DEFECT GROWTH DETECTION POTENTIAL USING GUIDED WAVES

A Thesis in
Engineering Science and Mechanics

by
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Submitted in Partial Fulfillment
of the Requirements
for the Degree of
Master of Science

August 2016
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ABSTRACT

Modern society relies on vast networks of infrastructure such as bridges, pipelines, railroads, and electric generating stations to name a few. Keeping infrastructure operating reliably and safely requires inspection and maintenance. In the United States, inspection and maintenance is especially important for aging infrastructure which is often kept in service beyond its intended lifespan. Inspection is carried out via a range of nondestructive evaluation (NDE) techniques depending on the application. Ultrasonic guided wave testing is a popular NDE technique because of its versatility and ability to quickly inspect large structures and to detect hidden defects. However, ultrasonic guided wave propagation is complex and requires an understanding of wave mechanics for effective inspection. In this thesis, different guided wave modes and frequencies are tested for tracking simulated crack growth in a steel pipe, based on the hypothesis that the effectiveness of the mode and frequency combinations will differ based on the wave structure. Along the way, many concepts relevant to NDE and ultrasonic guided waves such as maintenance philosophies, defect growth and fracture mechanics, guided wave excitation, dispersion principles, source influence, wave structure, noise, and variability in results are discussed.
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ACKNOWLEDGEMENTS

First of all I thank my adviser, Professor Joseph Rose, for his advice and encouragement, not only about research but also about graduate studies in general. I also thank everyone at Guided Wave (formerly FBS, Inc.) for helping me learn so much in the past several years. In particular, I thank Dr. Cody Borigo, who has always been generous in sharing his expertise of both the theoretical and practical aspects of ultrasonic guided waves with me. Last but not least, I give thanks to my parents for their incredible kindness and support of my education.
Chapter 1

Introduction

1.1 Problem Statement

The goal of this research is to use a theoretically driven, experimentally focused approach to investigate defect detection potential using ultrasonic guided waves, with a focus on tracking crack growth. Service defects such as fatigue cracks and corrosion commonly plague aging infrastructure. The ability to detect and locate such defects on large and often inaccessible structures is a challenge, but it is critical to the longevity and safety of infrastructure such as pipelines and bridges. Practically, defects must not only be detected, but the cost of inspection must be affordable since there are many structures that need to be inspected with limited maintenance budgets. For many cases, guided wave inspection provides a practical solution because it is quick, has the ability to locate hidden defects, and gives volumetric coverage. For pipelines, guided wave inspection is advantageous because it allows for the inspection of long sections of pipe from a single location, and has the potential to see defects hidden underneath coatings. In this thesis, several guided wave modes are tested for tracking the growth of a circumferential crack in pipe, and it is shown that certain modes and frequencies are effective while others are not. Along the way, many practical issues such as coupling, source influence, transducer types, wave structure, and predicting failure modes via fracture mechanics are also discussed.
1.2 Importance of Infrastructure

Every community needs functioning infrastructure to thrive. In the United States, local infrastructure is in place to provide basic necessities such as safe drinking water, electricity, telephone service, and sewers, as well as roads and bridges, to every community. On the regional and national scales, there are additional forms of public infrastructure such as: the interstate highway system, electric generating stations and the electric grid, dams, levees, ports, airports, pipelines, and railroads. Maintaining these vast networks of infrastructure so that they can continue functioning safely and reliably is both expensive and laborious.

Unfortunately, America’s infrastructure is in suboptimal condition on many fronts. According to a 2013 report by the American Society of Civil Engineers (ASCE), America’s infrastructure only earned an overall grade of D+ (using the familiar A to F school report card format), and will require an estimated $3.6 trillion in investment by 2020 [1]. Recently, dramatic failures of basic infrastructure that Americans typically take for granted have garnered great media coverage. For example, the collapse of the I-35W bridge across the Mississippi River in 2007 brought attention to the nation’s aging bridges, many of which are based on obsolete “fracture-critical” designs, meaning that due to poor load-path redundancy, the failure of a single structural member may trigger the collapse of the entire bridge [2]. Similarly, the contamination of public drinking water in Flint, Michigan from 2014-2016, due in part to aging pipes and austerity measures [3], led to a public outcry and placed municipal water supplies under increased scrutiny. In addition to being relied upon to transport safe drinking water, over 305,000 miles of pipeline are also used to transport natural gas in the United States, according to the U.S. Energy Information Administration [4]. When pipelines carrying hazardous materials such as natural gas fail, the effects can be immediate and catastrophic. For example, the explosion of a 30” pipeline
in San Bruno, California in 2010 caused eight deaths and registered as a magnitude 1.1 earthquake [5].

![Figure 1-1](image)

Figure 1-1. On August 1, 2007, the I-35W bridge over the Mississippi River in Minneapolis collapsed, killing 13 people and injuring 145 [4]. Investigation by the National Transportation Safety Board concluded that the bridge failed due to faulty design and increased weight from recent construction [5].

Clearly, maintaining our extensive networks of infrastructure is a broad, multi-faceted task. New infrastructure must be built for safety and longevity. For example, stringent codes can be used to prevent “fracture-critical” designs such as the collapsed I-35W bridge from being implemented in new construction. However, no matter how well designed and constructed our infrastructure becomes, it will undoubtedly require maintenance throughout its service life. This is especially important when structures or machines are used beyond the life expectancy that they were originally designed for - something which is becoming increasingly common. In Pennsylvania, for example, 45% of bridges are over 50 years old, and 17% are over 75 years old; but most bridges are only designed for 40-50 years of service [6]. In addition to being used for longer than the lifespans which they were originally designed for, bridges are also subjected to greater loads than were originally envisioned due to increased automobile traffic and especially due to increased heavy truck traffic [7]. Although bridges are an illustrative example, and receive
attention due to the possibility of sudden, dramatic failures, these same issues – old age, design obsolescence, and lack of effective maintenance – are prevalent in nearly all infrastructure systems, not just bridges. An excellent overview of the health of each type of infrastructure in the United States is provided by the 2013 ASCE report [1].

1.3 Maintenance Strategies

Before delving into any of the technical details of how infrastructure is inspected or maintained, it is helpful to first review general maintenance strategies. All maintenance is either reactive or preventative. Reactive maintenance simply means waiting for a break-down or failure before performing the necessary repairs. The maintenance is an after-the-fact reaction to a failure. For obvious reasons, reactive maintenance is not an acceptable strategy for maintaining critical systems, although it is still used in some cases (for example, patching pot-holes each spring could be considered reactive maintenance). Instead, preventative maintenance (PM) is used to keep critical infrastructure operating safely and reliably with minimal interruptions. Generally, preventative maintenance can be further classified into two subcategories: schedule-based and condition-based maintenance (CBM). In the schedule-based strategy, maintenance is performed periodically at intervals that are typically specified by the original equipment manufacturer (OEM) in the case of machinery, and by safety mandates in the case of public infrastructure. Changing the motor oil in a car every, say, 5,000 miles (in accordance with the owner’s manual) is a familiar example of a schedule-based maintenance program based on the recommendations of the OEM. Note that the condition of the oil is not actually evaluated. In fact, if the engine is in good condition and the car is primarily used on the highway, then the oil may not degrade for far more than 5,000 miles. In this case, the 5,000 mile service interval is a conservative estimate. Alternatively, if the operating conditions are severe (e.g. stop-and-go driving and excessive idling
time), the oil may already be contaminated or degraded after 5,000 miles, and the engine is then subject to excessive wear by using “dirty” oil. These cases illustrate that, typically, schedule-based maintenance relies on compromises. Ideally, the maintenance schedules are conservative, so that maintenance is almost always performed before damage or failure with some margin of safety. Reusing the motor oil change example clearly illustrates the downside of the schedule-based approach: consistently changing the oil before it is necessary to do so (possibly several thousand miles before necessary) results in significantly increased maintenance cost over the life of the vehicle with no added benefit; this is known as over-maintenance.

As the name suggests, the condition-based maintenance strategy is based on the condition of the structure or the machine, rather than on a rigid schedule. A major advantage of CBM is that maintenance is only performed when it is deemed necessary, rather than too soon or possibly too late. This can both reduce cost and extend service life. Reusing the motor oil example once more, a simple example of condition-based maintenance would be to periodically send a sample of the motor oil to a lab for analysis, and change the oil when the test results indicate that it has lost some of its lubricating properties or become contaminated [10]. Although the expense of this testing may be prohibitive for ordinary passenger cars, it makes more economic sense for larger engines (such as those used in commercial trucks) which require much more expensive oil changes.

Clearly, condition-based maintenance requires knowledge of the condition of the structure, machine; or as in the previous example, the lubricant, that is in question. In the case of motor oil, this requires sending a sample of the oil to a specialized testing laboratory for analysis. For structures such as bridges and pipelines, safety inspectors and engineers must be able to reliably detect defects and damage. Ideally, damage can be located while it’s still in its infancy, so that it can be “nipped in the bud” since an “ounce of prevention is worth a pound of cure” as the old sayings go. But reliably detecting small defects in large structures is no easy task. For
example, how can we detect when a bridge or a pipeline has developed a small fatigue crack? How can we detect corrosive pitting attack on a pipe that is buried underground? Further, when damage is detected, how can we reliably gauge whether or not that damage necessitates immediate repairs? Can we track damage growth?

Techniques for detecting and evaluating the severity of structural defects fall into the broad field of nondestructive evaluation (NDE, also referred to as nondestructive testing or NDT), which is introduced and briefly reviewed in the next section. Clearly, effective NDE techniques are required for condition-based maintenance, and condition-based maintenance is very advantageous for maintaining our infrastructure. This provides the growing impetus for NDE research and development.

