The Pennsylvania State University
The Graduate School
The Department of Engineering Science and Mechanics

PENETRATION POWER OF ULTRASONIC GUIDED WAVES
FOR PIPING AND WELL CASING INTEGRITY ANALYSIS

A Thesis in
Engineering Mechanics
by
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Submitted in Partial Fulfillment
of the Requirements
for the Degree of

Master of Science

December 2008
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ABSTRACT

Point source mechanical excitation methods are evaluated for the penetration power of the ultrasonic guided waves that they generate. An automatic center punch is selected for use in laboratory and field experiments because of the repeatable, large amplitude ultrasonic wave it generates. Laboratory experiments are conducted to investigate the effect of a threaded coupling and various realistic lateral boundary conditions on penetration power. A novel through-transmission technique using a down-hole fixture with two contact shear sensors is developed to study the mechanical integrity of steel casing for gas wells. Wave propagation is initiated at the top of the well through mechanical impact, which propagates flexural and torsional wave modes. The penetration power of ultrasonic guided waves using mechanical impacts is significantly larger than that of conventional piezoelectric elements. Different types of mechanical impacts, which vary in energy and in frequency are reviewed. Additionally, a shear transducer ring with high voltage excitation, used in pulse-echo mode, is also investigated.

The design of the down-hole fixture has the potential to be developed into a commercial well casing inspection device.
TABLE OF CONTENTS

LIST OF FIGURES .................................................................................................................. vi

LIST OF TABLES ...................................................................................................................... x

ACKNOWLEDGEMENTS ............................................................................................................ xi

Chapter 1 INTRODUCTION .................................................................................................... 1
  1.1 Motivation ..................................................................................................................... 1
  1.2 Inspection of piping and well casings .............................................................. 2
    1.2.1 Construction of gas storage well casing ............................................... 2
    1.2.2 Pigging .............................................................................................................. 5
    1.2.3 Ultrasonic guided waves ............................................................................ 6
  1.3 Limitations of current methods for gas well casing inspection .............. 6
  1.4 Proposed work ........................................................................................................ 7
    1.4.1 Objective ......................................................................................................... 8

Chapter 2 EXCITATION SOURCES ....................................................................................... 9
  2.1 Piezoelectric methods ......................................................................................... 9
    2.1.1 Ultrasonic transducers .............................................................................. 9
      2.1.1.1 Normal beam ultrasonic transducers ........................................... 9
      2.1.1.2 Angle beam ultrasonic transducers ............................................ 10
    2.1.2 High voltage phased array transducers ................................................. 11
  2.2 Mechanical impact methods ............................................................................. 12
    2.2.1 Hammer impact method ....................................................................... 12
    2.2.2 Ball impact methods ............................................................................. 14
      2.2.2.1 Pneumatic gun method ....................................................................... 14
      2.2.2.2 Spring mounted steel ball impact ............................................... 15
    2.2.3 Sonic horn excitation ............................................................................. 16
    2.2.4 Center punch impact ............................................................................. 16
  2.3 Comparison of piezoelectric source with mechanical impact ............ 17
    2.3.1 Normal beam transducer and pneumatic gun impact excitation........... 17

Chapter 3 RESULTS ON PENETRATION POWER OF VARIOUS ACTUATORS .................. 20
  3.1 Mechanical Methods .......................................................................................... 22
    3.1.1 Hammer Impact Method ........................................................................... 22
    3.1.2.1 Pneumatic gun impact ................................................................. 25
      3.1.2.2 Spring mounted steel ball impact ............................................... 27
    3.1.3 Impact with sonic horn: .......................................................................... 28
    3.1.4 Center punch impact ............................................................................. 32
LIST OF FIGURES

Figure 1.2: Typical natural gas storage well head [2].................................4
Figure 1.3: Natural gas well head in Dominion facility at North Canton, Ohio......4
Figure 1.4: A typical pipeline inspection gauge- PIG [3].................................5
Figure 2.1: Normal beam transducer on a steel pipe ..................................10
Figure 2.2: Angle beam transducer on a steel pipe....................................11
Figure 2.3: Teletest ring transducer [8].......................................................12
Figure 2.4: Piezoelectric hammer used for excitation .................................13
Figure 2.5: Pneumatic gun used in the experiment for excitation .................14
Figure 2.6: Spring mounted steel ball used for excitation ............................15
Figure 2.7: Sonic horn used for excitation of signal on the pipe ...................16
Figure 2.8: Automatic center punch [10].....................................................17
Figure 2.9: RF signal obtained from the pneumatic gun impact ....................18
Figure 2.10: RF signal obtained from the 50 kHz transducer .......................18
Figure 3.1: Phase velocity dispersion curve for 16” schedule 30 steel pipe ......20
Figure 3.2: Group velocity dispersion curve for 16” schedule 30 steel pipe .....21
Figure 3.3: Phase velocity dispersion curve for 4” schedule 40 steel pipe .......21
Figure 3.4: Group velocity dispersion curve for 4” schedule 40 steel pipe .......22
Figure 3.5: RF waveform from hammer impact on a 4” schedule 40 pipe .......23
Figure 3.6: FFT of the RF waveform obtained by the hammer impact method ..24
Figure 3.7: Experimental set up of pellet impact from pneumatic gun .............25
Figure 3.8: RF signal from a pneumatic gun pellet impact on 4” schedule 40 steel pipe ..........................................................26
Figure 3.9: Frequency response of the RF waveform from pellet impact ......27
Figure 3.10: RF signal from the impact of steel ball on 16” steel pipe .................28
Figure 3.11: Excitation from a sonic horn .................................................................29
Figure 3.12: RF waveform from sonic horn-signal received with transducer on top .................................................................................................................30
Figure 3.13: RF signal from sonic horn-signal received with transducer on bottom .....................................................................................................................30
Figure 3.14: FFT of the RF signal received with transducer on top of the pipe ....31
Figure 3.15: FFT of the RF signal received with transducer on bottom of pipe .......32
Figure 3.16: RF signal showing amplitude obtained from center punch excitation ....33
Figure 3.17: FFT showing 50 kHz central frequency from center punch excitation...33
Figure 3.18: Normal loading on a 28 feet long steel pipe ........................................34
Figure 3.19: Incident signal with 50 kHz frequency ................................................35
Figure 3.20: Natural focusing on the circumference of the pipe .............................35
Figure 3.21: RF signals received from the four sensors around the pipe .............36
Figure 3.22: Incident signal with 20 kHz frequency ...............................................37
Figure 3.23: RF signals received from the four receivers around pipe in case 2 ......37
Figure 3.24: RF signals received from four 50 kHz transducers around the pipe .....38
Figure 3.25: RF signal received from four accelerometers around the pipe ...........39
Figure 3.26: Experimental set up for measuring energy distribution .....................40
Figure 3.27: Transducer position around the circumference of pipe .....................41
Figure 3.28: RF Waveforms from 6 positions around the pipe - excitation by steel ball .................................................................................................................42
Figure 3.29: RF waveforms from 6 positions around the pipe - excitation by pneumatic gun impact .........................................................................................43
Figure 3.30: RF signals from 6 positions around the pipe - excitation from sonic horn ..................................................................................................................44
Figure 3.31: Power spectral density plot showing frequency - spring mounted steel ball excitation .................................45

Figure 3.32: Power spectral density plot showing frequency - pneumatic gun excitation ..................................................46

Figure 3.33: Power spectral density plot showing frequency – sonic horn excitation ..........................................................47

Figure 3.34: Normalized energy distribution around the circumference of steel pipe showing non-axisymmetric wave propagation ..................................48

Figure 3.35: Normalized energy distribution of 20 kHz frequency component from different excitations showing focusing ..............................................49

Figure 3.35: Normalized energy distribution of 40 kHz frequency component from different excitations showing axisymmetric wave propagation ...............50

Figure 3.36: Normalized energy distribution of 60 kHz frequency component from different excitations showing non-axisymmetric wave propagation ........51

Figure 4.1: Schematic diagram of the 4” schedule 40 steel pipe ............................................................53

Figure 4.2: Bare pipe in test position at CITEL and close up view of center punch excitation. The accelerometer used to trigger data collection is also visible ......54

Figure 4.3: (a) Coupled pipe, (b) Water layer loading outside the pipe ..................55

Figure 4.4: Comparison of RF waveforms obtained from center punch loadings ..........56

