Development of an ultrasonic NDE&T tool for yield detection in steel structures

Yilmaz Bingol

Louisiana State University and Agricultural and Mechanical College, yilmazbingol@yahoo.com

Follow this and additional works at: https://digitalcommons.lsu.edu/gradschool_dissertations

Part of the Civil and Environmental Engineering Commons

Recommended Citation

https://digitalcommons.lsu.edu/gradschool_dissertations/2470

This Dissertation is brought to you for free and open access by the Graduate School at LSU Digital Commons. It has been accepted for inclusion in LSU Doctoral Dissertations by an authorized graduate school editor of LSU Digital Commons. For more information, please contact gradetd@lsu.edu.
DEVELOPMENT OF AN ULTRASONIC NDE&T TOOL FOR YIELD DETECTION IN STEEL STRUCTURES

A Dissertation

Submitted to the Graduate Faculty of the Louisiana State University and Agricultural and Mechanical College in partial fulfillment of the requirements for the degree of Doctor of Philosophy

in

The Department of Civil and Environmental Engineering

by

Yilmaz Bingol
B.S., Yildiz Technical University, 2002
M.S., Istanbul Technical University, 2004
August 2008
DEDICATION

To my mother, Mujgan Bingol
for all of her endless support and self-sacrifice
and

to my father, Yildirim Bingol
for being my inspiration during and after his lifetime
ACKNOWLEDGMENTS

So many special people have contributed to the completion of the most important accomplishment of my educational life and it would not be possible without their help and support. To begin with, I would like to express my deepest appreciation and gratefulness to Dr. Ayman M. Okeil, my advisor. I will always be indebted to him for his guidance, support, patience and his confidence in me since the first day that I have started studying my degree. He has been an inspiration for me through every stage of this research and I have gained a lot from his knowledge and experience. Thank you Dr. Okeil for everything that you have done for me starting from the first day that you have contacted me about my application to LSU.

I also must acknowledge Dr. Hsiao-Chun Wu for helping me throughout my research and guiding me with his superior knowledge of signal processing. I am very grateful to him for introducing me to this complicating field and making it as easy as possible to understand with his patience and expertise.

I would also like to thank my committee members, Dr. George Z. Voyiadjis, Dr. Steve C. Cai and Robert I. Hynes, for their guidance and advice.

I am grateful to all my friends but especially to Erol Karadogan, Merve Tekmen, Cayan Oznel, and Firat Caglar, not only for being great friends, but also for becoming my family in Baton Rouge, thousands of miles away from my family.
TABLE OF CONTENTS

DEDICATION ........................................................................................................... ii

ACKNOWLEDGMENTS .......................................................................................... iii

ABSTRACT .............................................................................................................. vii

CHAPTER 1 - INTRODUCTION .............................................................................. 1
1.1 Background ........................................................................................................ 1
1.2 Nondestructive Evaluation and Testing (NDE&T) ........................................... 3
1.3 Motivation ........................................................................................................... 5
1.4 Scope ................................................................................................................... 6
1.5 Organization of Dissertation ............................................................................. 7

CHAPTER 2 - REVIEW OF THE RELATED LITERATURE ....................................... 9
2.1 Nondestructive Evaluation and Testing ............................................................ 9
   2.1.1 Liquid Penetrant Test (LPT) ........................................................................ 10
   2.1.2 Magnetic Particle Testing (MPT) ................................................................. 11
   2.1.3 Microwave and Ground Penetrating Radar (GPR) ....................................... 12
   2.1.4 Eddy Current Testing (ECT) ...................................................................... 14
   2.1.5 Radiography (X-Ray) ................................................................................ 15
   2.1.6 Impact-Echo Method .................................................................................. 16
   2.1.7 Acoustic Emission (AE) ............................................................................. 17
   2.1.8 Ultrasonic Inspection ................................................................................ 18
2.2 NDE&T in Civil Engineering ................................................................ .......... 21
   2.2.1 NDE&T for Determining Material Properties ............................................ 22
   2.2.2 NDE&T for Damage Detection .................................................................. 24
   2.2.3 NDE&T for Determining the Stress State .................................................. 29
2.3 Digital Signal Processing (DSP) and Its Applications in NDE&T .................... 35

CHAPTER 3 – TESTING SYSTEM, EXPERIMENTAL PROCEDURES AND TEST
DATABASE ............................................................................................................... 41
3.1 Ultrasonic Testing Setup ................................................................................. 41
   3.1.1 Ultrasonic Pulser/Receiver ....................................................................... 41
   3.1.2 Ultrasonic Transducers ............................................................................ 43
   3.1.3 PCI Digitizer Board .................................................................................. 46
   3.1.4 MTS 810 Hydraulic Testing System ......................................................... 47
   3.1.5 Personal Computer .................................................................................. 48
3.2 Experimental Procedure ................................................................................. 50
Appendix B3: Shear Transducer

APPENDIX C – SPECIFICATIONS OF THE ULTRASONIC COUPLANTS
Appendix C1: Brochure of the Ultragel II Couplant
Appendix C2: MSDS of the Ultragel II Couplant
Appendix C3: Brochure of the Shear Gel Couplant
Appendix C4: MSDS of the Shear Gel Couplant

APPENDIX D – TECHNICAL SPECIFICATIONS OF ACQIRIS DP310 PCI DIGITIZER

APPENDIX E – MILL TEST CERTIFICATES (MTC) OF THE TESTED MATERIALS
Appendix E1: MTC of the Type 1 Specimen Material
Appendix E2: MTC of the Type 2 Specimen Material
Appendix E3: MTC of the Type 3 Specimen Material
Appendix E4: MTC of the Type 4 Specimen Material

VITA
ABSTRACT

Nondestructive Evaluation and Testing (NDE&T) is a commonly used and rapidly growing field that offers successful solutions for health assessment of structures. NDE&T methods have gained increasing attention in the last few decades especially with the contribution of the advancements in computer and instrumentation technologies. The applications of numerous NDE&T methods in civil engineering mostly focus on material characterization and defect detection. Techniques for nondestructively identifying the stress state in materials, on the other hand, mostly rely on the Theory of Acoustoelasticity. However, the sensitivity and the accuracy of acoustoelasticity are affected by several factors such as the microstructure of the material, temperature conditions, and the type, propagation and polarization directions of the signals used.

This dissertation presents the results of an experimental study that investigates the changes in the characteristics of ultrasonic signals due to the applied stresses. Using a specially built testing system, ultrasonic signals were acquired from four different groups of steel specimens subjected to uniaxial tension below and above the yield stress of the material. The experimental database was first analyzed in terms of the acoustoelastic theory. Then, well known Digital Signal Processing (DSP) methods were used to calculate a total of seven time and frequency domain characteristics of the first three echoes of the acquired signals. The investigated time domain parameters were the peak positive amplitudes and the signal energies of the echoes, while the peak amplitude of the Fast Fourier and Chirp-Z Transforms, peak and peak-to-peak amplitudes and the root mean square of the Wavelet coefficients were used for the
spectral analyses. Even though the acoustoelastic effects can be very small for certain measurement cases and they can be influenced by several other factors, clear distinctions between prior to and post yielding were observed for all investigated time and frequency domain parameters. The results were further analyzed with statistical methods and Receiver Operating Characteristics (ROC) curves in order to investigate the potential of the presented study for being used as a nondestructive testing tool for yield detection in steel structures.
CHAPTER 1 - INTRODUCTION

1.1 Background

Health monitoring and assessment of the civil infrastructure is essential as it affects the communities that it serves. Infrastructure failures not only impact the quality of life, it may also jeopardize their safety. Hence, identification of structural deficiencies or their indications that may lead to undesirable consequences is of great importance. Such deficiencies include cracks, imperfections, material overstress and more. Conventional methods, such as visual inspection and tap test, have been used for a very long time but most of the structural deficiencies cannot be assessed using these traditional methods. Most such methods are subjective in nature in terms of detection capabilities, and are not scientific. Therefore, numerous advanced techniques have been developed by scientists and researchers for structural health assessment and monitoring in order to reach an acceptable level of accuracy and robustness.

Continuous monitoring of structures is an ideal and a desirable way of assessing the condition of structures through their service lives. Recently, this has been generally achieved by placing monitoring systems into the structures during the construction process. External as well as internal (embedded) gauges, fiber optic sensors, wireless systems are some of the components that constitute a modern monitoring system. With the data coming from inside the structure, these embedded systems provide much more information about a structure’s performance to better understand its durability and remaining life time (Kruger et al. 2005). However, since placement of the monitoring systems is required during the construction phase, these methods
deprive the majority of the existing structures whose safety and reliability need to be evaluated (Chang and Liu 2003).

There are many existing structures (e.g. dams, bridges, schools, hospitals and residential buildings) that have already exceeded or about to exceed their design lives. In addition to the safety issues due to aging, a considerable percentage of existing structures was built before the modern design codes and guidelines (e.g. seismic design codes) addressed the important safety requirements. According to the American Society of Civil Engineers’ Report Card for America’s Infrastructure report (ASCE 2005), 27.1% of the nation’s bridges are structurally deficient or functionally obsolete. Eliminating all bridge deficiencies with a 20 year plan is estimated to cost $9.4 billion a year while the annual cost of improving the transportation infrastructure conditions is $94 billion. The same report states that the estimated budget that is needed to bring the nation’s schools to good condition is as high as $268 billion where the total estimated 5 year investment needed to improve America’s infrastructure in 15 different categories, graded D (poor) in average, is approximately $1.6 trillion.

It is obvious that, the cost of improving infrastructure conditions is in many cases prohibitive. However, even before cost estimation, the condition of these structures needs to be identified so that they can be strengthened and repaired, if necessary, in order to be brought to acceptable levels of safety and reliability. During the assessment process, different problems may arise such as time constraints, budget and prioritization. Hence, the most important factor affecting the whole procedure is the capabilities and reliability of existing structural assessment methods. A very recent incident, the collapse of the I-35W Mississippi Bridge in Minneapolis, MN on August 1, 2007, provides a striking reminder of how an existing structure may be subjected to increasing loads in time and how incomprehensive inspection applications may result in catastrophic events. Therefore, structures with possible safety problems should urgently
be identified as the first step of the rehabilitation process. Secondly, the projects will have to be prioritized based on urgency and availability of funds. Furthermore, quick decisions should be made at this point as time is another important factor in the process. However, all these steps cannot be taken without reliable and robust methods and tools that can be used for structural health assessment.

### 1.2 Nondestructive Evaluation and Testing (NDE&T)

Nondestructive Evaluation and Testing (NDE&T) is a rapidly growing research field that offers solutions for health assessment of structures. In contrast to destructive testing methods, NDE&T techniques are based on examining materials and components without changing or destroying their usefulness. This enables NDE&T methods to be used to test structures while in service. They also overcome classical testing tools and methods as they are less time consuming. For example, the actual compressive strength of concrete in an existing structure is usually determined by testing of drilled cores. This is a time consuming and expensive testing technique since the specimens need to be taken to a laboratory and might also cause damage that weakens the structure since it is a destructive method. The Rebound (Schmidt) Hammer is another widely used testing method for determining elastic material properties of concrete. This method is not destructive and time consuming like the core test. However, the reliability of the results has always been questioned. Moreover, with few exceptions, traditional testing methods (core test, Schmidt Hammer, visual inspection, tap test, etc.) are not always capable of identifying anomalies and detecting defects extensively in existing structures.

These classical testing methods, mentioned above, were easy to conduct in the past, but NDE&T technology has been improving rapidly with the development of new technologies and the adaptation of helpful methods from different disciplines into this field. To be more specific,
advancements in computer technologies and testing devices as well as the adaptation of signal processing techniques have allowed researchers and scientists to develop many new NDE&T methods and applications.

NDE&T in civil engineering applications has been mostly used for applications such as determining material properties (e.g. concrete compressive strength, water-cement ratio, modulus of elasticity, dynamic modulus and Poisson’s ratio), to detecting defects (e.g. cracks/voids), and to locating embedded reinforcing steel. However, even though identification of material properties and damage detection are two essential methods of structural condition assessment, determining the actual stress conditions in an existing structure is another important concept in health monitoring of civil infrastructure.

A common method for determining actual stresses in materials and structures is using strain gauges where the measured deformations can be converted into stresses using identified material properties. The most important drawback of using this method is its inability to determine the existing stress condition prior to the attachment of strain gauges. One of the most well known experimental methods to determine the stress distribution in a material is photoelasticity (Kuske and Robertson 1974). Photoelasticity is based on a polarized light passing through certain types of materials that are optically birefringent. The speed at which each of the waves propagates depends on the level of principal stresses and the resulting phase shift of the light waves is used for measuring the applied stresses in transparent or translucent materials. Similar to photoelasticity, acoustoelasticity is another method widely used for stress measurement in materials. Acoustoelasticity is briefly the dependence of wave velocity on the stress state of the material through which it travels. Unlike photoelasticity, various types of materials (e.g. metals, wood, composites, etc.) can be tested with this technique using the linear relationship between the changes in the wave velocity and the applied strain. However, the
strength and accuracy of this method is directly related with material properties, the type of signals used, and the propagation and polarization direction of the waves. The theory and applications of acoustoelasticity will be covered in detail in the following chapters.

1.3 Motivation

Determination of material properties and detection of defects in structures are the two essential goals of structural health monitoring. However, structures under high risk might not always have material issues or defects, but might be subjected to very high stresses at critical locations due to connection and geometric conditions. High stress levels may cause extensive creep deformations in concrete structures or premature fatigue cracking in steel structures. Critical locations of highly concentrated stresses are generally where the structural defects and damages are initiated. For this reason, identification of distress zones can mitigate these types of damages in existing structures.

The literature review, presented in the second chapter, shows that a majority of the NDE&T studies in civil engineering are based on either determining material properties or detecting defects. Even though detection of defects is an essential aspect of structural health assessment and monitoring, a structure under risk of partial or total collapse might not necessarily be damaged. In such cases, identification and investigation of highly stressed locations becomes the major objective of the assessment process. However, there are only a few studies in the literature that investigated NDE&T for stress measurement in civil engineering and that are promising the development of a tool for identifying distress zones in civil engineering structures. As was mentioned earlier, most of these studies rely on the changes in wave velocity under applied elastic forces in structural materials such as steel, aluminum and wood. In
addition, few available studies that investigated acoustoelastic effects under plastic deformations and stresses are also discussed in the following chapters of this dissertation.

The main goal of this study is to develop an ultrasonic nondestructive evaluation and testing tool for health assessment and monitoring of the civil infrastructure. Similar to health monitoring techniques of human bodies (e.g. radiography, tomography, and stethoscopes), this developed NDE&T tool was planned to be able to listen, see, feel and analyze structures with the same sense. The focus of the presented testing tool and method is to investigate possible highly stressed critical sections in steel structures (e.g. connections and geometric discontinuities) for yield detection.

1.4 Scope

The beginning phase of this study was building of a special testing system. The literature and previous experimental studies were investigated in detail in order to determine the specifications and capabilities of the main units of the system. The components of the specially built testing system and their properties are explained further in detail in Chapter 3 of this dissertation. Using this testing system, plate type, dog-bone shaped Grade 36 steel specimens were tested under uniaxial tensile stresses. The loading was held at various stress levels, and ultrasonic measurements with commercial piezoelectric longitudinal and shear transducers were taken. The test specimens were loaded up to failure and ultrasonic signals were acquired in both the elastic and the plastic stress regions of the material. The digitized ultrasonic signals formed a database to which several analysis methods were applied.

The acquired signals were first analyzed in terms of acoustoelasticity. In addition, the presented study relies on the advancements in Digital Signal Processing (DSP) that are newly being incorporated into NDE&T. In addition to the well known Fast Fourier Transform (FFT),
Chirp-Z Transform (CZT) and Discrete Wavelet Transform (DWT) were used to analyze the ultrasonic signals in the frequency domain. The results for both the investigated time domain and the frequency domain parameters reveal that the wave velocity is not the only property of an ultrasonic signal that changes with the applied stresses. The findings of this dissertation show that the presented study has great potential for being used as an ultrasonic nondestructive testing tool for yield detection in steel structures.

1.5 Organization of Dissertation

The dissertation is organized in six chapters. Chapter 1 begins with an introduction that covers the background, the motivation, and scope of the presented ultrasonic nondestructive testing method. The significance of investigating the stress state of structural members in health assessment process is summarized and the lack of robust and reliable tools that can serve for this field is mentioned.

In the second chapter, most commonly used nondestructive testing methods and their applications are summarized. NDE&T in civil engineering is classified into three groups in this chapter based on its purposes (e.g. material characterization, defect detection and stress measurement) and the related literature for these three groups of nondestructive testing in civil engineering are presented as well as the literature of digital signal processing applications in NDE&T.

Chapter 3 illustrates the specially-built testing system, its main units and their specifications. The test procedures, properties of the materials and specimens, and the obtained test database are also presented in the same chapter.

In Chapter 4, the analysis of the database in light of the Theory of Acoustoelasticity is presented and the relative changes in the wave velocity for longitudinal and shear waves are
compared with each other and the theory. Results are discussed and limitations of acoustoelasticity are identified.

Chapter 5 illustrates the results for the investigated time and frequency domain parameters. The investigated parameters are the positive peak signal amplitude, signal energy, and the peak amplitudes of the Fast Fourier, Chirp-Z and Wavelet spectra. Statistical analysis of the results and further techniques that were used for classification of the data for yield detection are also discussed in Chapter 5.

Chapter 6 provides a summary of the effort, results and conclusions as well as the recommendations for future research. The potential of the presented study as a robust NDE&T tool for yield detection in steel structures is emphasized in this chapter and possible ways to improve capabilities and increase the reliability of the method are also covered.
CHAPTER 2 - REVIEW OF THE RELATED LITERATURE

2.1 Nondestructive Evaluation and Testing

Nondestructive Evaluation and Testing (NDE&T) is an interdisciplinary field that involves all the testing methods and tools that allow inspection of materials without interfering with their usefulness. The field is sometimes referred as Nondestructive Testing (NDT) or Nondestructive Evaluation (NDE). Even though both abbreviations are widely used, the term NDE is often addresses methods that are more quantitative in nature.

NDE&T is an important component of structural health assessment. The capability of testing structures without destroying them helped NDE&T methods gain even more popularity in time. Pipelines, oil platforms, power stations, railroads, aircrafts and infrastructure facilities such as schools and bridges are regularly being inspected by several different NDT methods to ensure their structural integrity. Even though there are several classical NDT methods that have been used for a long time, with the influence of the advancements in other technologies, modern NDE&T techniques are gaining an expanding role in almost all fields and are increasingly replacing classical evaluation and testing methods.

Classical evaluation methods rely on tap test, visual inspection and destructive tests such as concrete core test. The tap test is one of the oldest and most widely used NDT methods. It is based on tapping the inspected material with an object and listening to the changes in generated sounds as indications of flaws. Visual inspection is also another easy and an inexpensive
nondestructive method which usually does not require special equipment. It is generally used to assess the quality condition of the surface a structural component or a weld. Inspectors would be looking for indications of abnormalities such as cracks or dislocations in concrete members which may indicate that the member is overloaded or that a chemical attack (e.g. corrosion) is affecting the member.

Chain dragging is another classical NDT method which is a simple and effective method in detecting delaminations on large surfaces. Similar to the main idea of the tap test, this method is based on dragging a chain across the surface of specimens, such as concrete decks, and listening for significant changes in the tone which are indicators of delaminations. Existing bridge decks have been inspected using this technique and dragging chains across the bridge deck and listening for the lower frequency, hollow-drummy sounds, delaminations were evaluated (Olson 2004). Chain dragging is mature enough that a standard has been developed by the American Society of Testing and Materials (ASTM 2007).

In addition to the classical NDE&T methods, liquid penetrant test, magnetic particle inspection, microwave/ground penetrating radar, eddy current testing, radiography, impact-echo test, acoustic emission and ultrasonic inspection are other NDE&T techniques that are widely being used. These methods are briefly reviewed next.

2.1.1 Liquid Penetrant Test (LPT)

The Liquid Penetrant Test (LPT) is one of the earliest forms of NDT methods. This technique is actually is an extension of visual inspection and is used for detecting surface breaking flaws such as cracks on non-absorbent materials by applying colored penetrants. After surface preparation (cleaning, paint removal, etc.), these colored penetrants are applied to the surface by brushing, dipping or spraying, and the excess penetrant is cleaned after enough time for the liquid to
penetrate into cracks by capillary action. Then an absorbent developer, such as white dry powder, is applied to the cleaned surface. The developer draws the colored penetrant liquid out by reverse capillary action. The stain that remains on the developer due to the colored penetrant can then be seen by visual inspection as an indication of cracks. Florescent penetrants can be used for higher sensitivity; however, the surface requires to be viewed with ultraviolet (UV) light under darkened conditions.

Liquid penetrant inspection is a cheap, fast and a relatively simple surface inspection testing method. Therefore, it is very useful for many different fields such as aerospace and automotive industries for detecting fatigue cracks in welded steel structures and surfaces. Metals, glass, ceramics and plastics are materials that are commonly inspected using LPT. Extremely small defects that cannot be seen by visual inspection can be inspected with this method but on the other hand, LPT has important drawbacks such as being capable of only detecting surface breaking flaws and requiring surface preparation.

### 2.1.2 Magnetic Particle Testing (MPT)

The Magnetic Particle Testing (MPT) method is another NDE&T method which is used for detecting surface and near surface flaws of ferromagnetic materials such as steel and iron. The magnetic particle inspection method, along with liquid penetration inspection, is one of the oldest and most commonly used NDT methods currently in use today. This technique is based on using magnetic fields and fine magnetic particles, such as iron filings to detect flaws in components. The ferromagnetic material to be tested is first magnetized using an external magnetic field. When there is a crack close to or on the surface, magnetic poles are created at the edges of the crack. The air gap due to the crack cannot support as much magnetic field as the material, and therefore, the magnetic field spreads out (flux leakage). After magnetization,
similar to the purpose of the penetrant in LPT, magnetic particles are sprinkled on the surface. These particles are usually in dry or wet suspended form and they can either be a visible type that can be seen in normal white light, or a fluorescent type which requires the use of a black light to be visible. After gently cleaning the excess particles, the ones that are attracted at the flux leakage fields are used as the indications of flaws. The above process and how cracks cause flux leakage is illustrated in Figure 1.

![Figure 1: Effect of flux leakage in magnetic particle testing](image)

Magnetic particle method is being used in many different fields such as automotive, petrochemical, structural steel, power generation and aerospace industry. Underwater inspection is another area where magnetic particle inspection can be used to test offshore structures and underwater pipelines. Even though it is an easy, portable and a cost effective method, it can only be used for testing of ferromagnetic materials.

### 2.1.3 Microwave and Ground Penetrating Radar (GPR)

Microwave inspection techniques involve the propagation of electromagnetic waves from antennas at frequencies varying between 0.3 and 300 GHz in dielectric materials. Ground Penetrating Radar (GPR) is a reflected wave technique that employs a single
transmitting/receiving antenna (Chang and Liu 2003), and it uses electromagnetic radiation in the microwave band. Microwave inspection and GPR can be used for determining material properties, components of mixtures, and for detecting delaminations and voids in materials. The polarizability of microwave signals also allows this technique to be capable of giving information of cut or broken fibers inside a composite member. GPR is widely used for locating reinforcement bars in concrete, buried archeological structures, pipelines, sinkholes and landmines.

For material characterization, Mubarak et al. (2001) investigated utilizing microwaves for determining the water to cement ratio of fresh Portland cement based materials. Magnitude of reflection coefficient of a monopole antenna probe immersed in the materials was used in this study, and the method was proven to be a successful nondestructive method for quick and inexpensive determination of water to cement ratio in fresh Portland cement based materials. In a similar study, Bois et al. (2000) studied the statistical distributions of near-field microwave reflection property measurement of concrete with different mixtures and it was shown that, the coarse aggregate to cement ratio and water to cement ratio were correlated with statistical properties of well known Gaussian and uniform distributions. Al-Mattarneh et al. (2001) also conducted a study to apply microwave technique for determination of material properties of concrete. The effect of reflection coefficients on the water-to-cement ratio and the compressive strength of concrete were studied. In addition to its use for determining material properties, it can be found in the literature that, GPR was also used for identification of reinforcement locations and detection of voids in concrete structures (Maierhofer 2003; Shaw et al. 2005). Figure 2 illustrates the application of GPR surface scan for locating reinforcing bars in concrete structures and how the wave reflections indicate the locations of the bars.
2.1.4 Eddy Current Testing (ECT)

Eddy Current Testing (ECT) is an electromagnetic NDT technique where an electromagnetic probe is slid over a conductive object (Fiori and Burrascano 2001). Based on the principles of Faraday’s discovery of electromagnetism and electromagnetic induction, when the exciter coil (probe) is brought near the surface of a conductive component, it causes a magnetic field which induces circulating electric currents (eddy currents) in the component under inspection. These eddy currents are affected by some physical properties of the specimen such as thickness, presence of defects, surface profile and roughness, magnetic permeability and electrical conductivity.

The ECT method is extensively used in automotive, marine and aerospace industries for defect and corrosion detection, material sorting, thickness and displacement measurements, weld detection, conductivity and permeability measurements and hardness assessments. However, this
method can only be used for the inspection of conductive materials and it can only detect surface and near surface defects.

### 2.1.5 Radiography (X-Ray)

The use of radiography started with the invention of X-rays by Roentgen and gained quick popularity especially in medical applications. In addition to its current use for security systems (e.g. airport-luggage examinations), engineers also use both the conventional (film based) and computed radiography as an effective NDT method. X-rays and gamma rays are placed close to the materials and they are captured on films or scanned and stored as images by computers after passing through the materials for further investigation of the shadowy figures on the film or the digital image. Radiography is being used as an NDT technique in various fields such as aerospace, automotive, offshore and steel industries.

Niemann et al. (2002) studied X-ray back scatter technology (XBT) for the detection of buried landmines. A mobile X-ray scanner system was used to detect personal, anti-tank, inert and TNT-filled mines. It was concluded that XBT can be used for imaging buried land mines and it can also reveal a broad range of details inside mines. Theis and Kahrs (2002) described the structure, software setup, inspection procedure and advantages of fully automatic X-ray inspection systems for aluminum wheels. A commercial X-ray system with automatic inspection image processing was used to prove that the technique is an economic and a reliable method which can be used in the automotive industry.

Radiography has shown great progress in time and digital images have started being used instead of films. However, the testing tools are still not portable for every application and the safety of the personnel is an important issue in radiography testing.
2.1.6 Impact-Echo Method

The Impact-Echo method is a stress wave method for flaw detection in structural components which is based on monitoring the surface motion resulting from a short-duration mechanical impact (Carino 2001). The basic principle of impact-echo technique is introducing a stress pulse into the structure using an impact source such as a hammer or a ball drop. The impact generated stress waves travel between the surface and the defects that may exist in the structure and the reflected waves are monitored by transducers to detect the delaminations (Figure 3).

**Figure 3:** The impact echo method: mechanical impact is used to generate stress waves and a receiver next to the impact point measures the resulting surface motion (Carino 2001).

One of the several applications of the impact-echo method was to locate flaws within hardened concrete (Carino et al. 1986). Concrete slabs with known internal flaws were used in this experimental study to prove the reliability of the technique. Steel balls, with different diameters were dropped as a point source and a displacement transducer with a small contact area as a point receiver. It was concluded that, with further improvement in the instrumentation, this method can become a reliable nondestructive testing (NDT) technique for detecting flaws and discontinuities within hardened concrete.
Lin and Sansalone (1992) were the first researchers who applied the impact-echo method to nondestructive evaluation of reinforced concrete beams and columns. Different kinds of known delaminations such as voids, cracks and honeycombs were evaluated using a test system, which was composed of impactors, receiving transducer and a portable computer with a data acquisition card. Frequency-amplitude spectrums of columns with circular and square sections and beams/columns with rectangular sections were studied to prove the feasibility of impact-echo method and it was concluded that this method can be used successfully to detect flaws in beams and columns. In addition to the research projects above, impact-echo method was also used for damage assessment of concrete bridge decks and for monitoring the thickness of concrete slabs (Nazarian et al. 1997; Sansalone and Carino 1989; Tawhed and Gassman 2002).