1.4 Material Discontinuities and Defects

All real engineering materials contain defects on some scale. When these defects occur on the microscopic scale, they are generally regarded as inhomogeneities or discontinuities rather than defects. For example, metal alloys such as steel are made up of many tiny crystals (or grains), which are composed of atoms arranged in crystalline lattices. Inside steel there are various imperfections in the crystalline lattice (dislocations, vacancies, interstitials, etc.), impurities, voids, and possibly phase boundaries. These microstructural imperfections cause abrupt changes from homogeneity and material continuity, and are of great interest to metallurgists and materials scientists, who can tailor the elemental composition and use processes such as heat treating and cold working to alter the microstructure and achieve the desired material properties (e.g. stiffness, hardness, strength, ductility, corrosion resistance, fracture toughness, etc.). Typically, microscale defects are not the focus of NDE during the service life of a component.
Once a material’s engineering properties are found (typically via destructive testing of a sample), calculations based on the theory of continuum mechanics and strength of materials can be used for structural design, and approximations can be made using finite element analysis (FEA). The material properties used in these calculations take into account the microstructural discontinuities that are expected in the material. Problems arise, however, when defects are unusually large or numerous. For example, a large fatigue crack or corrosion pit on a beam causes a reduction in cross-sectional area, which increases the true stress and strain for a given load. Alternatively, perhaps the beam is made out of steel from bad batch that includes a high number of slag impurities due to poor processing, which significantly lessens the yield strength of the steel. In either case, these discontinuities, and their deleterious effects on the strength of the beam must be accounted for in any structural calculations. Ideally, structures are designed with generous factors of safety, which allows time for NDE to be used to find fatigue cracks and other macro-scale defects before they grow large enough to cause unsafe conditions.

One systematic way of classifying defects is their time of origin. Those that arise during the original production are inherent discontinuities, those that develop during forming, finishing, or processing steps are process discontinuities, and those that arise during the intended use of a part are service discontinuities [11]. A fascinating description of how various types of discontinuities can be introduced during manufacture and processing is provided in Chapter 2 of Hellier [11]. Ideally, materials that have diminished material properties due to high numbers of inherent and/or process discontinuities are flagged by quality control (which may involve the use of destructive or nondestructive evaluation techniques) and never make it to service.

Once a structural component makes it into service, macro-scale defects become the primary concern for most components. The two most common types of such defects, corrosion and cracking, each warrant a brief overview.
1.4.1 Corrosion

Corrosion is any naturally occurring degradation of materials resulting from either a chemical or electrochemical reaction. Generally speaking, it is a form of environmental degradation. Chemical corrosion affects polymers, while electrochemical corrosion frequently occurs on the surface of metals. Given enough time, the effects of corrosive attack on metal components can be devastating. In fact, it is estimated that roughly 5% of an industrialized nation’s income is devoted to corrosion prevention and maintaining or replacing products damaged by corrosion [12]. Electrochemical corrosion is really a combination of two chemical reactions, reduction and oxidation – together, these are referred to as a redox reaction. Take iron or an iron-based alloy such as steel for example: when the iron is exposed to an electrolyte solution and oxygen, the iron loses some of its valence electrons (i.e. it is oxidized). Note than any water which has not been deionized contains ions such as Na\(^+\) and Cl\(^-\), called electrolytes, which conduct electricity across the water. Thus, ordinary water serves as an effective electrolyte solution for corrosion. After oxidation, the free electrons then combine with oxygen that is dissolved in the electrolyte solution (i.e. the oxygen is reduced). The iron, which is missing some of its electrons, then combines with hydroxyl (OH\(^-\)) ions in the water to form iron oxide (rust). The conversion of iron to rust is undesirable. It is worth noting that electrochemical corrosion requires three necessary components to occur: a susceptible metal or metal alloy, oxygen, and an electrolyte solution (usually water with dissolved chlorides).

Although the basic corrosion reaction sounds simple in theory, in practice corrosion is a complex phenomenon that is affected by many environmental factors such as temperature, acidity, oxygen concentration, as well as electrolyte solution composition and concentration [13]. Additionally, material processing such as cold working can increase susceptibility to corrosion, while annealing can have the opposite effect [12]. For obvious reasons, there is great interest
among engineers in implementing cost-effective ways to protect structures from corrosion. Common methods of preventing or at least controlling corrosion include proper materials selection, protective paints and coatings, cathodic protection, and the use of chemical inhibitors [14].

Pitting is the most common, and detrimental, form of corrosion [14]. Pitting is a localized attack that creates small cavities, or pits, at locations that have become anodic (i.e. sites where oxidation takes place) relative to the surrounding area, which becomes cathodic (i.e. where reduction occurs). The negative effects of pitting corrosion are manifold. Pits roughen the surface, causing stress concentrations and possible nucleation sites for cracks. As the pits deepen, cross-sectional area is reduced significantly; this is a common problem in pipes and is referred to as wall-thinning [14]. If left unchecked, pitting can cause pipes to leak (at best) and can cause brittle fracture of pressurized pipes if a leak-before-break condition is not incorporated in the design. While a leaking water pipe may not be catastrophic, a leaking oil or gas pipeline is hazardous to both humans and the environment.

Although corrosion is a chemical process, it does not occur in a vacuum; often there are physical processes occurring simultaneously. Flow-accelerated corrosion (FAC) and erosion-corrosion are two examples of the complex interaction between chemical and physical degradation processes that can occur simultaneously in pipe flows. Stress corrosion cracking (SCC) is another example that can occur in any structure, especially those subject to cyclic loading; this will be covered further in the following section. For more detailed information on corrosion, see Chapter 17 of Callister [12] or the excellent information provided online by the National Association of Corrosion Engineers (NACE) [13].
1.4.2 Cracks

A crack is defined as any planar breach in a material that had previously been continuous [11]. In metal alloys, cracks can be introduced during the original production and processing. For example, differential contraction during the cooling of a cast component may result in internal cracks [11]. Cracks also occur during service, especially if the component is subject to cyclic tensile stresses. Cracks that grow due to cyclic loadings are known as fatigue cracks. Although we typically think of fatigue as a problem that affects moving parts and machinery, fatigue is also a serious issue for static parts such as beams, pressure vessels, and pipelines. For example, a beam that acts as a bridge girder supports a dead load (the weight of the bridge deck) but is also subjected to additional live cyclic loads due to traffic crossing the bridge. For a simple model, the loading history of such a girder could be described by a half rectified sine wave with a positive mean. The positive mean is the result of the dead load, and the sine wave represents the cyclic loading due to traffic. Pressure vessels may also experience fatigue from pressure cycling, since the hoop and longitudinal stresses are proportional to the internal pressure. Pipelines, even those that are not subject to significant internal pressure, may experience thermal fatigue crack growth due to cyclic temperature changes, temperature stratification in the flow, and/or rapid changes in temperature (thermal shock). Examples of thermal fatigue crack growth have been documented in nuclear power plant piping [15].

Crack-like discontinuities also frequently occur at welds due to lack-of-fusion between surfaces. Although these discontinuities have crack-like geometry, they are not considered true cracks by the strict definition since the material was not previously continuous. A more thorough
overview of weld discontinuities lies outside the scope of this thesis; for more detail see Chapter 2.4 of Hillier [11] or Chapter 1.9 of the author’s previous thesis [16].

1.4.3 Stress Corrosion Cracking

Stress corrosion cracking (SCC) is defined as cracking which is induced or accelerated due to the combined effects of tensile stress and a corrosive environment [17]. SCC is a particularly insidious defect: it reduces strength greatly but with very little metal loss, it is often difficult to detect, and it can trigger catastrophic failure by fast fracture [18]. To occur, SCC requires all of the conditions necessary for corrosion to occur (a susceptible material, oxygen, and electrolyte) as well as tensile stress to cause cracking. There are multiple modes of SCC, and some of the phenomena are quite complex. Perhaps the simplest example is when the rough surface resulting from pitting corrosion provides stress concentrations that encourage fatigue crack initiation. A more complicated example is the combination of corrosion and crack growth along grain boundaries in austenitic stainless steel. In this case, the chromium concentration along the grain boundaries is reduced due to the precipitation of chromium carbide, increasing the susceptibility of the grain boundaries to corrosion relative to the rest of the material. Applied tensile stress can act to open up cracks along grain boundaries, which allows for increased in-flow of both corrosive species (oxygen and electrolyte solution) and out-flow of corrosive products, thereby accelerating the rate of corrosion [18]. Clearly, there is a synergistic relationship between simultaneous chemical and mechanical processes in this case. For further reading on SCC, see the detailed information available from The Corrosion Doctors [17] and The National Physical Laboratory [18].
1.5 Crack Growth in Pipeline

Although the focus of this thesis is on investigating how to use guided wave propagation to best track crack growth, it is also valuable to include a brief discussion of how fatigue cracks form, how to prevent them, and how to predict when a crack may result in brittle fracture. These topics fall more under the realms of strength of materials, fracture mechanics, and materials science than nondestructive evaluation. However, a working knowledge of these topics is still valuable to anyone in the NDE field. For example, by understanding how and why fatigue cracks form, an NDE inspector can carry out more effective inspections by focusing on areas where cracks are likely to grow. Additionally, when designing a NDE or SHM program, it is often helpful to know approximately how small of defect must be reliably detected to ensure safe operation. In the case of fatigue crack growth, there is a critical crack size at which the failure mode changes from ductile to brittle fracture. NDE and SHM programs should be designed to reliably detect cracks that are smaller than the critical size by some margin of safety. On the other hand, some structures can tolerate extremely large cracks, and conducting an expensive and time consuming inspection program to locate tiny cracks would be unnecessary and wasteful. In both cases, knowledge of strength of materials and fracture mechanics is necessary to design a sensible inspection program.

This section is by no means meant to be a rigorous or thorough study of crack growth or fracture mechanics; these topics are both complex and expansive and could fill many theses on their own. Rather, this section is meant as a brief review which can also serve as an introduction for any readers who are unfamiliar with these topics. Readers who are already familiar with these topics may skip this section, and readers who want a more thorough review should refer to the sources which are cited throughout this section.
Along with corrosion, fatigue cracking is one of the most common defects found in many types of infrastructure, including piping. The life of a fatigue crack has 3 stages: initiation, propagation (also known as stable crack growth), and (if it is left untreated) fracture. The majority of a crack’s lifetime is spent in the propagation stage. Fatigue cracks typically initiate on the surface at a location where there is a stress concentration and/or a weakness in the material. The stress concentration could arise from a macroscopic defect, such as a deep scratch or gouge, a void in a weld, a large inclusion, or a delamination [19]; these are sometimes referred to as “starter flaws.” Clearly, removing stress concentrations reduces the likelihood of crack initiation. However, fatigue cracks do not require macroscopic starter flaws. During loading, deformation occurs in part due to “slip,” which is the relative sliding of crystallographic planes. Slip occurs along planes that are densely packed with atoms [12]. The number of densely packed, or slip planes, depends on the crystalline structure. Body-center cubic structures (BCC) (such as austenite) and face-centered cubic (FCC) (such as ferrite) structures have more possible slip planes than hexagonal close-packed (HPC) crystals [12], and are thus more susceptible to strain due to slip dislocations. Strain due to slip dislocations results in plastic deformation. This is in part why materials with BCC and FCC crystal structures tend to be ductile, and materials with HPC crystal structures tend to be brittle [12]. When a ductile metal alloy is subjected to cyclic loading it often undergoes small, repeated slip deformations. The slip dislocations can then “pile up” and form structures known as persistent slip bands (PSBs) [20], as shown in Figure 1-2. The PSBs roughen the surface topography which leads to stress concentration and fatigue crack initiation; this phenomenon is an interesting bridge between a microscale deformation mechanism and the evolution of macroscale defects.
Figure 1-2: Persistent slip bands (PSBs) may build up in ductile materials during cyclic loading; the resulting extrusions and intrusions serve as stress raisers for fatigue crack initiation.¹