Figure 4.5: Cement filled between PVC pipe and steel pipe surface .........................58

Figure 4.7: RF waveform from center punch excitation after 960 hrs of setting time ..........................................................60

Figure 4.8: Shear transducer ring excitation on (a) Coupled pipe (b) Bare pipe ........62

Figure 4.9: Shear ring transducer excitation on bare pipe .................................................63

Figure 4.11: Shear ring transducer excitation on coupled pipe ..............................64

Figure 4.10: Shear ring transducer excitation with internal water loading on pipe .......65

Figure 4.12: Shear transducer excitation with external water loading ..................66

Figure 4.13: Shear transducer ring excitation on pipe with cement collar ..............68
Figure 4.14: Shear ring transducer excitation for cement set time of 1 hr .................. 69
Figure 4.15: Shear ring transducer excitation for cement set time of 3 hrs ............... 70
Figure 4.16: Shear ring transducer excitation for cement set time of 960 hrs .......... 72
Figure 4.17: Effect of hardening time on the amplitude of the center punch generated signal ................................................................. 73
Figure 4.18: Effect of excitation frequencies on amplitude in different boundary conditions ......................................................................................... 74
Figure 4.19: Shear ring transducer excitation – amplitude reduction as cement hardens ........................................................................................................ 76
Figure 5.1: Gas storage well used in field test at Dominion facility ......................... 78
Figure 5.2: Schematic diagram of the gas storage well at Dominion storage facility ........................................................................................................ 79
Figure 5.3: Front and back side of the fixture holding shear transducer ................. 81
Figure 5.4: Two-piece tool connected with wire line used to carry sensors .......... 82
Figure 5.5: Center punch excitation on the steel pipe in the field test ...................... 83
Figure 5.6: Experiment set-up with sensors inside the well .................................... 83
Figure 5.7: Schematic diagram of the two-piece fixture with sensors inside the well ................................................................................................................. 84
Figure 5.8: RF waveforms obtained when sensor #1 depth is 10 ft from the top ...... 85
Figure 5.9: RF waveforms obtained when sensor #1 depth is 50 ft from the top ...... 86
Figure 5.10: RF waveforms obtained when top sensor #1 depth is 77 ft from the top ............................................................................................................. 87
Figure 5.11: Amplitude as a function of Sensor #1 depth ....................................... 90
Figure 5.12: Amplitude ratio as a function of depth of sensor #1 ......................... 91
LIST OF TABLES

Table 4-1: Comparison of amplitudes for different loading conditions of pipe ........57
Table 4-2: Amplitude as a function of cement setting time ........................................61
Table 4-3: Maximum amplitude for different conditions and frequencies ...............67
Table 4-4: Shear ring transducer excitation as cement collar hardens ....................71
Table 4-5: Energy loss in different boundary conditions compared to bare pipe ......75
Table 5-1: Amplitude and arrival time of the RF signal from sensor #1 and #2........88
Table 5-2: Travel time and amplitude ratio of the RF signals from sensor #1 & #2...89
ACKNOWLEDGEMENTS

I would like to thank the following people:

The members of Gas Storage Technology Consortium (GSTC) for funding this project, providing specimens, and allowing us to carry out experiments at their gas storage facility.

My advisor Dr. Cliff Lissenden, for his guidance throughout the project and his support to implement new ideas. A lot of support has been given by him during the field experiments. I would like to thank Dr. Joseph Rose for advising throughout the project. His participation in one of the field tests and help in analyzing the results is unforgettable.

Steve Owens, Russell Love and other FBS Inc. personnel for their cooperation throughout the project. Especially, Steve Owens for working with me on the fixture and allowing me to use the FBS equipment for my experiments.

The students of the Ultrasonic NDE lab for assisting and supporting me, especially Padma, Jay, Chang, Luke and Jerry for helping me in experiments.

My wife Gayathri for her love and constant encouragement in tough times.

My parents, Kesava murthy and Kadambini, my sisters Parimala and Madhulika and my uncle TVK Murthy and family for their love and support throughout my education.
Chapter 1
INTRODUCTION

1.1 Motivation

Pipelines are used in industries where there is a transmission of liquids, fluids, steam and natural gas. Utmost care should be taken for the inspection of these transmission modes as they would cause severe damage to humans and environment in the event of failure. Even though gas transmission through pipelines is treated as the safest mode of transport, great care should be taken in every stage of transport. There are lots of interstate and intrastate pipelines running through the country to cater to the needs of people. Most of the interstate pipeline companies depend on the underground storage facilities to balance the load demand and supply management. The underground storage gas reservoir facilities, employ injection or withdrawal wells for loading and extracting natural gas from these underground storage facilities. According to the estimates from the Department of Energy, there are over 14,000 injection/withdrawal wells [1] used by the interstate pipeline companies. Injection/withdrawal wells provide access to the pipelines near ground level to the underground storage facilities. Most of these underground storage facilities are depleted oil and gas reservoirs, as they are an economical and safe way of storing natural gas. The gas causes rapid corrosion in pipes [2] and so the wells which are connecting them to the ground pipelines should be safe enough to avoid leakage. Often, these wells are situated in what are now residential areas and so the safety
of these wells is a critical issue. A variety of inspection methods exist [4], with pigging being the most common [3]. But these can be time consuming and expensive, and sometimes it is not practical to insert a pig into a well. Long range guided wave detection through ultrasonic phased array systems [5] exist but these wells can extend beyond 4000 feet and the penetration of guided waves from ultrasonic sensors is somewhat limited. Thus, this project aims to improve the penetration power of ultrasonic guided waves by investigating mechanical impact methods as well as alternative ultrasonic techniques.

1.2 Inspection of piping and well casings

1.2.1 Construction of gas storage well casing

The gas storage well casing facilitates access to the underground storage reservoir to either inject gas for storage or withdraw gas for transmission and distribution. Generally, a well casing is a series of steel pipes installed in a freshly drilled hole. Four inch schedule 40 steel pipes are commonly employed. The surface casing is employed around the production casing to protect them from any other gases and also from surrounding water resources. The type of casing around the pipes also depends on the subsurface conditions. A typical gas well construction is shown in the Figure 1.1.
The surface and intermediate casings are usually cemented for extra protection from fresh water contamination. The tubing length varies depending on the depth of the storage reservoir and can exceed 11,000 feet. From the Figure 1.1, we can observe that the outer surface of the production casing is not accessible for inspection as other casings and cement surround it. Only a small portion of the well, which is generally called the well head, will extend above the ground. The well head contains valves, flanges and sometimes gauges. A typical well head is shown in Figure 1.2.
Figure 1.2 shows that the above ground access to the well casing for inspection is extremely limited. The gas well at the Dominion field in North Canton, Ohio where we acquired field data is unique in the sense that the surface of the production casing is accessible above ground as shown in Figure 1.3.

Figure 1.3: Natural gas well head in Dominion facility at North Canton, Ohio
1.2.2 Pigging

The pipeline companies periodically inspect pipelines for corrosion and other defects to ensure public safety. The inspection of pipelines is generally carried out with robotic devices called PIGS. The pig is sent into the pipe and it travels through the interior of the pipe evaluating the thickness, corrosion and defects like cracks all along the pipeline. Inspection with the help of a pig is known as pigging. There are different types of pigs available for inspection depending on the diameter of the pipe. A typical pig used for inspection is shown in Figure 1.4. Many pigs work on the magnetic flux leakage technique to detect the defects.

![Figure 1.4: A typical pipeline inspection gauge- PIG [3]](image)

The disadvantages with pigs are they are generally not flexible and so cannot be sent through valves. This technique is time-consuming and requires stopping the fluid flow, which makes the technique more expensive.
1.2.3 Ultrasonic guided waves

Ultrasonic guided waves are presently used for long range inspection of pipelines. Depending on the diameter and thickness of the pipe, the frequency of the guided waves to be excited is selected from a study of the dispersion curves. Long range guided wave inspection is achieved by installing transducers around the pipeline as a collar, which forms a ring transducer. Presently they are able to inspect around 25-30 meters of the pipeline at a time [5]. The possible guided wave modes in pipes are longitudinal, torsional and flexural modes and some have the ability to travel long distances. However, other modes can attenuate quickly depending on the boundary conditions of the pipe [7]. Recently, axisymmetric and non-axisymmetric waves are also generated with the help of ring transducers. Focusing of guided waves helps to carry out inspection in a particular area to ensure the integrity of the pipe. Inspection of buried pipes with guided waves is proven successful where there is very limited access to the pipeline.