2.1.7 Acoustic Emission (AE)

Acoustic Emission (AE) testing is based on listening to the sounds, which cannot be usually heard by human ear, to evaluate the state of health of a material or a structure in use. Unlike other NDT techniques where a source of energy is supplied to the tested object, in AE testing, the source of the signal is the tested material itself. Therefore, the AE tests are conducted while the material is under loading in order to listen to sounds generated by initiating or growing defects.

The method involves using ultrasonic microphones to detect flaws, cracks or imperfections. One of the advantages compared to other techniques is the recording of the damage process during the entire load history without any disturbance to the specimen (Grosse et al. 2003). However, testing environments are usually very noisy and therefore, acoustic emission signals are usually weak where noise reduction is very difficult. AE method is being used in wide range of applications including locating corrosion processes, monitoring welding...
applications and detecting damages in numerous structural systems (e.g. bridges, pipelines, storage tanks and off-shore platforms).

Li et al. (1998) performed AE monitoring on rebar corrosions in HCl solution and in reinforced concrete specimens by using the rebar as a waveguide. It was shown that there is a close relationship between corrosion rate and AE rate. It was also verified by the experiments that the AE technique can provide the true locations of rebar corrosion in concrete.

Hearn and Shield (1997) also studied the acoustic emission monitoring technique for detecting the crack initiation and propagation on cyclically loaded concrete beams. AE transducers, pre-amplifiers and an AE signal monitor were used to monitor crack initiation and propagation in three reinforced and two pre-stressed concrete beams. The experimental results were compared with visual observations. It was indicated that the observed formation or propagation of cracks in concrete was preceded by a significant increase in AE activity rate and it was shown that AE monitoring is a reliable method of determining active crack growth in reinforced concrete structures.

2.1.8 Ultrasonic Inspection

Ultrasonic inspection is a widely used NDE&T method which is based on high frequency ultrasound; i.e. sounds that cannot be detected by human ear. Typical ultrasonic testing inspection systems consist of a pulser/receiver, transducers and display devices. Although ultrasonic NDT is usually known for its applications to evaluate thickness, high frequency sound waves are being used to quantify some basic mechanical and structural properties of solids and liquids. Ultrasonic testing can also be used for flaw detection/evaluation, dimensional measurements and corrosion detection. With conventional piezoelectric transducers, high voltage electrical pulse produced by the pulser/receiver is converted to ultrasonic energy, which
propagates through the tested materials in terms of sound waves. If there is a discontinuity in the wave path, such as cracks and flaws, some part of the energy is reflected back and this reflected wave signal is transformed back into electrical signal by the transducer and displayed on the system screen. This basic procedure is shown in Figure 4. Ultrasonic inspection is being used in many fields like aerospace, automotive, medical, chemical, petro-chemical, engineering and offshore industries. This technique is an essential method in civil engineering research field. Numerous successful applications of ultrasonic NDE&T in civil engineering studying structural materials can be found in the literature.

![Figure 4: Principle of ultrasonic testing for detection of flaws/cracks.](image)

Yeh and Cheng (2003) studied ultrasonic nondestructive evaluation in order to develop a damage mechanics model for metals. Their proposed model accounts for stiffness degradation and damage evaluation of a metal medium with a measurement of ultrasonic velocity. A finite element simulation, that can describe the damage process, was developed and good agreement
was obtained from the comparisons of numerical and experimental results. Using the numerical data bank, it was demonstrated that the damage state can be obtained only using the ultrasonic velocity. McNamara et al. (2004) also studied ultrasonic guided waves to detect damage in railroad rails.

Ultrasonic NDE&T methods have been applied to concrete structures for various purposes such as thickness measurement, assessment of material properties (e.g. compressive strength, water to cement ratio, elastic moduli, etc.), evaluation of corrosion state and location of reinforcement and damage (cracks, micro-cracks, honeycomb and voids) detection (Shickert 2002). Toutanji (2000) studied ultrasonic signals propagating through different kinds of anomalies in concrete bridge decks. Twelve different specimens with varying crack types and sizes were tested by a test device which generates ultrasonic pulses and measures the time taken to pass from one transducer to the other. These signals were recorded by a personal computer, which is connected to the ultrasonic test system, to obtain the frequency spectra using Fast Fourier Transform (FFT) technique. Based on the comparisons of time and frequency domain waveform signals, it was concluded that ultrasonic pulse velocity technique can be used to provide information about the internal conditions of concrete bridge decks and to estimate crack sizes in structural members. In a similar study, feasibility of detecting internal defects in reinforced concrete beams using ultrasonic guided waves was investigated (Jung et al. 2002). The proposed technique was successful in defect detection in reinforced concrete beams with having no previous knowledge about the reinforcement locations.

In addition to its applications in damage detection, ultrasonic NDT methods were used by many researchers for determining material properties of concrete. Voigt et al. (2003) used ultrasonic wave reflections to determine the strength of early age mortar and concrete. Three different batches of concrete and mortar tested using a steel plate between the cementitious
material and the transducer to measure wave reflections (Figure 5a). These reflections were obtained in the time domain and then transformed into frequency domain using FFT algorithm (Figure 5b). According to the reflection loss–compressive strength relationship it was concluded that the loss in reflection is linearly related to the strength gain of mortar and concrete at early ages. Based on a similar approach, Akkaya et al. (2003) proposed a technique for predicting the concrete strength at early ages using ultrasonic wave reflection loss.

![Figure 5:](image)

**Figure 5:** (a) Schematic representation of the multiple reflection and transmission of ultrasonic waves at the steel-concrete interface and (b) time and frequency domain (FFT) graphs of reflected waves (Voigt et al. 2003).

### 2.2 NDE&T in Civil Engineering

NDE&T has gained a lot of attention from both researchers and practitioners in the civil engineering field in the last few decades. It is a reliable method for assessing the condition and monitoring the safety of civil engineering structures. Nondestructive evaluation is much more convenient and cost effective compared to destructive test methods. Furthermore, the recent advancements in other fields (e.g. electrical engineering, computer technologies) enhanced the capabilities of nondestructive testing methods and tools for civil engineering applications. Research and applications of NDE&T in civil engineering can be classified into three main
groups: (i) methods for determining material properties, (ii) methods for detecting damage in structures and (iii) methods for determining the stress state of materials. Previous studies related to these three areas of primary focus of NDE&T in civil engineering are presented next.

2.2.1 NDE&T for Determining Material Properties

Nondestructive testing methods in civil engineering mostly focus on concrete in terms of determining material properties. One of the studies in which NDE&T was used to determine long term material properties of concrete was presented by Anderson and Seals (1981). In order to predict the 28 and 90-day compressive strength of concrete they used 1 and 2-day pulse velocity. In the first experimental phase, six different mixtures were tested to establish the feasibility of using pulse velocity and resonant frequency to predict long term strength and to select a combination of procedures for the next phase. In the second experimental phase, six mixtures for four different aggregate combinations were tested using commercially available equipment. The effect of compositional variables, such as cement factor, water-cement ratio, air content and curing, were studied in this phase using pulse velocity and compressive strength. According to the results of these two sets of experiments, it was suggested that compositional variables must be taken into consideration for excellent prediction of 28 and 90-day compressive strength of concrete.

Other researchers also studied the compressive strength of early age mortar and concrete using NDE&T methods (Voigt et al. 2003). Three different batches of concrete and mortar tested using a steel plate between the cementitious material and the transducer to measure wave reflections. FFT algorithm was used to transform these time domain reflections into frequency domain. From the reflection loss – compressive strength relationship, it was concluded that the loss in reflection is linearly related to the strength gain of mortar and concrete at early ages.
Pascale et al. (2003) also used various nondestructive and destructive methods to assess the actual compressive strength of different concrete mixtures, with cube strength varying from 30 to 150 MPa. Analytical relationships were derived between estimated cube strength of concrete and results for pulse velocity, rebound hammer, pull-out, probe penetration, microcoring and combined methods (Figure 6). It was stated that the sensitivity of all non-destructive testing methods decreases with increasing strength levels. Other researchers also used different nondestructive methods (ultrasonic testing, sclerometric methods and pull-out method) to assess the compressive strength of concrete, varying between 24 and 105MPa, with the contribution of artificial neural networks (Hola and Schabowicz 2005; Schabowicz 2005).

**Figure 6:** Cube compressive strength versus (a) pulse velocity (b) rebound index and (c) pull out pressure (Pascale et al. 2003).
The dynamic modulus is another parameter that can be determined by NDE&T methods. Dropping small steel balls, Leming et al. (1998) obtained fundamental frequencies of concrete disks using an accelerometer and a data acquisition system. The output signal was analyzed with the Fast Fourier Transform (FFT) in order to obtain the fundamental frequency. The method was first used on steel and aluminum disks to ensure the accuracy of the technique and then, concrete disks and prisms were tested. It was concluded that this method can be used to determine the dynamic modulus of thin disks made of concrete, steel and aluminum. Microwave NDE&T methods were also used by several researchers in order to determine other parameters that affect the compressive strength of concrete such as the aggregate content and the water-to-cement ratio (Al-Mattarneh et al. 2001; Bois et al. 2000; Mubarak et al. 2001).

Nazarian et al. (1997) designed an ultrasonic instrument, which they named Lunch Box (Figure 7), to determine the thickness and quality (Young’s and shear moduli) of concrete slabs. Ultrasonic surface and body wave velocities were used to assess the quality and impact echo tests were conducted to determine the thickness. Using old and new Portland cement concrete slabs in experiments, it was concluded that the Lunch Box is useful for evaluating Portland cement concrete slabs and can easily collect data which is required for evaluating the quality and thickness of slabs.

2.2.2 NDE&T for Damage Detection

In addition to the NDE&T methods that are capable of determining material properties, there are many successful studies in the literature that focused on evaluating the damages in structures and materials. The Impact-Echo method has been one of the most effective NTE&T methods in damage detection of concrete structures. Carino et al. (1986) tested concrete slabs with known internal flaws, created by embedded polyurethane foam disks (Figure 8a) using a point source--
point receiver (Figure 8b) to locate flaws within hardened concrete. Steel balls, with diameters ranging from 4.0 to 9.9mm, were dropped as a point source and a displacement transducer with a small contact area as a point receiver. It was concluded that, with further improvement in the instrumentation, this method can become a reliable NDT technique for detecting flaws and discontinuities within hardened concrete.

Similarly, Sansalone and Carino (1989) used the impact-echo method for detecting delaminations in reinforced concrete slabs with and without overlays. In one of two laboratory studies, reinforced concrete slabs with unknown artificial delaminations were tested and, the locations and dimensions of simulated delaminations were detected. The second study involved testing of two reinforced concrete slabs with corrosion-induced delaminations before and after overlays. It was shown that the impact-echo method can successfully locate the delaminations in the slabs through the asphalt concrete overlays.

Figure 7: Picture of the Lunch Box developed by Nazarian et al. (1997).
In another study, the impact-echo method was used to assess damage in concrete bridge decks by Tawhed and Gassman (2002). Two slabs, removed from a maintenance bridge after suffering damage during service lives, were nondestructively evaluated in the laboratory with full scale static and dynamic load tests. The first slab was statically loaded to failure and the second one was tested in dynamic cyclic loading. Impact-echo tests were performed before, between, and after loading sequences. The proposed approach allowed for an earlier detection of damage than what was observed by visual inspection. Other researchers also used the impact echo method to evaluate different kinds of delaminations in reinforced concrete beams and columns (Lin and Sansalone 1992).

Ultrasonic testing methods are also being used for defect detection purposes in civil engineering. Sakata and Ohtsu (1995) studied ultrasonic spectroscopy as a nondestructive evaluation method in order to estimate crack depth in concrete members. Eight different mixtures were used to produce plain concrete specimens and artificial cracks were introduced by a diamond cutter. Spectral responses of sinusoidal waves were measured by attaching a transmitter.

Figure 8: (a) Plan and elevation view of concrete slab with embedded polyurethane disks and (b) schematic view of experimental test configuration of Carino et al. (1986).
and a receiver to the same surface of a specimen. The experimental results were compared with analytical results of two-dimensional resonance analysis by the boundary element method and it was concluded that the presented method can be used to estimate bending crack depths in plain and reinforced concrete members.

Jung et al. (2002) investigated the feasibility of using ultrasonic guided waves in order to detect internal defects (cracks, honeycombs and inclusions) in reinforced concrete beams. Full-scale reinforced concrete beam specimens were fabricated with honeycombs and artificial cracks at known locations. A data acquisition board was used to collect the signals and those signals were transformed into voltage amplitude-frequency curves. It was concluded that this technique can be used to detect defects in reinforced concrete beams without complex arrangement of sensors and without having knowledge about the reinforcement locations.

A self-compensating technique for sensitive detection and sizing of surface-breaking cracks in concrete structures was introduced by Popovics et al. (2000). Concrete specimens were prepared using different mixtures and controlled cracks were generated by a closed-loop loading scheme. The experimental setup that was used for the self-compensating wave transmission measurements is shown in Figure 9. According to the results of tested concrete specimens having notches, cracks and notch-initiated cracks, it was observed that absolute values of signal transmission show sensitivity to discontinuity depth in concrete regardless of whether the discontinuity is a notch or a crack. The proposed self-compensating measurements proved to demonstrate excellent potential for practical nondestructive detection and sizing of cracks in concrete members.

In addition to the aforementioned nondestructive methods that focus on damage detection in concrete numerous nondestructive testing studies can be found in the literature for damage assessment of prestressing tendons and reinforcement bars in concrete. Beard et al. (2003)
studied the effect of energy leakage of waves and defect geometry on the maximum inspection range of post-tensioning tendons. The experiments were based on guided waves excited at the free end of the tendon and the waves reflected from breaks or major defects were studied in order to determine the maximum possible inspection range for tendons of different diameters. Figure 10 illustrates the experimental configuration of the pulse-echo test used in this study.

Figure 9: Experimental setup for the self-compensating measurement of Popovics et al. (2000).

Investigation of the corrosion state of rebars in concrete with NDE&T methods was another area of interest for researchers and civil engineers. Monteiro et al. (1998) studied an electrical nondestructive testing method to locate the reinforcing bars and to determine their corrosion state without the need to remove the concrete cover. A multi-electrode electrical resistivity array was used to measure the complex impedance along the surface of the concrete specimen which was fabricated using four embedded reinforcing bars, each with a different surface preparation to simulate a variety of corrosion states. It was presented that the proposed method can be used as a surface-based nondestructive technique to estimate the corrosion state of reinforcing bars in concrete.
Acoustic emission is another NDT method that was used by several researchers for detection of damage in concrete and examination of the corrosion state of rebars (Hearn and Shield 1997; Li et al. 1998). Recently, radiography, microwave and electromagnetic radar NDT methods are also being used for studying concrete and the damages and debonding issues of fiber reinforced polymer (FRP) wrapped concrete (Vossoughi et al. 2007; Yu and Buyukozturk 2008; Feng et al. 2002).

2.2.3 NDE&T for Determining the Stress State

Even though the majority of the available NDT applications focus on determining material properties and detecting defects, investigation of the stress state of materials and structures has been another important concept in nondestructive health assessment. High stress levels in materials may lead to extensive creep deformations or premature fatigue cracking. These critical stresses are mostly caused by the applied stresses, residual stresses or a combination of both.

Applied stresses are the stresses that occur due to external loading or forces. Residual stresses, on the other hand, are stresses that exist in materials when no external forces are acting upon them and they are free from restraint. Main causes of residual stresses are processes (e.g.

Figure 10: Pulse-echo test configuration for the inspection of post-tensioning tendons using guided waves (Beard et al. 2003).
thermal expansion/contraction, diffusion, phase changes) and treatments (e.g. rolling, forging, drawing, etc.). Residual stresses are free from restraint and therefore, they do not necessarily maintain the equilibrium equations and they are unknown and uncontrollable (Ruud 1982). Residual stresses can be as high as the material’s yield strength and just like applied stresses, the residual stresses add directly to the stress state of the component (Chance and Bray 2001). The contribution of residual stresses to premature failure of metallic structures has long been recognized (Ruud 1982). High tensile residual stresses are generated in the heat affected zones due to welding and when applied stresses are added. These locations in structures become potential sites for crack initiation and propagation (Belassel et al. 2001). For this reason, measurement of applied residual stresses has been a main area of interest in NDE&T research studies. Stresses in materials cannot be directly measured by NDE&T methods but instead, the stress is related to the measure of secondary quantity such as elastic strain, speed of sound and magnetic signature that is directly dependent on the stress level (Withers et al. 2008).

X-Ray and neutron diffraction methods are commonly used NDT methods for stress measurement. They are based on the same principle where the changes between the interatomic planes due to stresses are measured with diffractometers. X-Rays however, have a very low depth of penetration in metals which allows the measurement of stresses in subsurface zone of about ten micrometers depth only (Walaszek et al. 2001). Therefore this method is generally used for surface and weld detections in nuclear and aerospace industries. Even though neutrons have a higher penetration power up to few centimeters (Pearce and Linton 2006; Roy et al. 2003), neutron diffraction tests need to be carried out at specialized nuclear reactor facilities, and the overall size of the components that can be tested is limited (Matzkanin and Yolken 2001) and therefore these methods are not commonly used in civil engineering applications.
Electromagnetic techniques are also being used for stress measurements by relating one or more of the magnetic properties of a material (permeability, Magnetostriiction, hysteresis, coercive force or magnetic domain wall motion during magnetization) with stress (Matzkanin and Yolken 2001). Such magnetic properties are especially affected by residual stresses (Lo et al. 2004). The most commonly electromagnetic stress measurement technique is the Barkhausen noise analysis. In this technique the reorientations of the magnetic domains of a ferromagnetic material are used. In ferromagnetic materials, Barkhausen noise signals are generated by the changes in the magnetization caused by the movement of the magnetic domain walls. The discontinuous movement of the magnetic domain walls induces a noise-like signal to a search coil and this signal is called Barkhausen noise (Lindgren and Lepisto 2004). Even though electromagnetic methods are not widely being used in civil engineering, they are being used for stress measurement of different components such as helicopter rotor blades, gas tribune engines, autofrettage gun tubes, steel suspension springs, railroad car axles, engine cylinder heads, etc.

Ultrasonic inspection, if not the only, is the most commonly used NDE&T method for stress measurement in civil engineering applications. Ultrasonic methods overcome the stress measurement techniques mentioned above having almost no restriction for the material to be tested, offering very portable in-situ testing solutions and allowing engineers to make deep stress measurements with very high signal penetration strength. Ultrasonic stress measurements methods rely on the changes in the wave velocity due to applied stresses. This phenomenon is known as the acoustoelastic effect. The linear dependencies of the wave velocity on the stress state have been studied for various stress measurement applications in civil engineering.

Steel prestressing tendons and bars have been studied by several researchers for stress measurement using ultrasonic NDT techniques. Di Scalea et al. (2003) used specially designed and constructed magnetostrictive transducers (Figure 11) in order to measure the tensile stresses.
in seven-wire helical steel strands that are widely used as load-carrying members in structures such as prestressed concrete structures, cable-stayed and suspension bridges. They have studied the geometrical and mechanical properties of helical wires in terms of acoustoelastic theory and recorded the changes in the wave velocities as a function of stress by measuring the arrival time delays of the signals. Even anomalous behavior of the strand at low stress levels (below 20% of the ultimate strength) was observed, it was concluded that the mismatch between the experimental and theoretical predictions are reduced at higher stress levels (above 48% of the ultimate strength). Similarly, Chen and Wissawapaisal (2001) studied the increasing time shift as a tensile stress prediction method in seven-wire steel strands. Based on the experimental and analytical results, it was indicated that the travelling time of the waves propagating inside the center wire of a seven-wire prestressing strand can be related to the applied stress level. Using the same approach, the stress state of prestressed bars was also studied by researchers (Chen and He 1992).

**Figure 11:** Test setup of magnetostrictive transducers for acoustoelastic measurement of wires; R=receiver, T=transmitter, D=transmitter-receiver distance (Di Scalea et al. 2003).
Bending stresses were also studied by researchers using the acoustoelastic phenomenon. Si-Chaib et al. (2001) used the variation of propagation velocities of the longitudinal and transversal polarized waves as a function of bending stresses applied on steel samples. Ultrasonic wave velocity measurements were taken at fibers that are subjected to tension and compression as well as the neutral fiber (i.e. the fiber on the neutral axis). The relative changes of wave velocities of longitudinal and shear waves with respect to the applied bending force and the potential of the presented method for evaluating acoustic properties of an elastically deformed homogeneous medium under bending is discussed. Sasaki et al. (2001) used the same approach for acoustoelastic stress measurement of wood in bending. They have studied longitudinal and shear wave velocities at different levels along the height of the specimen. Strain gauges were also placed on the specimen in order to measure the applied bending stresses more accurately. Even though the changes in the speed of ultrasonic waves were little, it was shown that the bending stresses obtained by the acoustoelastic technique agreed well with those obtained by numerical calculations and strain gauge readings. The acoustoelastic effect on shear waves propagating in wood was investigated in several studies (Hasegawa and Sasaki 2004a; Hasegawa and Sasaki 2004b; Hasegawa and Sasaki 2004c).

Instead of measuring the average stresses across the thickness of a material, the use of critically refracted waves (L_{CR}) was studied by researchers to be able to measure the effect of stresses near the surface (where the transducers are placed) only. In a typical L_{CR} test configuration, the incident longitudinal wave propagates through an angled wedge material (e.g. Plexiglas) then hits the boundary of the wedge and the tested material with a critical angle. This critical angle of the wedge is determined using the well known Snell’s law and the wedges of the transmitter and the receiver transducers are usually connected to each other with a space bar to maintain a known constant distance between the transducers constant. The critically refracted
longitudinal wave travels beneath the surface and provides higher acoustoelastic sensitivity than the longitudinal and shear waves that propagate along the thickness of the material. A simple illustration of an $L_{CR}$ test configuration is shown in Figure 12.

Santos and Bray (2000) used a computer based commercial equipment to study critically refracted longitudinal waves for stress measurement of thin bars. The results for the $L_{CR}$ measurements and placed strain gauges are compared and the method was concluded to be a solution for determining the magnitude of stresses in thin bars with an acceptable level of error. Similarly, Bray and Tang (2001) also investigated the use of the relative change in the travel time of the critically refracted waves for stress evaluation in steel plates and bars.

Acoustoelasticity was not only used for measuring stresses at certain locations or sections of materials, but also for scanning surfaces to come up with applied stress contour plots. Kino et al. (1979) measured the travel times of longitudinal waves through stressed aluminum panels. The panels with notches and holes were tested under uniaxial tension and the surfaces were scanned at a known applied stress level. The stress field obtained using acoustoelastic
measurements was compared with the theoretical one and the method is concluded to provide precise results for stress field imaging.

It can be seen from the related literature mentioned above that all of the nondestructive stress measurement methods rely on the theory of acoustoelasticity. It can also be noticed that the majority of these research studies were conducted in the last decade and even though they have promising results, researchers are continuously working on improving these techniques. There are still several important issues about the use of this method that need to be resolved for more reliable and accurate results. The effect of the type of signal used (e.g. longitudinal, shear, etc.), the propagation direction of the waves as well as the polarization direction for shear waves, the effect of temperature, acoustic changes under plastic deformations and the acoustoelastic nonlinearity can be counted as some of the most important challenges that researchers are working on overcoming. The acoustoelastic phenomenon will be covered in detail in Chapter 4 of this dissertation and the issues as well as the sources of errors in acoustoelastic stress measurement will be addressed.

2.3 Digital Signal Processing (DSP) and Its Applications in NDE&T

As the term suggests, Digital Signal Processing (DSP) is the science of processing signals by digital means. Most signals such as sound waves, visual images, vibrations etc., are generated by natural means. However, it is also possible to generate a signal synthetically, by using computers or other electronic devices. Digital signal processing includes all the techniques, mathematics and algorithms that are used to manipulate these signals after they are converted into digital form from analog form. The field of DSP has experienced rapid development during the past decades; on both the research and application fronts.
The history of DSP begins with the availability of and access to digital computers during 1960s. Radio detection and ranging (Radar), sound navigation and ranging (Sonar), oil and space exploration and medical imaging were the first areas in which DSP was being used until the invention of personal computers. During the 1980s and 1990s DSP became one of the most popular technologies in the commercial marketplace. Nowadays, it is used in a wide range of fields that affect the lives of most people with commercial products such as cell phones, multimedia PCs, modems and CD players. Now in the 21st century, DSP is being used by engineers and scientists for various goals such as telecommunication, speech generation and recognition, radar & sonar, image processing, oil and mineral prospecting, medical imaging and analysis, data acquisition and nondestructive testing and evaluation.

DSP has been playing an important role in nondestructive evaluation and testing since new methods were adapted to this field successfully. Many researchers developed reliable NDE&T tools that are incorporated with DSP methods. Fast Fourier Transform and Wavelet Transform are the most widely used DSP methods that help researchers investigate the signals in order to obtain the required information. In addition to these two well known transformation techniques, the Chirp-Z Transform (CZT) method was also used in this dissertation and therefore, its applications in NDE&T will be also addressed in this section. It should be noted that the theory of these three transformation techniques will be discussed further in the following chapters.

The Fast Fourier Transform (FFT) has been the most widely used method for analyzing signals in the frequency domain in NDE&T applications. Toutanji (2000) utilized the FFT for NDE&T applications in civil engineering. The experimental study involved testing concrete slabs with different depths of cracks. He studied the use of ultrasonic wave signals propagating concrete bridge decks and his interpretation of the signals relied on the use of Fast Fourier
Transform (FFT) technique to obtain the frequency spectra of the recorded waveforms. In an relatively earlier study Sansalone and Carino (1989) tested reinforced concrete slabs with embedded artificial delaminations using the impact-echo method. The waveforms were analyzed in the frequency domain using FFT, and the frequency components were related to the locations (depths) of the delaminations. In the first experimental phase of the study, the locations of unknown artificial delaminations were inspected successfully and in the second phase the feasibility of the method was investigated in the presence of asphalt overlays. Several other researchers also used FFT technique with various NDE&T methods (e.g. ultrasonic and impact-echo) for various purposes such as strength determination, crack evaluation and defect detection of concrete (Leming et al. 1998; Sakata and Ohtsu 1995; Voigt et al. 2003).

The Wavelet transform is another DSP method which has been receiving increased attention in NDE&T research lately because of its localization properties that adapt better to the signal characteristics compared to Fourier methods (Chen 1994). Signal decomposition properties of discrete wavelet transform (DWT) and its application to ultrasonic nondestructive testing was analyzed by Oruklu and Saniie (2004). Performance analyses of different wavelet kernels (e.g. Daubechies, Vaidyanathan, Symmlet, Coiflet and Battle-Lemarie) with respect to ultrasonic NDE applications were presented and the wavelet selection criteria for optimal flaw detection were developed (Figure 13). Important factors that affect flaw-to-clutter ratio performance were presented.