Once a fatigue crack is born, it continues to propagate or “grow” with each loading cycle. Most commonly, crack growth is due to tensile stress pulling the surfaces of the crack apart – this is called the opening mode or simply mode 1 crack displacement [19]. In piping, the tensile stress that drives mode 1 crack growth can come from one or more sources such as internal pressure, bending, residual stresses (such as in the heat-affected zone of a weld), or thermal stresses due to heating and cooling. The two other displacement modes are sliding (mode 2) and tearing (mode 3) [19]. Stable crack growth can occur slowly over thousands or even millions of cycles (high-cycle fatigue) or more rapidly over tens or hundreds of cycles (low-cycle fatigue). Once the crack reaches a critical size, fracture occurs. There are two possible types of fracture – ductile and brittle. Ductile fracture, also known as plastic flow or ductile tearing, is preceded by large amounts of plastic deformation, which serves as a warning of the impending fracture. Brittle fracture, on the other hand, involves crack propagation and fracture without any plastic

¹ Drawing adapted from the NDT Resource Center [20] and reproduced by the author.
deformation. Ductile fracture surfaces are often oriented approximately 45° from the loading direction since this is the orientation of the plane which has the greatest shear stress. This is in agreement with the maximum shear stress or Tresca yield criterion which states that yielding of ductile materials occurs where the maximum shear stress reaches a critical value [19]. In tensile tests, the result of this is observed as the “cup and cone” fracture surface with 45° angles. Unlike ductile fracture, brittle fracture (also known as cleavage fracture) typically results in a flat fracture surface [21] oriented such that the applied tensile load is normal to the fracture surface. This agrees with the maximum normal stress fracture criterion, which states that failure is expected when the largest principal normal stress reaches the failure strength of the material [19]. Fatigue cracks may eventually fracture in a brittle manner, even when in a normally ductile material [21].

![Figure 1-3: Cup and cone fracture surface indicative of ductile fracture (a) and flat fracture surface indicative of brittle fracture (b).](image)

Crack growth often leaves small markings called beach marks and striations on fatigue fracture surfaces; these are often examined in failure analyses. A beach mark indicates a stop or start in the loading history. For example, a fatigue crack in the axle of a train car would
accumulate a beach mark when the train is parked in between trips. Striations on the other hand, are created by each individual loading cycle. Using the train axle example, a striation would be created by each revolution of the axle. Thus, striations are typically very tiny (especially in cases of high-cycle fatigue) and require a high level of magnification to see. An example image of striations, taken with a scanning electron microscope (SEM) is shown in Figure 1-4.

![Figure 1-4: Scanning electron microscope (SEM) image of fatigue crack striations on the fracture surface of a stainless steel bicycle spoke. The striations are the diagonal lines which go from top-left to bottom-right. Magnification is 2000x.](image)

While beach marks and striations are very useful for engineers investigating failures, for infrastructure maintenance the goal is always to prevent fatigue cracks, or at least detect them and take corrective action before a failure investigation is necessary. At the design stage, ways to make a structure more resistant to fatigue crack fracture fall into three basic categories:

- Make the structure bigger and stronger (overbuilding)
- Reduce/eliminate stress concentrations
- Materials selection

---

2 Image taken by author with assistance from Scott Kralik of the ESM Department
Overbuilding is the simplest option. By making the structure bigger and stronger, the stresses and strains are lower for a given load. Since tensile stress is the driving force behind most crack growth, reducing stress reduces fatigue crack initiation and growth. All structural designs should already incorporate some degree of overbuilding to achieve a factor of safety. Structures that are designed and overbuilt to survive for prolonged periods while fatigue cracks propagate are said to be damage tolerant. However, overbuilding increases cost significantly, in materials and also possibly in labor. Modest overbuilding is part of a comprehensive method of reducing fatigue cracks, but is not a complete solution by itself.

Since fatigue cracks often initiate in areas of concentrated stress, reducing stress concentrations is a logical way to reduce fatigue cracking. Geometric stress concentrations occur at sudden changes in cross sectional area, sharp corners, holes, and notches. Whenever possible, such features should be eliminated from the design of structures which will be subject to cyclic loading. Even if these features cannot be eliminated entirely, stress concentrations can be reduced by using beveled or chamfered edges. Inherent and process discontinuities can also serve as starter flaws, creating stress concentrations that lead to crack initiation. Inclusions, kissing bonds, voids, gouges, and even scratches can lead to crack initiation. Although the many methods of preventing process discontinuities lie outside the scope of this thesis, some of them are quite simple. For example, polishing can be used to remove scratches.

Materials selection is incredibly important for building structures resistant to fatigue cracks, as well as for satisfying all other aspects of design criteria. Satisfying the various design criteria requires compromise between cost, strength, ductility, stiffness, corrosion resistance, weight and other factors. With so many different materials available, choosing the material that has the best set of material properties for a given application at an affordable price is not always simple. For those interested, a systematic and quantitative method to guide engineering materials selection decisions is provided in Chapter 3.8 of Dowling [19].
One material property that is very important for reducing fatigue crack fractures is *fracture toughness*, which is a measure of a material’s ability to resist fracture when a crack is present. If all of the methods of preventing fatigue cracks fail, a material with high fracture toughness will at least provide a longer life in the presence of cracks. Practically, this buys time for NDE inspections to detect and locate cracks before a catastrophic failure occurs.

### 1.5.1 Linear Elastic Fracture Mechanics (LEFM) Approach

The linear elastic fracture mechanics (LEFM) approach takes into account the crack geometry, the remotely applied stress, and the fracture toughness of the material to predict if and when fracture may occur. As the name suggests, LEFM relies on the assumption that the material behaves in a linear-elastic manner. Typically, structures are designed such that the building materials remain in the linear-elastic region (so that there is no permanent deformation under normal conditions), which makes this assumption valid for practical purposes. The LEFM approach begins by defining a quantity known as the *stress intensity factor*, $K$. The stress intensity factor is based on the linear theory of elasticity, and describes the severity of the crack as determined by the remotely applied stress, the crack size, and the geometry of both the crack and the structure [19]. The general form of the stress intensity factor for mode 1 cracks, which is given in chapter 8 of Dowling [19], is shown in equation 1.1 where $F$ is the geometric factor, $S$ is the remotely applied stress (the stress that would exist if there was no crack i.e. simply the force over the original area), and $a$ is the crack length. The subscript 1 refers to the mode 1 crack displacement.
Equation 1.1 \[ K_1 = FS\sqrt{\pi a} \]

When the stress intensity factor \( K_1 \) reaches a critical value \( K_{1c} \), brittle fracture is expected. The critical value \( K_{1c} \) is the fracture toughness of the material.

Equation 1.2 \[ K_1 = K_{1c} \] (brittle fracture expected)

An interesting observation can be made by replacing the remotely applied stress, \( S \), in Equation 1.1 with the yield strength of the material, \( \sigma_\circ \), and setting the stress intensity factor equal to the fracture toughness. Doing so and solving for the crack length gives the transition crack length, \( a_t \) [19].

Equation 1.3

\[
a_t = \frac{1}{\pi} \left( \frac{K_{1c}}{F\sigma_\circ} \right)^2
\]

When the crack length \( a > a_t \), then the stress \( \sigma < \sigma_\circ \) since all other parameters in equation 1.3 are relatively constant (the geometry factor \( F \) does have some dependence on the crack length \( a \), which should be considered for problems with a wide range of crack growth.) Cracks longer than the transition length \( a_t \) cause the stress intensity factor to reach the fracture toughness before the stress reaches the yield stress. In other words, failure is expected due to fracture (rather than plastic yielding) when the crack length has exceeded \( a_t \). Conversely, when the crack length is less than \( a_t \), failure is expected due to gross plastic yielding. In this case, the presence of the crack has not changed the failure mechanism, and there is little or no reduction in strength due to the crack [19]. Clearly, for infrastructure maintenance it is preferable to be able to reliably detect cracks before they reach the transition length.

When discussing fracture mechanics, it is also important to consider the environmental conditions. Engineers should be familiar with the concept of a ductile-brittle transition temperature (DBTT) which is present in some metals and metal alloys. Below the DBTT, a metal which is ductile at room temperature can become very brittle and prone to failure by crack propagation. To understand the origin DBTT, it is necessary to consider the mechanisms of
plastic deformation. At room temperature, plastic deformation occurs due to the motion of dislocations. There are many factors which affect resistance to dislocation motion, such as the atomic bonding, crystalline structure, temperature, grain boundaries, and obstacles such as solute atoms and precipitates [22]. In metals with FCC structures, the force required for dislocation motion is largely independent of temperature, thus there is no DBTT and FCC metals remain relatively ductile even at cold temperatures [22]. On the other hand, dislocation motion in BCC materials is strongly temperature dependent – as the temperature decreases, the resistance to dislocation motion increases, and there is a corresponding loss in ductility. Without the ability to deform plastically, the material cannot absorb energy (i.e. there is a loss of toughness) and brittle fracture becomes the failure mode. Perhaps the most famous example of DBTT related failures is the case of the mass-produced Allied transport ships, known as “Liberty Ships,” during World War II. The ships were constructed of a steel alloy which became brittle at the relatively low temperatures (around 40°F) experienced by the ships in the North Atlantic. Cracks originated at points of stress concentration and in some cases propagated around the entire hull of the ship, resulting in the ship breaking in two [12].

1.5.2 Pipeline Material

Pipelines are constructed from a range of steels depending on the intended application. Specifications and standards are set by industry organizations such as the American Iron and Steel Institute (AISI), the Society of Automotive Engineers (SAE), the American Petroleum Institute (API), and the American Society of the International Association for Testing and Materials (ASTM). Standards specify the weight percent of the alloying elements as well as the forming operations and any thermal processing. Three common specifications of pipe are ASTM
A53, A106, and API 5L. A53 is a general purpose carbon steel pipe grade used in generator plants, refineries, compressor stations, natural gas transmission, and steam conduction [23]. A106 is similar to A53 except for the addition of extra silicon to improve performance in high temperature environments such as steam lines and boiling plants [23]. API 5L is a grade of line pipe designed specifically for transmission of oil and natural gas [23]. Although API 5L is similar to A106 in composition, the requirements of the API 5L grade is more stringent; rework is not allowed, rolled grades are not acceptable, and more attention is given to toughness [24].