1.3 Limitations of current methods for gas well casing inspection

The inspection methods using ultrasonics and magnetic flux which are generally used to inspect pipelines can also be applied for well casing integrity monitoring. Although pigging is an expensive and time-consuming technique, it is the current standard practice. The depth of the gas well makes the application of long range guided waves from a single set up point quite difficult. Furthermore, cement encasement of steel casing takes ultrasonic energy from the steel and threaded couplings cause reflections of energy that further limit penetration power of ultrasonic energy. It would be very difficult
to use a pulse-echo method to inspect the entire well casing from the ground level, but other techniques will be explored. Pressure gauges are also used to inspect leakage in pipes as a pressure drops indicates the leakage. But this technique cannot identify the defect location and is not reliable.

1.4 Proposed work

The long range guided wave inspection technique can be applied to piping and well casing inspection, if the penetration power issue can be addressed. The input energy should be increased to achieve long range penetration of guided waves into the pipe. This depends on the voltage a piezoelectric material can handle but does not provide the necessary penetration into the pipe. So methods to increase the penetration power of the guided waves through mechanical impact methods are studied. As the energy reflected from defects will be difficult to receive, a novel through transmission technique lowering two sensors down a well is studied. Moreover, it has been proven that the through transmission technique works better than the pulse-echo technique for long range inspection. The energy excited in the pipe through mechanical impact methods is compared to that of conventional piezoelectric transducers.

Another method proposed to increase the penetration power of guided waves is employing a high voltage excitation for a shear transducer ring is reviewed. The high voltage is achieved with a voltage amplifier which is fed to the pulser of the shear transducer ring. This shear transducer ring does not need any couplant and axisymmetric modes can be generated in the pipe to carry out the inspection.
1.4.1 Objective

The objective of this project is to dramatically improve the penetration power of guided waves in piping for long range detection of defects like cracks and wall thinning from corrosion. A novel through transmission technique is proposed to evaluate piping and well casing integrity.
Chapter 2
EXCITATION SOURCES

2.1 Piezoelectric methods

Piezoelectric materials are commonly used for ultrasonic transducers because they couple mechanical displacement to an electric potential. Piezoelectric materials such as lead zirconate titanate (PZT) can be efficiently used as transmitters and receivers of ultrasound signals.

2.1.1 Ultrasonic transducers

2.1.1.1 Normal beam ultrasonic transducers

The normal beam transducer transmits and receives ultrasonic signals normal to the surface of the material in which the sound waves propagate. The construction of normal beam transducers is designed for efficient transmission and receiving of ultrasonic signals, such as matching layers between piezoelectric elements and the contact surface. A damping material is provided on the back of the piezoelectric element to damp its undesirable oscillations. The normal beam transducer was used in the experiments to receive the signal from the surface of the pipe as shown in Figure 2.1.
2.1.1.2 Angle beam ultrasonic transducers

The refraction and mode conversion of energy are used for transmitting sound beams into materials at various angles to the normal of the surface to increase the transmission efficiency. The angle can be achieved by introducing a Plexiglas wedge with desired angle. Sometimes the construction of the transducer is designed in a way that the angle beam is directly transmitted on to the surface of the test material. The angled beam transducers are used to excite guided waves efficiently in the materials and the angle of the wedge depends on the parameters like material properties, thickness, and diameter in case of a pipe. The angle beam transducer is shown in Figure 2.2.
2.1.2 High voltage phased array transducers

A high voltage phased array can also be used to increase the transmission efficiency or penetration power of ultrasonic guided waves. A ring transducer can be wrapped around the pipe and used to generate ultrasonic energy in the steel pipe. Such a ring can be used to generate axisymmetric waves in the pipe or focus energy at a prescribed location.

The transducers around the ring are excited with a tone burst voltage amplifier. The voltage amplifier used herein is part of a temate® system manufactured by Innerspec Technologies (Lynchburg, VA). Normally, the applied voltage to the transducers does not exceed 300 V, but here it can be as high as 1200 V. The transducers do not require couplant. They are pressed tightly to the surface of the pipe by air pressure. A ring transducer mounted on a steel pipe is shown in Figure 2.3.
2.2 Mechanical impact methods

2.2.1 Hammer impact method

The piezoelectric impact hammer was used in this experiment to excite the signal in the pipe by striking it on the surface of the pipe. The piezoelectric hammer, model number 408D06 manufactured by PCB Piezotronics Inc., was used and it is shown in Figure 2.4. The hammer consists of quartz inside a piezo element, which responds by giving electric pulses from mechanical impacts. The electric pulses are fed to the signal conditioner where the resonances are damped and the original signal can be observed through an oscilloscope. The signal conditioner can also be used to increase the gain of the received signal, but in the experiments conducted, no gain was used. The signal output from the hammer can also be used as a trigger to the oscilloscope to collect the signal from the other end of the pipe.
The impact tips used with the hammer can be changed for changing the frequency response generated. For the generation of low frequencies, extended mass is used with the impact tip. The impact tip transfers the force to the quartz element and the quartz responds with voltage pulses. In this experiment, the central frequency of the signals generated by the hammer was around 8 kHz, which is in the audible range frequency.
2.2.2 Ball impact methods

2.2.2.1 Pneumatic gun method

The pneumatic gun was employed to strike a BB on the surface of the pipe. One advantage over the hammer is that the BB has a smaller contact area, which increases the central frequency of the generated signal in the pipe. The BB used in the pneumatic gun was a copper coated steel ball having a 4.5 mm diameter. The power source is pneumatic pump action and a maximum velocity of 600 fps (183 m/s) can be achieved. The pneumatic gun used for the experiment is shown in the Figure 2.5.

![Pneumatic gun](image)

Figure 2.5: Pneumatic gun used in the experiment for excitation

The pneumatic gun can only take 4.5mm caliber BB. From the experiments, it was observed that the central frequency generated from the striking of BB on the pipe was around 45 kHz, which is in the ultrasonic frequency range.
2.2.2.2 Spring mounted steel ball impact

The spring mounted steel balls were used to strike the pipe and to generate the signal. The spring mounted steel balls used are similar to the steel balls used in impact-echo testing. The impact-echo testing used for non-destructive testing of concrete uses hardened steel balls mounted on springs as impactors. The dimensions of the steel balls can be varied depending on the thickness to be inspected. The frequency of the generated stress wave varies with the impactor [9]. The impactor used in this experiment is shown in Figure 2.6.

The steel ball used for the experiment has a diameter of 15.8 mm and it was soldered to the tip of a spring. The diameter of the steel ball can be varied to generate signals of different frequencies. The frequency generated from the steel ball used in the experiments was observed to be around 12 kHz. The frequencies generated by the pneumatic gun were larger than the frequencies generated by the steel ball, as the diameter of the BB is much smaller than the spring mounted steel ball.

Figure 2.6: Spring mounted steel ball used for excitation
2.2.3 Sonic horn excitation

A sonic horn was also used to strike the pipe and generate the signals. The sonic horn is used for joining plastics, welding metals, and for cell disruption in laboratories. They are also used for cleaning in some industrial applications. Sonic horns are generally available with resonance frequencies of 20, 30, 35, and 40 kHz. The sonic horns are connected to converters through a booster to facilitate increase in amplitude. The sonic horn used in the experiment is shown in Figure 2.7.

![Sonic horn](image)

Figure 2.7: Sonic horn used for excitation of signal on the pipe

2.2.4 Center punch impact

A center punch was also considered for excitation of ultrasonic signals in the pipe. The center punch is generally used for creating an indent prior to drilling a hole. A center punch is provided with a sharp tip in the front followed by screw type spring adjusters on the back. When the center punch is pushed on the surface of the work piece, the spring is
compressed until a release point. Then the force on the spring is released pushing the tip into the work piece. Once the spring is adjusted, it exerts approximately the same force on the surface every time it is used. The center punch used in the experiments is shown in Figure 2.8.

![Automatic center punch](image)

**Figure 2.8**: Automatic center punch [10]

### 2.3 Comparison of piezoelectric source with mechanical impact

The energy of the signal generated from piezoelectric elements is compared with that of the mechanical impact methods used to excite the signal.