In another study, Sun and Chang (2002) studied numerical simulations on a three span bridge under excitation. Using Wavelet Packet Transform, they decomposed the dynamic signals into wavelet packet components. In order to assess damage, Wavelet packet transform component energies were used as inputs into neural network classifiers and it was shown that this method can be used for different levels of damage assessment, including identifying damage
occurrence, location and severity. Rizzo and Di Scalea (2004) examined wave propagation problem in multi-wire strands that are commonly used in civil engineering structures as cable stays and prestressing tendons. A broad-band laser ultrasonic setup and a Wavelet transform processing were used to examine the wave dispersion and attenuation in seven-wire strands. Laser ultrasonic measurements of the central and peripheral wires were taken at zero load and two load levels of %45 and %70 of the ultimate tensile strength of the strands. A joint time-frequency analysis based on Wavelet transform was applied to the signals and it was concluded that the proposed study proved successful to characterize the dispersive and attenuating behavior of the lowest-order longitudinal and flexural modes and as a function of the applied load.

Denoising was another application of Wavelet decomposition and reconstruction in the NDE&T field. Signals from multi-wire steel strands were deconstructed with Discrete Wavelet Transform (DWT) and a few wavelet coefficients above a certain threshold value were considered to represent the signal as the remaining coefficients were discarded at the reconstruction phase (Rizzo and Di Scalea 2005; Rizzo et al. 2007). Figure 14 illustrates this
procedure with the plots of the waveforms of direct signal and defect reflection as well as the wavelet coefficients at 6th level of decomposition.

The Chirp-Z Transform (CZT) method is another transformation method which is basically a spiral way of implementing the Z-transform with user defined initial frequency and frequency increment parameters. This transformation technique and a special version of it, the Segmented Chirp-Z Transform (SCZT) were used in few nondestructive testing studies for measuring the damage growth in structural materials and for determining the quality of the bonding in adhesively bonded structures (Daponte et al. 1995; Nair et al. 1991).

The performance of the CZT was analyzed in this dissertation along with the Fast Fourier and Wavelet transformation techniques. In addition to the calculated time domain parameters (the peak amplitude and signal energy), the peak amplitudes of these three transformation methods were used as the frequency domain parameters for studying the effect of yielding on the characteristics of ultrasonic signals. The experimental setup, test procedures and the test database formed for this dissertation is presented in the following chapter.
Figure 14: (a) Direct signal (b) reflection from a defect (c) DWT coefficients at 6th level of decomposition for direct signal (d) DWT coefficients at 6th level of decomposition for defect reflection (e) DWT coefficients for direct signal after 20% thresholding (f) DWT coefficients for defect reflection after 20% thresholding (g) reconstructed direct signal (h) reconstructed defect reflection (Rizzo et al. 2007).
CHAPTER 3 – TESTING SYSTEM, EXPERIMENTAL PROCEDURES AND TEST DATABASE

3.1 Ultrasonic Testing Setup

A wide range market research was conducted prior to building the testing system for this research. It was revealed that there are many available commercial ultrasonic equipment for specific needs (e.g. flaw detectors, rebar locators, thickness gages, etc.) and with various capabilities. Even though these available equipments are being successfully used in the field, a special testing system that would satisfy the specific requirements of this research study was deemed necessary to build a system from individual components. The necessity stems from the fact that most of the commercial available equipment are ‘black boxes’ that lend a little flexibility or raw information to the user.

The testing system used in the experimental phase of this dissertation is composed of five main units. They are (1) the ultrasonic pulser/receiver, (2) transducers, (3) PCI digitizer board, (4) MTS hydraulic testing unit, and (5) a personal computer. The specifications, capabilities and other properties of these five units of the testing system are presented next.

3.1.1 Ultrasonic Pulser/Receiver

The ultrasonic pulser/receiver is the core of the testing system and therefore, similar previous experimental studies were investigated before purchasing the device as well as considering the needs of the current study. It is a well known fact in ultrasonic testing that, the frequency of the used waves is the most important factor in ultrasonic testing of materials. Generally, low
frequency signals are preferred for materials with coarse grain size to reduce the noise and to improve the signals’ capabilities to represent the investigated properties of the material. For example, concrete is generally tested with ultrasonic frequencies roughly between 24 – 150 kHz while a frequency range of 150 – 500 kHz is used for wood. For metals, mostly high frequency ultrasound (above 1 MHz) is desired in ultrasonic testing because of its superior beam directivity and lateral resolution characteristics.

Generally, the majority of the commercially available ultrasonic pulser/receivers are operable at either low or high frequencies. Even though the main focus of this dissertation is steel structures, a pulser/receiver that can be operated with a wide range of frequencies was purchased to be able to test materials with various properties in future research. Panametrics Model 5900PR pulser/receiver, with a maximum bandwidth range of 1 kHz – 200 MHz was used in this research. This device is computer-controllable through GPIB (IEEE-488) and RS-232 communication ports and has multi-position switchable low pass (200, 100, 50, 20 MHz) and high pass (1 kHz, 1, 3 or 10 MHz) filters. The pulse repetition frequency can also be set to values varying between 200 Hz and 20 kHz. The data sheet of the pulser/receiver including detailed technical specifications of the device is presented in Appendix A of this dissertation.

Figure 15: Panametrics Model 5900PR pulser/receiver.
Panametrics 5900PR can be operated with Pulse - Echo (PE), Through Transmission (TT) or External Pulser (EXT) modes and the test parameters can be set and viewed using the keypad and the LCD screen on the front panel of the device (Figure 15). The Through Transmission (TT) and the Pulse – Echo (PE) are the two test modes that were used in this research. They are explained further in Section 3.2 of this dissertation.

3.1.2 Ultrasonic Transducers

The ultrasonic transducers constitute the second main element of the testing system. As was mentioned earlier, the frequency is one of main factors that affect the capability and the reliability of ultrasonic testing. Furthermore, the type of waves being used for testing directly affects the results especially in acoustoelastic measurements. Longitudinal and shear waves are widely used in ultrasonic testing. For longitudinal waves, the propagation and the particle motion directions are the same while they are perpendicular to each other for shear waves (Figure 16). Therefore the polarization direction is another important factor that has to be taken into consideration for the latter case.

Figure 16: The principle of longitudinal and shear waves (Olympus NDT 2006).
There are numerous types of transducers in the market for ultrasonic testing that have various ways of interacting with the tested material (e.g. contact, angle beam, immersion, delay line, dual element transducers). Ultrasonic transducers can also be characterized with the way of generating ultrasound (e.g. piezoelectric transducers, electromagnetic-acoustic transducers). Piezoelectric transducers generate ultrasound by converting electrical energy to mechanical energy and vice versa when receiving signals. On the other hand, electromagnetic – acoustic transducers use magnetostriction for generating mechanical pulses.

In this study, longitudinal and shear contact piezoelectric transducers were used. Initially, a pair of 10 MHz Panametrics, Model V112, longitudinal wave fingertip size transducers (Serial Numbers: 556719 and 556721) were used for PE and TT tests. In the latter stages, along with the longitudinal transducers, a 5 MHz Panametrics, Model V156, shear wave fingertip size transducer (Serial Numbers: 586245) was used for PE tests. The diameter and the height of these cylindrical contact transducers are 0.35 and 0.42in, respectively. All three transducers are shown in Figure 17. Detailed technical specifications of the transducers including the signal waveforms and frequency spectra are presented in Appendix B.
The transducers were connected to the pulser-receiver with special double-shielded cables that provide low cable noise for better performance in high frequency applications (Figure 17). Piezoelectric contact transducers require a coupling medium between the transducer and the tested material due to the high acoustic impedance mismatch between air and solids. When there is air present, almost all of the ultrasonic energy is reflected and not transmitted. Therefore couplants are used to displace the air and enable more sound energy to propagate into the tested material. Even though water, oil and glycerin are commonly used for this purpose, there are also commercial couplants for special tests where specific issues (e.g. high/low temperatures, effective surface wetting, corrosion inhabitation, high viscosity couplants, etc.) need to be taken into consideration.

In this study, Sonotech Inc.’s Ultragel II couplant (viscosity ≈ 80,000 cps) with a wide range of operating temperature range (-10° to 210°F) was used for measurements with the longitudinal transducers. This commercial couplant has slow drying and good wetting characteristics that provides improved transducer lubrication and better coupling on oily and dirty surfaces.

Shear waves, on the other hand, do not propagate in liquids and therefore they require couplants with higher viscosity values compared to the ones that can be used with longitudinal waves. For the shear wave ultrasonic measurements, Sonotech Inc.’s Shear Gel couplant, with a viscosity value approximately higher than 4,000,000 cps, was used. This couplant material is very sticky but it can be removed using warm water without harming the transducers. The specifications and material safety data sheets (MSDS) of these two couplants are presented in Appendix C.
3.1.3 PCI Digitizer Board

The ultrasonic signals that are received by the RF output of the pulser/receiver are in analog form. The acquired ultrasonic signals need to be digitized so that they can be stored and processed using computers. The sampling rate is the most important factor in digitizing signals and is desired to be as high as possible for better resolution in signals.

Considering the importance of high resolution and sampling rate, Acqiris PCI digitizer, Model DP310, was purchased and installed in the computer controlling the pulser receiver in order to digitize the acquired analog waveforms. This 12-bit digitizer has a maximum sampling rate of 420 MS/s with a 4 Mpoint onboard acquisition memory. The technical specifications of the digitizer are presented in Appendix D.

The digitizer can be controlled with specific codes using C/C++, Visual Basic, MATLAB and LabVIEW as well the accompanying AcqirisLive software. AcqirisLive is an application to demonstrate and control the capabilities of the digitizer that has two control panel modes: namely, the Oscilloscope Mode and the Transient Recorder Mode. Both modes provide the same capabilities but display the settings slightly differently.

In the Oscilloscope Mode, the user selects the time window (time per division) and the sampling rate is adjusted to the fastest possible within the limits of the available memory. In the Transient Mode, the capture window, the sampling rate and the number of samples is selected by the user. The Transient mode was used for the ultrasonic tests in this study and the acquired and digitized are stored in the computer to be used for future signal processing applications. The control panel view for the Transient Recorder Mode can be seen in Figure 18.
The MTS 810 Hydraulic Materials Testing System, which was already available in the Louisiana State University, Civil and Environmental Engineering, Strength of Materials Laboratory, was another main unit of the testing system (Figure 19). The system was used to apply the desired levels of uniaxial tensile stresses to the test specimens at which ultrasonic measurements were aimed to be taken. This hydraulic testing machine has a load capacity of 50kips and it is controlled by a personal computer using Model 793.10 MultiPurpose TestWare® Software through TestStar II controller. This software allows applying user defined test procedures that

Figure 18: The control panel view for the Transient Mode of the AcqirisLive Software.

3.1.4 MTS 810 Hydraulic Testing System

The MTS 810 Hydraulic Materials Testing System, which was already available in the Louisiana State University, Civil and Environmental Engineering, Strength of Materials Laboratory, was another main unit of the testing system (Figure 19). The system was used to apply the desired levels of uniaxial tensile stresses to the test specimens at which ultrasonic measurements were aimed to be taken. This hydraulic testing machine has a load capacity of 50kips and it is controlled by a personal computer using Model 793.10 MultiPurpose TestWare® Software through TestStar II controller. This software allows applying user defined test procedures that
can include command, data acquisition, event detection, and external control instructions. The target stress levels are programmed in the test procedures and ultrasonic signals were acquired at these stresses.

![Figure 19: MTS 810 Hydraulic Materials Testing System.](image)

### 3.1.5 Personal Computer

The final unit of the testing system is a personal computer that is equipped with the PCI digitizer card. The RF output port of the pulser/receiver is connected to the input channel of the digitizer card. The computer controls both the pulser/receiver through RS 232 port and the digitizer through the AcqirisLive Software. The acquired signals are stored in the computer and signal processing methods are applied using MATLAB software.

The complete ultrasonic testing setup for the through – transmission (TT) test mode and the connections of the main units of the system are illustrated in Figure 20. While the specimens
are being tested under uniaxial tensile stresses applied by the MTS 810 Hydraulic Testing System, the loading is held at specified levels for the ultrasonic measurements to be taken. The transmitted signal propagates through the material and the received signal reaches back to the pulser/receiver. The analog waveform leaving the RF output of the pulser/receiver is stored in the computer after being digitized by PCI digitizer board.

Figure 20: The experimental setup and the connections of the main units.
3.2 Experimental Procedure

Using the specially built test setup presented in the previous section, steel specimens were tested and ultrasonic signals were acquired. The specifications of the specimens, material properties and test procedures are explained next.

3.2.1 Specimen Preparation and Material Properties

The specimens used in this experimental study are obtained from four batches of Grade 36 steel plates. The dog bone shaped specimens were obtained by cutting these four plates using a hydrocut waterjet machine. The thicknesses of the plates and therefore the thicknesses of the specimens vary between 1/8 and 3/8 of an inch. Other dimensions of the specimens are the dimensions of the rectangular sheet-type standard specimen following ASTM Standard E8-04 (ASTM 2004). Figure 21 shows the dimensions of the specimens.

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>W - Width</td>
<td>0.5</td>
</tr>
<tr>
<td>R - Radius of fillet</td>
<td>0.5</td>
</tr>
<tr>
<td>L - Overall length</td>
<td>8</td>
</tr>
<tr>
<td>A - Length of reduced section</td>
<td>3.35</td>
</tr>
<tr>
<td>B - Length of grip section</td>
<td>2</td>
</tr>
<tr>
<td>C - Width of grip section</td>
<td>0.75</td>
</tr>
</tbody>
</table>

**Figure 21:** Dimensions of the dog bone shaped specimens.
In terms of thicknesses the specimens were classified into four groups based on the plate that they were cut from. Furthermore, even though the plates are supposed to have same material properties of Grade 36 steel, they vary in terms of mechanical properties and chemical composition according to the mill test certificates (Appendix E) obtained from the steel companies that the plates were provided from. The designations of the four types of specimens, their thicknesses and material properties based on the mill test certificates are listed in Table 1.

Table 1: The four specimen groups and their material properties based on mill test certificates.

<table>
<thead>
<tr>
<th>Specimen Type</th>
<th>Specimen Thickness</th>
<th>Avg. Mechanical Properties</th>
<th>Chemical Decomposition (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Tensile Str.</td>
<td>Yield Str.</td>
</tr>
<tr>
<td>Type 1</td>
<td>1/4</td>
<td>63.1</td>
<td>46.3</td>
</tr>
<tr>
<td>Type 2</td>
<td>3/8</td>
<td>61.7</td>
<td>50.7</td>
</tr>
<tr>
<td>Type 3</td>
<td>1/4</td>
<td>65.3</td>
<td>43.5</td>
</tr>
<tr>
<td>Type 4</td>
<td>1/8</td>
<td>63.3</td>
<td>46.9</td>
</tr>
</tbody>
</table>

It can be seen from the test results of the mill test certificate specimens (Appendix E) that the mechanical properties show variations. Therefore, prior to the ultrasonic tests, the mechanical properties of the materials in tension are identified using the MTS 810 Testing System mentioned earlier with a loading rate of 0.125in/min. The strains were acquired using a one inch gage length MTS extensometer (Model No: 634.11E–24). All three channels of the testing system (force, displacement and strain data) were stored and used to obtain the stress-strain relationship for coupons from all specimen groups. The results are presented in Figures 22-25. According to the material test results, the yield strength values are calculated as 45, 50, 43.5 and 38.5 ksi, while the ultimate strength values are 68.6, 64.4, 60.5 and 58 ksi, respectively.
Figure 22: Stress-strain curve of the Type 1 specimen material.

Figure 23: Stress-strain curve of the Type 2 specimen material.
Figure 24: Stress-strain curve of the Type 3 specimen material.

Figure 25: Stress-strain curve of the Type 4 specimen material.
3.2.2 Test Procedures

The specially built ultrasonic testing system was used to test four different types of specimens with the aforementioned material properties. Ultrasonic measurements were taken at target stress levels by piezoelectric longitudinal and shear wave transducers using the through transmission and pulse–echo test modes. The basic steps of the experiments and the test procedures are explained in detail in this section of the dissertation.

The first step of the experimental procedure was investigation of the surface conditions of the specimens. The surfaces of the specimens where the transducers were going to be placed were cleaned and specimens that have considerably rough surfaces were sanded. Secondly, the exact dimensions of the specimens were measured with a digital caliper. The measured cross-sectional area was used to calculate the force values that correspond to the target stress levels for ultrasonic measurements. These force values were entered to the Model 793.10 MultiPurpose TestWare® Software (controlling the MTS 810 testing system) to define special test procedures so that loading can be held for ultrasonic measurements.

A stress resolution of 10 ksi was used for all tested specimens in the elastic range of the materials. For stress levels close to and beyond yielding, higher stress resolution values (i.e. smaller stress increments) between 2.5 and 5 ksi were programmed in the defined test procedures. Even though the exact target stress values are programmed in the test procedures, the loading could only be held at stress levels close to these target values due to the accuracy of the testing system. Therefore, the actual stress values applied by the MTS testing machine were recorded during ultrasonic measurements and these exact values are used for analyzing the results.
Longitudinal wave ultrasonic measurements were taken using the through transmission (TT) and the pulse–echo (PE) test modes of the pulser/receiver while only the PE mode was used for the measurements with the shear wave transducer. The measurements were taken at the midsection of the specimens for most of experiments. However, for some tests, two additional measurements were taken from sections on the specimen as close as possible to the top and bottom heads of the hydraulic testing system.

Ultragel II and Shear Gel commercial couplants were used to provide a coupling medium between the transducers and the specimens. A plastic light–weight C-clamp was used to attach the transducers onto the specimens. However, the transducers were detached in between measurements (during loading) for safety purposes. Two possible important sources of error arise in ultrasonic testing at this point one of which is maintaining sufficient amount of couplant not to induce measurement errors (Wu 1989). This issue was handled by adding more couplant material to the surface of the specimen, if necessary, before every ultrasonic measurement.

The second challenge throughout the experiments was the amount of tightening of the C-clamp, which also affects the acquired signals in terms of amplitude (DosSantos and Bray 2002). Trial measurements during the calibration of the testing system showed that the measured amplitudes of the signals increase with increasing tightening force up to a point and then stays constant. Therefore, the C-clamp was tightened as much as possible at every measurement to overcome this error cause as much as possible. The way how the transducers attached to the specimen with the C-clamp and the measurement setup for a TT test mode is illustrated in Figure 26.

The same pulser/receiver setup options (pulse repetition frequency, voltage gain, pulse energy, etc.) were used for all of the measurements. The switchable multi-position high-pass and low-pass filters of the pulser-receiver were set to the lowest and the highest positions.
respectively during the ultrasonic measurements to disable filtering the signals with the device. The transient recorder mode of the AcqirisLive software was used to digitize the signals and a sampling rate of 400 Megasamples/second (i.e. time increment of 2.5 ns) was selected for all the signals in this study. All acquired signals were stored in the computer in text file format to implement digital signal processing methods for the analysis of the results.

![Figure 26: Ultrasonic measurement setup for through transmission testing mode](image)

**Figure 26:** Ultrasonic measurement setup for through transmission testing mode
3.3 Experimental Database

A total of twenty-eight ultrasonic tests were conducted on four different types of steel specimens. The first four tests were pilot tests where the Type1 specimens were tested in the material’s elastic region (up to 40ksi). Following the pilot tests, full-tests with twenty-four specimens (six specimens of each four types) were conducted where the specimens were loaded up to failure. The specimen that was used for the pilot tests was used as the specimen of the first full test. The loading procedures were held at target stress levels and ultrasonic measurements were taken at these stress levels before and after yielding.

For fifteen of the twenty-four full tests, ultrasonic signals propagating through the midsection of the specimens were acquired, while three section locations (top, mid and bottom) were used for the ultrasonic measurements in the remaining tests. In all the ultrasonic tests, the transducers were placed so that the signals would propagate through the thickness of the specimens in a direction perpendicular to the loading. The experimental database of this dissertation is composed of 582 ultrasonic signals. Summary of specimen designations, tests procedures, ultrasonic measurement details, and the target stress levels for the ultrasonic measurements are presented in Table 2. It should be noted that the stress values in Table 2 are the target stress levels at which ultrasonic measurements were planned to be taken. However, exact stress values, at which the ultrasonic tests were conducted, were recorded and used in the analyses of results.
Table 2: Summary of the experimental database.

<table>
<thead>
<tr>
<th>Specimen Picture</th>
<th>Test #</th>
<th>Specimen Thickness</th>
<th>Ultrasonic Wave Type</th>
<th>Ultrasonic Test Mode</th>
<th>Measurement Locations</th>
<th>Target Stress Levels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type1 Test 1</td>
<td></td>
<td>1/4”</td>
<td>Longitudinal</td>
<td>Through Transmission</td>
<td>Mid Section</td>
<td>0, 10, 20, 30 and 40 ksi</td>
</tr>
<tr>
<td>Type1 Test 2</td>
<td></td>
<td>1/4”</td>
<td>Longitudinal</td>
<td>Through Transmission</td>
<td>Mid Section</td>
<td>0, 10, 20, 30 and 40 ksi</td>
</tr>
<tr>
<td>Type1 Test 3</td>
<td></td>
<td>1/4”</td>
<td>Longitudinal</td>
<td>Pulse - Echo</td>
<td>Mid Section</td>
<td>0, 10, 20, 30 and 40 ksi</td>
</tr>
<tr>
<td>Type1 Test 4</td>
<td></td>
<td>1/4”</td>
<td>Longitudinal</td>
<td>Pulse - Echo</td>
<td>Mid Section</td>
<td>0, 10, 20, 30 and 40 ksi</td>
</tr>
<tr>
<td>Type1 Test 5</td>
<td></td>
<td>1/4”</td>
<td>Longitudinal</td>
<td>Through Transmission</td>
<td>Mid Section</td>
<td>0, 10, 20, 30, 40, 45, 50, 55, 60, 65 and 68 ksi</td>
</tr>
<tr>
<td>Type1 Test 6</td>
<td></td>
<td>1/4”</td>
<td>Longitudinal</td>
<td>Through Transmission</td>
<td>Mid Section</td>
<td>0, 10, 20, 30, 40, 45, 50, 55, 60, 65 and 68 ksi</td>
</tr>
<tr>
<td>Specimen Picture</td>
<td>Test #</td>
<td>Specimen Thickness</td>
<td>Ultrasonic Wave Type</td>
<td>Ultrasonic Test Mode</td>
<td>Measurement Locations</td>
<td>Target Stress Levels</td>
</tr>
<tr>
<td>------------------</td>
<td>-----------</td>
<td>--------------------</td>
<td>----------------------</td>
<td>----------------------</td>
<td>-----------------------</td>
<td>------------------------------------------------</td>
</tr>
<tr>
<td>Type1 Test 7</td>
<td></td>
<td>1/4&quot;</td>
<td>Longitudinal</td>
<td>Through Transmission</td>
<td>Mid Section</td>
<td>0, 10, 20, 30, 40, 42, 44, 45, 48, 50, 55, 60, 62, 65 and 68 ksi</td>
</tr>
<tr>
<td>Type2 Test 8</td>
<td></td>
<td>3/8&quot;</td>
<td>Longitudinal</td>
<td>Through Transmission</td>
<td>Mid Section</td>
<td>0, 10, 20, 30, 40, 42.5, 45, 47.5, 50, 52.5, 55, 57.5, 60 and 62.5 ksi</td>
</tr>
<tr>
<td>Type3 Test 9</td>
<td></td>
<td>1/4&quot;</td>
<td>Longitudinal</td>
<td>Through Transmission</td>
<td>Mid Section</td>
<td>0, 10, 20, 30, 40, 42.5, 45, 47.5, 50, 52.5, 55, 57.5 and 60 ksi</td>
</tr>
<tr>
<td>Type4 Test 10</td>
<td></td>
<td>3/8&quot;</td>
<td>Longitudinal</td>
<td>Through Transmission</td>
<td>Top, Mid and Bottom Section</td>
<td>0, 10, 20, 30, 40, 42.5, 45, 47.5, 50, 52.5, 55, 57.5 and 60 ksi</td>
</tr>
<tr>
<td>Type3 Test 11</td>
<td></td>
<td>1/4&quot;</td>
<td>Longitudinal</td>
<td>Through Transmission</td>
<td>Top, Mid and Bottom Section</td>
<td>0, 10, 20, 30, 40, 42.5, 45, 47.5, 50, 52.5, 55, 57.5 and 60 ksi</td>
</tr>
<tr>
<td>Type4 Test 12</td>
<td></td>
<td>1/8&quot;</td>
<td>Longitudinal</td>
<td>Through Transmission</td>
<td>Top, Mid and Bottom Section</td>
<td>0, 10, 20, 30, 35, 37.5, 42.5, 45, 47.5, 50, 52.5 and 55 ksi</td>
</tr>
</tbody>
</table>
Table 2: Continued.

<table>
<thead>
<tr>
<th>Specimen Picture</th>
<th>Test #</th>
<th>Specimen Thickness</th>
<th>Ultrasonic Wave Type</th>
<th>Ultrasonic Test Mode</th>
<th>Measurement Locations</th>
<th>Target Stress Levels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type4 Test 13</td>
<td>13</td>
<td>1/8&quot;</td>
<td>Longitudinal</td>
<td>Through Transmission</td>
<td>Top, Mid and Bottom Section</td>
<td>0, 10, 20, 30, 35, 37.5, 40, 42.5, 45, 50 and 52.5 ksi</td>
</tr>
<tr>
<td>Type4 Test 14</td>
<td>14</td>
<td>1/8&quot;</td>
<td>Longitudinal</td>
<td>Through Transmission</td>
<td>Top, Mid and Bottom Section</td>
<td>0, 10, 20, 30, 35, 37.5, 42.5, 47.5, 52.5 and 57.5 ksi</td>
</tr>
<tr>
<td>Type2 Test 15</td>
<td>15</td>
<td>3/8&quot;</td>
<td>Longitudinal</td>
<td>Through Transmission</td>
<td>Top, Mid and Bottom Section</td>
<td>0, 10, 20, 30, 42.5, 45, 47.5, 50, 52.5, 55, 57.5, 60 and 62.5 ksi</td>
</tr>
<tr>
<td>Type3 Test 16</td>
<td>16</td>
<td>1/4&quot;</td>
<td>Longitudinal</td>
<td>Through Transmission</td>
<td>Top, Mid and Bottom Section</td>
<td>0, 10, 20, 30, 42.5, 45, 47.5, 50, 52.5, 55, 57.5, 60, 62.5 and 65 ksi</td>
</tr>
<tr>
<td>Type1 Test 17</td>
<td>17</td>
<td>1/4&quot;</td>
<td>Longitudinal</td>
<td>Through Transmission</td>
<td>Top, Mid and Bottom Section</td>
<td>0, 10, 20, 30, 42.5, 45, 47.5, 50, 52.5, 55, 57.5, 60, 62.5 and 65 ksi</td>
</tr>
<tr>
<td>Type1 Test 18</td>
<td>18</td>
<td>1/4&quot;</td>
<td>Longitudinal and Shear (Par.)</td>
<td>Through Transmission and Pulse - Echo</td>
<td>Mid Section</td>
<td>0, 10, 20, 30, 42.5, 45, 47.5, 50, 52.5, 55, 57.5, 60, 62.5, 65 and 67.5 ksi</td>
</tr>
</tbody>
</table>
Table 2: Continued.