Despite the stringent standards applied to line pipe manufacture, failures can still occur in service. Typically failures occur due to one or more factors such as defect growth (corrosion or fatigue cracking), weld failures, or excavation damage [25]. Operating temperatures below the DBTT are a threat to pipelines in cold and wintry climates due to the decrease in ductility and increased chances of brittle fracture. A classic illustration of the effects of cold weather on the fracture mechanism of pipelines was given by Vander Voort in 1997 [26]. Two API 5L pipes were tested, one at 56 °F and the other at -15 °F. Each pipe was pressurized and had a notch cut in it along the axial direction to serve as a starter flaw. A small explosive charge was then detonated near the notch on each pipe. At 56 °F, a crack propagated from the notch at approximately 280 ft/s and stopped after a short distance. The crack did go all of the way through the wall of the pipe, but the fracture was ductile. At -15 °F, the crack propagated at the much higher rate of 2,200 ft/s and reached the entire length of the pipe. At this low temperature, the pipe did not have enough fracture toughness to arrest the crack propagation, and the fracture was fully brittle.
### 1.5.3 Semi-Elliptical Surface Cracks

In order to use LEFM, the approximate shape of the crack must be known so that a suitable geometric factor $F$ can be used to determine the stress intensity factor, as shown in Equation 1.1. Typically, a semi-elliptical or elliptical shape is assumed for surface cracks in the literature. For relatively simple geometries, such as a semi-elliptical surface crack in a plate, geometric factors are widely available in stress intensity factor handbooks. However, a semi-elliptical crack in a pipe is a more complex geometry; $F$ depends not only on the length and depth of the crack but also on the radius and wall thickness of the pipe. Approximate geometric factors for semi-elliptical circumferential cracks in pipes and rods under tension and bending loads are listed in a 1985 NASA technical report by Raju and Newman [27]. A sample of these geometric factors is shown in Table 1-1.
Table 1-1: Geometric factors for semi-elliptical circumferential cracks under tension loading in pipe.\(^3\) \(R_i\) is the inner radius of the pipe, \(t\) the wall thickness, \(d\) is the crack depth. Columns labelled A correspond to the geometric factor at the deepest part of the crack, B corresponds to the geometric factor at the free surface.

<table>
<thead>
<tr>
<th>(\frac{R_i}{t})</th>
<th>(d/t = 0.2)</th>
<th>(d/t = 0.5)</th>
<th>(a/t = 0.8)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A</td>
<td>B</td>
<td>A</td>
</tr>
<tr>
<td>1</td>
<td>1.113</td>
<td>0.943</td>
<td>1.226</td>
</tr>
<tr>
<td>2</td>
<td>1.05</td>
<td>0.937</td>
<td>1.194</td>
</tr>
<tr>
<td>3</td>
<td>1.101</td>
<td>0.933</td>
<td>1.178</td>
</tr>
<tr>
<td>4</td>
<td>1.097</td>
<td>0.930</td>
<td>1.167</td>
</tr>
</tbody>
</table>

The values in Table 1-1 correspond to \(F\) in a slightly modified version of Equation 1.1, shown below in Equation 1.4.

\[
K = SF \sqrt{\frac{d}{Q}}
\]

Equation 1.4

Where \(Q\) is the shape factor for an ellipse, calculated from Equation 1.5 below, where \(c\) is one half the arc length of the crack.

\[
Q = 1 + 1.464(d/c)^{1.65} \quad (\text{for } d/c < 1)
\]

Equation 1.5

1.5.4 Example Calculation

Equipped with a basic knowledge of LEFM and the geometric factors provided by Raju and Newman, we can make simple calculations to estimate whether brittle fracture will occur, assuming we know the operating conditions and fracture toughness of the pipe material.

\(^3\) Table reproduced from the NASA report by Raju and Newman [27].
Unfortunately, the fracture toughness of pipe grades such as A53 and API 5L is not widely published in the literature, perhaps because it is dependent on the sub-grade of pipe (API 5L comes in approximately ten subgrades, and is also available in “supplementary requirements” which differ in fracture toughness.) In absence of readily available fracture toughness data, one way to compare steels is by the carbon content; all other things being equal, an increase in carbon content decreases ductility and increases brittleness.

Table 1-2: Material Properties of common steel grades.

<table>
<thead>
<tr>
<th></th>
<th>Wt. % Carbon</th>
<th>Fracture Toughness, $K_{1c}$ ($\text{MPa}\sqrt{m}$)</th>
<th>Yield Strength, $\sigma_o$ Min. (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>API 5L</td>
<td>0.16-0.17$^4$</td>
<td>?</td>
<td>359 – 483$^4$ (depending on subgrade)</td>
</tr>
<tr>
<td>ASTM A517 F</td>
<td>0.10-0.20$^5$</td>
<td>187$^5$</td>
<td>690$^5$</td>
</tr>
<tr>
<td>A53</td>
<td>0.25 (grade A)$^6$</td>
<td>?</td>
<td>206 (grade A)$^6$</td>
</tr>
<tr>
<td></td>
<td>0.30 (grade B)$^6$</td>
<td>?</td>
<td>241 (grade B)$^6$</td>
</tr>
<tr>
<td>AISI 4130</td>
<td>0.28-0.33$^5$</td>
<td>110$^5$</td>
<td>1090$^5$</td>
</tr>
</tbody>
</table>

From Table 1-2, we can see that API 5L and A517 F are relatively similar in both carbon content and yield strength, which indicates that these two steels may also exhibit similar fracture toughness. For the purpose of a sample calculation, it is then assumed that the fracture toughness $K_{1c}$ of API 5L is approximately $187 \text{MPa}\sqrt{m}$. If we choose the dimensions of a semi-elliptical crack, say $d = 0.23''$ and $\text{length} = 0.97$ in a 4''diameter schedule 40 pipe, we can proceed to determine the approximate stress that result in brittle fracture. A depth of $d = 0.23''$ corresponds

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$^4$ Material properties of API 5L from PM International Suppliers, LLC [24]
$^5$ Material properties of ASTM A517 F and AISI 4130 from Dowling [19]
$^6$ Material properties of A53 from U.S. Steel Tubular Products [23]
to half arc length \( c = 0.49'' \), and shape factor \( Q = 1.42 \) by Equation 1.5. From Table 1-1, the geometric factor \( F \) is determined to be approximately 1.25. Substituting these values into equation 1.4 gives:

Equation 1.6

\[
K_{1c} = (1.25)S_c \sqrt{0.004114\pi}
\]

Assuming \( K_{1c} = 187 \) gives a critical stress, \( S_c \), of 1,316 MPa, which is roughly 3x the yield strength of API 5L. Therefore, it is expected that the pipe would fail by gross plastic yielding before brittle fracture would occur due to a crack of this size. Note that this size is almost as large as a semi-elliptical crack can become in a 4” schedule 40 pipe before becoming a through crack and causing the pipe to leak. Another quick test to determine the likely failure mode is to use Equation 1.3, which solves for the transition crack depth \( d_t \). Applying this equation while taking into account the shape factor \( Q \) gives the following:

Equation 1.7

\[
d_t = \frac{Q}{\pi} \left( \frac{K_{1c}}{\sigma_{oF}} \right)^2
\]

Substituting in the appropriate values and using yield stress \( \sigma_o = 400 \) MPa (the middle of the range for API 5L) gives a transition crack depth \( d_t = 0.063 \) meters. For cracks shallower than this transition depth, the failure mode is expected to remain ductile because the yield strength is exceeded before the fracture toughness is reached. For a 4” diameter schedule 40 pipe, wall thickness is only 0.635 cm, which is an order of magnitude less than the transition depth. Therefore, brittle fracture is not expected because the crack would become a through-crack well before brittle fracture would become the failure mode, at least at room temperature. At extremely cold temperatures, below the DBTT, brittle fracture may still be a possibility due to the reduction in fracture toughness associated with cold temperature.
1.6 Overview of Nondestructive Evaluation (NDE)

Before going into the details of ultrasonic testing, it is instructive to first review the broader field of NDE. To start, a general (yet clear and concise) definition of nondestructive evaluation is provided by Hellier in *Handbook of Nondestructive Evaluation, 2nd E.* [11]:

NDE is an examination, test, or evaluation performed on any type of test object without changing or altering that object in any way, in order to determine the absence or presence of conditions or discontinuities that may have an effect on the usefulness or serviceability of the object. (Hellier 1.1)

Using this definition, many simple tests can be considered forms of NDE. For example, visually inspecting the surface of an object for cracks or corrosion using just the naked eye is a simple nondestructive evaluation. The human sense of hearing also lends itself well to nondestructive evaluations; in fact the expressions “sound as a bell” and “the ring of truth” originate from the practice of tapping a bell and listening for changes in pitch indicative of cracking [11]. Evaluations based upon using sound waves audible to the human ear are known as sonic testing. Of course, modern technology makes it possible to send and receive sound waves at frequencies above the audible range (the audible range for humans is roughly 20 Hz – 20 kHz), which are generally more sensitive to small defects – this is known as ultrasonic testing.

In addition to visual inspection and sonic testing, there are other techniques that build on the same defect detection principles, as well as techniques that are based on entirely different physical laws. For example, dye-penetrant testing and inspection using a microscope or other visual aid are both enhanced forms of visual inspection. Ultrasonic testing, ultrasonic guided wave testing, and acoustic emissions testing all use acoustic energy, but are also each a separate discipline in their own right. Other common techniques based on various physical phenomena include: magnetic particle testing, radiographic testing, eddy current testing, thermal infrared
testing, and digital radiography. Although there are many fascinating details about the various NDE techniques, a detailed overview is outside the scope of this thesis. For further reading, see the overview included in the author’s previous thesis [12] or the more comprehensive overview provided by Hellier [11] for greater detail.