#### 2.3.1 Normal beam transducer and pneumatic gun impact excitation

A 50 kHz normal beam transducer was used in the through-transmission method employed on the steel pipe. The receiving transducer was a distance of 9 ft (2.75m) from the transmitting transducer. The signals were collected from the receiver which was aligned along the length of the pipe with the transmitting transducer. A comparison of excitation signals was made between the normal beam transducer and pneumatic gun impact. The impact from the gun was made on the surface of the pipe and the response is received with a 50 kHz transducer which is aligned with the impact point. The response
from the gun impact and normal beam transducer is shown in Figure 2.9 and Figure 2.10 respectively.

Figure 2.9: RF signal obtained from the pneumatic gun impact

Figure 2.10: RF signal obtained from the 50 kHz transducer
From the responses obtained from the receiver, we can observe the amplitudes of the first echo of the RF signal from both excitations. The amplitude of the signal generated by the pneumatic gun is significantly larger than that of the conventional 50 kHz transducer.
Chapter 3

RESULTS ON PENETRATION POWER OF VARIOUS ACTUATORS

The results from the various loading methods are shown and the achievable penetration power is discussed. The methods considered have been broadly described as mechanical methods and piezo electric element methods. The experiments have been conducted on a 4 inch (102mm) schedule 40 steel pipe and 16 inch (406.4mm) schedule 30 steel pipe. In order to determine the group velocities in these steel pipes, we study their dispersion curves [11]. The phase velocity and group velocity dispersion curves for a 16 inch (406.4mm) steel pipe are shown in Figure 3.1 and Figure 3.2 respectively.

Figure 3.1: Phase velocity dispersion curve for 16” schedule 30 steel pipe
The phase velocity and group velocity dispersion curves for 4” schedule 40 steel pipe are shown in Figure 3.3 and Figure 3.4 respectively.

Figure 3.2: Group velocity dispersion curve for 16” schedule 30 steel pipe

Figure 3.3: Phase velocity dispersion curve for 4” schedule 40 steel pipe
Mechanical Methods

3.1 Hammer Impact Method

The piezoelectric hammer was used to excite ultrasonic waves in a steel pipe and the signals were received from the other end of the pipe. As the hammer strikes the pipe, the piezo element at the tip of the hammer gives an electric pulse which can be fed to the data acquisition system through a voltage amplifier. This electric pulse was used as a trigger for the data acquisition system to acquire the signal from the receiver at the other end of the pipe. The test was conducted on a 4” (102 mm) schedule 40 pipe which is 12 ft (3650 mm) in length. The signal received with a piezoelectric transducer on the other end of the pipe depicts a ring down pattern [12] as shown below in Figure 3.5.

Figure 3.4: Group velocity dispersion curve for 4” schedule 40 steel pipe
The amplitude was observed as 4V from peak to peak in the RF signal obtained. The phase velocity and group velocity dispersion curves for a 4” schedule 40 steel pipe is shown in Figure 3.3 and Figure 3.4 respectively are used in group velocity analysis. In order to calculate the group velocity from the dispersion curve, we should calculate the frequency of the obtained RF signal. The FFT of the obtained RF signal is shown in Figure 3.6 and the central frequency is noted as 8 kHz. The group velocity calculated from the dispersion curve is approximately 2500 m/s. From Figure 3.5, we are able to distinguish the echoes from noise until at least 100,000µs. By having the values of time and velocity, we are able to estimate a distance of 250 m (820 ft).
Pellet Impact Methods

Mechanical impact was considered as a means to generate ultrasonic waves in the steel pipe. The idea was drawn from the impact-echo testing [9] made on concrete to evaluate its integrity. Two types of impact methods were investigated; a BB shot from a pneumatic gun and a steel ball on a spring.

Figure 3.6: FFT of the RF waveform obtained by the hammer impact method
3.1.2.1 Pneumatic gun impact

A pneumatic gun was used to fire a BB at the outer surface of the steel pipe. The BB was fired from the pneumatic gun with an acceleration of 182.9 m/s$^2$ (600 ft/s$^2$). The experimental set up using the pneumatic gun is shown in Figure 3.7.

![Experimental set up of pellet impact from pneumatic gun](image)

A piezoelectric transducer was used as a trigger to the DAQ system. When the pellet strikes the pipe on the surface, stress waves are generated in the pipe. The transducer receives the signals and triggers the DAQ system. A 50 kHz piezoelectric transducer is used at a length of 9 ft (2.75 m) from the impact point on the steel pipe and the received RF signal is shown in Figure 3.8. As the receiving transducer is aligned with the impact point, it is referred to as 0 degrees.
The experiment was done on a 4" (102 mm) schedule 40 steel pipe of length 12 ft (3.65 m). As the multiple back wall echoes superimpose with each other, the RF signal in Figure 3.8 does not have a smooth ring down pattern because data were not acquired for a long enough time. The amplitude of the RF signal is approximately 4V peak to peak. The signal was collected only up to a time of 10,000 µs, due to limitations of the DAQ system. Also, the overlap of back wall echoes with the original signal makes it difficult to distinguish the modes. The central frequency of the RF signal is observed from its FFT, shown in Figure 3.9 to be around 45 kHz.

Figure 3.8: RF signal from a pneumatic gun pellet impact on 4” schedule 40 steel pipe
Steel balls are used to strike the pipe and to generate the stress waves as described in Chapter 2. A piezoelectric transducer or an accelerometer can be used as a trigger for the DAQ system. The signals are received from the other end of a steel pipe. In this experiment, the steel pipe has a 16” (406.4 mm) diameter with 28 ft (8.536 m) in length. A ring down pattern was observed in the RF signal received at the other end of the steel pipe as shown Figure 3.10. The amplitude of the RF signal is measured as approximately 5V peak to peak. As the steel pipe is 28 ft (8.536 m) in length, a better ring down pattern was observed in this RF signal. By comparing the RF signals of both BB and pellet impacts, we see that the amplitude due to the BB is larger than the
amplitude from the spring mounted steel ball. As the central frequency is around 20 kHz, the group velocity is approximately as 2500 m/s.

![Graph of RF signal from the impact of steel ball on 16” steel pipe]

**Figure 3.10:** RF signal from the impact of steel ball on 16” steel pipe

### 3.1.3 Impact with sonic horn:

A sonic horn, also known as an ultrasonic welding machine, can be used to generate an ultrasonic signal into the pipe. The resonance frequency of the ultrasonic welder we used was 40 kHz. The sonic horn provides a good excitation which can be used to inspect long distances, as the amplitudes of the signals are very high. The sonic
horn, if gated, provides a good control on excitation. The use of the sonic horn for impact is shown in Figure 3.11.

Figure 3.11: Excitation from a sonic horn

In this experiment, the sonic horn is used to impact the surface of a steel pipe of 16” (406.4 mm) diameter and 28 ft (8.536 m) long. The inspected pipe has corrosion located on the pipe at a distance of 11 feet from the receiving end. An accelerometer was used as a trigger for the DAQ system. The RF signals obtained from receiving transducers on the top and bottom of the pipe are shown in Figure 3.12 and Figure 3.13.
Figure 3.12: RF waveform from sonic horn, signal received with transducer on top

Figure 3.13: RF signal from sonic horn, signal received with transducer on bottom
The RF signal is received with a 50 kHz transducer on the top of the steel pipe aligned with the impact point. The sonic horn is used to impact the steel pipe on the surface manually. The frequency responses of the RF signals are shown in Figure 3.14 and Figure 3.15 for the top and bottom receivers respectively. The steel pipe used for this experiment is 16” (406.4mm) in diameter and 28 ft (8.53m) in length. The pipe has a 0.04 m² corrosion spot on the top surface. Since the corrosion is on the top of pipe we can observe a difference in the frequency response of the RF signals. The bottom transducer provides a smooth resonance frequency response where as the frequency response from the top is different. This difference in frequency response can be used to distinguish a good pipe from a defected pipe.

Figure 3.14: FFT of the RF signal received with transducer on top of the pipe
3.1.4 Center punch impact

A center punch was used for excitation on a 4” (102mm) schedule 40 steel pipe of length 12 feet (3.65m). In order to prevent the sharp tip of the center punch to damage the surface of the pipe, a round steel shim of dia 0.5” (12.7mm) is used. The excitation provides almost a constant force every time it is used. The signal is received by a 50 kHz transducer from the other end of the pipe. The RF waveform showing the amplitude as a function of time is shown in Figure 3.16.
The amplitude of the RF signal shown is approximately 8V from peak to peak. The frequency response from the excitation is shown in Figure 3.17 and the central frequency is observed as almost 50 kHz.