<table>
<thead>
<tr>
<th>Test #</th>
<th>Specimen Thickness</th>
<th>Ultrasonic Wave Type</th>
<th>Ultrasonic Test Mode</th>
<th>Measurement Locations</th>
<th>Target Stress Levels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type1 Test 19</td>
<td>1/4&quot;</td>
<td>Longitudinal</td>
<td>Through Transmission and Pulse - Echo</td>
<td>Top, Mid and Bottom Section</td>
<td>0, 10, 20, 30, 40, 42.5, 45, 47.5, 50, 52.5, 55, 57.5, 60, 62.5, 65 and 67.5 ksi</td>
</tr>
<tr>
<td>Type3 Test 20</td>
<td>1/4&quot;</td>
<td>Longitudinal</td>
<td>Through Transmission</td>
<td>Mid Section</td>
<td>0, 10, 20, 30, 40, 42.5, 45, 47.5, 50, 52.5, 55, 57.5, 60, 62.5, 65 and 67.5 ksi</td>
</tr>
<tr>
<td>Type3 Test 21</td>
<td>1/4&quot;</td>
<td>Shear (Ver.)</td>
<td>Pulse - Echo</td>
<td>Mid Section</td>
<td>0, 10, 20, 30, 40, 42.5, 45, 47.5, 50, 52.5, 55, 57.5 and 60 ksi</td>
</tr>
<tr>
<td>Type3 Test 22</td>
<td>1/4&quot;</td>
<td>Shear (Par.)</td>
<td>Pulse - Echo</td>
<td>Mid Section</td>
<td>0, 10, 20, 30, 40, 42.5, 45, 47.5, 50, 52.5, 55, 57.5 and 60 ksi</td>
</tr>
<tr>
<td>Type2 Test 23</td>
<td>3/8&quot;</td>
<td>Longitudinal</td>
<td>Through Transmission</td>
<td>Mid Section</td>
<td>0, 10, 20, 30, 40, 42.5, 45, 47.5, 50, 52.5, 55, 57.5, 60 and 62.5 ksi</td>
</tr>
<tr>
<td>Type2 Test 24</td>
<td>3/8&quot;</td>
<td>Shear (Ver.)</td>
<td>Pulse - Echo</td>
<td>Mid Section</td>
<td>0, 10, 20, 30, 40, 42.5, 45, 47.5, 50, 52.5, 55, 57.5, 60 and 62.5 ksi</td>
</tr>
</tbody>
</table>
Table 2: Continued.

<table>
<thead>
<tr>
<th>Specimen Picture</th>
<th>Test #</th>
<th>Specimen Thickness</th>
<th>Ultrasonic Wave Type</th>
<th>Ultrasonic Test Mode</th>
<th>Measurement Locations</th>
<th>Target Stress Levels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type2 Test 25</td>
<td></td>
<td>3/8&quot;</td>
<td>Shear (Par.)</td>
<td>Pulse - Echo</td>
<td>Mid Section</td>
<td>0, 10, 20, 30, 40, 42.5, 45, 47.5, 50, 52.5, 55, 57.5, 60 and 62.5 ksi</td>
</tr>
<tr>
<td>Type4 Test 26</td>
<td></td>
<td>1/8&quot;</td>
<td>Longitudinal</td>
<td>Through Transmission</td>
<td>Mid Section</td>
<td>0, 10, 20, 30, 35, 37.5, 42.5, 47.5, 52.5 and 57.5 ksi</td>
</tr>
<tr>
<td>Type4 Test 27</td>
<td></td>
<td>1/8&quot;</td>
<td>Shear (Ver.)</td>
<td>Pulse - Echo</td>
<td>Mid Section</td>
<td>0, 10, 20, 30, 35, 37.5, 40, 42.5, 47.5 and 55 ksi</td>
</tr>
<tr>
<td>Type4 Test 28</td>
<td></td>
<td>1/8&quot;</td>
<td>Shear (Par.)</td>
<td>Pulse - Echo</td>
<td>Mid Section</td>
<td>0, 10, 20, 30, 35, 37.5, 42.5, 47.5, 52.5 and 57.5 ksi</td>
</tr>
</tbody>
</table>
CHAPTER 4 – ACOUSTOELASTIC ANALYSIS OF THE EXPERIMENTAL DATABASE

The acoustoelastic effect has been widely used as a nondestructive testing method for investigating the stress state of materials since the theory was introduced. Many researchers proposed numerous methods for stress measurement based on acoustoelasticity. Therefore, the acoustoelastic analysis constitutes the beginning step of the analysis of the experimental database. This chapter, first, presents the background, theory, applications, challenges and the complications of acoustoelasticity. Then the methodology of acoustoelastic analysis of the acquired signals is explained, and finally, the acoustoelastic results for both the longitudinal and shear waves are presented in the light of the theory.

4.1 Theory of Acoustoelasticity

The background of acoustoelasticity, the mathematical theory, the factors that affect acoustoelastic measurements and the complications of the theory are discussed next.

4.1.1 Introduction to Acoustoelasticity

The Theory of Acoustoelasticity, or the acoustoelastic effect, is basically the dependence of acoustic wave velocity, on the stress state of the material through which it travels. Acoustoelasticity is based on the continuum theory of small disturbances (e.g. ultrasonic waves) superimposed on an elastically deformed medium (Duquennoy et al. 1999). The acoustoelasticity phenomenon is similar in a sense to the well known photoelasticity method (Kino et al. 1979). Photoelasticity is based on a polarized light passing through a transparent material that is
optically birefringent. Birefringence causes the polarized light to refract into two orthogonal planes, along the axes of principal stresses. The magnitude of the principal stresses directly affects the speed at which each of the waves propagate and the resulting phase shift of the light waves is used for measuring the applied stresses. Similarly, acoustoelastic effect causes changes in the velocity of the elastic wave that is propagating through the material and these relative changes are related to the level of present applied or residual stresses.

The theory of acoustoelasticity was first introduced by Hughes and Kelly (1953). Based on Murnaghan’s model for finite deformations and third-order terms in the strain-energy expressions (1951), they formulated the relationships between the elastic wave velocities in solids and stresses. The expressions for the Third Order Elastic Constants (TOEC), that are required along with the Lamé constants to describe the characteristics of a material, were also presented. These expressions were later summarized and the acoustoelastic constants were introduced (Egle and Bray 1976). These constants are specific for every material and they relate the effects of stress field to the ultrasonic wave velocities. A specific acoustoelastic constant is associated with each type of ultrasonic wave (e.g. bulk wave, surface wave), to a loading direction and its propagation and polarization directions if the material is anisotropic (Duquennoy et al. 1999). The mathematical expressions for the Lamé, third-order elastic and acoustoelastic constants are presented in Section 4.1.2.

Acoustoelasticity first found applications in predicting the applied stresses in materials. Starting from late 1950’s, scientists used acoustoelasticity as a nondestructive method for predicting the stress levels of materials, first being Bergman and Shahbender (1958) and Benson and Raelson (1959). After the discovery of the effects of material processing methods (e.g. casting, rolling, forging, drawing) on the third order elastic constants, acoustoelasticity started being used for measuring residual stresses. Although the intensity and accuracy of acoustoelastic
stress measurement technique is very sensitive to certain factors (e.g. material characteristics, type of signal used, propagation and polarization direction), it has been widely used for nondestructive measurement of residual and applied stresses in engineering materials such as aluminum, wood and steel (Chen and He 1992; Sasaki et al. 2001; Schneider 2001; DosSantos and Bray 2002; Hasegawa and Sasaki 2004a; Hasegawa and Sasaki 2004b; Hasegawa and Sasaki 2004c).

4.1.2 Formulation of Acoustoelasticity

Acoustoelasticity is the dependence of ultrasonic wave velocity on stress state of the material through which it travels. The velocity of acoustic waves in solids depends on the material's mass and elastic properties. Very simply, the velocity of an acoustic wave in a material can be formulated as

\[ C = \sqrt{\frac{\kappa}{\rho}} \]  

where \( C \) is the phase velocity, \( \rho \) is the density and \( \kappa \) is a parameter combining the material’s modulus of elasticity \( E \) and Poisson’s ratio \( \nu \), or the Lamé constants \( \lambda \) and \( \mu \). The specific \( \kappa \) values for longitudinal and shear waves are expressed as

\[ \kappa_L = 2\lambda + \mu = \frac{E(1 - \nu)}{(1 + \nu)(1 - 2\nu)} \]  

\[ \kappa_S = \mu = \frac{E}{2(1 + \nu)} \]  

respectively. A body's density and elasticity change under stresses, and therefore this change results in variation in the acoustic wave velocity. Hughes and Kelly (1953) developed the modern theory of acoustoelasticity using Murnaghan’s theory of finite deformations (1951). A
general infinitesimal strain superimposed upon a homogenous triaxial finite strain with the coordinate axes as principal axes was represented by

\[ x_r = A_r a_r + U_r(a), \quad r = 1, 2, 3 \]  

(4)

where coordinates \((a_1, a_2, a_3)\) and \((x_1, x_2, x_3)\) represent the original position and the final position of a point in the body, respectively, while \(U_r(a)\) are the general functions of all the \(a\)'s that is satisfying the condition

\[ U_r(a) \ll A_r - 1 \]  

(5)

The Lagrangian strain components are then given by

\[ \eta_{rs} = \alpha_r \delta_{rs} + A_r A_s e_{rs} \]  

(6)

where \(\delta_{rs}\) is the Kronecker delta function, the \(e_{rs}\) are the ordinary infinitesimal strains computed from a state of general triaxial finite strain given by the \(\alpha_r\) and they can be expressed as

\[ \delta_{rs} = \begin{cases} 1 & \text{if } r = s \\ 0 & \text{if } r \neq s \end{cases} \]  

(7)

\[ e_{rs} = \frac{1}{2} \left( \frac{\partial U_r}{\partial x_s} + \frac{\partial U_s}{\partial x_r} \right) \]  

(8)

\[ \alpha_r = \frac{1}{2} \left( A_r^2 - 1 \right) \]  

(9)

For an isotropic body, the strain energy is a function of the strain invariants which are defined by

\[ I_1 = \delta_{s}^r \eta_{rs} \]  

(10)

\[ I_2 = \frac{1}{2!} \delta_{su}^{rt} \eta_{rs} \eta_{tu} \]  

(11)

\[ I_3 = \frac{1}{3!} \delta_{suw}^{rtv} \eta_{rs} \eta_{tu} \eta_{vw} \]  

(12)

where the \(\delta\)'s are the general Kronecker delta functions. Using the strain invariants, the strain energy per unit mass were expressed as (Murnaghan 1951)
\[
\phi = \frac{1}{2} (\lambda + 2\mu) l_1^2 - 2\mu l_2 - \frac{1}{3} (l + 2m) l_1^3 - 2ml_1 l_2 + nl_3
\]  
(13)

where \(\lambda\) and \(\mu\) are the Lamé constants and \(l, m,\) and \(n\) are called the Murnaghan constants. The density is given by

\[
\rho = \frac{\rho_o}{(1 + 2I_1 + 4I_2 + 8I_3)}
\]  
(14)

where \(\rho_o\) is the initial density at zero strain. The stresses were then expressed as

\[
\sigma_{rs} = \sigma_{rs}^o + \sum_{tu} C_{rstu} \frac{\partial U_t}{\partial x_u}
\]  
(15)

where

\[
\sigma_{rs}^o = [\lambda + (l - m - \lambda)\theta + (\lambda + m - \mu)\alpha_r] \theta \delta_{rs} + 2\mu (\alpha_r + 2\alpha_r^2) \delta_{rs} + \]

\[
m \sum_{t} \alpha_t^2 \delta_{rs} + \frac{1}{2} m \sum_{tu} \delta_{stu}^{rst} \alpha_t \alpha_u
\]  
(16)

\[
\theta = \alpha_1 + \alpha_2 + \alpha_3
\]  
(17)

and

\[
C_{rstu} = [\lambda + 2(l - \lambda - m)\theta + 2(\lambda + m)(\alpha_r + \alpha_t) - 2\mu\alpha_r] \delta_{rs} \delta_{rs} +
\]

\[
[\mu + (\lambda + m - \mu)\theta + 2\mu (\alpha_r + \alpha_s + \alpha_u)] [\delta_{rt} \delta_{su} + \delta_{ru} \delta_{st}] + \frac{1}{2} n \sum_v (\delta_{svu}^{rst} + \delta_{svu}^{rst}) \alpha_v
\]  
(18)

Then \(U_r\) are assumed to be

\[
U_r = F_r \left( \sum_s N_s x_s - Vt \right)
\]  
(19)

In Equation 19, the \(N_s\) are components of a unit vector in any direction and the \(U\)'s thus represent a plane wave propagated in the direction \(N_s\). The velocity, \(V\), was determined by solving

\[
Det \left| \sum_{ru} C_{rstu} N_r N_u - V^2 \delta_{st} \right| = 0
\]  
(20)
In the case of wave propagation along the x axis was only, the solution of the determinant in Equation 20 leads to

\[
\rho_0 V_1^2 = \lambda + 2\mu + (2l + \lambda)\theta + (4m + 4\lambda + 10\mu)\alpha_1
\]

(21a)

\[
\rho_0 V_2^2 = \mu + (\lambda + m)\theta + 4\mu\alpha_1 + 2\mu\alpha_2 + \frac{1}{2}n\alpha_3
\]

(21b)

\[
\rho_0 V_3^2 = \mu + (\lambda + m)\theta + 4\mu\alpha_1 + 2\mu\alpha_3 + \frac{1}{2}n\alpha_2
\]

(21c)

Later, the velocity solutions was simplified for uniaxial stress conditions by Egle and Bray (1976). For the uniaxial stress case, the strains are

\[
\alpha_1 = \varepsilon \quad \text{and} \quad \alpha_2 = \alpha_3 = -\nu\varepsilon
\]

Then the five unique wave speeds were determined from Equations 21a, b and c.

\[
\rho_0 V_{11}^2 = \lambda + 2\mu + [4(\lambda + 2\mu) + 2(\mu + 2m) + \nu(1 + 2l/\lambda)]\varepsilon
\]

(22a)

\[
\rho_0 V_{12}^2 = \rho_0 V_{13}^2 = \mu + [4\mu + \nu(n/2) + m(1 - 2\nu)]\varepsilon
\]

(22b)

\[
\rho_0 V_{22}^2 = \lambda + 2\mu + [2l(1 - 2\nu) - 4\nu(m + \lambda + 2\mu)]\varepsilon
\]

(22c)

\[
\rho_0 V_{21}^2 = \rho_0 V_{31}^2 = \mu + [(\lambda + 2\mu + m)(1 - 2\nu) + \frac{1}{2}n\nu]\varepsilon
\]

(22d)

\[
\rho_0 V_{23}^2 = \rho_0 V_{32}^2 = \mu + [(\lambda + m)(1 - 2\nu) - 6\nu\mu - \frac{1}{2}n]\varepsilon
\]

(22e)

The relative sensitivity of the variation of the velocity with the strain were given by the equations

\[
\frac{dV_{11}/V_{11}^0}{d\varepsilon} = 2 + \frac{\mu + 2m + \nu(\lambda + 2l/\lambda)}{\lambda + 2\mu}
\]

(23a)

\[
\frac{dV_{12}/V_{12}^0}{d\varepsilon} = 2 + \frac{\nu n}{4\mu} + \frac{m}{2(\lambda + \mu)}
\]

(23b)

\[
\frac{dV_{22}/V_{22}^0}{d\varepsilon} = -2\nu\left(1 + \frac{m - \mu l/\lambda}{\lambda + 2\mu}\right)
\]

(23c)

\[
\frac{dV_{21}/V_{21}^0}{d\varepsilon} = \frac{\lambda + 2\mu + m}{2(\lambda + \mu)} + \frac{\nu n}{4\mu}
\]

(23d)

\[
\frac{dV_{23}/V_{23}^0}{d\varepsilon} = \frac{(m - 2\lambda)}{2(\lambda + \mu)} + \frac{n}{4\mu}
\]

(23e)
where the velocities with the superscript ‘0’ represent the velocities at zero axial strain conditions. The first and the second subscripts of the velocities represent the direction of the wave propagation and the particle motion (i.e. polarization direction), respectively.

Figure 27: Possible orthogonal directions and designations of velocities in solids (Bray and Tang 2001).

Figure 27 illustrates the designations of the possible perpendicular and parallel directions of wave velocities in solids relative to the uniaxial stress. Based on this designation, the velocities that have the same direction of wave propagation and polarization correspond to longitudinal waves (e.g. $V_{11}$, $V_{22}$, $V_{33}$), while others represent shear waves. Equation 23 represents the sensitivity of the dependence of the longitudinal and shear wave velocities on the stress state of the material. This concept is further discussed next.
4.1.3 Factors Affecting Acoustoelastic Measurements

The main interest in acoustoelastic stress measurement is investigating the relative changes in wave velocities versus changing strains. However, velocity measurements are influenced by several competing effects that fall into two categories: those arising from the ultrasonic measurement technique and those intrinsic to the specimen or the material (Pao et al. 1984).

The effects that arise from the ultrasonic measurement technique are transducer related issues. Ultrasonic waves in solids are mainly of two types (Si-Chaib et al. 2001). The first type is called the compression or longitudinal waves, where the particle motion is parallel to the direction of the wave propagation. The second type represents shear or transversal waves for which the particle displacement is perpendicular to the direction of wave propagation. The velocities for three possible perpendicular paths that an ultrasonic wave can travel through a material subjected to uniaxial stresses were presented in Figure 27. The relative changes in these wave velocities with stress were studied by several researchers (Hughes and Kelly 1953; Santos and Bray 2000; Bray and Tang 2001).

Egle and Bray (1976) experimentally investigated the variations in wave velocities with the strain (Equation 23) for railroad rail specimens. The specimens were loaded uniaxially in tension and compression and the relative change in the wave speed was measured under different strain levels (Figure 28). It can be seen from Figure 28 that the variation in the velocity of the longitudinal waves propagating parallel to the load is much greater than any other waves and it is followed by the shear waves when the particles vibrate in the direction of the load. Furthermore, longitudinal waves propagating across the thickness of the specimen do not show sufficient variation in the time of flight to be used to verify the change in the bulk stress (Santos and Bray 2000). In addition to the wave propagation and polarization direction, the type of applied load
also has an effect on the sign of the relative variation of the wave velocity. $V_{22}$ and $V_{23}$ velocities increase under tension meanwhile others show a decreasing trend.

![Figure 28: Relative changes in wave speed with strain (Egle and Bray 1976).](image)

Ultrasonic signal characteristics of the transducer such as the frequency and the shape of the pulse may also have an influence on the acoustoelastic measurements. In applications like investigation of steel bars or multi-wire steel strands, ultrasonic signals propagate as guided waves with a dispersive behavior and the propagation velocity changes with the signal frequency (Rizzo and Di Scalea 2003). Furthermore, even though the acoustoelastic theory relies on linear dependency of ultrasonic wave velocity on the strains, the use of wide band signals instead of narrow band ones can result in significant nonlinearity in some materials (Mishakin et al. 2006).
Finally, the use of a coupling medium for contact transducers is another factor that can effect acoustoelastic measurements. The irreproducibility of the coupling between transducers and specimen is the source of much of the difficulty encountered in making acoustoelastic measurements (Pao et al. 1984).

Acoustoelastic measurement of stresses has competing effects also intrinsic to the specimen materials. The uniformity of the microstructure and material anisotropy are two important material factors that affect the accuracy of acoustoelastic measurements (Sgalla and Vangi 2004; Pao et al. 1984). The presence of residual stresses is another factor that should be taken into account in acoustoelastic stress measurement. The lattices, under residual stresses, will have different elastic properties than the unstressed lattices, and this will affect the velocity at which a stress wave propagates (Stobbe 2005). Finally, temperature conditions during measurements also need to be taken into consideration and temperature corrections for wave velocity changes has to be made (Szelazek 1994).

### 4.2 Acoustoelasticity for Plastic Deformations

Acoustoelasticity and the formulations presented earlier rely on the elastic changes in the strain of materials. As was mentioned in Section 4.1.3, acoustoelastic measurements are strongly affected by the microstructure of the tested material. It is well known that plastic deformation is accompanied by microstructural material property changes, and also that these changes affect the macroscopic plastic response of the material (Kobayashi 1998). Reorientations due to plastic deformations and inhomogeneous localization of the plastic strain (e.g. localized slip bands) characterize the plastic instability. Ultrasonic signal propagation properties are directly affected by these changes in the material properties, and therefore, the acoustoelastic theory explained in Section 4.1.2 need to be modified for cases where plastic deformations are present.
Several researchers have been studying this issue in order to develop theoretical models for acoustoelasticity in plastically deformed materials (Gamer and Pao 1983; Johnson 1981). Later, these theories were modified by others, however, the proposed methods either considered the effect of only small plastic deformations (Pao et al. 1991), or the experimental data was not adequate enough to examine the accuracy of the methods (Kobayashi 1986). Even though theoretical studies considering large plastic strain ranges were later carried out (Kobayashi 1998), the experimental research in the literature investigating acoustoelastic responses to plastic deformations is very limited.

Wu (1989) studied the relaxation of acoustoelastic birefringence. Carbon steel specimens were loaded up to the plastic range and after unloading the specimens, acoustoelastic measurements were taken at different times. It was shown that, the measured acoustoelastic birefringence values decrease in time and stabilize after an hour of relaxation time. In another study, Daami et al. (1987) studied the effect of small plastic deformations (below 1% strain) in steel, aluminum, brass and pure titanium. Comparing the acoustic birefringence results for the tested materials, it was concluded that material characterization is required for accurate acoustoelastic stress measurement and that the plastic deformations cause changes of varying degree in acoustic response, depending on the material.

Wong and Johnson (1990) conducted ultrasonic measurements with both longitudinal and shear waves on aluminum subjected to elastic-plastic deformations. It was shown that the changes in wave velocities continue to increase or decrease at a slower rate during plastic deformations than the rate in the elastic range. Figure 29 summarizes the results of this study as it illustrates the relation between the velocity change and strain for aluminum tested with uniaxial compression and tension. Few other researchers (Kwun 1985; Wu et al. 1991) presented similar results for the acoustoelastic response of steel in plastic deformations below 3%.
The literature review for acoustoelastic measurements at stresses far beyond yielding revealed only a single study where Tang and Bray (1996) used critically refracted longitudinal waves to study the relationship between the travel time versus applied stresses. A measurement system maintaining constant distance between the transmitter and receiver transducer was used to measure the time of flight, and it was shown that, the travel time before yielding increases very little compared to the severe jumps in the plastic range (Figure 30).

It is clear that, there are very limited studies in the literature investigating the acoustoelastic response of materials under plastic deformations. The present research studies show that the acoustoelastic response of a material is affected by various factors and is
considerably different in the plastic range of stresses. Furthermore, the rate of change in the velocity of signals for plastic deformations is specific to the type of material. Acoustoelastic stress measurement methods, therefore, needs to be improved even more and supported with more experimental data for higher accuracy in stress measurement.

![Figure 30: Lcr travel time versus applied stresses (Tang and Bray 1996).]

Although this dissertation mainly focuses on several time and frequency domain characteristics of ultrasonic signals for measurement of stress levels in steel, the experimental database was used to investigate the acoustoelastic response of steel prior to and beyond yielding.

### 4.3 Acoustoelastic Results

Acoustoelastic analysis is based on studying the relative changes in the wave velocity with respect to the strain level in the material. The key point in acoustoelastic stress measurement is the requirement for the wave velocity of the unstressed case. This issue becomes one of the most
important factors in acoustoelastic testing that affects the accuracy of the measurements. Moreover, the choice of signal type (i.e. longitudinal or shear wave), and the polarization direction of the latter case also directly affects the stress evaluation.

The experimental database, therefore, was first investigated in terms of acoustoelasticity. The time of flight values of the ultrasonic waves were calculated by measuring the distance between several characteristic points of consecutive echoes. The dependences of the wave velocities on the applied stress and strain levels were studied for longitudinal waves as well as shear waves with perpendicular and parallel polarizations to the loading direction. The analysis method and the results are presented next.

4.3.1 Acoustoelastic Analysis of Ultrasonic Signals

As was presented in Table 2, both longitudinal and shear wave measurements were taken during the experiments. During all ultrasonic measurements the transducers were placed on the specimens so that the signals propagate through the thickness in a perpendicular direction to the loading. The longitudinal signal measurements were mostly conducted with the through transmission test mode, while the single shear transducer was operated with the pulse – echo mode polarized parallel and perpendicular to the applied stress direction. However, more tests were conducted with the longitudinal transducers since the shear transducer was available in later stages of the research. Therefore, the acoustoelastic analysis results are presented in two separate sections; Section 4.3.2 is based on only the preliminary longitudinal measurement results, while Section 4.3.3 analyzes acoustoelasticity for both the longitudinal and the shear waves. The three transducer configurations are illustrated in Figure 31. Even though the longitudinal transducer configuration in Figure 31-a is for through transmission mode, the pulse – echo mode was used several tests. The shear transducers are fabricated so that the cable input direction is parallel to
the direction of particle motion (polarization). Since the transducers were detached between the ultrasonic measurements (during loading), it was hard to maintain the exact same polarization angle at every shear wave measurement. Even though the precision of perpendicular (Figure 31-b) and parallel polarization (Figure 31-c) were double-checked visually before measurements, little errors in due to the small changes in polarization angle may be present in the results. Based on the velocity designations presented in Figure 27, the ultrasonic measurements illustrated in Figure 31 correspond to the wave velocities $V_{22}$, $V_{23}$ and $V_{21}$, respectively.

![Configuration of the transducers](image)

**Figure 31:** Configuration of the transducers (a) longitudinal transducers for the through transmission mode, (b) shear wave transducer polarized perpendicular to loading, and (c) shear wave transducer polarized parallel to loading.

The acoustoelastic analysis of the experimental database is based on measuring the time of flight (TOF) between the consecutive echoes of signals acquired at target stress levels. Even though the acquired length of signals include more than three echoes, the TOF measurements were made using only the first three echoes to avoid echoes with low signal to noise ratios. A longitudinal
signal acquired using the through transmission mode for the unstressed case is illustrated in Figure 32 where it can be seen that the level of signal noise is small enough to be negligible for acoustoelastic measurements. Therefore, no denoising or filtering method was applied to the signals before acoustoelastic measurements.

![Figure 32: Illustration of a longitudinal signal with multiple echoes.](image)

The TOF values (between the first three echoes) were measured using three different critical points on the echoes; namely the positive peak amplitudes, negative peak amplitudes and the points of zero intersections. The locations of these three points of interest were detected and recorded using special MATLAB algorithms. The positive and negative peaks were directly obtained from an algorithm that locates maximum and minimum peaks of the echoes. The zero intersection locations were calculated using linear interpolation between the two detected data points.
points (in the segment that has a left-end bound of the first positive or the first negative peak) just above and just below zero amplitude. These three methods for calculating the TOF between the echoes are presented in Figure 33. Two values of TOF between the first three echoes were obtained for each three methods at every target stress level that the loading was held for ultrasonic measurements. The average of these two values were then taken, and used for calculating the relative change in the wave velocity.

\[
\frac{\Delta V}{V_0} = \frac{V_i - V_0}{V_0} = \frac{d_i/t_i - d_0/t_0}{d_0/t_0}
\]

(24)

where \( V, d \) and \( t \) are the wave velocity, signal propagation distance (i.e. specimen thickness) and the TOF values. The subscript ‘i’ denotes the stress case and subscript ‘0’ denotes values

**Figure 33:** Illustration of the three methods used for calculating the time of flight (TOF) values between the first three echoes.
obtained from the unstressed condition. The initial thicknesses of the specimens, through which the signals propagate, are measured with a digital caliper and therefore, the $d_0$ values are known. The transverse strains in the elastic range of the tested materials are not higher than an approximate level of $\% 0.8$. Therefore, the changes in the specimen thickness can be neglected and the specimen thickness at a certain stress level then becomes

$$d = d_i = d_0$$  \hspace{1cm} (25)$$

for all elastic strain/stress levels. When Equation 24 is modified, the percentage of change in the wave velocity can then be expressed as

$$\frac{\Delta V}{V_0} (\%) = \frac{d/t_i - d/t_0}{d/t_0} \times 100 = \frac{1/t_i - 1/t_0}{1/t_0} \times 100 = \frac{t_0 - t_i}{t_0} \times 100$$  \hspace{1cm} (26)$$

For the plastic strain levels, the actual strains should be measured during the test, at the stress levels where ultrasonic measurements are taken. This usually is achieved by attaching strain gauges on the test specimens in the transverse directions. However, because of the small specimen thicknesses and test setup, transverse strains could not be measured. Therefore, the assumption in Equation 25 was also extended for the plastic stress levels. This would sure cause errors in velocity measurements for plastic strains but the obtained results still provide useful information for understanding the acoustoelastic response of the tested steel. Besides, the main focus of this research was not the accurately establishing the acoustoelastic response of steel.