Without going to great lengths to describe each of the various NDE techniques, there are still a few general principles that must be emphasized. First of all, none of the NDE techniques are perfect; each has its own limitations. Nor are any of the techniques fool-proof; each technique is only as effective as the inspectors who carry out the test and analyze the results, thus skilled personnel are essential. Also, it would be foolish to claim that one technique is superior to another without first specifying the application, since each technique has its own strengths and weaknesses, as shown for the case of in-service pipe inspection in Table 1-3 below. Notice that ultrasonic guided waves are an excellent inspection technique for piping, based off of the criteria presented in the table. There are many variables related to performance, cost, reliability, and ease-of-use which all factor into determining what the optimal NDE technique for a given application is. In fact, since each technique has its own strengths and weaknesses, it is not uncommon to combine multiple techniques for a more thorough inspection. For example, a form of visual inspection (perhaps liquid penetrant) could be used to find surface cracks, and ultrasonic testing could then be used to detect defects beneath the surface. Alternatively, two techniques could be used together to find the same type of defect – for example, eddy current testing could be combined with ultrasonic testing or visual inspection to detect service cracks. When possible, redundancy in inspection methods is desirable because the overall probably of detection is increased when using multiple techniques.
Table 1-3. Comparison of NDE techniques for in-service pipe inspection.

<table>
<thead>
<tr>
<th></th>
<th>Visual</th>
<th>Liquid Penetrant</th>
<th>Magnetic Particle</th>
<th>Radiographic</th>
<th>Eddy Current</th>
<th>Ultrasonic bulk waves</th>
<th>Ultrasonic guided Waves</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detects surface defects</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Detects subsurface defects</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>Detects defects under coatings</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Long range inspection</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>Volumetric</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Fast Inspection time</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>✓</td>
</tr>
</tbody>
</table>
1.6.1 Structural Health Monitoring

From the general definition in the previous section, the NDE approach may involve periodic inspections. The time interval between inspections is based off the expected rate of damage and the cost of inspection. Ideally, structures could be thoroughly inspected every day, or every hour, or even every minute, but that is not practical – or is it? Instead of performing periodic inspections, another strategy is to install permanently embedded sensors and collect data continuously or near continuously. This strategy, often which incorporates conventional NDE techniques, is known as structural health monitoring (SHM). Besides offering continuous monitoring, SHM holds several other advantages. For example, in conventional NDE methods, a defect often must be recognized without making comparisons to baseline data. For complex structures, this can pose a problem, since it is often unclear what signal characteristics are indicative of a defect, and what signal characteristics are to be expected for the undamaged structure. With the SHM strategy, the data is always compared to data collected from a relatively undamaged, or baseline, state. The inspector (or perhaps the computer algorithm, if the system is automated) merely has to detect changes in the signal that are indicative of defect genesis and growth. Since the system is running continuously or near continuously, there is plenty of data to make comparison with. This strategy can be effective for detecting relatively small defects, and can also be used to track the evolution (typically growth) of defects such as fatigue cracks or corrosion pits. The ability to track defect growth allows for estimation of the defect growth rate, which can be used to estimate the remaining service life until repair is necessary – this is extremely useful for making condition-based maintenance decisions. Another advantage of SHM
is that data is collected while the structure or machine is in use, or online. NDE is typically performed while the structure or machine is shut down, or offline. For some applications, time spent offline can cause serious disruption or loss of productivity, so it is generally advantageous to minimize time spent offline – after all, that is one of the main goals of preventative maintenance!

Of course, SHM is not without caveats. For outdoor applications, SHM sensors must be tough enough to stand up to the environment. If active sensors are used, they will also require a power source of some sort, be it energy harvesting, a battery, or an external power supply. Finally, comparing data to a baseline state requires that a ceteris paribus or “all other things being equal” assumption is satisfied. For example, data collected on sunny 100°F day may not be directly comparable to baseline data that was taken on a frigid day. To work around issues such as this, environmental data compensation methods are often required.

A brief comparison of NDE and SHM is given in table 1-2. For further reading on SHM strategies and applications, there are many textbooks available such as those by Balageas and Fritzen [28] or Karbhari and Ansari [29].
Table 1-4. Differences between NDE and SHM. Adopted from Rose [30]

<table>
<thead>
<tr>
<th>NDE</th>
<th>SHM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Offline evaluation</td>
<td>Online evaluation</td>
</tr>
<tr>
<td>Find existing damage</td>
<td>Determine structural health and remaining service life</td>
</tr>
<tr>
<td>Cost and labor of inspection</td>
<td>Reduced cost and labor</td>
</tr>
<tr>
<td>Baseline not required</td>
<td>Baseline required</td>
</tr>
<tr>
<td>Less frequent evaluation</td>
<td>Environmental data compensation methods required</td>
</tr>
</tbody>
</table>
Chapter 2
Guided Wave Fundamentals

Ultrasonic guided waves (UGW) have become increasingly popular for a variety of NDT and SHM applications in the past 15 years. For example, guided waves can be effective for the inspection of rails, plates, and pipes (as shown in Table 1-2); as well as for inspecting aircraft structures and composite materials. The tremendous advances of UGW inspection have been made possible by both an increased understanding of fundamental guided wave theory and by the increase in computational power available to engineers and scientists [30]. Modern finite element methods and powerful computers have made modeling that was previously difficult (or impossible) ago relatively quick and easy (the challenge now lies primarily in interpreting results, rather than in the computation itself). These advances in modeling have made it possible to study wave propagation in structures with complex geometries, which has opened new practical applications. However, despite all of these advances in computation and modeling, understanding the basics of guided wave theory is still essential to correctly interpreting results and carrying out successful experiments. To begin to understand the theory behind guided waves, it is helpful to first review some fundamental topics of acoustics, such as wave propagation and elastic wave speed.
2.1 Wave Propagation

A wave is defined as a disturbance that conveys energy through space in a manner that depends on both position and time [31]. Examples of waves abound in nature, including mechanical waves, electromagnetic radiation, and even gravitational waves [32]. Although the mathematical descriptions are similar, here we will focus only on mechanical waves. One important physical distinction is that mechanical waves require a medium to propagate through, while electromagnetic radiation and gravitational waves can propagate across empty space. This is because mechanical waves are characterized by oscillating particles of matter. Clearly, if there are no particles, or if there are vast regions occupied by extraordinarily few particles (as in outer space), mechanical waves cannot propagate.

The manner in which particles oscillate relative to the direction of energy transport (i.e. the direction of wave travel) is used to classify mechanical waves. In longitudinal waves, the particles oscillate parallel to the direction that the wave is travelling. Such waves are also called pressure waves or p-waves because they are characterized by alternating compressions and rarefactions. Sound waves in air are a familiar example of longitudinal waves, but longitudinal waves can also propagate through solids and liquids.

Transverse waves, also called shear or s-waves, are characterized by particle motion that is perpendicular to the direction that the wave is traveling. Shear waves cannot propagate through fluids that are ideal or nearly ideal because such fluids cannot support shear stresses, and shear stress is necessary to create the restoring force that drives shear waves. In reality, ideal fluids do not exist; every fluid has some degree of compressibility and viscosity. However, many fluids, such as water and air, have very little viscosity and can be considered non-viscous for practical purposes. Shear waves cannot exist in these fluids because there is insufficient viscosity to support shear stresses.
Notice that longitudinal and shear waves can both be described without mention of surfaces or boundaries. This is because longitudinal and shear waves can travel through infinite media; they do not necessarily require boundaries or boundary conditions to exist. Waves that exist independent of boundary effects are referred to as \textit{bulk waves} and those that are characterized by the effects of boundaries are referred to as \textit{guided waves}; guided waves will be discussed in further detail in Chapter 2.3. For now, it is important to note that many guided waves can also be classified as longitudinal or shear waves based on their particle motion.

\textit{Surface waves}, which are characterized by circular or elliptical particle motion near the surface, are an example of guided waves because they are guided along by the surface – clearly, these waves are characterized by boundary effects. Ocean waves, which are commonly caused by wind pressure on the surface, are a perfect example of surface waves in nature [33]. If you observed a buoy from a stationary frame of reference as an ocean wave passed by, you would notice that the buoy moved forward and upward when the wave hit, and then dropped down and moved backwards as the wave passed. The motions of the water particles follow circular paths similar to the buoy.

\subsection{2.2 Elastic Wave Speed}

Different types of waves travel at different velocities in different media. Note that although the term “wave velocity” is typically used in wave mechanics, “wave speed” is perhaps more appropriate in this context since we are referring only to the magnitude of the velocity vector; this is often referred to as the “speed of sound.” The velocity of bulk waves is determined by the
material properties of the medium, and these effects can be understood easily by making analogies with a mass-spring model.

Consider a grid of masses interconnected by coil springs. Each mass represents an atom, and the springs represent inter-atomic bonds that hold the atoms together. When an elastic wave propagates through the mass-spring system, the masses oscillate about their resting positions due to the restoring forces provided by the springs. Wave speed increases with increased stiffness of the springs (or inter-atomic bonds) because stiffer springs require less displacement to build up the force necessary to push or pull the next mass (or atom) [11], in accordance with Hooke’s Law. The material parameter that describes stiffness, or elasticity, in tension and compression is Young’s Modulus of Elasticity, denoted by E, which engineers should be familiar with from course work in strength of materials. Since Young’s Modulus describes the material response during compression and rarefaction, it relates to longitudinal waves. Longitudinal wave speed is also affected by Poisson’s ratio, which is the ratio of transverse to longitudinal strain during uniaxial loading. Transverse wave speed can be described in a similar manner as longitudinal waves with two exceptions. First, for shear waves the restoring force is a function of the elasticity for shear loading – this is known as the modulus of rigidity or shear modulus and is denoted by G. Secondly, shear wave velocity is not a function of Poisson’s ratio. Both longitudinal and transverse wave speeds are inversely proportional to mass density; this is because lighter atoms will undergo greater acceleration for a given applied force, which leads to increased wave speed.

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

Eq. 2.1

Equation 2.1 describes the bulk longitudinal wave speed in an isotropic material as function of Young’s Modulus (E), Poisson’s ratio (\( \nu \)), and mass density (\( \rho \)) [30].
Equation 2.2 describes the transverse longitudinal wave speed in an isotropic material as a function of the modulus of rigidity ($G$) and the mass density ($\rho$) [30].

Equations 2.1 and 2.3 both apply to bulk waves; guided waves often have different velocities depending on mode and frequency. As a general rule, for most materials the bulk transverse wave speed $C_T$ is about one half of the longitudinal bulk wave speed $C_L$.