![Time vs Amplitude graph](image1.png)

**Figure 3.16**: RF signal showing amplitude obtained from center punch excitation

The amplitude of the RF signal shown is approximately 8V from peak to peak. The frequency response from the excitation is shown in Figure 3.17 and the central frequency is observed as almost 50 kHz.

![Frequency vs Amplitude graph](image2.png)

**Figure 3.17**: FFT showing 50 kHz central frequency from center punch excitation
3.2 Verification of axisymmetric property

3.2.1 Finite element models

A finite element analysis was performed on the 16 inch schedule 30 pipe. The commercial software ABAQUS was used in the simulations. In the modeling, a normal loading was applied to the top surface, just like a hammer impact and the out-of-plane displacement signals were observed at the end of steel pipe at a distance of 27 ft (0.711m) as shown in Figure 3.18.

![Figure 3.18: Normal loading on a 28 feet long steel pipe](image)

The out of plane displacements were calculated at four points located 0°, 90°, 180° and 270° around the circumference from the model. Tone burst (12 cycles with Hanning window) excitations of 50 and 20 kHz were applied.
**Case 1: Incident signal with 50 kHz frequency**

In this model, the element size was taken as 0.01m, so that the dimension will be less than 1/10\(^{th}\) of the wavelength of the signal in the steel pipe. The incident signal used was shown in Figure 3.19. With this incident frequency, natural focusing was observed at some points on the surface of the pipe as shown in Figure 3.20.

![Figure 3.19: Incident signal with 50 kHz frequency](image1)

![Figure 3.20: Natural focusing on the circumference of the pipe](image2)
The out of plane displacement signals received from the transducer positions around the circumference of the pipe are shown in Figure 3.19. The propagating wave has longitudinal, torsional and flexural components. The signals shown in Figure 3.21 indicate that the wave is not axisymmetric at this point along the pipe length.

![Figure 3.21: RF signals received from the four sensors around the pipe](image)

**Case 2:** Incident signal with 20 kHz frequency

The incident signal is shown in Figure 3.22. In this model, the element size was taken as 0.025 m. The out of plane displacements are received from the simulation at the four positions around the circumference of the pipe are shown in Figure 3.23.
The out of plane displacements from the received signals are compared in amplitudes. When comparing the axisymmetric nature of the propagating waves from 20
kHz and 50 kHz we can observe that the higher frequency results in a more uniform wave front.

3.2.2 Experimental Results

The finite element model geometry is the same as the pipe on which experiments were conducted. The wave was excited by impacting the pipe with a hammer, which is acting like a point source. The RF signals were received by the transducers from four positions as shown in Figure 3.24.

![RF signals received from four 50 kHz transducers around the pipe](image)

Figure 3.24: RF signals received from four 50 kHz transducers around the pipe

The experiment results shown in Figure 3.24 can be compared with the finite element model results from case 1 shown in Figure 3.21. The experiment was repeated with accelerometers as receivers and the hammer impact as the point source of loading. The accelerometers were used in place of 50 kHz transducers to see the 20 kHz frequency component present in the propagating signal. The RF signals received from the
accelerometers around the circumference of the pipe are shown in Figure 3.25 and can be compared with the RF signals received in the finite element model case 2 shown in Figure 3.21. From Figure 3.25, we observe that the amplitudes are approximately the same at all four positions, even though the loading is a single point source, which indicates a fairly uniform (axisymmetric) distribution of energy.

![Figure 3.25: RF signal received from four accelerometers around the pipe](image)

3.3 Energy Distribution around the pipe with excitation from mechanical impacts

In this experiment, the mechanical impact methods already described are used to excite waves in the steel pipe. The steel pipe is of 28 ft in length and 16 inch in diameter. The 50 kHz transducers were used to receive the signal at a distance of 27 ft from the loading point. The transducers were placed around the circumference of the pipe at three
positions, 120° apart from each other, and then rotated by an angle of 60°. Two data sets are collected, together effectively covering 6 different positions around the circumference of the steel pipe. An oscilloscope was used to collect the signal from the transducers and an accelerometer was used to trigger the oscilloscope. The impact methods: pneumatic gun fired BB, spring mounted steel ball, and sonic horn were used. The set up of the experiment was shown in Figure 3.26. In the figure, the pipe was covered with a plastic to prevent direct contact with rain water.

Figure 3.26: Experimental set up for measuring energy distribution

The receiving transducer configurations are shown in Figure 3.27. The excitation point is aligned with transducer number 6. RF waveforms, frequency responses, and circumferential energy distributions are analyzed for each excitation method.
3.3.1 Time-amplitude plots from each position around the circumference

The time-amplitude plots, generally termed as RF waveforms, are plotted from the data received from the sensors in 6 positions. Figure 3.28 shows the RF waveforms obtained from transducers 1 to 6 for a steel ball excitation. Since the excitation source is aligned with transducer 6, we observe that the amplitude from transducer 6 is the highest. The amplitudes of the RF signals collected from the 6 positions on the steel pipe are different, thus the energy distribution is not uniform. The RF waveforms analyzed from the data obtained from 6 positions when the excitation is the pneumatic gun are shown in Figure 3.29. Similarly, the RF waveforms plotted for data received from 6 positions when the excitation is done by sonic horn are shown in Figure 3.30.
Figure 3.28: RF Waveforms from 6 positions around the pipe - excitation by steel ball
Figure 3.29: RF waveforms from 6 positions around the pipe - excitation by pneumatic gun impact
Figure 3.30: RF signals from 6 positions around the pipe – excitation from sonic horn
3.3.2 Power Spectral Density plots

The Power spectral density (PSD) describes how the power of the signal is distributed with the frequency. The power spectral density is used here to study the response as it effectively defines the individual frequency content present in the data collected from the receiver. The PSD plotted for each transducer position for the excitation from a spring mounted steel ball are shown in Figure 3.31.

Figure 3.31: Power spectral density plot showing frequency - spring mounted steel ball excitation
In Figure 3.31 we observe that the main frequency component is around 12 kHz in every position around the circumference of the pipe. The frequency obtained from the excitation of spring mounted steel ball is in the audible range.

The power spectral density plot obtained from pneumatic gun excitation is shown in Figure 3.32. The main frequency component present in the excitation of pneumatic gun method is observed as around 40 kHz.

Figure 3.32: Power spectral density plot showing frequency - pneumatic gun excitation
The power spectral density plot from the 6 positions on the pipe when the excitation is from sonic horn is shown in Figure 3.33.

Figure 3.33: Power spectral density plot showing frequency–sonic horn excitation

The PSD plots indicate that the sonic horn excitation produced a 40 kHz central frequency. We can also observe that the power of the frequency is higher when compared with the power obtained from other excitation methods. From these PSD plots, the circumferential energy distribution profiles are plotted based on the frequencies.
3.3.3 Circumferential Energy distribution

The PSD plots are used to plot the energy distribution around the circumference of the steel pipe. The normalized energy distribution for different excitation sources are shown in Figure 3.34.

![Normalized energy distribution around circumference for different loading](image)

**Figure 3.34:** Normalized energy distribution around the circumference of steel pipe showing non-axisymmetric wave propagation

From Figure 3.34, we can observe the distribution of energy from the pneumatic gun method, spring mounted steel ball method and sonic horn method. The excitation was made at transducer position 6 and because of that all the excitations have maximum
energy in that position. In order to study the energy distribution based on individual frequency responses obtained from the PSD plots, the normalized energy distributions for 20, 40 and 60 kHz were considered as shown in the Figure 3.35, Figure 3.35 and Figure 3.36 respectively. Ultrasonic energy at 20 kHz is concentrated in line with the excitation source. At 40 and 60 kHz the energy distribution is more spread out than at 20 kHz, but more data would need to be acquired to draw reasonable conclusions.