For every stress level, the two TOF values obtained between the first three echoes were first averaged and then used for calculating the percentage relative change in the wave velocity at that stress level. The three relative velocity change values calculated for each of the three aforementioned TOF measurement methods were also averaged to be used for the graphical representation of the results. The preliminary acoustoelastic measurements taken with the initial set of tests (Test1 through Test19) with longitudinal transducers are presented in Section 4.3.2,
while the results for longitudinal and shear waves (polarized in two perpendicular directions) are compared in Section 4.3.3.

4.3.2 Preliminary Acoustoelastic Results

Using the methods mentioned in the previous section, the relative changes in the longitudinal wave velocities are calculated for all four groups of specimens. A monotonic increasing load was applied to specimens up to failure and ultrasonic measurements were taken at the target stress levels. The changes in the wave velocities were calculated using the procedures described in the previous section. The results were then investigated versus both the strains and stresses. The graphical representations of the results are presented in Figures 34 through 41 for all four groups of specimens.

Figure 34: Relative changes in the longitudinal wave velocity vs. the applied tensile strains for group of Type1 specimens.
Figure 35: Relative changes in the longitudinal wave velocity vs. the applied tensile stresses for group of Type1 specimens.

Figure 36: Relative changes in the longitudinal wave velocity vs. the applied tensile strains for group of Type2 specimens.
Figure 37: Relative changes in the longitudinal wave velocity vs. the applied tensile stresses for group of Type2 specimens.

Figure 38: Relative changes in the longitudinal wave velocity vs. the applied tensile strains for group of Type3 specimens.
**Figure 39:** Relative changes in the longitudinal wave velocity vs. the applied tensile stresses for group of Type3 specimens.

**Figure 40:** Relative changes in the longitudinal wave velocity vs. the applied tensile strains for group of Type4 specimens.
It can be seen from the graphical results that the dependence of the ultrasonic velocity on the uniaxial strains is linear as the theory suggests (Figures 34, 36, 38 and 40). Moreover, the relative wave velocity increases with increasing tensile strains which also correlates with the theory and the experimental results of Egle and Bray (1976) on railroad rail steel. However, even though the four groups of specimens are hypothetically made of the same material (Grade 36 steel), the acoustoelastic constants (i.e. the slope of the lines) of the four groups are different. The highest and the lowest acoustoelastic constants were calculated for the Type1 and Type3 specimens, respectively while the acoustoelastic constants of the Type2 and Type4 specimens are relatively close to each other. These variations in the acoustoelastic constants may be due to the several complications and challenges in acoustoelastic stress measurement methods such as the effect of microstructure or the accurate determination of the unstressed case wave velocity.

**Figure 41:** Relative changes in the longitudinal wave velocity vs. the applied tensile stresses for group of Type4 specimens.
When the changes in the velocities are investigated versus the applied uniaxial stresses (Figures 35, 37, 39 and 41), the stress values were normalized with the yield strength of the tested group of specimens and the x-axes values are presented as percentages of the yield strength. Acoustoelastic measurements reveal very little or no changes in the elastic range of the material. For stresses above the yield strength, on the other hand, the relative changes in wave velocities show sudden and intense increases. This nonlinear increase in the wave velocity after yielding was also observed by Tang and Bray (1996).

The differences between the acoustoelastic responses of elastic and plastic strains are not analyzed or presented in this section due to the inconsistency of the results in the elastic range of the material. However the results of both the longitudinal and the shear wave (polarized perpendicular and parallel to the loading direction) measurements are presented in the following section in order to examine and differentiate the acoustoelastic responses in the elastic and plastic stress levels.

**4.3.3 Acoustoelastic Analysis of Longitudinal and Shear Waves in Steel**

Following the preliminary acoustoelastic measurements of longitudinal waves travelling perpendicular to the applied stresses, further tests were conducted on the four specimen groups where both longitudinal and shear wave transducers were used. Two polarization directions (perpendicular and parallel to the loading direction) were used for the measurements with the shear transducer.

The results obtained from the preliminary tests prompted a change in the signal acquisition process. More than one signal was acquired from the unstressed condition and the calculated TOF flight values were averaged and used for determining the relative changes in velocities to avoid the errors associated with the initial measurement. The acoustoelastic
responses are investigated both in the elastic and plastic regions of the material and the results are presented in graphical form for all four groups of specimens.

First, Type1 specimens were tested under monotonic increasing tensile stresses. Ultrasonic measurements were taken with longitudinal and shear waves at target stress levels at which the loading was held. The acoustoelastic results within the elastic range of the material is presented in Figure 42 for longitudinal and shear waves. It first can be seen that the velocity of longitudinal waves propagating perpendicular to the applied axial load increases with increasing strains while a decreasing trend is observed for shear waves polarized parallel to the loading. The same behavior was addressed in the literature for steel by Egle and Bray (1976) and their experimental results (Figure 28). The designations of the wave velocities used for testing Type1 specimens based on Figure 27 are $V_{22}$ (longitudinal wave propagating perpendicular to the loading) and $V_{21}$ (shear waves polarized parallel to the axial load).

![Graph](image)

**Figure 42:** Relative changes in the wave velocities vs. the elastic strain for longitudinal waves and shear waves polarized parallel to the loading direction (Type1 Specimen).
Based on the theory of acoustoelasticity and previous experimental studies, shear waves polarized parallel to the loading direction are more sensitive to the changes in the applied uniaxial stress than longitudinal waves propagating through the thickness of the material. Figure 42 confirms the theoretical predictions as a lower acoustoelastic constant (slope of the trendline) was determined for the longitudinal wave measurements.

When the results are investigated considering both the elastic and plastic stress levels, similar behavior to the results presented in the preliminary tests (see Section 4.3.2) were revealed. The relative changes in the wave velocities increase exponentially after yielding for both longitudinal and shear wave measurements. Figure 43 illustrates the absolute changes in the wave velocities versus the applied uniaxial tensile stresses for both the longitudinal and shear waves for Type1 specimen group. The stress values are normalized with the yield strength of the material and presented as a percentage of yield stress on the abscissa in Figure 43.

![Relative changes in wave velocities vs. uniaxial tensile stresses](image)

**Figure 43:** Relative changes in the wave velocities vs. uniaxial tensile stresses for longitudinal waves and shear waves polarized parallel to the loading direction (Type1 Specimen).
Additional ultrasonic tests with a shear transducer polarized perpendicular to the loading direction were conducted on Type2 specimens. The relative changes in the wave velocities versus the applied uniaxial tensile strains are presented in Figure 44 for all three types of acoustoelastic measurements within the elastic range.

![Figure 44](image_url)

**Figure 44:** Relative changes in the wave velocities vs. the elastic strain for longitudinal waves and shear waves polarized parallel and perpendicular to the loading direction (Type2 Specimen).

The acoustoelastic response of Type2 specimen group in the elastic range is in agreement with the theory where the shear waves propagating and polarized perpendicular to the direction of loading ($V_{23}$ based on the designation in Figure 27) have the lowest variation (i.e. acoustoelastic constant or trendline slope) with the axial strains (Santos and Bray 2000). Therefore these waves are the weakest candidates to be used in acoustoelastic stress measurement. When the acoustoelastic measurements are investigated versus the applied stresses for Type 2 specimens, similar results are obtained (Figure 45).
Similar ultrasonic tests were also conducted on Type3 and Type4 group of specimens with a total of three transducer configurations (longitudinal, shear polarized perpendicular and parallel). The graphical results are presented in Figures 46 through 49. Except for the acoustoelastic measurements of Type4 specimens with shear transducers polarized perpendicular to the loading direction (Figure 49), all results are qualitatively in agreement, where the highest sensitivity of velocities on the applied axial strains was measured for shear waves travelling perpendicular but polarized parallel to the loading direction. However, even though all specimen materials are structurally similar (Grade 36), the acoustoelastic constants (trendline slopes) of the three measurement configurations show variations. Therefore, very little or localized changes in the material properties and small errors made during acoustoelastic measurements may lead to serious inaccurate estimates of the state of stress in existing structures.

**Figure 45**: Relative changes in the wave velocities vs. uniaxial tensile stresses for longitudinal waves and shear waves polarized parallel and perpendicular to the loading direction (Type2 Specimen).
**Figure 46:** Relative changes in the wave velocities vs. the elastic strain for longitudinal waves and shear waves polarized parallel and perpendicular to the loading direction (Type3 Specimen).

**Figure 47:** Relative changes in the wave velocities vs. uniaxial tensile stresses for longitudinal waves and shear waves polarized parallel and perpendicular to the loading direction (Type3 Specimen).
**Figure 48:** Relative changes in the wave velocities vs. the elastic strain for longitudinal waves and shear waves polarized parallel and perpendicular to the loading direction (Type 4 Specimen).

**Figure 49:** Relative changes in the wave velocities vs. uniaxial tensile stresses for longitudinal waves and shear waves polarized parallel and perpendicular to the loading direction (Type 4 Specimen).
4.4 Summary

In this chapter, the theory of acoustoelasticity was reviewed. It was applied on the signals in the test database, and the results were discussed. Based on these results, it can be said that acoustoelastic stress measurement methods suffer from a host of complications and factors other than stresses affecting the ultrasonic wave velocity (see Section 4.1.3). These complications arise from factors such as the measurement method, microstructure of the material and the temperature. Taking into consideration of all these factors that affect the accuracy of stress measurement may not be very practical in cases where fast and reliable stress condition assessment is necessary. Furthermore the lack of experimental studies investigating the acoustoelastic response of materials under plastic deformations causes acoustoelasticity to be very challenging method for measurement of stresses where plastic strain levels are reached.
CHAPTER 5 – CHARACTERISTICS OF ULTRASONIC WAVES AT DIFFERENT STRESS LEVELS

Ultrasonic wave characteristics are known to be affected by the stress state of the material through which the signal propagates. The literature shows that the magnitude of these changes in signal characteristics is directly related with testing methods and material properties. As was presented historically in Chapter 4, the relationship between applied stress and ultrasonic wave velocity has been the focus of theoretical and experimental investigations. Wave velocities were used for determining stress states in various materials. In addition to ultrasonic wave velocity, changes in several other signal characteristics such as the resonance and center frequency, Debye temperature and Grüneisen parameter were also investigated with increasing tensile stresses (Fukuhara and Sampei 2000; Takahashi et al. 1978).

However, other than the acoustoelastic phenomenon, the changes in the signal characteristics mentioned above have not been commonly used for determining the stress state in structural materials. This is either because more experimental research is needed, or the magnitude of changes in the investigated parameters was not strong enough for practical use in stress measurement. Even the acoustoelastic theory, which has been extensively used as a nondestructive stress measurement technique in various fields, has certain complications and challenges as was mentioned in Section 4.1.3. Furthermore, the majority of the research on acoustoelastic stress measurement considers the relative changes in the wave velocities only in the elastic stress range of materials. With few exceptions, the literature review revealed that more
experimental research has to be done in order to study the changes in the ultrasonic signal characteristics with applied stresses especially beyond yielding.

The presented dissertation, instead of the studying the aforementioned signal characteristics, investigates the dependency of several time and frequency domain characteristics of ultrasonic signals on the tensile stresses. As of time domain parameters, the peak positive amplitude and the signal energy of the echoes were analyzed. For the spectral analysis, three transformation methods; namely, the Fast Fourier, Chirp-Z and Wavelet Transforms, were used.

The first phase of studying the experimental database of acquired ultrasonic signals was determining the number of echoes to be considered for further analysis. Later, the windowed echoes are used for obtaining the time and frequency domain parameters mentioned above and the changes in these parameters were studied with changing tensile stresses. Finally, the results are analyzed statistically and the performance of the presented study for yield detection in steel structures is tested with Receiver Operating Characteristic (ROC) analysis. All the procedures for the analyzing the database, investigated time and frequency domain parameters, the experimental and statistical results are presented next.

5.1 Signal-to-Noise Ratio Analysis and Filtering of Signals

With the test setup presented in Section 3.1, ultrasonic signals with multiple back surface echoes are acquired (Figure 32). As an ultrasonic signal propagates between the two parallel surfaces of the tested material, the amplitudes of the consecutive back surface echoes decay due to attenuation.

On the other hand, decreases in the signal amplitudes with increasing stresses (in the plastic range of the tested material) were observed during the preliminary experiments of this study. These decreases in the signal amplitude lead to more obtrusive levels of background noise
for increasing number of echoes. Therefore, the strength of echoes relative to the background noise had to be measured in order to determine the number of echoes to be considered for the analysis of results. This measure is actually a well known electrical engineering concept named Signal-to-Noise Ratio (SNR) and it is expressed as

\[
SNR = 10 \log_{10} \frac{P_S}{P_N} (dB) \tag{27}
\]

where \( P_S \) and \( P_N \) are the power of the meaningful segment of the signal and the power of the background noise, respectively. The power of a discrete signal, \( x[i] \), with a length, \( L \), is determined by

\[
P = \frac{1}{L} \sum_{i=1}^{L} |x[i]|^2 \tag{28}
\]

A total number of ninety-two signals from the test database were used for SNR analysis. Each signal was manually divided into twelve segments, six of which were the first six echoes, and the remaining were the corresponding segments of background noise. Figure 51 illustrates the segmentation of the first six echoes (designated with ‘\( S’ \)) and the corresponding background noises (designated with ‘\( N’ \)). Using Equations 27 and 28, SNR values are computed for the first six echoes of the ninety-two signals.

The calculated SNR values for a specific echo do not show significant variations while the material is subjected stresses in the elastic range. However, SNR values begin to decrease starting from the yield stress level. For simplicity, the calculated SNR values of only the first echo are presented versus the applied tensile stress level in Figure 50. It can be seen that, SNR values for the first echo of signals acquired from the specimens in the elastic range are mostly above 25 dB, while the values drop down to 15 dB level for increasing plastic deformations.
Figure 50: Manual segmentation of the signals into six echoes for SNR analysis.

Figure 51: SNR values of the first echo vs. the level of applied tensile stresses.
The SNR values also decrease with increasing number of echoes due to attenuation. For the third echo, the calculated minimum SNR values are just above 10 dB level, while they drop down to approximately 8, 6 and 5 dB levels for the fourth, fifth and sixth echoes, respectively. The decrease in the SNR values for the signals acquired at the unstressed case and at a stress level in the plastic range (65 ksi) of the specimen material is illustrated in Figure 52. It can be seen that the SNR gradually decreases with the increasing number of echoes as well as increasing stress levels.

Figure 52: SNR values of the first six echoes for the unstressed case and for a stress case beyond yielding.

Considering the SNR analysis results, an acceptable level of SNR had to be determined. Researchers have been studying various methods to improve the signal-to-noise ratio of ultrasonic NDE signals (Honarvar et al. 2004; Liu et al. 2006) but a good signal-to-noise ratio value is peculiar to the type of testing and it is mostly determined based on the testing...
personnel’s judgment. For this study, the first three echoes are considered to have acceptable SNR and determined to be used for time and frequency domain analyses of the results.

In terms of filtering, a simple signal filtering method, Moving Average Filter (MAF), was decided to be used since the background noise was relatively low and signal overlapping was not present because of the selected low pulse repetition frequency of the pulser/receiver. The MAF is a very simple type of Finite Impulse Response (FIR) filters. It is commonly used for filtering time domain encoded signals due to its simplicity and ease of use (Smith 2002). Moving average filters basically a specified number of data points of the input signal. The five point moving average filter used in this study is expressed as

\[ y[i] = \frac{1}{5} \sum_{j=0}^{4} x[i + j] \]  

(29)

where \( x[i] \) and \( y[i] \) are the input and the output signals, respectively. The first three echoes of all the signals in the database were filtered using Equation 29 so that they can be analyzed with the methods that will be covered in Section 5.2.

The processes before filtering, namely; the segmentation of the signals and determination of the echoes to be used, were done manually for the analysis of the results in this dissertation. The start and the endpoints of the meaningful signals and the corresponding background noises were recorded manually while the first three echoes were chosen to be used for further analysis based on the SNR observations. However, development of an algorithm (in collaboration with Dr. Hsiao-Chun Wu from the Department of Electrical and Computer Engineering of Louisiana State University) for automating these steps and eliminating the human effort has been the main focus of the research while this dissertation was being written. The details of the algorithm for automating the segmentation of signals and selection of the echoes will be further discussed in Chapter 6.
All the first three echoes of the signals in the experimental database were manually windowed and filtered with the five point MAF. The echoes are then analyzed with signal processing applications in order to obtain the investigated time and frequency domain parameters, and the used analysis methods are presented next.

### 5.2 Investigated Signal Characteristics

During the initial ultrasonic tests, changes in the amplitude of the signals were visually observed during acquisition, especially for stresses above yielding. The first echoes of the signals acquired at zero and 55 ksi stresses of the experiment Type1-Test5 are shown in Figure 53 to illustrate the decrease in the amplitude. This fact was scientifically investigated in this dissertation in order to develop an ultrasonic testing tool for studying tensile stress levels in steel.

![Figure 53: The observed decrease in the signal amplitude for high stress cases (Type1-Test5).](image-url)
The first three echoes of the segmented signals are analyzed in both the time and frequency domains. For the time domain analysis, the changes in the peak positive amplitudes and the signal energy values with the applied tensile stress were investigated for all four groups of specimens explained in Section 3.2.1. The frequency domain parameters include the peak amplitudes of the Fast Fourier, Chirp-Z Transforms as well as several more parameters related to Wavelet coefficients. The experimental results are presented in Section 5.3 however, all the methods used, and the investigated parameters are presented next.

5.2.1 Time Domain Parameters

The time domain analysis of the experimental database consists of two methods, one of which is the detection of the peak amplitudes of the first three echoes of the acquired signals (Figure 54). A MATLAB algorithm was used to detect the positive peaks and the detected values were recorded. Three separate data sets were built for each conducted ultrasonic test containing the peak amplitudes of the first, second and third echoes of the signals acquired from the specimen at the target stress levels. In order to avoid the effect of changes in test settings, all data sets were normalized with the peak amplitude of its unstressed case echo.

In addition to the peak amplitudes, signal energies of the first three echoes were calculated as the second investigated time domain parameter in this study. The signal energy for a discrete signal \( x[i] \) of length \( N \) is expressed as

\[
E = \sum_{i=1}^{N} |x[i]|^2
\]  

(30)

Similar to the peak amplitude data sets, all calculated signal energy data sets of the first, second and third echoes were normalized with the signal energy of its unstressed case echo to avoid effects of the changes in test settings on the experimental results.
5.2.2 Frequency Domain Parameters

For the spectral analysis of the experimental database three DSP transformation techniques, namely; the Fast Fourier Transform (FFT), Discrete Wavelet Transform (DWT), and the Chirp-Z Transform (CZT), were used. First, the changes in the peak amplitudes of the FFT and CZT spectra were investigated with applied tensile stresses. Later, the Discrete Wavelet Transform was used to decompose the first three echoes, and three parameters wavelet coefficient parameters, namely; the maximum wavelet coefficient, peak-to-peak amplitude and the root mean square of the coefficients were calculated. The theory of these three transformations and the computation of the investigated frequency domain signal characteristics are explained next.

5.2.2.1 Fast Fourier Transform (FFT) Analysis

The first spectral analysis method used was the well known Fast Fourier Transform. The FFT is a powerful and efficient algorithm of implementing the Discrete Fourier Transform (DFT) as it
considerably reduces the amount of computation. FFT was first introduced by Cooley and Tukey (1965) and since then, it has been frequently used in many fields for various applications including NDE&T in civil engineering. The DFT of a discrete sequence, \( x[n] \), is

\[
X_k = \sum_{n=0}^{N-1} x[n] e^{-j(2\pi/N)nk} \quad k = 0, ..., N - 1
\]  

The FFT algorithm implements the above equation of length \( N \) with a frequency resolution of \( \Delta f = f_s / N \), where \( f_s \) is the fixed sampling frequency (Wang 1990). Therefore, in order to increase the frequency resolution of the FFT algorithm, \( N \) should be picked as large as practical (Daponte et al. 1995). Some FFT algorithms require \( N \) to be a power two and therefore signals either need to be truncated or zeros have to be padded to the dataset.

The spectra for the first three echoes of the signals in the test database were computed with the default FFT function of MATLAB using the closest power of two for \( N \), and the maximum FFT amplitudes were recorded. The same normalization process (normalizing the data sets with the unstressed case value) with the time domain parameters was applied to the FFT peak amplitudes to avoid the changes in the test settings.

### 5.2.2.2 Chirp-Z Transform (CZT) Analysis

As a second spectral analysis method, the Chirp-Z Transform (CZT) was used. The reason why this transformation method was chosen, was its capability to increase the frequency resolution without any zero padding (Nair et al. 1991). The CZT achieves the computation of the Z-Transform of a sequence, \( x(n) \), with \( N \) samples

\[
X(z_k) = \sum_{n=0}^{N-1} x(n) z_k^{-n} \quad n = 0, 1, ..., N - 1
\]  

by assuming
\[ z_k^{-n} = A^{-n} W^{nk} \quad k = 0, 1, ..., M - 1 \]  
(33)

where \( M \) is an arbitrary integer, and the terms \( A \) and \( W \) are complex numbers in the form of

\[ A = A_0 e^{j \omega_0} \quad \text{and} \quad W = W_0 e^{-j \Delta \omega_c} \]  
(34)

The terms \( \omega_0 \) and \( \Delta \omega_c \) are the initial angular frequency and the angular frequency increment in the Z-plane, respectively. The FFT samples the data along the unit circle in the Z-plane (Figure 55-b) while the Chirp-Z transform uses a spiral path (Figure 55-a). The two parameters in Figure 55-b: the initial spiral radius, \( A_0 \), and the spiral parameter, \( W_0 \), which identifies the direction of the spiral (towards the origin or outside the unit circle), are chosen by the user of the algorithm.

**Figure 55:** (a) FFT represented as samples taken around the unit circle, (b) The Chirp-Z Transform parameters: the spiral parameter \( W_0 \), frequency increment \( \Delta f_c \), initial frequency \( f_0 \), angular frequency increment \( \Delta \omega_c \) (Nair et al. 1991).

For the spectral analysis of the first three echoes with the CZT, the transformation length of 2048 was chosen. The \( A \) and \( W \) complex terms were chosen as the defined default values of the CZT function of MATLAB’s Signal Processing Toolbox. The maximum amplitudes of the
obtained frequency spectra were recorded for all three echoes, and each data set of CZT peak amplitudes were normalized with the value of the unstressed case.

Using the two DSP techniques mentioned so far, the normalized peak amplitudes were used as the first two parameters for investigating the dependence of frequency domain signal characteristics on the stress state of steel. Based on the first observations on the results, it should be noted that, except revealing a little smoother spectra, the results for the FTT and the CZT did not show significant differences for the ultrasonic signals analyzed in this study. The FFT and the CZT of the first echo of the 50 ksi tensile stress ultrasonic measurement for experiment Type1-Test6 are shown in Figure 56.

5.2.2.3 Discrete Wavelet Transform (DWT) Analysis

Considering the close results obtained from the FFT and CZT analyses, a third transformation method, The Discrete Wavelet Transform (DWT), was used for analyzing the test database. The first three echoes of the acquired signals are decomposed into the approximate and detail wavelet coefficients, and three features of the approximate wavelet coefficients (the maximum amplitude, peak-to-peak amplitude and the root mean square) are calculated.

Wavelet transform analysis uses little local wavelike functions known as mother wavelets or often, wavelets. Mother wavelets are used to transform the signal under investigation into another representation which presents the signal information in a more useful form and this transformation process is, mathematically, a convolution of the mother wavelet function with the signal (Addison 2002). When compared to the traditional Fourier Transforms that lose the tie resolution of non-stationary signals, wavelet transforms retain both the time and the frequency resolution (Rizzo and Di Scalea 2005).
Even though the theory of wavelet transforms were discovered by mathematicians earlier, they were first applied in geophysics in the mid 1980s to analyze data from seismic surveys, which were used in oil and mineral exploration (Boggess and Narcowich 2001). Starting from the 1990s, wavelet transform analysis has been applied to numerous fields from climate analysis to the analysis of financial indices, from heart monitoring to the condition monitoring of rotating machinery, from signal denoising to the denoising of images, from crack surface characterization to the characterization of turbulent intermittency, from video image compression to the compression of medical signal records, and so on (Addison 2002).

Wavelet analysis in NDE&T applications is mostly focuses on denoising signals (Gurley and Kareem 1999; Oruklu and Saniie 2004; Jiang et al. 2007; Rizzo et al. 2007), however, in this

![Figure 56: The FFT and the CZT of the first echo acquired from Type1-Test6 specimen at 50 ksi tensile stress.](image-url)
study, wavelets were used to decompose the signals so that the aforementioned features of the wavelet coefficients can be computed. The wavelet transform of a function $f(t)$ is

$$W_{j,n} = \int_{-\infty}^{+\infty} f(t) \psi(t)_j^* \, dt$$

(35)

where $\psi(t)^*$ is the conjugate of $\psi(t)$, the mother wavelet function, and $W_{j,n}$ are the wavelet coefficients. The decomposition of a signal is basically a series of wavelet transforms applied on the signal at the beginning level and then on the approximate wavelet coefficients for the following steps. The filter bank tree of three level signal decomposition used in this study is illustrated in Figure 57.

![Filter Bank Tree](image)

**Figure 57**: Three level wavelet decomposition by filter bank tree: The approximate (cA$_i$) and detail (cD$_i$) wavelet coefficients (Rizzo and Di Scalea 2005).
The terms DWLF and DWHF in Figure 57 are the discrete wavelet transform low-pass and high-pass filters, respectively. These filters are associated with type of mother wavelet used. Some of the commonly used wavelets are the Haar, Daubechies, Symlet, Coiflet, Morlet, Biorthogonal, Mexican hat and the Morlet functions. The choice of wavelet is very crucial for the success of the DWT. When the wavelet matches the shape of the signal well, then a large transform value is obtained (Addison 2002). Therefore, different mother wavelet functions that are most likely to match the shape of the echoes were used in this study. The three types of wavelets used for computing the DWT with MATLAB were the Symlet7, Biorthogonal 1.3, and the Biorthogonal 1.5 (Figure 58). Goodness of fit tests were performed on these functions and the Biorthogonal 1.3 mother wavelet observed to match the shape of the echoes slightly better than the other two functions.

![Figure 58: The shapes of a typical acquired echo and the used mother wavelets.](image-url)
All the echoes are analyzed with a three level wavelet decomposition using the aforementioned mother wavelets. The obtained approximate wavelet coefficients (designated as $cA_3$ in Figure 58) were used to calculate the three investigation parameters, namely; the peak amplitude, peak-to-peak amplitude and the root mean square (RMS). The peak and peak-to-peak amplitudes are illustrated in Figure 59 and the RMS of a discrete sequence, $x(n)$, with length $n$ is

$$RMS = \sqrt{\frac{1}{n} \sum_{i=1}^{n} x_i^2}$$  \hspace{1cm} (36)$$

The dependence of three parameters on the applied tensile stress level of the specimens is studied and the results for all the time and signal domain parameters (signal amplitudes, signal energies, FFT and CZT peaks and the three features of the wavelet coefficients) are presented next.