### 2.3 Guided Waves

As stated in the previous sections, guided waves are those which rely on boundary conditions in order to exist. Guided waves can travel along surfaces, interfaces, or throughout the volume structures (so long as they are still affected by boundary conditions.) The particle motion of guided waves can be longitudinal, transverse, or elliptical depending on the mode. Because of the boundary effects, guided wave phenomena are inherently more complex than bulk wave propagation. However, with an understanding of guided wave mechanics, this complexity can be used to great effect for NDE. In fact, guided wave inspection offers numerous advantages compared to conventional bulk wave inspection. For example, since guided waves propagate along structures, large areas can be inspected from a single location. This is especially advantageous for applications such as pipe and plate inspection. Also, guided waves can be extremely sensitive to small defects, depending on mode and frequency selection. A comparison of bulk and guided waves is provided in Table 2-1.
A more qualitative and intuitive way to think of guided waves is in terms of interference phenomena. In ultrasonic testing, a transducer is used to essentially pump sound energy into the structure at a specified frequency and angle of incidence (in the case of an angle beam probe) or wavelength (in the case of a magnetostrictive transducer). This results in many waves (both longitudinal and shear) reflecting, refracting, and undergoing mode conversion inside of the structure. The waves superimpose and interfere with each other, and also undergo mode conversion when they impinge on boundaries at oblique angles. The resulting interference between the waves can be totally constructive, destructive, or intermediate. Guided wave modes exist where the interference is predominantly constructive. In essence, a guided wave mode is a constructive interference pattern created by the interactions of many bulk waves. There are many possible constructive interference patterns that occur at different frequencies and propagate at different velocities; this is why there are many possible guided wave modes in any given

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7 Table produced by the author.
structure. It is important to note that the various guided wave modes have unique characteristics. Each mode has a unique particle displacement profile (known as wave structure) and travels at unique velocity. In practice, certain guided wave modes are found to be easier to excite and more sensitive to defects, while other modes are often less useful. To find any of these guided wave modes, one can consider the complicated geometric interference problem, or alternatively the problem could be solved by using the governing equations with the appropriate boundary conditions. This method, the classical wave mechanics approach, is presented in the next section.

### 2.3.1 Governing Equations

Bulk and guided waves are both governed by the same set of partial differential equations, but guided wave solutions differ due to the enforcement of specific boundary conditions [30]. Plane waves are governed by the famous wave equation (Eq. 2.3), where $t$ represents time, $u$ represents the particle displacement, and $c$ is the wave velocity.

\[
\nabla^2 u = \frac{1}{c^2} \frac{\partial^2 u}{\partial t^2}
\]

Eq. 2.3

For the general three-dimensional case with isotropic media, guided wave solutions must also satisfy Navier’s equations of motion (Eq. 2.4), where $\lambda$ and $\mu$ are the Lamé parameters [30]. Lamé’s second parameter, $\mu$, is identical to the shear modulus $G$.

\[
\mu \nabla^2 u(x, t) + (\lambda + \mu) \nabla \nabla \cdot u(x, t) = \rho \frac{\partial^2 u(x, t)}{\partial t^2}
\]

Eq. 2.4

Equation 2.4 is also directly applicable to the case of a pipe with traction-free boundary conditions. We will further examine the case of a seamless, carbon steel pipe with traction free boundary conditions (as used in the experiments for this thesis), using
chapter 10.2 of Rose [30] as a guide. However, rather than reproduce the entire solution (which is quite long and rigorous, and also available in detail in Rose), the following paragraphs will highlight some of the key concepts.

If we consider the properties of the steel to be isotropic, we can use Helmholtz’s theorem from vector calculus to simplify the problem by decomposing the displacement field into the sum of the gradient of a scalar potential, $\Phi$, and the curl of a vector potential, $A$. These represent the dilatational and constant-volume components of the displacement field, respectively.

$$\vec{U} = \nabla \Phi + \nabla \times \vec{A}$$  

Eq. 2.5

In reality, the steel likely has some anisotropy related to changes in the crystalline orientation that occur during plastic deformation. Such deformations occur during the forming operations that are part of the manufacturing process. The resulting anisotropy is known as stress anisotropy because it is often associated with residual stresses. However, for seamless steel pipes, it is typically assumed that the anisotropy is relatively minor [34] and thus the Helmholtz decomposition is applicable.

The next logical step in the solution is to consider the boundary conditions. The inner and outer surfaces of the pipe are traction-free, this gives six boundary conditions. The pipe also has boundary conditions at either end, but these are less clear. In fact, it is preferable to treat the pipe as infinitely long so that the ends need not be considered, and instead use an equal volume or gauge invariance condition. This condition simply means that the volume of the pipe is constant because the gauge, or thickness, of the pipe wall is constant along the length. Mathematically, gauge invariance is defined in equation 2.6.
Substituting the decomposed form of the displacement field given in Equation 2.5 into Navier’s governing wave equation (2.4) gives two new partial differential equations, where the constants \( C_L \) and \( C_T \) represent the bulk longitudinal and transverse wave velocities, respectively. Notice that these are classic wave equations, one for longitudinal and one for shear waves.

\[
\mathbf{v} \cdot \mathbf{a} = 0
\]  

(Eq. 2.6)

\[
\nabla^2 \Phi = \frac{1}{c_L} \frac{\partial^2 \Phi}{\partial t^2}
\]  

(Eq. 2.7)

\[
\nabla^2 \mathbf{a} = \frac{1}{c_T} \frac{\partial^2 \mathbf{a}}{\partial t^2}
\]  

(Eq. 2.8)

To solve these two equations, the potentials \( \Phi \) and \( \mathbf{a} \) are both written in cylindrical coordinates based on the theory of elasticity. To find longitudinal mode solutions, separation of variables is performed using the expressions of potentials originally presented by Gazis in 1959 [35] and the continuity condition in the circumferential direction (continuity between \( \Theta \) and \( \Theta + 2\pi \)) is applied. For torsional (transverse) mode solutions, alternative solutions which were presented by Sun, Zhang, and Rose in 2005 are used [36]. After a bit of algebraic manipulation, the solutions can then be found using Bessel functions which eventually lead to eigenvalue problems. The last step is to apply the gauge invariance and traction-free boundary conditions. The eigenvalues can then be used to make dispersion curves for the pipe, an example of which is shown in Figure 2.1.
Figure 2-1: Dispersion curves show where guided wave modes exist in the velocity and frequency domains. In this example, longitudinal modes are shown in black and transverse modes are shown in red.  

2.3.2 Dispersion Principles

In wave mechanics, dispersion denotes a relationship between velocity and frequency. To explain dispersion, the concepts of group velocity and phase velocity must be understood. These fundamental concepts apply to many different fields (including fluid dynamics, optics, and telecommunications) and each field uses slightly different nomenclature to describe the same phenomena. Group velocity is the velocity of the wave packet, also known as the envelope or modulation, which contains multiple sine waves within; these make up what is known as the carrier wave. The carrier wave is typically much greater in frequency than the envelope. The envelope is essentially a smooth outline of the signal.

The velocity of the envelope, or the group of waves, is the group velocity and the velocities of the sine waves that make up the carrier wave are the phase velocities. Group velocity is the velocity of energy transport and phase velocity is the speed at which a single point, or phase (such as a minima or maxima) on the wave moves. In NDE, relatively short pulse signals, called tone bursts, are typically used instead of continuous waves. This results in a distribution of frequencies inside the carrier wave, known as bandwidth, because a pulse of finite length cannot produce a single, isolated frequency. The pulse has a center frequency and is composed of a superposition of sine waves at similar, but different, frequencies. If the number of cycles in the tone burst is increased, the frequency bandwidth decreases and vice versa. Because the velocity is dependent on frequency, the individual sine waves inside of the envelope move at

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8 Plot produced by Li Zhang (FBS Inc.) and used with permission.
slightly different velocities. Over time, this difference in velocities causes the phases to spread out, which distorts the shape of the envelope, typically in the form of elongation. This is called *pulse spreading*, and it makes it clear why the word “dispersion” (which is defined by Merriam-Webster as “the action or process of distributing things over a wide area”) is used to describe the phenomenon.

Dispersion curves, such as in Figure 2.1, are essential in guided wave inspection. They are maps that illustrate where wave modes exist in terms of frequency and velocity. From dispersion curves, we can tailor the frequency and angle (in the case of angle beam excitation) or the frequency and wavelength (in the case of magnetostrictive excitation) of the transducer set-up to excite a particular guided wave mode. Trying to conduct a guided wave experiment without a dispersion curve is like looking for a house in an unfamiliar place without a map; the chances of exciting the desired mode by luck alone are slim.

The phase velocity and group velocity dispersion curves so useful for NDE do not arise directly from solving the theoretical wave mechanics problem as Chapter 2.3.1, however. The wave mechanics problem is often solved in the frequency domain, using the angular frequency, $\omega$, and the wave number, $k$.

\begin{equation}
\omega = 2\pi f
\end{equation}

\begin{equation}
k = \frac{2\pi}{\lambda}
\end{equation}

To construct the phase velocity dispersion curve from the frequency spectrum, the wavenumber is plotted as a function of angular frequency. Then equations 2.11 and 2.12 can be used to find the phase and group velocities, respectively.

\begin{equation}
c_p = \frac{\omega}{k}
\end{equation}

\begin{equation}
c_g = \frac{d\omega}{dk}
\end{equation}
By substituting $k = \omega/c_p$ into Equation 2.12, the following relationship between group velocity, phase velocity, and frequency can be found, as shown in Chapter 9.4 of Rose [30]:

$$c_g = c_p^2 \left[ c_p - f \frac{dc_p}{df} \right]^{-1}$$

Eq. 2.13

Assuming the wave mechanics problem has been solved, and the phase velocity data has been found using Equation 2.11, it is relatively simple to write a computer program which uses Equation 2.13 to find the group velocity data, which can then be used to plot the group velocity dispersion curves. The one point that requires care is handling the derivative $\frac{dc_p}{df}$. A true derivative, which is defined as the slope at a point, requires infinitesimally small changes in both the independent and dependent variables – this is the that we are familiar with from calculus. However, when working with a discrete set of data, such as a list of phase velocity and frequency values, a true derivative does not exist because there are gaps in the data; it is not a continuous function. Therefore, the derivative must be approximated, typically using a finite difference method such as the forward difference, backward difference, or central difference. These approximations result in error that can make the $c_g$ dispersion curve appear jagged, and larger gaps, or steps, in between the data points increase the magnitude of this error. An example of a group velocity dispersion curve with some error from the numerical derivatives is shown below in Figure 2-2. Whenever possible, it is preferable to use the central difference method because it results in error of $O(h^2)$ (where $h$ is the step size and is <1), while the forward and backward difference result in error of $O(h)$ [37]. Another way to decrease the error in the calculated $c_g$ values is to use a smaller step size when calculating the $c_p$ values. This way, each finite difference used to approximate the derivative in Eq. 2.13 covers a narrow range, resulting in less error. As the number of steps goes to infinity and the step size, or range, of the finite difference approaches zero, the result approaches that of a true derivative.
Figure 2-2: Group velocity dispersion curves for the longitudinal guided wave modes in a 4” schedule 40 steel pipe. Notice jaggedness due to error in numerical derivative. \(^9\)

\(^9\) Group velocity dispersion curve produced by the author
Chapter 3
Guided Wave Excitation and Practical Considerations

The previous chapter laid much of the theoretical groundwork for guided wave propagation. However, there are also many other practical aspects which must be considered. For example, how do we go about exciting specific guided wave modes? What unintended effects does our test equipment (namely the pulser and transducer) have on the excitation, and how do these agree or disagree with the assumptions of the classical wave mechanics problem? These important topics, known as excitation and source influence, must be understood in order to bridge the gap between theoretical wave mechanics and practical NDE inspection. Because source influence is a function of the source, before going into further detail on source influence, the two types of excitation sources used in this thesis should first be introduced.