Figure 3.35: Normalized energy distribution of 20 kHz frequency component from different excitations showing focusing
Figure 3.35: Normalized energy distribution of 40 kHz frequency component from different excitations showing axisymmetric wave propagation
Figure 3.36: Normalized energy distribution of 60 kHz frequency component from different excitations showing non-axisymmetric wave propagation
Chapter 4

EXPERIMENTS WITH DIFFERENT BOUNDARY CONDITIONS

Methods proposed to increase penetration power are applied to a 4” schedule 40 steel casing obtained from Equitrans. One length of pipe is approximately 20ft (6m) long and another length of pipe is approximately 21ft (6.4m) long and contains a threaded coupling near the center. The coupling was joined in the field by Equitrans using standard equipment. The mechanical impact methods like center punch, steel ball, and sonic horn, are used for the excitation source. Additionally, a ring of shear transducers excited by a high voltage amplifier was used. However, only results from the center punch impactor and the ring transducer will be presented. A 50 kHz piezo stack transducer mounted 18ft (5.48m) away from the excitation source is the receiver as shown in Figure 4.1. The well where the field test is conducted is a 4” schedule 40 steel pipe with a steel surface casing around it. The gas well is a series of steel pipes connected with threaded coupling. The gas well in the field is surrounded by water, trapped in between the production casing and the surface casing. For safety purposes, the gas well is filled with brine solution and below a certain depth, cement is provided as a casing for the gas well. In order to mimic the boundary conditions in the field, different boundary conditions are studied in the laboratory. The different test configurations studied include:

- bare steel casing,
- steel casing containing a threaded coupling,
- steel casing (no coupling) filled with water,
• steel casing (no coupling) surrounded by water contained in a 6” (0.15m) PVC pipe 10 ft long,
• steel casing (no coupling) surrounded by cement contained in a 6” (0.15m) PVC pipe 10ft (3.04m) long.

Figure 4.1: Schematic diagram of the 4” schedule 40 steel pipe

4.1 Center punch impactor results

Advantages of the center punch excitation are that it is simple to use and it is repeatable. A steel shim is used between the center punch and steel pipe to prevent damaging the surface of the pipe. The test set up on bare pipe is shown in Figure 4.2.
An accelerometer is used to trigger the data acquisition system. The experiment is repeated on a pipe with a threaded coupling as shown in Figure 4.3a. The bare pipe is filled with water throughout its length and the experiment is repeated. A 6 inch (0.15m) schedule 40 PVC pipe of length 10 feet (3.04m) is mounted around the steel pipe as shown in Figure 4.3b. One end of the PVC pipe is sealed and then filled with water.
The waveforms received from center punch excitation on bare pipe, pipe with a threaded coupling, pipe filled with water, and pipe with external water loading are shown in Figure 4.4.
Figure 4.4: Comparison of RF waveforms obtained from center punch loadings: (a) bare pipe, (b) coupled pipe, (c) water loading inside, (d) water layer outside.
From Figure 4.4, it can be observed that the coupled pipe reflects much of the higher frequency energy, and the water loading inside or outside absorbs the higher frequency components relative to the bare pipe. The arrival time in the case of externally water loaded pipe is less than the other configurations. The guided wave modes with high velocity may have traveled through the water layer outside the pipe and thus arrived sooner than the waves that traveled through the pipe. The fact that the external water loading was only over a 10 ft length, while the internal water loading was over the length of the pipe, may explain the difference in amplitude reductions. The amplitudes of the received signals are shown in the Table 4-1.

Table 4-1: Comparison of amplitudes for different loading conditions of pipe

<table>
<thead>
<tr>
<th>Pipe Condition</th>
<th>Bare pipe</th>
<th>Coupled pipe</th>
<th>Internal water loading</th>
<th>External water loading</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amplitude(V)</td>
<td>4.9</td>
<td>2.3</td>
<td>1.2</td>
<td>1.5</td>
</tr>
</tbody>
</table>

4.2 Center punch excitation on a bare pipe encased in cement

The experiment is conducted on a bare pipe encased in cement. The 6” schedule 40 PVC pipe surrounding the steel pipe is filled with cement. The cement composition used in this mixture is approximately 50% neat cement, 10% sand and 40% water [14]. The water content is selected as a compromise between the setting time and
workability. Cement is filled in between the PVC pipe and the steel pipe as shown in Figure 4.5.

![Cement filled between PVC pipe and steel pipe surface](image)

**Figure 4.5:** Cement filled between PVC pipe and steel pipe surface

The excitation is applied to the bottom end of the pipe and the signal is received at the top end for different times during the hardening of the cement. Data are collected at 1, 3, 15 and 24 hrs. The waveforms are shown for these times in Figure 4.6.
Figure 4.6: Comparison of RF waveforms at different cement set times: (a) 1 hr (b) 3 hrs (c) 15 hrs (d) 24 hrs
From Figure 4.6, we can observe that the amplitude increases as the setting time of cement increases from 1 hr to 24 hrs. More of the guided wave energy remains in the steel pipe as the cement hardens. The center punch excitation is made on the cement loaded pipe after 960 hrs (40 days) and the RF signal obtained from the 50 kHz sensor is shown in Figure 4.7. The amplitudes of the received signals are measured and shown in the Table 4-2. An increase in amplitude is observed compared to the previous measurements as the cement dries off and is no more bonding to the steel surface of the pipe.

![RF waveform from center punch excitation after 960 hrs of setting time](image)

**Figure 4.7**: RF waveform from center punch excitation after 960 hrs of setting time
4.3 Shear transducer ring excitation

A shear transducer ring is used for the excitation of axisymmetric guided waves in the pipe. A high voltage from amplifier is used for pulsing. This is a pulse-echo technique and the excitation is applied on bare pipe, coupled pipe, pipe with water inside, and pipe with external water loading. All of the experiments with the center punch used through-transmission. The laboratory set up is shown in Figure 4.8. Shear transducer ring excitations are applied to the same boundary conditions as the center punch. A 6 cycle tone burst with central frequencies of 30, 40, 50, and 60 kHz is used. The waveforms received for the bare pipe, pipe with water loading inside, the pipe with a threaded coupling and pipe with external water loading are shown in Figures 4.9, 4.10, 4.11, and 4.12 respectively. Each figure shows the results for 30, 40, 50, and 60 kHz excitations.

Table 4-2: Amplitude as a function of cement setting time

<table>
<thead>
<tr>
<th>Time after loading (hrs)</th>
<th>Bare pipe</th>
<th>1</th>
<th>3</th>
<th>15</th>
<th>24</th>
<th>960</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amplitude (V)</td>
<td>4.9</td>
<td>0.046</td>
<td>0.1</td>
<td>3.5</td>
<td>2.9</td>
<td>3.9</td>
</tr>
</tbody>
</table>
Figure 4.8: Shear transducer ring excitation on (a) Coupled pipe (b) Bare pipe
Figure 4.9: Shear ring transducer excitation on bare pipe
Figure 4.11: Shear ring transducer excitation on coupled pipe
Figure 4.10: Shear ring transducer excitation with internal water loading on pipe
Figure 4.12: Shear transducer excitation with external water loading
The amplitudes for the various boundary conditions are shown in Table 4-3 for each frequency.

Table 4-3: Maximum amplitude for different conditions and frequencies

<table>
<thead>
<tr>
<th>Condition</th>
<th>30 kHz</th>
<th>40 kHz</th>
<th>50 kHz</th>
<th>60 kHz</th>
<th>100 kHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bare Pipe</td>
<td>0.25</td>
<td>0.18</td>
<td>0.17</td>
<td>0.17</td>
<td>-</td>
</tr>
<tr>
<td>Coupled pipe</td>
<td>0.13</td>
<td>0.075</td>
<td>0.092</td>
<td>0.044</td>
<td>-</td>
</tr>
<tr>
<td>Water loading inside the pipe</td>
<td>0.22</td>
<td>0.11</td>
<td>0.19</td>
<td>0.15</td>
<td>-</td>
</tr>
<tr>
<td>Water loading outside the pipe</td>
<td>0.07</td>
<td>-</td>
<td>0.07</td>
<td>0.08</td>
<td>0.07</td>
</tr>
</tbody>
</table>

4.4 Shear transducer ring excitation of cement encased pipe

The shear transducer ring is used to excite shear waves in the pipe as the cement collar hardens. A high voltage is given to the pulser for the excitation. The set up of shear transducer ring is as shown in Figure 4.13.
The shear transducer ring is also employed when the cement collar is placed and hardening around the pipe. Excitation frequencies of 30, 40, 50, and 60 kHz are used and results are plotted in Figures 4.14 and 4.15 for set times of 1 hr and 3 hrs respectively.
Figure 4.14: Shear ring transducer excitation for cement set time of 1 hr
Figure 4.15: Shear ring transducer excitation for cement set time of 3 hrs
The amplitudes from the received signals at every excitation frequency are measured and are shown in Table 4-4.