![Figure 59: The illustration of the three investigated features of the wavelet coefficients.](image)
5.3 Results of Time and Frequency Domain Analyses

All the time and frequency domain signal parameters are calculated as explained in Section 5.2. The data values that were calculated with the same analysis method and that belong to the same specimen, same ultrasonic measurement location (top, mid or bottom), and the same echo number (1\textsuperscript{st}, 2\textsuperscript{nd}, or 3\textsuperscript{rd} Echo) forms a data set. Each data set was normalized with its unstressed case value to avoid the changes in test settings.

For simplicity, the analysis results are presented in two separate sections. In Section 5.3.1, the results for Type1 group of specimens are explained in detail, while Section 5.3.2 discusses the results for the other three groups of specimens.

5.3.1 Experimental Results for Type1 Specimen Group

The experimental results of the four pilot tests and the six full tests conducted on Type1 specimens are presented in this section. The time domain parameters, the peak amplitude and signal energy, and the frequency domain parameters, the FFT and CZT peak amplitudes, peak amplitude, peak-to-peak amplitude and the RMS of wavelet coefficients, are studied graphically versus the applied stresses.

The database is divided into three stress intervals for the graphical representations one of which corresponds to the elastic range of the specimen materials (represented with red circle markers in Figures 60-70). The second interval is a transition interval where the stresses are between 100\% and 115\% of yield strength (represented with blue triangle markers in Figures 60-70), while the final interval corresponds to stresses above 115\% of the yield strength (represented with yellow diamond markers in Figures 60-70). The changes in the two time domain parameters are plotted versus the applied tensile stresses as percentage of the yield stress and the ratio of strains to the yield strain in log scale for Type1 specimens in Figures 60-63.
**Figure 60:** Normalized peak amplitudes vs. applied stresses for Type1 specimen group.

**Figure 61:** Normalized peak amplitudes vs. the ratio of strains to the yield strain for Type1 specimen group.
Figure 62: Normalized signal energies vs. applied stresses for Type1 specimen group.

Figure 63: Normalized signal energies vs. the ratio of strains to the yield strain for Type1 specimen group.
It can be seen in Figures 60 and 61 that, the normalized peak amplitudes in the first stress interval (before yielding) are scattered approximately around 1.0 level mostly in a range between 0.8 and 1.2 and Figures 62-63 show that this range is a little bit wider for the signal energies as the values are mostly distributed between 0.8 and 1.4. The main reason for this variation is mainly due to the little errors associated with the ultrasonic measurement taken at the unstressed case during the early experiments. In order to overcome this issue, several ultrasonic measurements were taken at the unstressed condition and these measurements were averaged before being used for normalizing the data sets.

After yielding, the normalized values for both methods show a sudden decreasing trend in the transition interval. The decrease in the transition interval is more intense for the signal energies compared to the peak amplitudes as the values drop down to levels even below 0.05, while they fall a little bit below 0.2 for the peak amplitudes.

Following the sudden decrease in the transition interval, the final stress interval shows a more stable behavior compared to the first stress interval (Bingol and Okeil 2008). Both the peak amplitude and the signal energy data points are distributed below a certain level until failure. It can be said that the normalized data points in this final interval are mostly below 0.6 for the peak amplitude. Meanwhile, the upper limit for the signal energy method in this final interval is roughly below 0.4. It is clear that, except the magnitude of the decrease in the transition interval, the results for the two time domain parameters correlate as they both reveal considerable distinctions between prior to and post yielding of the specimen material.

In order to investigate the effects of the applied stresses on the frequency domain characteristics, the results are first analyzed with the FFT and the CZT and the results are presented in graphical form in Figures 64 through 67.
Figure 64: Normalized FFT peak amplitudes vs. applied stresses for Type1 specimen group.

Figure 65: Normalized FFT peak amplitudes vs. the ratio of strains to the yield strain for Type1 specimen group.
Figure 66: Normalized CZT peak amplitudes vs. applied stresses for Type1 specimen group.

Figure 67: Normalized CZT peak amplitudes vs. the ratio of strains to the yield strain for Type1 specimen group.
The graphical representation of the results for the FFT and CZT peak amplitudes show similar results with the time domain parameters. The normalized values are distributed mostly in a range between 0.8 and 1.2, however, it can easily be noticed that the values in the first interval are less scattered compared with the time domain peak amplitude and the signal energy values. The sudden decrease in the transition interval that was illustrated in the analysis of the time domain parameters can also be observed for the FFT and CZT amplitudes in Figures 64 to 67. In the final interval, the normalized FFT and CZT amplitudes are below 0.6, mostly scattered between 0.2 and 0.4.

It can even be visually observed that the results for the Fast Fourier and Chirp-Z Transform amplitude methods reveal very close results. Therefore, for further frequency domain investigation, the experimental database was analyzed with the Discrete Wavelet Transform (DWT) using three different mother wavelets (Symlet7, Biorthogonal 1.3 and Biorthogonal 1.5). The calculated wavelet coefficients are used to compute three features, namely; the peak amplitude, peak-to-peak amplitude and the root mean square values.

Similar to the representation of the results for the aforementioned time and frequency domain parameters, the changes in the three wavelet coefficient features are illustrated versus the applied stresses. Very close results were obtained for the three mother wavelets used. Therefore, for simplicity, only the results for the DWT decomposition with the Biorthogonal 1.3 mother wavelet are presented in Figures 68 through 70.

The results for all of the three wavelet coefficient parameters reveal very close outcomes with each other, while they correlate with the results of all time and frequency domain parameters analyzed above. Similarly, the normalized values before yielding are scattered mostly above 0.9 levels, while they are accumulated above 0.6 for all three wavelet coefficient features.
**Figure 68:** The normalized peak amplitudes of the approximate wavelet coefficients vs. applied stresses (wavelet decomposition with Biorthogonal 1.3 mother wavelet).

**Figure 69:** The normalized peak-to-peak amplitudes of the approximate wavelet coefficients vs. applied stresses (wavelet decomposition with Biorthogonal 1.3 mother wavelet).
When Figures 68-70 are investigated more closely, it can be observed that the normalized root mean square (RMS) values show more consistency in the first stress interval. Furthermore, the distinction between the data prior to and after the transition interval is clearer for the normalized peak-to-peak amplitudes and RMS values.

All of the presented results so far, show similar behavior in all the three stress intervals. Even though there are clear distinctions between prior to and after yielding for all analysis methods, their performance and accuracy when used as the main parameter for nondestructively detecting yield in steel had to be compared and further studied by scientific means. Therefore, the results were analyzed statistically (Section 5.4) and threshold values were determined with Receiver Operating Characteristic (ROC) curves in order to classify the data before and after yielding (Section 5.5). Yet, the test results for other specimen groups are presented before then.

**Figure 70:** The normalized RMS values of the approximate wavelet coefficients vs. applied stresses (wavelet decomposition with Biorthogonal 1.3 mother wavelet).
5.3.2 Results for Type2, 3 and 4 Specimen Groups

Similar to the graphical analysis of Type1 specimen group, the results for the other three types of specimens were also studied. The experimental database for Type2, 3 and 4 groups of specimens were used to calculate the time domain parameters, the peak amplitude and signal energy, and the frequency domain parameters, the FFT and CZT peak amplitudes. The calculated parameters versus the applied stresses were studied considering the three stress intervals used in Section 5.2 and the graphical results are presented in this section.

To begin with, the experimental results of the Type2 specimen group are presented. The changes in the normalized peak amplitudes, signal energies, FFT and CZT peak amplitudes are plotted versus the applied tensile stresses as percentage of the yield stress in Figures 71-74. The red circle and the blue triangle markers represent the elastic range and the transition intervals, respectively, while the yellow diamond markers represent the final stress interval.

![Graph](image)

**Figure 71:** Normalized peak amplitudes vs. applied stresses for Type2 specimen group.
Figure 72: Normalized signal energies vs. applied stresses for Type2 specimen group.

Figure 73: Normalized FFT peak amplitudes vs. applied stresses for Type2 specimen group.
It can be seen from the graphical representations of the changes in the investigated parameters for Type2 specimen group that the normalized values show a decreasing trend after certain stress levels in agreement with the results for Type1 specimens. However, unlike Type1 specimens, the distinctions between the first and final intervals are not as clear except for the signal energies. Furthermore, the results show differences with the ones for Type1 specimens as the normalized values tend to start decreasing before the material reaches its yield strength.

When Figures 71-74 are closely examined, it can be seen that the normalized values are scattered around 1.0 level until 80% of yield strength for all methods, then keep decreasing up to the yield strength. Beyond yield, the normalized values are mostly stay in a range between 0.6 and 0.8 for the FFT and CZT peak amplitude methods, while they are even lower (below 0.5) for the signal energy method. Therefore, even though the stress intervals that were used for Type1
specimens were also used in Figures 71-74, the transition interval for Type2 specimens can be considered as the stress range between the 80% and the yield strength of the material as the decreasing trend falls in this interval.

The experimental results of the Type2 specimen group, presented as the dependency of the investigated time and frequency domain parameters on the stress levels, are in agreement with the results for Type1 specimens despite the fact that the distinctions between the first and the final stress intervals are not as clear as the ones for Type1 specimens. Especially for the time domain peak amplitude method, the normalized values do not show much potential for being used as a yield detection parameter because of the difficulties in classifying the data prior to and after yielding. For the FFT and CZT peak amplitude methods, the results are a little better than the ones for the time domain peak amplitudes. Signal energy method, on the other hand, overcomes other three investigated parameters showing clearer distinctions between the elastic and plastic strain levels and therefore, having greater potential for being used as a nondestructive yield detection technique.

The results for Type3 specimens were also analyzed with the same time and frequency domain parameters with the Type1 and Type2 specimens. The calculated values for the first three echoes of the acquired ultrasonic signals are graphically illustrated with the changing tensile stress levels in Figures 75-78. The results for the time domain parameters for the Type3 specimens are very close to the ones obtained for Type1 and Type2 specimens. The normalized values in the elastic range (first stress interval) are scattered mostly between the range of 0.8 and 1.2 (Figures 75-76). The normalized peak amplitude and signal energy values start decreasing drastically starting approximately around 90% of yield stresses, while they mostly fall below 0.5 and 0.3 levels for the peak amplitude and signal energy methods, respectively.
Figure 75: Normalized peak amplitudes vs. applied stresses for Type3 specimen group.

Figure 76: Normalized signal energies vs. applied stresses for Type3 specimen group.
Figure 77: Normalized FFT peak amplitudes vs. applied stresses for Type3 specimen group.

Figure 78: Normalized CZT peak amplitudes vs. applied stresses for Type3 specimen group.
On the other hand, the results for the FFT and CZT peak amplitudes reveal more consistent results in the first stress interval as the normalized values are mostly between 0.8 and 1.0. Furthermore, different than the results for the time and frequency domain parameters of Type1 and Type2, and the time domain parameters of Type3 specimens, the decreases in the FFT and CZT amplitudes are relatively linear in the transition and the final stress intervals (Figures 77-78).

When the graphical representations of the results for Type3 specimens are analyzed, it can be concluded that all four investigated parameters are affected by the presence of applied plastic strains in the specimen material, just like the experimental results for Type1 and Type2 specimen materials. In agreement with the experimental results of other specimen groups, the signal energy method for Type3 specimens show greater potential for being used for yield detection as the differences between the normalized values for elastic and plastic stress cases are larger when compared with other methods.

Finally, the same analysis methods were applied to the experimental database for the Type4 specimen group. Changes in the peak amplitudes, signal energies, the FFT and CZT peak amplitudes with increasing tensile stresses are illustrated in Figures 79-82. Unlike the results for the other three specimen groups, the calculated time and frequency domain parameters for Type4 specimens almost do not show a definite behavior. Except the slight decreases detected for the ultrasonic measurements that were taken just before the failure, the data points are mostly scattered between 0.8 and 1.2 for the peak amplitude, FFT and CZT peak amplitude methods, while this range for the signal energies is between 0.6 and 1.4. It can be concluded that, the effect of plastic strains on the investigated parameters for Type4 specimen material is not strong enough to enable these methods for being used as yield detection in steel.
Figure 79: Normalized peak amplitudes vs. applied stresses for Type4 specimen group.

Figure 80: Normalized signal energies vs. applied stresses for Type4 specimen group.
Figure 81: Normalized FFT peak amplitudes vs. applied stresses for Type4 specimen group.

Figure 82: Normalized CZT peak amplitudes vs. applied stresses for Type4 specimen group.
All of the results presented above for the four different specimen groups show that the presence of plastic tensile strains in steel has an effect on the investigated time and frequency domain characteristics of ultrasonic signals. Even though these effects may be minimal for a material like Type4 specimen, they can also be significant enough for other steels (having differences in composition, microstructure and forming method) to be used with ultrasonic nondestructive testing methods for yield detection in steel structures.

The reasons that are likely to cause these changes in the investigated time and frequency domain parameters will be further discussed in Chapter 6, but prior to the conclusions on this dissertation, the potentialities of the presented methods for being used as nondestructive testing tools for yield detection were statistically analyzed and optimum threshold values that satisfy the minimum detection errors were determined with Receiver Operating Curves (ROC).

5.4 Statistical Analysis of the Experimental Results

Following the graphical analyses, the results of all investigated parameters were analyzed statistically. As was mentioned in Section 5.3, the experimental results of Type1 specimen group represent the potential of the investigated parameters, to be used for yield detection, better than the ones for other three groups of specimens. Therefore, for simplicity, detailed statistical analyses were performed on the experimental results of Type1 specimen group and presented in this dissertation.

As the first step of the statistical analysis, the mean and the standard deviation values for all of the investigated parameters in the three stress intervals that were used for the graphical representation. The calculated mean and the standard deviation values of the seven time and frequency domain parameters, namely; the peak amplitude, signal energy, FFT and CZT peak
amplitudes, peak and peak-to-peak (PTP) amplitudes and the root mean square (RMS) of wavelet coefficients, are presented in Table 3.

**Table 3:** Statistical descriptors of the seven investigated parameters for Type1 specimen tests.

<table>
<thead>
<tr>
<th>Investigated Method</th>
<th>Statistical Parameters</th>
<th>Stress Interval (% of Yield Stress)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>≤100%</td>
</tr>
<tr>
<td>Peak Amplitude</td>
<td>Mean</td>
<td>1.063</td>
</tr>
<tr>
<td></td>
<td>Std. Dev.</td>
<td>0.111</td>
</tr>
<tr>
<td>Signal Energy</td>
<td>Mean</td>
<td>1.100</td>
</tr>
<tr>
<td></td>
<td>Std. Dev.</td>
<td>0.200</td>
</tr>
<tr>
<td>FFT Peak Amplitude</td>
<td>Mean</td>
<td>1.032</td>
</tr>
<tr>
<td></td>
<td>Std. Dev.</td>
<td>0.086</td>
</tr>
<tr>
<td>CZT Peak Amplitude</td>
<td>Mean</td>
<td>1.032</td>
</tr>
<tr>
<td></td>
<td>Std. Dev.</td>
<td>0.086</td>
</tr>
<tr>
<td>Wavelet Coefficient Peak Amplitude</td>
<td>Mean</td>
<td>1.091</td>
</tr>
<tr>
<td></td>
<td>Std. Dev.</td>
<td>0.140</td>
</tr>
<tr>
<td>Wavelet Coefficient Peak-to-Peak Amp.</td>
<td>Mean</td>
<td>1.077</td>
</tr>
<tr>
<td></td>
<td>Std. Dev.</td>
<td>0.120</td>
</tr>
<tr>
<td>Wavelet Coefficient RMS</td>
<td>Mean</td>
<td>1.061</td>
</tr>
<tr>
<td></td>
<td>Std. Dev.</td>
<td>0.094</td>
</tr>
</tbody>
</table>

It can be seen from Table 3 that, the statistical descriptors are in agreement with the graphical results as the mean values for the first stress interval are very close to 1.0 for all seven methods. Furthermore, when the graphical results are recalled, it can be stated that the normalized data points were scattered less in the first interval for the frequency domain parameters. This fact is confirmed by the statistical results, as the FFT, CZT and Wavelet methods have lower standard deviation values in this interval. Therefore, the spectral analysis parameters can be considered as more consistent methods for representing the behavior before yielding of steel.
Since the transition interval represents the sharp decrease between the two neighboring intervals, the mean and the standard deviation values for this interval do not have an important statistical meaning. However, the main criterion for determining the most effective method for yield detection is the intensity of the decrease in this interval (i.e. the drop in the mean values of before and after yielding). When the mean values of the final interval (above 115% of yield strength) are analyzed, it can be seen that normalized signal energy values show a larger decrease compared to the other six methods. Therefore, even though all investigated parameters show great potential for being used as a yield detection technique, signal energy method overcomes others having a higher dependence on the stress state of steel.

Further statistical analysis was then conducted on the results of the signal energy method. To begin with, a statistical distribution (e.g. normal, lognormal) was intended to be fit to the whole data values for the signal energy. However, due to the cluster of the data points above 0.8 and below 0.4 levels, the results cannot be represented with a single mode probability distribution. Therefore several bimodal distributions were generated considering different combinations of normal and lognormal distributions. A total contribution factor of one was distributed between the two defined probability distributions and the goodness-of-fit was measured using Chi-Square test.

The best bimodal probability function with the lowest Chi-Square value was found to be a combination of two lognormal distributions and it is shown with green color in Figure 83. This bimodal distribution clearly shows around which levels the data points before and after yielding are accumulated. The distance between the peaks of the two modes of the distribution supports the success of signal energy method for being used for yield detection. The fitted distributions for the other six methods are not presented in this dissertation, but the distance between the
peaks of the two modes are found to be closer for them as the intensity of the decrease in normalized values after yielding are smaller.

![Illustration of the fitted distributions to the signal energy data for the Type1 specimen data.](image)

**Figure 83:** Illustration of the fitted distributions to the signal energy data for the Type1 specimen data.

However, in order to use the database more efficiently for yield detection, the data points corresponding to before and after yield are also analyzed separately for fitting probability distributions. Based on the Chi-Square goodness-of-fit test results, two lognormal distributions were picked to represent the data of the first and the final intervals and they are demonstrated in Figure 83 with red and yellow colors, respectively. Both distributions correspond to data values varying between zero and infinity. Similar to the results of the bimodal distribution that was defined for the entire data, it can be seen that the two lognormal distributions do not overlap around high probability values.
In addition to the previously used final stress interval (beyond 115% of yield stress), more lognormal distributions were defined to fit wider final intervals starting from 110, 105 and 100% of yield stress of the specimen material. The cumulative areas above certain normalized levels of these four distributions are presented in Figure 84 with the cumulative area below these levels of the lognormal distribution that was defined for the first (elastic) stress interval. In other words, the curve for the elastic stress range is actually the Cumulative Distribution Function (CDF), while the curves for the plastic stress ranges are the inverse CDFs of the fitted distributions.

![Figure 84: Cumulative areas under the fitted lognormal distributions.](image)

It can be seen in Figure 84 that, the curve for the stress levels above 115% of yield does not overlap with the one for the elastic range (first interval). However, the more the plastic (final)
stress interval is widened (i.e. the transition interval is narrowed down); the more the curves overlap with the one for the elastic range as they are shifted towards the upper right corner of the figure. It can be concluded that, when a narrower or no transition interval is considered, the probability of detecting yield in steel decreases as the fitted distributions of the elastic and the plastic stress data overlap more.

The results of the statistical analysis provide very useful information about the performances of the investigated parameters as nondestructive yield detection methods. However, practical use of the presented study requires determination of threshold levels for yield detection. These threshold levels have to be identified specifically for the investigated time or frequency parameter, and they have to be determined in such a way that satisfies an optimum detection rate. For this reason, the experimental results were studied using Receiver Operating Characteristic (ROC) curves and the determination of threshold values for yield detection is discussed next.

5.5 Receiver Operating Characteristics (ROC) Analysis

The experimental and the statistical analysis results show that there are clear distinctions between pre- and post-yielding of specimen materials for all of the investigated parameters. The intense changes in the signal characteristics due to plastic strains can be used to establish threshold levels for classifying the data for detection of yielding. These threshold values have to be determined in such a way that they satisfy an optimum detection rate. Therefore, a technique that can analyze the performance of classifiers, namely the Receiver Operating Characteristic (ROC) analysis, was performed for determining the threshold values.

ROC analysis is a two-dimensional graphical technique for visualizing, organizing and selecting classifiers based on their performances (Fawcett 2006). ROC curves have been used for
determining classifiers in applications such as medical decision making and filter performance analysis (Vining and Gladish 1992; Kolan et al. 2007). ROC analysis is performed on the two sets of data (positives and negatives) that are being classified and the ROC curves are usually plotted with the false positive rate (FPR) versus the true positive rate (TPR) while a decision threshold value is varied across the full classifier range (Marzban 2004) in order to determine the optimal classifier that minimizes the FPR. The terms TPR and FPR can be expressed as:

\[
TPR = \frac{Correctly\, Classified\, Positives}{P} \quad \text{(37)}
\]

\[
FPR = \frac{Incorrectly\, Classified\, Negatives}{N} \quad \text{(38)}
\]

where \( P \) and \( N \) are the total number of positives and negatives, respectively.

**Figure 85:** A typical ROC curve and its characteristic points.
ROC curves always pass through the points (0, 0) and (1, 1) as demonstrated in Figure 85. The point (0, 0) represents the classifier that can detect neither the true nor the false positives while (1, 1) point can detect all positive cases but also all of the negatives. With the same sense, the x=y line corresponds to classifiers that can randomly guess the positives, which is basically nothing better than tossing a coin. Therefore, the performance of an ROC curve is determined by measuring how far it is from x=y line, and how close it is to the upper left corner of the graph. Thus, the ROC Curve-2 in Figure 85 has a better performance compared to Curve-1.

Another way of measuring the performance of ROC curves is calculating the area under the curve (AUC) as a scalar value (Bradley 1997). Since the maximum values of true positive and false positive rates are 1, the maximum AUC can also be 1. Therefore, the performance of an ROC curve increases as the AUC value becomes closer to 1. On the other hand, no realistic classifier can have an AUC less than 0.5 as random guessing produces the diagonal line x=y (Fawcett 2006). When the AUC is considered as the performance measurement method for the two curves in Figure 85, Curve-2 shows a better performance than that of Curve-1 as it has a larger AUC.

In this study, two different ROC analyses were performed on the investigated parameters for the experimental results of Type1 specimen group. In the first analysis case, the database was only divided into two stress intervals (before and after yield stress), while the second case includes the additional transition interval that was used in the graphical and statistical analysis of results in Sections 5.3 and 5.4. In other words, the first analysis case studies the performances of threshold values classifying data before and after yield strength, while the second case is for classifying the data before and after 115% of yield strength.

The values of thresholds were varied between zero and the next higher tenth of the maximum obtained normalized data and the TPR and FPR values were calculated at every
threshold level. For simplicity, the TPR, FPR, and the calculated AUC values of the signal energy method for two analysis cases on Type1 specimen group experimental results are presented in Table 4.

**Table 4: TPR, FPR and AUC values for the two ROC analysis cases on signal energy method.**

<table>
<thead>
<tr>
<th>Analysis Case 1</th>
<th>Analysis Case 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Threshold</td>
<td>TPR</td>
</tr>
<tr>
<td>0.00</td>
<td>0.000</td>
</tr>
<tr>
<td>0.10</td>
<td>0.185</td>
</tr>
<tr>
<td>0.20</td>
<td>0.630</td>
</tr>
<tr>
<td>0.30</td>
<td>0.696</td>
</tr>
<tr>
<td>0.40</td>
<td>0.733</td>
</tr>
<tr>
<td>0.50</td>
<td>0.756</td>
</tr>
<tr>
<td>0.60</td>
<td>0.770</td>
</tr>
<tr>
<td>0.70</td>
<td>0.830</td>
</tr>
<tr>
<td>0.80</td>
<td>0.867</td>
</tr>
<tr>
<td>0.90</td>
<td>0.867</td>
</tr>
<tr>
<td>1.00</td>
<td>0.889</td>
</tr>
<tr>
<td>1.20</td>
<td>1.000</td>
</tr>
<tr>
<td>1.40</td>
<td>1.000</td>
</tr>
<tr>
<td>1.60</td>
<td>1.000</td>
</tr>
<tr>
<td>1.80</td>
<td>1.000</td>
</tr>
<tr>
<td>2.00</td>
<td>1.000</td>
</tr>
</tbody>
</table>

AUC = 0.9464

<table>
<thead>
<tr>
<th>Threshold</th>
<th>TPR</th>
<th>FPR</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.80</td>
<td>0.986</td>
<td>1.000</td>
</tr>
<tr>
<td>2.00</td>
<td>1.000</td>
<td>1.000</td>
</tr>
</tbody>
</table>

AUC = 0.9994

It can be seen from Table 4 that, for the first analysis case, a threshold of 0.7, which corresponds to 0% false detection rate, can detect the data points beyond yield with detection rate of 83%. If 100% detection rate is desired, a minimum of 1.2 threshold value has to be used; however, 73% false detection rate is associated with this threshold level. An optimum threshold level for the
first analysis case may be 1.0 level, which results in a detection rate of 88.9% and a false detection rate of 18.7%.

For the second analysis case, the detection rate goes up to 93.5% for no false detection with a threshold value of 0.24. If 100% yield detection rate is desired, there is a risk of 2.8% false detection. It can be seen from the TPR and FPR values for the second analysis case that, for the signal energy method can detect conditions where the applied stresses in steel is above 115% of yield strength with considerably high detection rates and with low risk of error. Even though the TPR and FPR values for only the signal energy method are presented in Table 4, the potentialities of all investigated parameters were studied. The ROC curves of the time domain (peak amplitude and signal energy) and frequency domain (FFT and CZT peaks, and the three measures of Wavelet coefficients) parameters for the two analysis cases are illustrated in Figures 86-92. It can be seen from Figures 86-92 that, all ROC curves are close to the upper left corner of the graphs, especially for the second analysis case. Calculated TPR and FPR values of the second analysis case for these three methods reveal that, they also can successfully detect yielding as a highest false detection rate of 4.2% is associated with 100% detection rate. Having AUC values higher than 0.95 for the first and 0.99 for the second analysis case, all methods can be considered as very successful classification parameters for yield detection in steel.

The ROC analysis results, in conclusion, show that certain threshold values can be defined for all investigated methods, and their performances can be measured based on the level of desired detection rate and the associated rate of false detection. These threshold values can be practically used with the presented ultrasonic nondestructive testing method and all of the investigated parameters for yield detection in steel structures.
Figure 86: ROC Curves of the peak amplitude method for the two analysis cases.

Figure 87: ROC Curves of the signal energy method for the two analysis cases.
Figure 88: ROC Curves of the FFT peak amplitude method for the two analysis cases.

Figure 89: ROC Curves of the CZT peak amplitude method for the two analysis cases.
Figure 90: ROC Curves of the Wavelet peak amplitude method for the two analysis cases.

Figure 91: ROC Curves of the Wavelet peak-to-peak (PTP) amplitude method for the two analysis cases.
Figure 92: ROC Curves of the Wavelet root mean square (RMS) method for the two analysis cases.
CHAPTER 6 – SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

Constituting the final chapter of this dissertation, Chapter 6, first, summarizes the background, motivation, scope and the methodology of the presented study. Conclusions based on the results of the ultrasonic experiments are then discussed and followed by recommendations for future research.

6.1 Summary

Structural health monitoring is an important field in civil engineering. Identification of defects in structures is one of the fundamental tasks of health monitoring. There are many existing structures that have already exceeded or about to exceed their design lives. Continuous or periodic assessment of the safety and reliability of these structures may prevent catastrophic and costly events from occurring. Several traditional testing methods such as visual inspection, concrete core, rebound hammer, chain dragging and tap tests have been used for a very long time. However, some of these methods are not scientific while others either have very limited capabilities in detecting defects or are time consuming. Therefore, researchers and scientists have developed numerous testing tools and methods for health monitoring of the civil infrastructure in order to achieve acceptable levels of accuracy and robustness.