3.1 Angle beam Excitation

To target a specific guided wave mode, it is necessary to control both frequency and phase velocity. By doing so, different regions on the dispersion curve can be excited. Frequency is always controlled by the pulser, and is measured in cycles/second or Hertz (Hz). The optimal frequency depends on the structure, the type of inspection, and on which guided wave mode is desired.

One way to control phase velocity is to use oblique incidence and Snell’s law of refraction, shown in Eq. 3.1. Snell’s law describes the refraction that occurs when a wave
encounters an interface between two different materials at an inclined angle. An excellent geometric derivation of Snell’s law is provided in chapter 4.3 of Rose [30].

![Figure 3.1. Oblique incidence.](image)

\[ c_1\sin \theta_1 = c_2\sin \theta_2 \]

Angle beam probes, which consist of a piezoelectric transducer mounted on wedge made from acrylic glass (known as PMMA or Plexiglas), are used to generate waves at specified angles of oblique incidence. Angle beam probes are typically built for a fixed angle, but variable angle probes are also available for experimental applications.
For guided wave excitation, Snell’s law can be simplified further. Since the wave that is excited in material 2 is a guided wave, it travels along the structure; thus $\Theta_2 = 90^\circ$. The velocity in material 1 is simply the bulk longitudinal wave velocity in acrylic glass, which is approximately 2,670 m/s – this is referred to as $c_{L,w}$ because it is the longitudinal velocity in the wedge. The angle of incidence, $\Theta_1$, is the independent variable which is controlled by the operator. The wave velocity in material 2, $c_2$, is the phase velocity, $c_p$, of the excited guided wave mode. Making these substitutions and rearranging to solve for the phase velocity gives Eq. 3.2, which illustrates how the phase velocity can be controlled by varying the angle of incidence. The angle-beam probe offers great flexibility because a range of $c_p$ values, and thus a range of possible modes, can be generated with a single probe and transducer.

$$c_p = \frac{c_{L,w}}{\sin \Theta_1}$$

Eq. 3.2
One important consideration when using an angle beam probe is acoustic coupling. Sound must be able to pass efficiently from the transducer into the structure that is being inspected. Air gaps between the transducer and the shoe, the shoe and the wedge, or the wedge and test piece will all prevent this. Acoustic coupling can be achieved using pressure (called *dry coupling*) or spreading a thin layer of acoustic couplant along the interfaces and also applying light pressure. Common couplants for ultrasonic testing include water, water-based gels, oil and grease, and glycerin based gels. In this thesis the commercially available water-based couplant *Ultragel II*, which is made by Sonotech, Inc., was used. Although some of the ingredients of Ultragel II are withheld as “trade secrets,” we do know that in addition to water it contains propylene glycol and glycerin (which act as thickeners and extend the drying time) and corrosion inhibitors which prevent the gel from causing any corrosion of the structure being inspected. After all, if the couplant caused corrosion then this technique would not be truly nondestructive! Ultragel II is also very safe to work with because it is stable and nonhazardous.
3.2 Comb transducers

Linear array, or comb type, transducers offer a second way to control phase velocity. Instead of using a single transducer at an oblique angle of incidence, multiple normal beam transducers are used to control phase velocity by specifying the wavelength directly. The comb consists of a row of long, narrow transducer elements (sometimes called “fingers”) which are parallel to each other. The spacing between the elements determines the wavelength of the guided wave mode which will be excited. Figure 3.2 shows the cross section of a comb transducer set-up. The wavelength of the guided wave that is generated is equal to twice the comb spacing. Typically, the comb spacing is equal to the finger width (i.e. the width of each element is half the period) because this configuration generates the most intense wave [30]. Recall the relationship between frequency, wavelength, and phase velocity shown in Eq. 3.4 to see how the phase velocity depends on wavelength.

![Figure 3-2: Linear-array comb transducer.](Image produced by the author.)
Compared to angle beam probes, one advantage of comb transducers is that there are fewer interfaces that require coupling, and thus less chance of error due to variability in coupling. A fixed angle beam probe requires coupling between the transducer and the wedge as well as between the wedge and the structure. A variable angle beam probe requires an additional interface to be coupled due to the shoe that sits between the transducer and the wedge. By comparison, comb transducers are placed directly on the structure, so there is only a single interface that requires coupling. One limitation of comb transducers is that, by their nature, they are only suited to exciting a specific wave length. For experimental purposes, where it is often informative to test multiple wavelengths, this is a disadvantage compared to variable angle beam probes. In practice, it could make sense to use a variable angle beam probe for the initial investigation, and then switch to using a comb transducer once the ideal wavelength has been determined.

3.3 Magnetostrictive Transducers

In addition to using piezoelectric elements, another method of exciting waves using comb transducers is by employing the magnetostrictive effect. The magnetostrictive effect describes the phenomenon whereby ferromagnetic materials undergo slight changes in dimension when in the presence of a magnetic field. In theory, magnetostriction could be used to excite stress waves directly inside of a steel structure since steel is ferromagnetic and therefore exhibits some degree of magnetostriction. However, the magnetostrictive response of steel is relatively weak and

\[
\lambda = 2a
\]

\[
c_p = f \cdot \lambda
\]
would require a very strong magnetic field to be of any use. In practice, a thin layer of a different alloy such as iron-cobalt (FeCo), which exhibits much stronger magnetostrictive properties than steel, is bonded to the structure so that elastic waves can be generated more efficiently.

Obviously, the FeCo must be acoustically coupled to the structure. There are various ways of accomplishing this including bonding the FeCo to the structure using double-sided tape or epoxy. The FeCo can then be left in place and used for multiple inspections.

Although a detailed description of magnetostriction is outside the scope of this thesis, a working understanding is still valuable for practical use. FeCo, like all other ferromagnetic materials, is characterized by many tiny grains which each possess a magnetic moment. Therefore each grain can be thought of as a microscopic bar magnet. Normally, these tiny bar magnets, or more properly magnetic domains, are oriented at random. However, they can be aligned by “poling” or “biasing” the material with a permanent magnet. In practice, this means swiping the FeCo strip several times with a magnet, being mindful to slide the magnet in the same direction each time. Once the magnetic domains have been aligned, they can then be cyclically aligned and misaligned in unison by applying an alternating magnetic field [38]. This causes cyclic expansions and contractions in the FeCo and is known as the Joule effect. Conversely, stress waves in a magnetostrictive material result in an alternating magnetic field – this is known as inverse magnetostriction or the Villari effect [40] and can be used to convert acoustic energy to electromagnetic energy. A conceptual illustration of the magnetostrictive effect is shown in Figure 3.3. The elastic wave is transferred from the FeCo to the pipe through the epoxy, where it then propagates along the pipe as a guided wave. Typically, magnetostrictive systems such as the one described here are used to generate horizontally polarized shear (SH) waves. For those interested, a wealth of information is provided on magnetostriction from both the materials science and applications perspectives by Lacheisserie [41].
3.3.1 MsS® Circuits

A magnetostrictive transducer system requires two basic parts: a suitable magnetostrictive material and an alternating magnetic field. The magnetostrictive material is typically iron-cobalt (FeCo), as described in the previous section. The alternating magnetic field is provided by passing an AC signal from the pulser through a coil which is located directly on top of the FeCo. The coil can be either a ribbon cable or a flexible printed circuit board (FPCB). FPCBs are more commonly referred to by the trade name MsS®, which is short for Magnetostriective Sensor. MsS® circuits were originally developed by the Southwest Research Institute (SwRI) for inspecting suspension bridge cables in the early 1990s [40]. An example of two FPCBs is shown in figure 3-4. Note the extremely fine traces of wire which make up the fingers of the coils. These two coils have different spacing because they are designed to produce two different wavelengths.

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11 Image used with permission from Rose [39].
Figure 3-4: An example of two FPCB sensors for a magnetostrictive transducer system.

Compared to the piezoelectric comb transducers described in Chapter 3.2, the comb transducers used in FPCBs have one important difference. In a piezoelectric comb transducer, the polarity is the same in each finger at any given time. For example, at the instant when the pulser provides a voltage with the same polarity as the poling voltage of the piezoelectric crystal, each finger experiences this voltage and each finger expands in response to this voltage. Conversely, when the applied voltage is opposite in polarity to the poling voltage, each finger will contract along its poling axis. The fingers work in unison.

FPCB type comb transducers, on the other hand, work on a different principle. Electric current flows out of the pulser, up one finger, around a bend, and then down the next finger in a continuous loop - each finger generates its own magnetic field, but they are in opposite directions. One field is clockwise and the other is counter clockwise. As a result of this, while the first finger is causing the magnetostrictive material to contract, the second finger is causing it to expand or vice versa. Each finger acts locally on the region of FeCo directly underneath it.
When one finger is generating a peak in the acoustic wave, the fingers on either side of it are causing valleys. Due to the AC signal passed through the coil, each finger alternates between causing expansions and contractions.

Ribbon cable type transducers work similarly to FPCBs; they are both essentially comb transducers and they are both very thin and lightweight, but there are a few important differences. Ribbon cables consist of much thicker traces of wire, which results in a lower impedance and poorer impedance matching with the pulser. FPCBs also offer great versatility; the fingers can be curved for natural focusing, and the shape of the ends can be designed to reduce unwanted waves from being generated in the lateral directions.