Table 4-4: Shear ring transducer excitation as cement collar hardens

<table>
<thead>
<tr>
<th>Amplitude(V)</th>
<th>30kHz</th>
<th>40kHz</th>
<th>50kHz</th>
<th>60kHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 hr</td>
<td>0.11</td>
<td>0.07</td>
<td>0.045</td>
<td>0.04</td>
</tr>
<tr>
<td>3 hrs</td>
<td>0.11</td>
<td>0.05</td>
<td>0.04</td>
<td>0.02</td>
</tr>
</tbody>
</table>

The experiment was repeated after 15 and 24 and 960 hrs (40 days) of cement hardening, and it was observed that the shear waves attenuated very rapidly. The reflection of the excited shear wave is not observed in any of the frequencies after 15 hrs of set time. The RF waveforms after 960 hrs of cement hardening when excited at 30 and 40 kHz frequencies is shown in Figure 4.16 From the figure we can observe the reflected signal from the cement position and no reflected echo from the other end of the pipe is observed as the total shear energy leaked into the cement [13].
4.5 Analysis of results

4.5.1 Center punch excitation – different loadings on pipe

Energy transmitted by the center punch for different boundary conditions is reported in Table 4.1. Energy losses relative to the bare pipe are calculated to be:

1) Energy loss due to a threaded coupling = $20 \log(2.3/4.9) = -6.56 \text{ dB}$

2) Energy loss due to water inside the pipe = $20 \log(1.195/4.9) = -12.25 \text{ dB}$

3) Energy loss due to water layer outside the pipe = $20 \log(1.5/4.9) = -10.28 \text{ dB}$
4.5.2 Center punch excitation – pipe with cement collar

From the Table 4-2, we can observe the amplitude levels increase as the cement hardening time increases. As the cement hardens the collar attenuates less energy and the received signal increases in amplitude as shown in Figure 4.17.

![Center punch excitation on cement loading](image)

Figure 4.17: Effect of hardening time on the amplitude of the center punch generated signal

4.5.3 Shear ring transducer – different loadings on pipe

The amplitudes of the signals received from the shear wave excitation at different frequencies are plotted in Figure 4.18 for different boundary conditions of pipe. For each loading condition the low frequency excitation resulted in higher amplitude. As the frequency increases, the amplitudes decrease. The excitation frequencies were varied up to 100 kHz and a constant decrease in amplitude is observed.
The energy loss in different loading conditions compared to a bare pipe at different frequencies excited is shown in Table 4-5. The energy lost in a coupled pipe is around 6 dB from 30 to 50 kHz frequencies and it is less than compared with mechanical excitation. The energy loss with water loading outside is greater than that of water loading inside. This may be due to the shear wave excitation on the outer surface of the pipe. The water loading inside did not affect the shear wave propagation behaving as a half layer. But when compared to the mechanical impact excitation which is a longitudinal wave excitation, the shear wave excitation has less affected by the water loading.

Figure 4.18: Effect of excitation frequencies on amplitude in different boundary conditions
4.5.4 Shear ring transducer excitation – cement encased pipe

The amplitudes for different frequencies at different cement hardening times are shown in Figure 4.19. When the setting time is 1 hr, the shear waves easily pass through the pipe without leaking into the cement, the reflected signals are recorded. After 3 hrs of hardening, the amplitudes of the received signals decrease compared with the initial readings. After 15 hrs of hardening, all the energy leaks into the cement and nothing is reflected back to the shear transducer receiver.
4.5.5 Summary

The center punch excitation and shear ring transducer excitation is applied on different boundary conditions of pipe. The center punch excitation is observed as an efficient method of excitation as the energy propagated is greater than shear transducer excitation. The effect of center punch excitation on cement loading is observed at different setting times. The energy propagation increases as the hardening time increases. But in case of shear wave excitation on cement loading, the energy propagation decreases as the hardening time increases.

Figure 4.19: Shear ring transducer excitation – amplitude reduction as cement hardens
Chapter 5

A NOVEL THROUGH TRANSMISSION EXPERIMENT ON A GAS STORAGE WELL

Field tests have been conducted on a natural gas storage well owned by Dominion Inc, North Canton, OH. The well tested is unique in that it is an observation well that is not under pressure and has accessible production casing above ground. The purpose of the well is to measure the fluid level, which is approximately 600 ft. The storage reservoir level is about 3700 ft. Figure 5.1 is a photo of the site showing the well head.

With an eye toward well casing mechanical integrity evaluation, the objective of the field testing is to determine the penetration power of mechanical impact excitation sources under realistic conditions. The through transmission mode of testing having the excitation source at ground level and a down-hole sensor was planned. It is necessary to know what effect the threaded couplings between casing segments and other realistic boundary conditions have on the penetration power of the ultrasonic energy in order to design an optimal inspection system.
5.1 Gas storage well construction

A schematic of the observation well is shown in Figure 5.2. The 4” schedule 40 production casing extends down to the reservoir. The 8” surface casing extends down below the fluid level and is encased within a cement collar. The gap between the production casing and the surface casing is most likely filled with ground water. Below the flange of the production casing there is an exposed 7” above the surface casing. This is a suitable location for actuating guided waves although much ultrasonic energy will be diverted through the split rings, which support the entire weight of the production casing, into the surface casing.
Figure 5.2: Schematic diagram of the gas storage well at Dominion storage facility

- Valve
- Flange
- Ground level
- 8.6” surface casing
- Cement collar
- 4” schedule 40 pipe
- 590 feet - brine level
- 660 feet
- 1751 feet
- 3721 feet
- Reservoir
5.2 Inspection challenges

During planning for the field testing it was decided to introduce ultrasonic guided waves into the production casing by mechanically loading its outer surface above ground level. Removal of the well cap above the flange on the production casing provides access to the well for a down-hole sensor. In consultation with Dominion, a tool was designed that could be lowered by a wire line down into the well. For simplicity, a fixture to hold an air-coupled transducer was designed. This circumvented the need for contact with the casing, as well as the need for couplant. However, the signal from the guided waves was completely overwhelmed by another signal, which apparently comes from the presence of standing waves in the well. A second tool that is based on shear contact sensors was designed.

5.3 Fixture construction and operation

The fixture design is that of a two piece tool. Two sensors are strapped together with cable 13 ft apart. Each sensor is a shear transducer contact element. The transducer is coupled to the inside of the casing by mechanical force only, no liquid couplant is used. The contact force is applied by inflating an air bladder to 10 psi pressure. The fixture is constructed with a PVC pipe to contain both the shear transducer and on the opposite side, the air bladder. The dual sensors (which are a fixed distance apart) are lowered into the casing with a wire line. When the fixture reaches the prescribed depth the air bladders are inflated, which press the shear transducers into contact with the inner surface of the
casing. After measurements are taken the air bladders are emptied and the fixture is lowered further into the casing and the process repeated. Photographs of the fixtures are shown in Figure 5.3.

Figure 5.3: Front and back side of the fixture holding shear transducer

The distance between sensors was fixed in this experiment, but it could be easily adjusted without changing the principle of operation. The two-piece tool is shown in Figure 5.4. Coaxial cable carries the received signal to the computer for data acquisition.
In this experiment the fixture was lowered in 5 ft increments, with the first data acquired when the top sensor was 10 ft below the excitation source. Data were taken at 14 depths, with the center punch used as the excitation source each time. At each depth, data were acquired ten times and then averaged together and the averaged waveform was

Figure 5.4: Two-piece tool connected with wire line used to carry sensors
then saved for analysis. The field test set up, including the accelerometer used to trigger data collection, is shown in Figure 5.5.

Figure 5.5: Center punch excitation on the steel pipe in the field test

Figure 5.6: Experiment set-up with sensors inside the well
Figure 5.6 shows the experiment set-up with sensors inside the well. Air compressor used to inflate the air bladders is also shown. A schematic diagram of the fixture down in the well is shown in Figure 5.7.

Figure 5.7: Schematic diagram of the two-piece fixture with sensors inside the well
5.4 Field test results

The data acquired from the two sensors when the top sensor (#1) is located 10 ft below the excitation source is shown in Figure 5.8.