Nondestructive Evaluation and Testing (NDE&T) is a very active and rapidly growing field that offers various solutions for structural health assessment and monitoring. Unlike destructive testing methods, NDE&T techniques examine materials and structures without
destroying their usefulness which enables civil engineers to test structures while they are in service. The majority of NDE&T applications in civil engineering focus on determining material properties, detecting defects and locating embedded reinforcing bars in concrete. Although material characterization and defect detection are very important health assessment tasks, determination of actual stresses may be more important in certain cases. Even though some structures do not have visible or detectable damages, high localized stresses are likely to occur in the presence of critical loads and complex geometric details (Connor et al. 2007).

Methods for determining the actual stress state in existing structures, on the other hand, rely on the acoustoelastic theory, which is basically the effect of stresses in the material on the velocity of the ultrasonic wave propagating through it. However, as discussed comprehensively in Chapter 4, the accuracy of testing methods using this theory is very sensitive to several factors associated with the testing conditions and the material properties. Furthermore, the acoustoelastic response of plastically deformed materials is still not defined conclusively as there are only a few studies in the literature investigating this problem.

The main goal of this study is to develop an ultrasonic nondestructive evaluation and testing tool for identification and investigation of highly stressed zones in steel structures. For this reason, a special multiple-unit testing system, explained in Section 3.1, was first built. Using this testing system, four groups of plate-type dog bone shaped Grade 36 steel specimens were tested under monotonically increasing tensile stresses, and ultrasonic measurements were taken at different stress levels with longitudinal and shear wave transducers. A total of twenty eight tests (four pilot tests and twenty four full tests) were conducted, and the acquired ultrasonic signals formed a test database to which several digital signal processing methods were applied.

The test database was first investigated with acoustoelastic analysis. Longitudinal wave measurements were taken through the thickness of the specimen in the perpendicular direction to
the loading. For the shear wave measurements two polarization directions, parallel and perpendicular to the stress direction, were used. In order to obtain the time of flight values, the distance between the zero intersections, positive and negative peaks of the first three echoes were measured and averaged. The relative changes in the longitudinal and shear wave velocities were studied versus applied elastic and plastic strains.

Following the investigation of the acoustoelastic response of the four specimen materials, the experimental database was used to calculate several time and frequency domain characteristics of the signals. Based on the results of the signal-to-noise ratio analysis, only the first three echoes of the acquired signals were decided to be considered for the analysis. The time domain analyses included studying the peak positive amplitudes and the signal energies of the first three echoes.

For the spectral analysis, the Fast Fourier Transform (FFT) and the Chirp-Z Transform (CZT) methods were used first, and the peak amplitudes of the transformations were recorded for the first three echoes. In the later stages of the research, the echoes were decomposed with Discrete Wavelet Transform (DWT) using three different mother wavelets. The peak and peak-to-peak amplitudes, and the root mean square values of the approximate wavelet coefficients were also recorded.

All time and frequency domain parameters were normalized with the unstressed value of the corresponding data set to avoid the effect of changes in the test settings. The dependences of all parameters on the stress state of the material were studied for all four specimen groups considering three stress intervals; namely before yield, after high yield and a transition interval in between. It was shown that, presence of plastic deformations alters the results for the investigated parameters. For all the time and frequency domain signal characteristics, clear distinctions between stress levels prior to and beyond yielding were observed.
In order to quantify the distinctions between investigated parameters, statistical descriptors (mean and standard deviation) of the data in each stress interval were calculated for all investigated methods. Furthermore, Receiver Operating Characteristics (ROC) analyses were performed to analyze the performances of the proposed methods for being used as a nondestructive testing tool for yield detection in steel structures.

6.2 Conclusions

The results of the acoustoelastic analysis, presented in Section 4.3, are in agreement with the theory of acoustoelasticity as the shear waves propagating perpendicular and polarized parallel to the loading direction are more sensitive to the changes in the elastic strains than longitudinal signals propagating through the thickness of the material. As was expected, the velocities of the ultrasonic waves increase for the latter case with increasing elastic strains, while they decrease for the former. Except for the Type4 specimen group, shear waves polarized parallel to the loading direction were observed to be the least stress-sensitive ultrasonic wave configuration.

The relative changes in the wave velocities were observed to have linear relationships when plotted versus tensile strains. However, when they are studied versus the stresses, the results revealed small changes before yielding followed by exponential increases in the plastic range of the materials. Even though, the acoustoelastic analysis results correlate with the theory, it was shown that the acoustoelastic effect for the tested steel is very small and hard to measure, especially for the elastic stress range. Furthermore, the variations in the measured acoustoelastic constants for different specimens (which are hypothetically made of the same material) show how the microstructure can affect acoustoelastic stress measurements.

The analysis results of the investigated time and signal domain characteristics show very close behaviors except Type4 specimen group. The graphical representations of the results show
that the normalized parameters do not change significantly in the elastic stress range of the material. However, this behavior was followed by a sudden decrease beyond yielding, the normalized values fall below a certain level which can clearly classify the data into two groups based on the clear distinction between the values for elastic and plastic stress levels.

The decrease in the normalized time and frequency domain parameters were observed to be more intense for Type1 and Type3 specimen groups than Type2, while they showed almost no dependence on applied stresses for Type4 specimens. The difference between the results for the former (Type1 and Type3 specimens), where sudden decreases in the normalized time and frequency parameters started just after yielding, and the latter (Type2 specimens) is that the decrease occurred earlier; after approximately 80% of yield strength.

It is well known that plastic deformation is accompanied by microstructural material property changes, and that ultrasonic wave propagation is influenced by this plastic behavior (Kobayashi 1998). Polycrystalline materials like steel is expected to be isotropic if their grains are randomly oriented (Wu et al. 1991). However, most practical engineering materials exhibit inhomogeneous anisotropy caused by material texture or microstructure which is introduced by the manufacturing processes like rolling and heat treatment that tend to align the grains in a preferred orientation (Kobayashi 1986). Previous studies have shown that these preferred orientations remain unchanged or change very little during elastic deformations and their effect on the acoustic response can therefore be neglected. Reorientation of grains due to plastic deformations, on the other hand, needs to be taken into account for acoustic measurements. Furthermore, plastic deformation causes changes to a varying degree in acoustic response, depending on the type of material (Daami et al. 1987), and dislocation effects can be significant even during deformations which are well below the yield limit of the material (Wong and Johnson 1990).
When the experimental results for the changes in the signal characteristics are evaluated in light of microstructural mechanism explained above, the sudden decreases in the normalized values after material yielding can be understood. The results show that after the yield strength is reached, the attenuation of the signals increase. Attenuation is basically the decay rate of a signal as it propagates through a material and it is a combination of absorption and scattering. Reorientation of the grains starting from early plastic strains for Type1 and Type3 specimen groups, results in decreases in the amplitude of the echoes after yielding which directly affects the other investigated time and frequency domain parameters. For Type2 specimen, the decrease in the normalized signal characteristics start approximately after %80 of the yield stress, and this may be associated with the dislocation effects occurring before the initiation of yielding. The results for Type4 specimens, on the other hand, do not reveal any attenuation decreases related with dislocation mechanisms in early post-yield stress levels. The only decrease happens at the highest stress level.

The experimental results for the investigated parameters, overall, show great potential for being used as a nondestructive yield detection method. The clear distinctions between the normalized data values prior to and after yielding increase the accuracy of the proposed methods for detection of yielding. The decrease in the amplitudes after yield results in more intense decreases for the signal energy method as all of the amplitudes of the echoes are squared for the calculation of signal energy, therefore, this method has greater potential than the other time and frequency domain parameters to be used for yield detection in steel structures.

In order to investigate the performances of the proposed methods in yield detection, the experimental results were first used to calculate the statistical descriptors, the mean and the standard deviation, of the data that was analyzed in three stress intervals. The calculated mean values in the first (elastic) stress interval are very close to 1.0. The mean values for the final
stress interval demonstrate the decrease in all of the parameters due to plastic strains. The standard deviation values, on the other hand, is a measure of the consistency of the data in the first and the final intervals since they can be considered to be scattered in a narrow range. The frequency domain parameters, in that sense, perform better than the time domain parameters as the normalized values are less scattered in the elastic and plastic stress intervals.

Following the statistical analysis, the results were investigated with Receiver Operating Characteristics (ROC) curves for determining optimum threshold levels for classifying the data for yield detection. Two ROC analysis cases were presented, one of which divides the stress range into two at the yield strength, while the second one considers the transition interval (between 100 and 115% of yield stress) with the elastic interval. ROC analysis results show that threshold levels having very high yield detection rates with a very small rate of false detection can be determined for practical use of the proposed methods.

In summary, all of the investigated parameters show great potential for being used as a parameter in ultrasonic nondestructive yield detection in steel. The clear distinctions between the normalized values can be used to determine threshold values for each method in order to detect yield in steel with optimum detection and false detection rate combination. The practical application of the proposed methods can be achieved by acquiring ultrasonic signals from the critical location of a structure to be investigated and from an unstressed location or a dummy (unstressed) specimen of the same material. After normalizing the calculated signal parameters of the critical section by the ones for the unstressed signal, the predefined threshold levels can be used to determine if stress level present in the investigated section is below or above the yield stress. Although the presented study reveals promising results for the development of an ultrasonic nondestructive testing tool for yield detection, several factors affecting the accuracy and the reliability of the measurements still need to be taken studied in future research.
Recommendations for improving the proposed testing tool and method are presented next, in addition to the discussion of other available testing tools and methods that can be used to investigate the presented signal characteristics.

6.3 Recommendations for Future Research

Based on the experimental results, recommendations for future research for the development of an ultrasonic NDE&T tool for yield detection in steel structures are presented in two separate sections next. The first section which covers the factors that need to be further investigated in future research with the proposed ultrasonic testing system, while the second section discusses the adaptation of other testing tools and methods that may improve the performance of the investigated parameters for yield detection in steel structures.

6.3.1 Improvement of the Presented Testing Method

There are several factors related to the experimental procedure and the analysis of the acquired signals. These factors include: (1) the effects of microstructure, (2) temperature, (3) measurement of the transverse strains using strain gauges, and (4) automating the segmentation and choice of echo. Further investigation of these factors in future research is warranted to improve the performance of the presented study.

As was explained in previous sections of this dissertation, ultrasonic measurements are considerably affected by the temperature conditions and the microstructural properties of the tested material. All the experiments used in building the test database for this dissertation were conducted under laboratory conditions where the changes in the temperature were minimal. However, in order to be able to use the presented method and a nondestructive in-situ testing method, the effect of various temperature conditions needs to be investigated in future research.
The microstructural properties and the preferred orientation (rolling) directions of the specimen materials also affect the acoustic response of materials especially in the presence of plastic strains. The experimental results show that the effect of microstructural changes of the material is a very important fact that has to be thoroughly analyzed for evaluating experimental results of ultrasonic tests on steel subjected to plastic strains. Therefore, the investigation of microstructural properties of the specimen materials may be very useful for improvement and successful application of the presented method to different types of steels.

Prior to the ultrasonic tests, the types of specimen groups were tested for mechanical properties and the stress-strain curves were obtained for each specimen material. During the ultrasonic measurements strain gauges could not be placed to measure strains because of the small size of specimens. Therefore, for the graphical representation of results, the longitudinal strain values corresponding to the target stress levels were obtained from the material tests conducted earlier. The transverse strains, on the other hand could not be measured. The use of strain gauges, both in longitudinal and transverse directions is highly recommended for future ultrasonic tests. This additional testing arrangement would result in more accurate evaluation of the investigated parameters versus applied strains.

Finally, automating the analysis of the experimental database for the future research can provide faster results. The segmentation of the acquired signals into echoes was done manually and three echoes were considered for further analysis based on the calculated signal-to-noise ratio (SNR) values. However, during the preparation of this dissertation, development of an algorithm for automating these steps and eliminating the human effort was studied in collaboration with Dr. Hsiao-Chun Wu from the Department of Electrical and Computer Engineering of Louisiana State University. This algorithm basically segments all the echoes in the acquired signal and calculates the signal-to-noise ratio of the segmented echoes. Then, using
a defined threshold SNR value, the algorithm discards the echoes that have a lower SNR than the chosen threshold. The remaining echoes are stored for further signal processing. Eliminating the human effort in the time consuming phases of the experimental analysis is essential for developing applications for yield detection where fast human-error free results will be required.

6.3.2 Adaptation of Different Testing Tools and Methods

In addition to the recommendations made on improvement of the presented techniques for future research, the use of different equipment and methods for yield detection in steel structures are discussed in this section. A few different testing tools and methods that have been used for ultrasonic measurements in the literature, namely; critically refracted longitudinal (L_{CR}) waves, Electromagnetic-Acoustic Transducers (EMATs) and ultrasonic nonlinearity parameter, are described and their advantages for being used in future research are explained.

Even though the acoustoelastic effect is highest for the longitudinal wave travelling along the direction of loading, placement of transducers on the tested material in order to achieve this measurement case is not always possible. To overcome this issue, researchers presented the use of critically refracted longitudinal (L_{CR}) waves for surface and subsurface acoustoelastic stress measurement (Tang and Bray 1996; Bray and Tang 2001; Bray 2001; Chance and Bray 2001). A typical experimental setup for the L_{CR} measurement is illustrated in Figure 12. Successful applications of L_{CR} measurements were found in the literature, and therefore, the investigation of this testing setup for ultrasonic yield detection may be useful for future research.

One of the most important complications of measurement and sources of error in ultrasonic tests with conventional piezoelectric transducers is the requirement for a coupling medium between the transducers and the tested material. Uneven use of ultrasonic couplant material in different tests results in significant differences in the acquired echoes. A relatively
new advancement in the ultrasonic nondestructive testing field that eliminates this source of error is the Electromagnetic-Acoustic Transducers (EMATs). In EMATs, a high-current radio frequency signal in a coil induces an eddy current within the test material, and this current then interacts with an externally applied magnetic field to produce a mechanical force. Basically, unlike conventional piezoelectric transducers, EMATs use magnetostriction and the Lorentz forces, instead of electrical energy, to generate acoustic waves. The most important advantages of EMATs are that they do not require couplant usage like piezoelectric transducers and therefore, their sensitivity to the surface conditions is minimal. EMATs were used by several researchers for determining applied and residual stresses (Schramm et al. 1996; Clark et al. 2000; Schneider 2001), and their use in the future research of the presented ultrasonic yield detection method is recommended as the measurement errors associated with the use of a couplant material will be minimized.

Finally, the investigation of a quantitative measure of elastic wave nonlinearity, namely the acoustic nonlinearity parameter ($\beta$), is recommended for future research. The acoustic nonlinearity parameter is basically related with the ratio of fundamental and second harmonic displacements, velocities or the amplitudes (Bermes et al. 2007). The acoustic nonlinearity parameter has been used mostly for assessment and characterization of fatigue damage (Cantrell and Yost 2001; Cantrell 2006; Morris et al. 1979; Nagy 1998). The investigation of the acoustic nonlinearity parameter in the future research on ultrasonic yield detection is recommended as the elastic–plastic deformation of the material causes acoustic nonlinearity (Kim et al. 2006). However, unlike the signals excited by the transducers used in this study, ultrasonic signals that can generate higher harmonic frequencies are required to be used so that the acoustic nonlinearity parameter can be measured.
REFERENCE LIST


ASTM (2007). "ASTM D4580-03 Standard Practice for Measuring Delaminations in Concrete Bridge Decks by Sounding.".


APPENDIX A - BROCHURE AND TECHNICAL SPECS OF PANAMETRICS 5900PR PULSER/RECEIVER

5800PR, 5900PR
Computer Controlled Pulser- Receivers

5627RPP-1
Remote Pulser Preampifier

Features - 5800PR, 5900PR
- Broadband negative spike excitation is optimized for the frequency band of each instrument.
- Adjustable pulse energy and damping from a regulated voltage source for optimizing pulse shape.
- Rise times < 1 μs are available for ultra high frequency inspection.
- 100 μj of available energy for conventional frequency applications.
- Internal pulse frequency source is crystal stabilized and uses a frequency divider to select PRI rate.
- External pulser mode allows use of an external pulse generator in conjunction with each instrument's receiver electronics.
- Superior isolation of receiver from pulser main bang when operating in through transmission mode.
- Multi-position switchable high and low pass filters optimize main bang recovery and noise response.
- Packaged in a rack-adeptable 16.7” x 3.5” (419 mm x 88.9 mm) instrument cabinet.

Ultrasonic Pulser- Receivers

The computer-controlled pulser-receiver family incorporates design features to ensure optimal signal response. The pulser- receivers are designed to provide broadband excitation for maximum broadband transducer performance. Pulser architecture ensures fast rise times that when coupled with instrument selectable energy and damping options optimize the excitation pulse for the frequency of inspection. Pulse stability is achieved through the use of a fixed, regulated high voltage source. Each model's broadband receiver is designed with a combination of input attenuation, output attenuation and gain stages for a wide dynamic range, low noise, and high resolution sensitivity adjustments. All attenuators use relay switched resistors for accuracy and stability. In addition, high and low pass filters improve main bang recovery and noise response.

Panametrics-NDT pulser-receivers provide the perfect building blocks for ultrasonic flaw detection, thickness gaging, material characterization, and transducer characterization. Local control and instrument memory is ideal for ensuring repeatable results in manual test setups. With computer control of individual settings through CP16 or RS-232, test parameters may be derived and then programmed for production volume analysis.

Two Models To Fit Your Testing Needs
Model 5800PR: 35 MHz (-3 dB) ultrasonic bandwidth is ideal for general purpose ultrasonic testing with a wide variety of metals, plastics, composites and biomaterials.
Model 5900PR: 200 MHz (-3 dB) ultrasonic bandwidth permits testing in applications where conventional instruments fail to provide adequate resolution. This unit is typically used with broadband transducers in the frequency range of 10 to 125 MHz with thin or non-attenuating materials.

5627RPP-1 Preampifier
This 5627RPP-1 Remote Pulser Preamp is available as an option for the 5900PR 200 MHz Bandwidth Pulser-Receiver. The 5627RPP-1 permits use of an optimum short cable from the pulser to the transducer to avoid degradation due to attenuation and cable reflections that can occur at long cable lengths. This small, lightweight package can be hand-held or mounted to a structure and drive up to 500 feet of cable back to the 5900PR host receiver for remote applications.
### Specifications

<table>
<thead>
<tr>
<th>Feature</th>
<th>5800PR</th>
<th>5900PR</th>
<th>5627RPP-1 (requires 5900PR)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pulser</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pulse Type (main bang)</td>
<td>Negative Impulse</td>
<td>Typical: 7 ns, 10 ns max</td>
<td>Typical: &lt;1 ns, 2 ns max</td>
</tr>
<tr>
<td>Rise Time 10% to 90%</td>
<td>Typical: &lt;1 ns, 2 ns max</td>
<td>Typical: &lt;2 ns</td>
<td></td>
</tr>
<tr>
<td>Available Pulse Voltage (no load)</td>
<td>300 V</td>
<td>220 V</td>
<td>150 V</td>
</tr>
<tr>
<td>Available Pulse Energy (typical)</td>
<td>12.5, 25, 50, 100 pules</td>
<td>1, 2, 4, 8, 16, 32 pules</td>
<td>1, 2, 4, and 8 pules</td>
</tr>
<tr>
<td><strong>Damping</strong></td>
<td>Two damping menus selectable: Std. 25, 50, 100, 500 ohms Ext. 15, 17, 21, 25, 36, 50, 100 or 500 ohms</td>
<td>7, 10, 15, 20, 26, 30, 40, 50 ohms</td>
<td>6 to 50 ohms ±10% continuously adjustable</td>
</tr>
<tr>
<td>Mode</td>
<td>Pulse Echo, Through Transmission, or External Pulse</td>
<td>Pulse Echo</td>
<td></td>
</tr>
<tr>
<td>Isolation (74 dB min)</td>
<td>Typical: 78 dB at 10 MHz (74 dB min)</td>
<td>Typical: 90 dB at 10 MHz (46 dB min)</td>
<td></td>
</tr>
<tr>
<td>Remote Pulse Preamp</td>
<td>N/A</td>
<td>Compatible with 5627RPP-1</td>
<td>N/A</td>
</tr>
<tr>
<td><strong>Pulse Repetition Rate Internal</strong></td>
<td>Two frequency menus selectable: Std. 100, 200, 500, 1 k, 2 k, 5 k, 10 kHz Ext. 100, 200, 500, 1 k, 2 k, 5 k, 10 k, 20 kHz</td>
<td>200, 500, 1 k, 2 k, 5 k, 10 kHz</td>
<td>N/A</td>
</tr>
<tr>
<td><strong>Pulse Repetition Rate External</strong></td>
<td>0.1 kHz</td>
<td>0.2 kHz</td>
<td>0.2 kHz by external trigger pulse</td>
</tr>
<tr>
<td>Synch Output Pulse</td>
<td>Pos. TTL compatible, precedes main bang by approx. 50 ns</td>
<td>Pos. TTL compatible, precedes main bang by approx. 230 ns</td>
<td>N/A</td>
</tr>
<tr>
<td>External Trigger Input</td>
<td>TTL and HCMOS compatible, capacitor coupled, optocoupled, dual isolators accept either polarity</td>
<td>TTL compatible, furnished by 5900PR synch output</td>
<td></td>
</tr>
</tbody>
</table>

### RECEIVER

<table>
<thead>
<tr>
<th>Feature</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Bandwidth</td>
<td>1 kHz – 35 MHz (&lt;3 dB)</td>
<td>1 kHz – 200 MHz (&lt;3 dB)</td>
<td>10 kHz – 150 MHz (&lt;3 dB)</td>
</tr>
<tr>
<td>Voltage Gain (RL = 50 ohms)</td>
<td>20, 40, 60 dB</td>
<td>26, 40, 54 dB</td>
<td>24 dB ± 2 dB</td>
</tr>
<tr>
<td>Phase</td>
<td>100° inverting</td>
<td>Select 0 or 180°</td>
<td>N/A</td>
</tr>
<tr>
<td>Attenuation (Coarse)</td>
<td>10, 20, 30, 40, 50 dB</td>
<td>10, 20, 30, 40, 50 dB</td>
<td>N/A</td>
</tr>
<tr>
<td>Attenuation (Fine)</td>
<td>0.25, 1.25, 2.5, 5, 10 dB</td>
<td>0.5, 1.25, 2.5, 5, 10 dB</td>
<td>N/A</td>
</tr>
<tr>
<td>High Pass Filter</td>
<td>1 k, 10 k, 30 k, 100 kHz</td>
<td>1 k, 1, 3, or 10 MHz</td>
<td>N/A</td>
</tr>
<tr>
<td>Low Pass Filter</td>
<td>35, 20, 10, 5 MHz</td>
<td>200, 100, 50, 20 MHz</td>
<td>N/A</td>
</tr>
<tr>
<td>Noise (referred to input)</td>
<td>80 µV peak-peak typical, BW=35 MHz</td>
<td>120 µV peak-peak typical, BW=200 MHz</td>
<td>Typically 60 µV peak-peak referred to the input, BW=150 MHz</td>
</tr>
<tr>
<td>Max Signal Output</td>
<td>+/-1 V pk, terminated in 50 ohms</td>
<td>+/-1 V pk, terminated in 50 ohms</td>
<td>±0.3 V pk, terminated in 50 ohms</td>
</tr>
<tr>
<td>Input Impedance</td>
<td>500 ohms for signals &lt; 0.5 V pk 100 ohms for signals &gt; 0.5 V pk with coarse attenuator set &lt; -10 dB</td>
<td>50 ohms for signals &lt; 0.5 V pk 0.20 Ohms at levels &gt; 0.5 V pk with coarse attenuator set &lt; -10 dB</td>
<td></td>
</tr>
<tr>
<td>Output Impedance</td>
<td>50 ohms</td>
<td>50 ohms</td>
<td>50 ohms</td>
</tr>
<tr>
<td>Maximum Input Power</td>
<td>0.25 W</td>
<td>0.25 W</td>
<td>N/A</td>
</tr>
<tr>
<td>Power Main Requirements</td>
<td>100V/20/20/240 VAC, +/-12.5%</td>
<td>Uses power entry module with detachable power cord 50/60 Hz</td>
<td>Supplied through 5900PR; requires 5627CS cable set</td>
</tr>
<tr>
<td>Operating Temperature</td>
<td>12°C – 12°C F (0°F to 50°C)</td>
<td>12°C – 12°C F (0°F to 50°C)</td>
<td>N/A</td>
</tr>
<tr>
<td>Size</td>
<td>16.7 x 3.5 x 12.7 (419 mm x 89.9 mm x 315 mm)</td>
<td>5.3 x 3 x 1.57 (134.6 mm x 76.2 mm x 42.4 mm)</td>
<td>1.2 x 0.6 x 0.27 (30.5 x 16.2 x 6.8 mm)</td>
</tr>
<tr>
<td>Weight</td>
<td>13.3 lbs (6.0 kg)</td>
<td>16 lbs (7.27 kg)</td>
<td>1.2 lbs (550 grams)</td>
</tr>
</tbody>
</table>

### Standard Inclusions

The 5900PR and 5900PR are shipped with an instruction manual, power cord, RS-232 cable as well as two BCB-58-4 cables and 50 ohm terminators for connection to an oscilloscope. In addition, the 5900PR includes a low impedance Microdot® transducer cable.

---

*Specifications are subject to change without notice.*

---

**OLYMPUS**

www.olympuspid.com
info@olympuspid.com

OLYMPUS NOT

OLYMPUS NOT UK LTD.,
12 Typhoo Way, Thame, Oxfordshire, OW2 6PA, UK
OLYMPUS HONG KONG LTD.,
17th Floor, Sun Life Center, 882 King's Road, Kowloon, Hong Kong
OLYMPUS AUSTRALIA PTY LTD.,
PO Box 254, Blackburn South, Victoria 3130, Australia

Copyright 2005 by Olympus NOT. All rights reserved. All specifications are subject to change without notice.
APPENDIX B – TECHNICAL SPECIFICATIONS OF THE ULTRASONIC TRANSUDCERS

Appendix B1: Longitudinal Transducer-1
TRANSDUCER DESCRIPTION

PART NO.: V112
SERIAL NO.: 555721
DESIGNATION: CONTACT

FREQUENCY: 10.00 MHz
ELEMENT SIZE: .25 in. DIA.

TEST INSTRUMENTATION

PULSER/RECEIVER: PANAMETRICS 5052PR 3Ep019
DIGITAL OSCILLOSCOPE: LeCroy LT342 / SN: LT34201114
TEST PROGRAM: TP103-3 VER. 1005UJ
CABLE: RG 174/U LENGTH: 4FT

TEST CONDITIONS

PULSER SETTING: ENERGY: 1; DAMPING: 50 OHMS
RECEIVER SETTING: ATTN: 42dB; GAIN: 40dB
TARGET: 1 in. SILICA
JOB CODE: TP2000

MEASUREMENTS PER ASTM E1065

WAVEFORM DURATION: -140DB LEVEL --- .120 US
-90DB LEVEL --- .130 US
-40DB LEVEL --- 1.000 US

SPECTRUM MEASURANDS:
CENTER FREQ. --- 10.24 MHz
PEAK FREQUENCY --- 11.12 MHz
-6DB BANDWIDTH --- 97.15 %

COMMENTS:

** ACCEPTED

TECHNICIAN: [Signature]

DATE: 07-31-2006
**TRANSDUCER DESCRIPTION**

**PART NO.:** V156  
**SERIAL NO.:** 595245  
**DESIGNATION:** CONTACT  
**FREQUENCY:** 5.00 MHz  
**ELEMENT SIZE:** 25 in. Dia.

