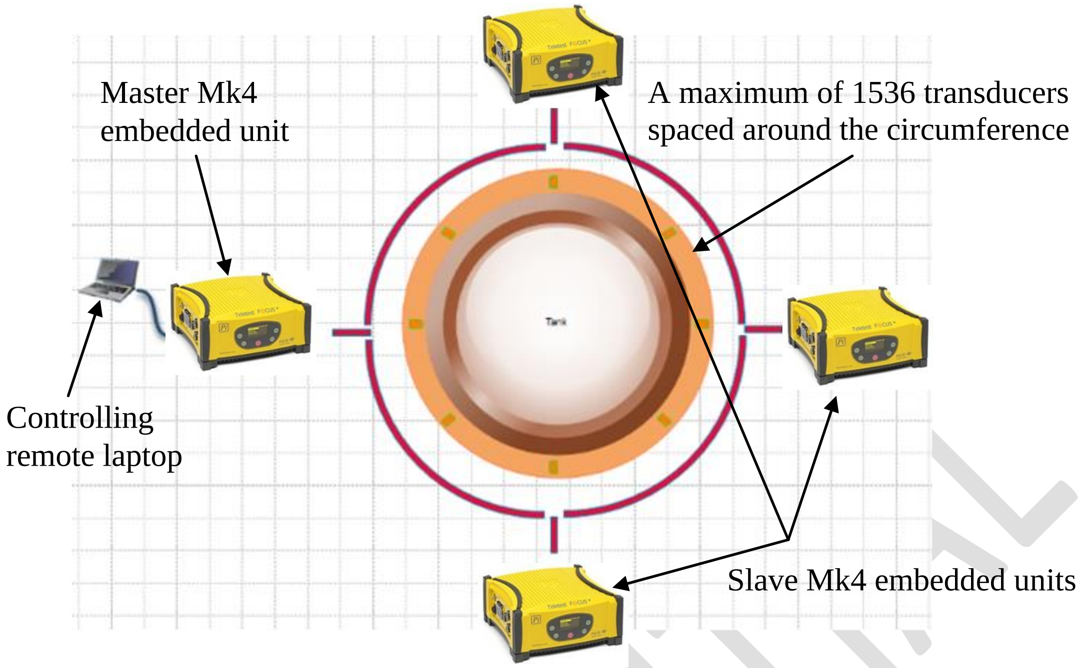


Figure 5-1. Daisy chaining concept using TeletestFocus™ Mk4 units.

Figure 5-1 shows the basic concept that is being adopted to enable more than one signal TeletestFocus™ Mk4 to be used in a configuration. Up to four separate units will have the ability to synchronise as one unit. This will allow for a total of 1536 transducers to be employed on a structure, whereas the current maximum is 384 for a single unit working autonomously.

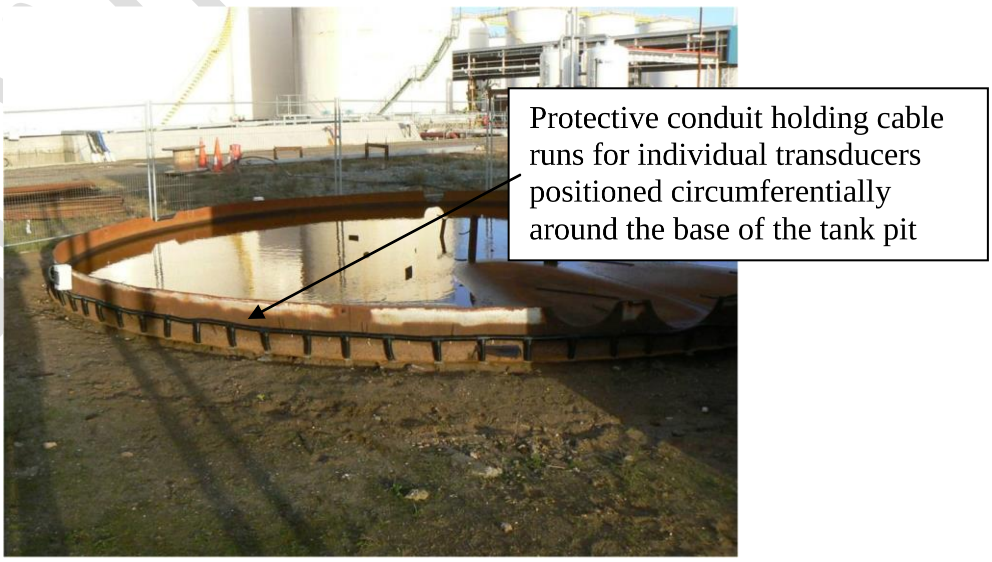


Figure 5-2. Experimental test setup for a tank pit located at Vopak UK using TeletestFocus™ Mk4's in daisy link configuration

Figure 5-2 shows a picture of experimental work currently being carried at Vopak UK on a LRUT inspection of a tank bit. Although the Mk4 units are not shown in this picture the concept is shown in Figure 5-1 where the cable runs for the transducers can clearly be seen.

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