Figure 5.8: RF waveforms obtained when sensor #1 depth is 10 ft from the top

We can observe that the amplitude of the signal recorded from the bottom sensor (#2) is less compared with that of the first sensor as the second sensor is at a distance of 23 ft. The energy loss is approximately 5.65 dB. The RF waveforms obtained when the top sensor (#1) is 50 ft below the source are shown in Figure 5.9.
The RF waveforms obtained when the top sensor (#1) is 77 ft below the source is shown in Figure 5.10.

Figure 5.9: RF waveforms obtained when sensor #1 depth is 50 ft from the top
The RF waveform obtained from every increment of depth are measured and plotted as shown in Table 5.1.

Figure 5.10: RF waveforms obtained when top sensor #1 depth is 77 ft from the top
The difference in arrival times at sensors #1 and #2 is calculated to obtain the wave travel time over 13 ft. The amplitude ratio $A_2/A_1$, sensor #2 divided by sensor #1, is also calculated for each depth. Travel times and amplitude ratios are shown in Table 5.2. The average travel time is 1.3 ms, enabling the group velocity to be calculated, $13\text{ ft}/1.3\text{ ms} = 10\text{ ft}/\text{ms} = 3050\text{ m/s}$.

<table>
<thead>
<tr>
<th>Depth of sensor 1 (in feet)</th>
<th>SENSOR 1</th>
<th>Depth of sensor 2 (in feet)</th>
<th>SENSOR 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arrival time (ms)</td>
<td>Amplitude (V)</td>
<td>Arrival time (ms)</td>
<td>Amplitude (V)</td>
</tr>
<tr>
<td>10</td>
<td>0.89</td>
<td>0.16</td>
<td>23</td>
</tr>
<tr>
<td>15</td>
<td>1.4</td>
<td>0.105</td>
<td>28</td>
</tr>
<tr>
<td>20</td>
<td>1.8</td>
<td>0.188</td>
<td>33</td>
</tr>
<tr>
<td>25</td>
<td>2.28</td>
<td>0.114</td>
<td>38</td>
</tr>
<tr>
<td>30</td>
<td>2.8</td>
<td>0.079</td>
<td>43</td>
</tr>
<tr>
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<td>83</td>
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<tr>
<td>77</td>
<td>7.15</td>
<td>0.065</td>
<td>88</td>
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</table>
The amplitudes shown in Table 5.1 are plotted in Figure 5.11, showing generally decreasing amplitude with depth. It would be desirable to extrapolate the decrease in amplitude until it intersects the noise floor, but the non-uniformity in these data makes this not practical. The rotation of the second fixture is restricted by the wire line. The rotation will not affect the signal much as it is evident from the theoretical simulations that the signal becomes more axisymmetric as it propagates through the pipe. The

<table>
<thead>
<tr>
<th>Depth of sensor 1 (ft)</th>
<th>Travel time from sensor 1 to sensor 2 (ms)</th>
<th>Amplitude ratio A2/A1</th>
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<td>0.46</td>
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<tr>
<td><strong>Average arrival time</strong></td>
<td><strong>= 1.30ms</strong></td>
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</table>
amplitude ratio is often a far better feature to analyze, thus data from Table 5.2 are plotted in Figure 5.12. For a continuous pristine casing, the expectation is that the amplitude ratio be constant. Threaded coupling and defects would cause the amplitude ratio to change. The oscillations in the amplitude ratio shown in Figure 5.12 suggest the presence of couplings or defects, but more data are required to make any definitive conclusions.

Figure 5.11: Amplitude as a function of Sensor #1 depth
From Figure 5.11, we can observe the amplitude from sensor#1 and sensor#2 varies in the same pattern until around 35 feet. From that depth, the plot from the two sensors is different. This is due to the coupling at approximately 34 feet from the ground level. In figure 5.12, the ratio of the amplitudes from two sensors as a function of depth of sensor#1 is plotted. As the two sensors are lowered down for every 5 feet, we can observe a sharp dip in the plot at a depth where coupling is located. Similarly any defect in the casing should yield a decrease in the amplitude ratio and be easily detected.

![Figure 5.12: Amplitude ratio as a function of depth of sensor #1](image)

5.5 Summary

A new novel technique is developed for the inspection of natural gas storage well and experiment is conducted in the Dominion storage facility. The designed two sensor tool is lowered at every 5 feet for inspection. Amplitude decrease is observed as the sensors were moved down. The arrival times are measured for two sensors at every step.
and the group velocity of the wave is calculated as approximately 3050 m/s. The difference in arrival times is almost constant in every step. The lowering of the sensor fixture for every 1 foot to record data helps to study the location of threaded couplings and analyze the integrity of gas well.
The propagation of ultrasonic guided waves in a pipe has been studied for a variety of excitation sources with a focus on penetration power of the ultrasonic energy. Amplitudes and frequencies were determined in laboratory experiments and the wavefront from a point source was found to exhibit natural focusing as far as 20 ft from the source for a 16” diameter pipe. There are quite a few nondestructive evaluation applications where this is an important consideration, including for example well casings, pipelines, and difficult to access piping in power generation and chemical plants.

Natural gas well production casing is often 4” schedule 40 steel pipe. Laboratory and field experiments were conducted on this pipe. The focus of the laboratory tests was to determine the effect that threaded couplings and boundary conditions have on penetration power. The boundary conditions considered were water loading inside the pipe, water loading outside the pipe, and the presence of a cement collar around the pipe. Both mechanical impact loading and a ring of shear transducers were used to excite the stress waves. A standard threaded coupling results in a 6 dB loss. The water loading attenuated the ultrasonic energy in the steel pipe from a mechanical impact to an even larger extent. The energy lost with water loading on pipe is around 12 dB. Results from placement of the cement collar indicate that the penetration of the stress waves excited by mechanical impact increases as the cement hardens, but that the reverse is true when the
excitation is a ring of shear transducers. These results suggest that it is unlikely that the penetration power is on the order of thousands of feet. Thus, it appears necessary to place sensors periodically inside the pipe or move a sensor along the pipe.

The field tests were intended to check the applicability of a two-piece casing inspection tool. A two-piece tool was designed and built by inserting a shear transducer into a PVC pipe that fits inside the casing. It is a contact transducer and an air bladder was used to apply and remove the contact force. Two fixtures were strapped together with a spacing of 13 ft. The excitation source was at ground level and the two-piece tool was lowered into the well with data taken in 5 ft intervals. A depth of almost 90 feet is inspected in the field test. Even at 90 feet depth, the sensors are sensitive and no gain was used in receiving data. The data from the sensors was analyzed to check the coupling condition. The shear wave velocity propagating in the casing is calculated as 3000 m/s. This is a through-transmission technique that makes inspection over any length possible by moving the two-piece tool. Methods can be developed in future work to change the frequency of excitation in order to increase the penetration even further. Fine tuning the signal analysis and pattern recognition algorithms in the future will help in determining defect position, type, and approximate size.
BIBLIOGRAPHY

5. http://www.ndt.net/article/wcndt00/papers/idn166/idn166.htm
Appendix A

NON-TECHNICAL ABSTRACT

Storage of natural gas in underground facilities requires steel piping, also called gas well casing, to transfer the natural gas from the reservoir to the transmission and distribution pipeline networks. The ambient environment can deteriorate the structural integrity of the steel piping (which includes tubing, casing, piping, and pipelines). The leakage of gas may lead to many problems, from contamination of underground water resources to a blowout. To ensure the safety of the public and the environment, it is necessary to monitor the integrity of these mechanical systems. The present monitoring methods are not reliable, time consuming and hence expensive.

Guided wave ultrasonics is an emerging inspection technique that enables long range inspection from a single point on the pipeline. Great advances have recently been made in tuning and focusing to improve sensitivity to defects. The work herein focuses on the penetration power of guided waves. To achieve long range inspection of pipes, as in gas wells, the excitation energy needs to be increased. In this project, mechanical impact techniques, which are sometimes used in the inspection of concrete water pipes, and high voltage piezoelectric methods are investigated. A novel technique based on through transmission with two receivers is investigated for inspection. The objective of the project is mainly to increase the penetration power of guided waves and also investigate the detectability of defects in long range pipe inspection. The results of the
project will help to improve the safety of pipelines, ensure reliability of inspection, and reduce the inspection time and hence maintenance costs.