**TEST INSTRUMENTATION**

**PULSER/RECEIVER:** PANAMETRICS 5052UA #1  
**DIGITAL OSCILLOSCOPE:** LeCroy LT342 / SN: LT34202249  
**TEST PROGRAM:** TP103-3 VER: 1075L9  
**CABLE:** RG-174/U LENGTH: 4FT.

**TEST CONDITIONS**

**PULSER SETTING:** ENERGY: 1 ; DAMPING: 60 OHMS  
**RECEIVER SETTING:** ATTN: 54db ; GAIN: 40dB  
**TARGET:** 1 in. SILICA  
**JOB CODE:** TP200

**MEASUREMENTS PER ASTM E1065**

<table>
<thead>
<tr>
<th>Waveform Duration</th>
<th>Spectrum Measurands</th>
</tr>
</thead>
<tbody>
<tr>
<td>-140dB LEVEL ---</td>
<td>CENTER FREQ. --- 5.45 MHz</td>
</tr>
<tr>
<td>20dB LEVEL ---</td>
<td>PEAK FREQ. --- 4.54 MHz</td>
</tr>
<tr>
<td>40dB LEVEL ---</td>
<td>-6DB BANDWIDTH --- 83.27 %</td>
</tr>
</tbody>
</table>

**COMMENTS:**

This unit was tested using a system that applies uniform pressure to the transducer to insure product integrity, therefore the sensitivity demonstrated on this certification can only be duplicated under similar conditions.

**ACCEPTED**

**TECHNICIAN (3) **  
**DATE:** 06-08-2007

---

**OLYMPUS**

Tel: 781-419-3900  
www.olympusndt.com
APPENDIX C – SPECIFICATIONS OF THE ULTRASONIC COUPLANTS

Appendix C1: Brochure of the Ultragel II Couplant

ULTRAGEL II® ultrasonic couplant

Ultragel II has a 30+ year history as the most frequently specified and used NDT ultrasonic couplant in the world. It is Sonotech’s premier water based couplant for performance and ferrous corrosion inhibition for use in flaw detection, thickness gaging, flow metering, and acoustic emission testing at extended ambient temperatures.

Temperature Operating Range
-10° to 210°F (-23° to 99°C)

Benefits
• Increased acoustic impedance for reduced surface noise
• Extended temperature range
• Slow drying with good transducer lubrication
• Good wetting characteristics on oily or dirty surfaces
• Stable couplant that holds on vertical and overhead surfaces and fills depressions in rough surfaces

Safety
• Non-flammable and non-irritating
• No silicones or petroleum distillates
• No heavy metals incorporated into formula

Removal
• Water-soluble; easily removed with a water rinse
• Isopropyl alcohol or 100% ethyl alcohol will also remove Ultragel II

Chemical Analysis and Certification
Independent laboratory analysis of Chlorine, Fluorine and Sulfur referencing ASTM procedures is furnished with each shipment at no additional charge. Spectrochemical, Graphite Furnace, Atomic Absorption analysis, or heavy metal certification is available at additional charge.

Chemistry
Halogens..............................................<50 ppm
Sulfur..................................................<50 ppm

Acoustic Transmission
Optimal transmission requires that an ultrasonic couplant have no air bubbles that can reflect, scatter, and attenuate sound waves. Sonotech’s unique processing eliminates couplant air bubbles.

Corrosion Inhibition
A basic premise in NDT is that it must be truly non-destructive. The couplant must not cause detrimental metallurgical damage to the part through corrosion. Sonotech has developed a sensitive ferrous corrosion test and rating system for our couplants that evaluates both surface and crevice corrosion.
• Ultragel II contains a ferrous corrosion inhibitor with a relative effectiveness rating of 90 (refer to Sonotech’s Couplant Ferrous Corrosion Characteristics Chart) and is compatible with most composites and metals, except magnesium.

Ultragel II has been tested and approved to:
• ASTM F519 Hydrogen Embrittlement testing on high strength steel
• PWA 36700/36804 Hot corrosion testing on High Temperature Alloys AMS 5544 (Waspalloy), 5536 (Hastelloy X), 6359 (Ferrous based alloys), 4037 (Aluminum), 5608 (Haynes 188), 5608 (Greek Ascoloy) and 4375 (Magnesium) and on gas turbine blade coatings PWA 286 and 275.
• Boeing Specifications BAC 5988 (adhesive bonds), BAC 5980 (composites), BAC 5439-PSE22.
• Pratt and Whitney PWA 36604, MCL E-205 Type II or ASTM F945, Stress Corrosion Cracking testing on Titanium Alloys.

Properties
Viscosity .............................................~80,000 cps
(Brockfield Haupold Spindle E @ 1.5 rpm)
Velocity .............................................1.69–0.05 mm/sec
Acoustic Impedance .....................1.85–0.05 MRayls
pH .....................................................7.8–5

1 At ambient temperature.
Appendix C2: MSDS of the Ultragel II Couplant

Section 1 - Material Identification
Product: ULTRAGEL II®
Synonym: Nondestructive Testing (NDT) ultrasonic couplant
Manufacturer: Sonotech, Inc.
Date Prepared: 05/07
Emergency Phone: 900-458-4254 / 360-671-9121

Section 2 - Ingredients
Proprietary

Section 3 - Health Hazards

<table>
<thead>
<tr>
<th>Primary Route</th>
<th>Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eyes</td>
<td>No</td>
</tr>
<tr>
<td>Skin</td>
<td>Yes</td>
</tr>
<tr>
<td>Inhalation</td>
<td>No</td>
</tr>
<tr>
<td>Ingestion</td>
<td>No</td>
</tr>
</tbody>
</table>

Section 4 - First Aid
Eyes: Flush with water for 15 minutes
Skin: Wash with water
Inhalation: Not applicable
Ingestion: Call physician if large quantities involved

Section 5 - Fire and Explosion Data
Flash Point: N/A
Upper Exposure Limit: None
Lower Exposure Limit: None
Extinguishing media: All types
Special Precautions: None
Unusual Hazards: None

Section 6 - Accidental Release
Scoop or wipe up excess. Wash with water. Sprinkle with traction material if spill not cleaned immediately.

Section 7 - Storage and Handling
Storage & Handling Precautions: Store near room temperature away from sunlight. Material is slippery.

Section 8 - Exposure Controls
Respiratory Protection: Not required
Ventilation: Not required
Protective Gloves: May be required if sensitivity exists
Eye Protection: As required by work environment
Other Controls: Not required

Section 9 - Physical Data
Boiling Point: Not determined
Density: 1.06 g/cc
Vapor Density: Not determined
Vapor Pressure: Not available
Volatile Organic Compounds: 1.4 lbs/gal
Percent Solids: <2%
Solubility in water: Complete
Appearance & Odor: Blue gel, fragrant odor

Section 10 - Reactivity Data
Stability: Stable
Hazardous Polymerization: Will not occur
Hazardous Decomposition Products: None known
Incompatibility: None known

Section 11 - Toxicology Information
Oral toxicity: Not known
Skin irritation: Not known
Eye Irritation: Not known
Known / Suspected Carcinogens: None

Section 12 - Ecological Information
No Data

Section 13 - Disposal
Follow applicable federal, state, and local regulations.

Section 14 - Transportation Information
Domestic Regulations: None
DOT Designation: None
Hazard Class: None
ID Number: None
Packing Group: None
International Regulations: None known

Section 15 - Regulatory Information
WHMIS: Not a Controlled Product
EPCRA 311/312/313 Categories: None

This Material Safety Data Sheet (MSDS) has been prepared in compliance with the Federal OSHA Hazard Communication Standard, 29 CFR 1910.1200. Sonotech believes this information to be reliable and up to date as of the date of this publication, but makes no warranty that it is. If this MSDS is more than three years old, you should contact Sonotech at the phone number provided above to verify that this sheet is current.
Appendix C3: Brochure of the Shear Gel Couplant

**Shear Gel** shear wave couplant

Shear Gel provides coupling for shear wave generated by normal incidence (zero degree) shear wave transducers.

**Temperature Operating Range:**
40° to 90°F (4° to 32°C)

**Benefits**
- Environmentally benign formula

**Safety**
- Non-flammable, Non-irritating, orally nontoxic
- Contains NO naptha, oil, glycerine, hydrocarbons, heavy metals, harsh surfactants, glycol ethers, nitriles, silicones, petroleum distillates, dyes or fragrances

**Environmental Awareness**
Sonotech developed environmentally benign couplants to minimize impact on the environment. Shear Gel contains biodegradable materials, safe for disposal. The likelihood of skin irritation has been reduced through the use of cosmetic grade ingredients.

Environmentally benign couplants are designed specifically for applications where couplant may not be removed by the inspector, may later be removed by weather, or could come into contact with animals, humans, and waterways.

**Removal**
- Water-soluble; remove with warm water

**Properties**

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Viscosity</td>
<td>&gt;4,000,000cps</td>
</tr>
<tr>
<td>Density</td>
<td>1.4 to 1.6 g/cc</td>
</tr>
</tbody>
</table>

1 At ambient temperature.

**Packaging**
4 oz (100g) tube

---

SONOTECH®
774 Marine Drive, Bellingham, WA 98225-1530  
sonotech@sonotech-inc.com  
Order Phone: 800-458-4254  
Fax 360-671-9024  
www.sonotech-inc.com
Appendix C4: MSDS of the Shear Gel Couplant

Section 1 - Material Identification
Product: SHEAR GEL®
Synonym: Ultrasonic Couplant
Manufacturer: Sonotech, Inc.
Date Prepared: 1/07
Emergency Phone: 800-458-4254 / 360-671-9121

Section 2 - Ingredients (>0.1% by WT)
Component | CAS
Proprietary | N/A
All required ingredients are listed on TSCA inventory.

Section 3 - Health Hazards
<table>
<thead>
<tr>
<th>Primary Route</th>
<th>Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eyes</td>
<td>No Transient irritation</td>
</tr>
<tr>
<td>Skin</td>
<td>Yes None expected</td>
</tr>
<tr>
<td>Inhalation</td>
<td>No None expected</td>
</tr>
<tr>
<td>Ingestion</td>
<td>No None expected</td>
</tr>
</tbody>
</table>

Section 4 - First Aid
Eyes: Flush with water for 15 minutes.
Skin: Wash with water
Inhalation: N/A
Ingestion: Treat symptoms

Section 5 - Fire and Explosion Data
Flash Point (method): N/A
Upper Exposure Limit: None
Lower Exposure Limit: None
Extinguishing media: All standard firefighting media
Special Precautions: Not determined
Unusual Hazards: None

Section 6 - Accidental Release
Wipe up excess. Wash with water. Sprinkle with traction material if spill not cleaned immediately.

Section 7 - Storage and Handling
Storage & Handling Precautions: Store at room temperature. Material is sticky.

Section 8 - Exposure Controls
Respiratory Protection: Not required
Ventilation: Not required
Protective Gloves: Not required within operating range
Eye Protection: Not required within operating range
Other Controls: Not required within operating range (40 to 90°F)

Section 9 - Physical Data
Boiling Range: >220°F
Density: >1.0 g/cm³
Vapor Density: Not known
Vapor Pressure (temp): N/A
Volatile Organic Compounds: None
Percent Solids: <2%
Solubility in water: Complete
Appearance & Odor: Dark brown, high viscosity, neutral odor

Section 10 - Reactivity Data
Stability: Stable
Hazardous Polymerization: Will not occur
Hazardous Decomposition Products: None known
Incompatibility: None known

Section 11 - Toxicology Information
Oral toxicity: Nontoxic
Skin irritation: Not determined
Eye Irritation: Not determined
Known / Suspected Carcinogens: None

Section 12 - Ecological Information
Not known

Section 13 - Disposal
Follow applicable federal, state, and local regulations.

Section 14 - Transportation Information
Domestic Regulations: None
DOT Designation: None
Hazard Class: None
ID Number: None
Packaging Group: None
International Regulations: None known

Section 15 - Regulatory Information
WHMIS: Not a Controlled Product
EPCRA 311/312 Categories: None

This Material Safety Data Sheet (MSDS) has been prepared in compliance with the Federal OSHA Hazard Communication Standard, 29 CFR 1910.1209. Sonotech believes this information to be reliable and up to date as of the date of this publication, but makes no warranty that it is. If this MSDS is more than three years old, you should contact Sonotech at the phone number provided above to verify that this sheet is current.
APPENDIX D – TECHNICAL SPECIFICATIONS OF ACQIRIS DP310 PCI DIGITIZER

DP310
12-bit
100 MHz
400 MS/s

PCI Digitizer for Frequency Domain Applications

HRes SR
HF In
Ctrl I/O
PCI Digitizer for Frequency Domain Applications
Model DP310

Single-channel, 12-bit, 100 MHz, 400 MS/s, 64 kpoint or 4 Mpoint acquisition memory

**Standard Input - 50 Ω BNC**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bandwidth (-3 dB)</td>
<td>DC to 100 MHz</td>
</tr>
<tr>
<td>Full Scale Range (FSR)</td>
<td>250 mV, 500 mV, 1 V, 2 V, 5 V and 10 V</td>
</tr>
<tr>
<td>Impedance</td>
<td>50 Ω ± 1% @ DC</td>
</tr>
<tr>
<td>Connector</td>
<td>BNC, gold-plated</td>
</tr>
<tr>
<td>Offset</td>
<td>±1 V for 250, ±500 mV and 1 V FS</td>
</tr>
<tr>
<td></td>
<td>±2 V for 2 V FS</td>
</tr>
<tr>
<td></td>
<td>±5 V for 5 V FS</td>
</tr>
<tr>
<td></td>
<td>±10 V for 10 V FS</td>
</tr>
<tr>
<td>Coupling</td>
<td>DC into 50 Ω BNC</td>
</tr>
<tr>
<td>Maximum Input Voltage</td>
<td>±10 V DC (Ω FS) or ±10 V RMS at 50 Ω</td>
</tr>
<tr>
<td>Bandwidth Limit Filter</td>
<td>35 MHz 2-pole Bessel filter</td>
</tr>
</tbody>
</table>

**HF Input - 50 Ω SMA**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bandwidth (-3 dB)</td>
<td>1 to 300 MHz</td>
</tr>
<tr>
<td>Full Scale Range (FSR)</td>
<td>±8 dBm (1.75 V FS) typical</td>
</tr>
<tr>
<td>Impedance</td>
<td>50 Ω ± 5%, AC-coupled</td>
</tr>
<tr>
<td>Connector</td>
<td>SMA, gold-plated</td>
</tr>
<tr>
<td>Coupling</td>
<td>AC</td>
</tr>
<tr>
<td>Maximum Input Voltage</td>
<td>5 V RMS/AC component @ 50 Ω</td>
</tr>
<tr>
<td></td>
<td>50 V DC</td>
</tr>
</tbody>
</table>

**Digital Conversion**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample Rate</td>
<td>100 S/s to 400 MS/s</td>
</tr>
<tr>
<td>SR Adjustment Granularity</td>
<td>&lt; 0.25% of SR</td>
</tr>
<tr>
<td></td>
<td>500 kS/s in 200–400 MS/s range</td>
</tr>
<tr>
<td>Resolution</td>
<td>12 bits (1:4096)</td>
</tr>
<tr>
<td>Sparkle Code Rate*</td>
<td>10¹² typical @ 200 MS/s</td>
</tr>
<tr>
<td></td>
<td>10⁳ typical @ 400 MS/s</td>
</tr>
<tr>
<td>Differential Nonlinearity</td>
<td>±0.5 LS</td>
</tr>
<tr>
<td>Acquisition Memories</td>
<td>64 kpoints and 4 Mpoints (optional)</td>
</tr>
</tbody>
</table>

**Clock or Reference Input**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Connector</td>
<td>MMCX, gold-plated</td>
</tr>
<tr>
<td>Minimum Amplitude</td>
<td>1 V p-p, p-k</td>
</tr>
<tr>
<td>Ext. Clock Threshold</td>
<td>Variable between -2 V and +2 V</td>
</tr>
<tr>
<td>Impedance</td>
<td>50 Ω</td>
</tr>
<tr>
<td>Maximum Input Voltage</td>
<td>±2 V DC</td>
</tr>
<tr>
<td>Ext. Reference Frequency</td>
<td>10 MHz ± 10%</td>
</tr>
<tr>
<td>Ext. Clock Frequency</td>
<td>From 50 MHz to 400 MHz</td>
</tr>
<tr>
<td></td>
<td>SR defined with sparing</td>
</tr>
</tbody>
</table>

**Time Base**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clock Accuracy</td>
<td>Better than ±2 ppm</td>
</tr>
<tr>
<td>Sampling Jitter</td>
<td>&lt; 1 ps RMS for 10 ms record length</td>
</tr>
<tr>
<td>Acquisition Modes</td>
<td>Single shot</td>
</tr>
<tr>
<td></td>
<td>Sequence: 1 to 100 segments (optional 8000)</td>
</tr>
<tr>
<td></td>
<td>Dead-time: &lt; 1 μs</td>
</tr>
<tr>
<td>Residual Phase Modulation</td>
<td>0.3° RMS typical @ 400 MS/s</td>
</tr>
<tr>
<td></td>
<td>0.2° RMS typical @ 200 MS/s</td>
</tr>
<tr>
<td></td>
<td>100 kHz to 100 MHz</td>
</tr>
</tbody>
</table>

**Control I/O (A & B)**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Connector</td>
<td>MMCX, gold-plated</td>
</tr>
<tr>
<td>Signals</td>
<td>TTL &amp; CMOS compatible (3.3 V)</td>
</tr>
<tr>
<td>Input</td>
<td>Trigger enable</td>
</tr>
<tr>
<td>Output</td>
<td>10 MHz reference clock (50 Ω output impedance, reverse terminated) Acquisition active Trigger ready Acquisition skipping to next segment</td>
</tr>
</tbody>
</table>
### Trigger (Internal and External)

<table>
<thead>
<tr>
<th>Internal Trigger Input</th>
<th>External Trigger Input</th>
<th>TV Trigger</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bandwidth DC to 100 MHz (3 dB)</td>
<td>EN16, gold-plated</td>
<td>Trigger for positive modulation</td>
</tr>
<tr>
<td>Threshold adjust range: same as vertical FSR</td>
<td>Impedance: 50 Ω/50 Ω</td>
<td>Line &amp; Frame selection (odd &amp; even)</td>
</tr>
<tr>
<td>Trigger sensitivity DC to 100 MHz &gt; 10% FS</td>
<td>Bandwidth DC to 300 MHz (3 dB)</td>
<td>Standards:</td>
</tr>
<tr>
<td>Trigger on pk-pk signal: &gt; 15% FS</td>
<td>Threshold adjust range: 3/3 V</td>
<td>B/G (625 lines/50 frames, PAL)</td>
</tr>
<tr>
<td>Pretrigger</td>
<td>Maximum input voltage: ±5 V DC</td>
<td>L (625 lines/50 frames, SECAM)</td>
</tr>
<tr>
<td>Adjustable to 100% of horizontal full scale</td>
<td>Trigger sensitivity DC to 300 MHz &gt; 10% FS</td>
<td>M (525 lines/60 frames, NTS C)</td>
</tr>
<tr>
<td>Posttrigger</td>
<td></td>
<td>Coupling:</td>
</tr>
<tr>
<td>Adjustable up to 100 kpoints</td>
<td></td>
<td>AC, LF reject and DC</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Modes:</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Edge, positive and negative</td>
</tr>
</tbody>
</table>

### Trigger Output

<table>
<thead>
<tr>
<th>Output level</th>
<th>Connector</th>
<th>Coupling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adjustable in range ±2.5 V (no load)</td>
<td>MMCX</td>
<td>DC</td>
</tr>
<tr>
<td>Amplitude ±0.8 V (no load)</td>
<td>Rise/fall time 2.5 ns</td>
<td>Output Impedance 50 Ω</td>
</tr>
<tr>
<td>±15 mA max</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### System Performance

<table>
<thead>
<tr>
<th>DC Accuracy</th>
<th>SNR</th>
<th>SFDR (&lt; 25 MHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; ±0.5% of FS (standard input)</td>
<td>&gt; 51 dB (standard input)</td>
<td>&gt; 75 dB (standard input)</td>
</tr>
<tr>
<td>Integral Non Linearity</td>
<td>&gt; 64 dB (BW: 0.35 MHz)</td>
<td>&gt; 75 dB (BW: 1 MHz)</td>
</tr>
<tr>
<td>&lt; ±0.025% of FS</td>
<td>&gt; 64 dB (BW: 1 MHz)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>THD (&lt;25 MHz signal)</td>
<td>THD (&lt;25 MHz signal)</td>
</tr>
<tr>
<td></td>
<td>&lt; ±71 dB (standard input)</td>
<td>&lt; ±73 dB (BW: 1 MHz)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### PC System Requirements

<table>
<thead>
<tr>
<th>Processor</th>
<th>Operating System</th>
</tr>
</thead>
<tbody>
<tr>
<td>130 MHz Pentium (or higher)</td>
<td>Windows 95/98/NT4.0/2000/XP</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Memory</th>
<th>Hard Drive Space</th>
</tr>
</thead>
<tbody>
<tr>
<td>64 MB RAM (more is recommended when working with several cards with large acquisition memories)</td>
<td>20 MB Minimum</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CD Drive</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
</tbody>
</table>

### General

<table>
<thead>
<tr>
<th>Power Consumption (typ.)</th>
<th>Current Requirements (max.)</th>
<th>Warranty</th>
</tr>
</thead>
<tbody>
<tr>
<td>At 1 V 15, 400 MHz</td>
<td>12 V 0.5 A</td>
<td>3 years</td>
</tr>
<tr>
<td>&lt; 17 W with standard memory option</td>
<td>5 V 0.8 A</td>
<td></td>
</tr>
<tr>
<td>&lt; 17 W with maximum memory option</td>
<td>3.3 V 1 A (1.5 A with max. memory option)</td>
<td></td>
</tr>
<tr>
<td>-12 V 0.1 A</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Front-Panel LEDs indicate digitizer status: Green: ready for trigger; Yellow: module identification; Red: trigger

### Environmental and Physical

<table>
<thead>
<tr>
<th>Operating Temperature</th>
<th>Shock*</th>
</tr>
</thead>
<tbody>
<tr>
<td>0°C to 40°C</td>
<td>30 G, half-sine pulse</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Required Airflow</th>
<th>Vibration*</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt; 3 lbf (2 m/s)</td>
<td>5-500 Hz, random</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Relative Humidity*</th>
<th>Safety</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 to 95% (non-condensing)</td>
<td>Complies with EN 61010-1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Operating Environment</th>
<th>EMC Immunity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Complies with EN61326-1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Dimensions</th>
<th>EMC Emissions</th>
</tr>
</thead>
<tbody>
<tr>
<td>PCI full-length standard</td>
<td>Complies with EN61326-1 Class A for radiated emissions</td>
</tr>
</tbody>
</table>

Front panel complies with IEEE 1101.10

CE Certification and Compliance

* As defined by MIL-PRF-28800F Class 3
APPENDIX E – MILL TEST CERTIFICATES (MTC) OF THE TESTED MATERIALS

Appendix E1: MTC of the Type 1 Specimen Material
Appendix E2: MTC of the Type 2 Specimen Material

<table>
<thead>
<tr>
<th>Item No.</th>
<th>Material No.</th>
<th>Test No.</th>
<th>Date of Issue</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Chemical Composition (wt%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Carbon</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Manganese</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Silicon</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Phosphorus</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Sulphur</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Chromium</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Nickel</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Copper</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Molybdenum</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Nickel</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Vanadium</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Titanium</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Tungsten</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Carbon Steel</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Stainless Steel</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Duplex Steel</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Nickel-Cr Stainless Steel</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Monel</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Inconel</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Hastelloy</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>202 Stainless Steel</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>304 Stainless Steel</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>316 Stainless Steel</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>321 Stainless Steel</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>904L Stainless Steel</td>
</tr>
</tbody>
</table>

*Note: The table above contains the chemical composition of the Type 2 specimen material.*
## Appendix E3: MTC of the Type 3 Specimen Material

### Description of Goods
- **Type of Package**: Hot rolled coils non-kill
- **Quantity**: 425 coils
- **Weight**: 1,330 kg
- **Dimensions**: Length: 1220 mm, Width: 1220 mm, Thickness: 1220 mm
- **Material Grade**: A36-2

### Chemical Compositions (%)

<table>
<thead>
<tr>
<th>No</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>S</th>
<th>P</th>
<th>Cr</th>
<th>Ni</th>
<th>Cu</th>
<th>Al</th>
<th>Mg</th>
<th>Ti</th>
<th>V</th>
<th>Cr</th>
<th>Mo</th>
<th>Al</th>
<th>Nb</th>
<th>Cu</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>1</td>
<td>0.16</td>
<td>0.06</td>
<td>0.24</td>
<td>0.015</td>
<td>0.02</td>
<td>0.0005</td>
<td>0</td>
<td>0.003</td>
<td>0.04</td>
<td>0.004</td>
<td>0.005</td>
<td>0.005</td>
<td>0.005</td>
<td>0.005</td>
<td>0.005</td>
<td>0.005</td>
<td>0.005</td>
</tr>
<tr>
<td>2</td>
<td>0.16</td>
<td>0.06</td>
<td>0.24</td>
<td>0.015</td>
<td>0.02</td>
<td>0.0005</td>
<td>0</td>
<td>0.003</td>
<td>0.04</td>
<td>0.004</td>
<td>0.005</td>
<td>0.005</td>
<td>0.005</td>
<td>0.005</td>
<td>0.005</td>
<td>0.005</td>
<td>0.005</td>
</tr>
<tr>
<td>3</td>
<td>0.16</td>
<td>0.06</td>
<td>0.24</td>
<td>0.015</td>
<td>0.02</td>
<td>0.0005</td>
<td>0</td>
<td>0.003</td>
<td>0.04</td>
<td>0.004</td>
<td>0.005</td>
<td>0.005</td>
<td>0.005</td>
<td>0.005</td>
<td>0.005</td>
<td>0.005</td>
<td>0.005</td>
</tr>
</tbody>
</table>

### Mechanical Characteristics

<table>
<thead>
<tr>
<th>No</th>
<th>Tensile Strength</th>
<th>Yield Strength</th>
<th>Elongation</th>
<th>Reduction of Area</th>
<th>Impact Test</th>
<th>Cold Bend Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>450</td>
<td>300</td>
<td>34</td>
<td>34</td>
<td>25°C, U, U</td>
<td>Non-metallic inclusions</td>
</tr>
<tr>
<td>2</td>
<td>450</td>
<td>300</td>
<td>34</td>
<td>34</td>
<td>25°C, U, U</td>
<td>Non-metallic inclusions</td>
</tr>
<tr>
<td>3</td>
<td>450</td>
<td>300</td>
<td>34</td>
<td>34</td>
<td>25°C, U, U</td>
<td>Non-metallic inclusions</td>
</tr>
</tbody>
</table>

### Note

* This is a sample of the MTC (Material Test Certificate) for Type 3 specimen material. It includes details on the chemical compositions, mechanical characteristics, and other relevant specifications. The data is verified and certified to meet the required standards.
Appendix E4: MTC of the Type 4 Specimen Material
VITA

Yilmaz Bingol was born in Istanbul, Turkey, in September, 1980. He graduated from FMV Nisantasi Isik High School in 1998 and received a Bachelor of Science degree, majoring in civil engineering, in 2002, from Yildiz Technical University in Istanbul, Turkey. After receiving his Master of Science degree in civil (structural/earthquake) engineering from Istanbul Technical University in 2004, he moved to Baton Rouge in August 2008, and joined Louisiana State University to begin his Doctor of Philosophy degree in civil engineering. Since then, he has been working as a graduate research assistant at the Department of Civil and Environmental Engineering of Louisiana State University under the supervision of Dr. Ayman M. Okeil.