3.4 Source Influence

Guided wave dispersion curve calculations are based on the assumption of an infinite continuous plane wave at a specific frequency [30]. In reality, guided waves are produced by transient signals and transducers of finite dimensions. The transient signal causes a frequency spectrum, and the finite-sized loading area causes a phase velocity spectrum. Therefore, it is not possible to excite a single, isolated point on the dispersion curve because there is always bandwidth in both the frequency and phase velocity spectra. Rather, a “region” or “zone” is excited. Increased the number of cycles in the pulse decreases the frequency spectrum, and increasing the dimensions of the loading area decreases the phase velocity spectrum – these two techniques can be used to reduce the size of the excitation spectrum. In practice, it is important to consider source influence when working with modes that are in close proximity on the dispersion
curve. It is preferable to isolate a single mode (since this makes this signal simpler), but this is not always possible due to source influence.

In addition to the phase velocity and frequency spectra, there are other practical effects which could be considered forms of source influence. Transducers have a tendency to ring due to underdamping, which increases the effective number of cycles slightly; hence the frequency bandwidth is changed. There is also some uptake time in the transducer, where the transducer’s response “catches up” to the beginning of the pulse. This is especially true when the output of the pulser is a square wave. The lesson to be learned is that the signal that comes out of the transducer is never identical to the signal that comes out of the pulser.
Chapter 4

Experiment 1: NDE of External Crack Growth in Pipe with an Angle Beam Probe

For the first experiment, a 4” diameter schedule 40 steel pipe was chosen as a test bed to study detection and monitoring of external surface crack growth. The primary goals of the experiment were three fold: to determine which longitudinal guided wave modes can be excited realistically in the pipe for NDE purposes using a single angle beam transducer, to evaluate the modes for sensitivity to crack growth, and to study the effects of coupling variability. The test began with baseline data, and then a simulated crack was introduced and “grown” progressively larger until the maximum depth of the cut equaled the wall thickness of the pipe. Data was collected at each increment of crack growth from distances of 1, 2, and 3 feet away from the defect. Because data would need to be compared as the crack grew, and also because this experiment would serve as a reference point for experiments 2 and 3, great care was taken to make the experiment as consistent and repeatable as possible. Despite these best efforts, there was still some variability in the results, as there is in any legitimate experiment. These sources of error, along with other insights, will be discussed throughout this chapter.

4.1 Equipment

The following basic equipment was used for experiment 1:

- 79.5” (6 feet and 7.5 inches) long, 4” diameter schedule 40 steel pipe;
  henceforth referred to as “the test pipe”
- Variable angle beam transducer wedge and shoe
- Magma pulser box and receiver
- Dell E6400 Laptop computer with Guided Wave Workstation software program
- Composite piezo-electric transducer with center frequency of 500 kHz
- BNC cable to connect pulser/receiver to transducer
- Dremel tool with right-angle attachment and cutting disc
- Pipe stands to hold pipe during test

The test pipe was generously donated by FBS, Inc. for use in the experiments associated with this thesis. The pipe did have one pre-existing flaw, a small “ground-out” defect that had been made for a previous test. Fortunately, the pipe still had plenty of undamaged areas where new tests could be conducted without interference from the pre-existing defect. Since the pipe had been sitting outside in the weather for approximately 1 year, there was a layer of rust over the entire surface. Visual inspection revealed that despite the corroded appearance of the pipe, there was no significant pitting. Clearly, the surface of the pipe would need to be sanded down to remove the rust wherever the transducer would be mounted, but other than that the mild corrosion would not pose a problem for the experiments.
For excitation, an acrylic glass variable angle beam wedge and broadband composite piezoelectric transducer with a resonant frequency of 500 kHz were chosen. This combination made it possible (in theory at least) to excite most points on the dispersion curve; the phase velocity could be tuned by varying the angle of incidence and the broadband transducer provided a wide effective range of approximately 250 to 800 kHz.
The 500 kHz transducer used is a commercially available model made by General Electric (also similar to Krautkramer models) with dimensions of 31x42x19 (width by length by height, all in millimeters). Composite transducers such as this were originally developed by Professors Newnham and Cross at Penn State, and typically consist of piezoelectric rods in an epoxy matrix [42]. This is known as a 1-3 piezo composite because the piezo elements only have connectivity in 1 of 3 spatial dimensions [42]. Compared to bulk piezo ceramic transducers, composites offer lower impedance, better damping (to reduce ringing) [42], improved frequency bandwidth, and less undesired lateral vibrations. The fundamental resonant frequency of the transducer is determined by the thickness of the piezo elements; the piezo element vibrates at a wavelength equal to twice its thickness [43].
4.2 Mode Selection

Based on the phase velocity dispersion curve (Figure 4-2) and Snell’s law for guided waves (Equation 3.2), four guided wave mode groups were targeted for initial investigation: the L(m,2) group at $f = 250$ kHz and $c_p \approx 5500$ m/s, the L(m,3) and L(m,4) groups at $f = 500$ kHz and $c_p \approx 6500$ m/s, and the L(m,5) group at $f = 750$ kHz and $c_p \approx 8000$ m/s.

![Figure 4-3: Phase velocity dispersion curve for 4” schedule 40 steel pipe. Torsional modes are shown in red, longitudinal modes are shown in black.](image)

Multiple factors were considered to determine which modes should be targeted for inspection. Firstly, it is not possible to excite all of the modes on the dispersion curve with the

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12 Plot produced by Li Zhang (FBS Inc.) and used with permission.
equipment that was used; limitations are posed by the dimensions of the transducer, the frequency range, and by Snell’s law. A single 31mm wide transducer only provides a relatively small partial loading around the circumference of the pipe; therefore entire mode groups (or families) are excited rather than just the $L(0,n)$ axisymmetric modes. Additionally, the piezoelectric transducer becomes less efficient at frequencies away from its fundamental resonant frequency of 500 kHz, thus inspections outside of the range of approximately $250 – 750$ kHz are not recommended with this transducer. The angle wedge system also limits the range of the phase velocity spectrum that can be excited. From equation 4.2, it is clear that the excited phase velocity cannot be less than the bulk longitudinal wave speed in the wedge, which is about $2,670$ m/s in the case of acrylic glass, because $|\sin \Theta_1| \leq 1$. This inability to excite low phase velocities rules out the $L(m,1)$ mode group and also the $L(m,2)$ group at frequencies greater than about 500 kHz, since the phase velocities of these modes are less than $2,670$ m/s. To excite these modes using oblique incidence, a different wedge constructed of a material with a slower bulk longitudinal wave velocity is required.

$$c_p = \frac{c_{lw}}{\sin \Theta_1}$$

Eq. 4.2

Another important consideration in mode selection is isolation. As discussed in Chapter 3.4 on source influence, it is often impossible to excite a single point on the phase velocity dispersion curve due to bandwidth in both the frequency and phase velocity spectra. If a given point is targeted for excitation, say $f = 500$ kHz and $c_p = 6,500$ m/s for example, a region of frequency and phase velocity values centered around $(500, 6500)$ will be excited, although the excitation will be most intense near the center. The size of the excitation region is influenced by the dimensions of the loading area (i.e. the dimensions of the transducer) and the frequency bandwidth of the signal. Modes and mode groups that are located in close proximity to the center
of the excitation region on the dispersion curve may be excited simultaneously; generally this is undesirable for guided wave inspection. Different modes, especially those in different mode groups, propagate at different group velocities. When multiple mode groups are excited, a single defect may appear as multiple reflections with different arrival times. When inspecting a structure that may have multiple defects, or other reflectors such as end walls, simultaneous mode group excitation can result in a signal that is “crowded” with reflections and difficult to interpret. For practical inspections, simplicity is an outstanding quality. Simultaneous excitation of modes from the same group is difficult to prevent, but also less troublesome because these modes tend to travel at similar group velocities. Notice on the dispersion curve in Figure 4-3 that the L(m,3) and L(m,4) groups are in very close proximity near \( f = 500 \text{ kHz} \), and may be excited simultaneously. Despite this, these two modes were chosen as possibilities for inspection at 500 kHz because 500 kHz is the center frequency of the transducer, and therefore it would be desirable to be able to inspect at 500 kHz since this is most efficient frequency of the transducer. Even though simultaneous mode excitation might make this impractical, it is still good to test and verify before ruling out the possibility.

It is also important to keep in mind that, in practice, there is no guarantee that every single mode on the dispersion curve is excitable, even if it lies within the range of frequency and \( c_p \) values that can be reached by your equipment. This has to do, in part, with wave structure. Certain guided wave modes may have very little out-of-plane displacement at the surface, which means they will not be excited efficiently by an angle-beam transducer. Other modes may have large particle displacements at the surface, making them easy to excite, but may also lack particle displacement at depth and therefore be ineffective for detecting growth in subsurface defects. Clearly, the use of dispersion curves is a necessary starting point for guided wave inspection, but additional testing is required for optimal mode selection.
4.3 Pulser and Receiver Settings

The following settings were used throughout experiments 1, 2, and 3:

- 4 cycle tone burst
- 27 dB of gain
- Pulse voltage: 300V
- Sampling rate: 10 MHz
- Pulse repetition frequency (PRF): 10 Hz

A 4 cycle tone burst was chosen based on the advice of experienced Engineers at FBS, Inc. Keep in mind that the pulser actually produces a square wave, but it is effectively filtered into a tone burst by the transducer – since the piezoelectric response of the transducer is not instant, it cannot produce a square wave. Also, there is some ringing in the transducer that remains after the initial 4 cycles due to under-damping. This ringing effectively increases the number of cycles from 4 to 5 or perhaps 6. These “extra” cycles that occur during ringing decrease in amplitude as the signal decays due to damping. Although using a greater number of cycles, for example 10 instead of 4, would decrease the frequency bandwidth and potentially make the mode selection more precise, this was not chosen because increasing the number of cycles can lead to other issues. For example, increasing the number of cycles can further increase the ringing in the transducer, increase the size of the main bang (which makes the transducer blind to nearby defects), and decrease axial resolution.

27 dB of gain was chosen to amplify the received signal because this amount of amplification worked well with the available axis scaling on the Workstation software, such that small signals (with amplitudes barely above the noise floor) could be seen, without clipping larger signals from the end-wall. 27dB is not a standard or a magic number, it was merely chosen because it worked conveniently with the equipment used in these experiments.
The remaining settings (pulse voltage, PRF, and sampling rate) were all chosen based on the recommendation of Engineers at FBS, Inc. These are the standard values used for this type of experiment.

4.4 Simulated Crack Growth

To study defect growth, it is necessary to either perform longitudinal studies as real service defects grow, or to grow your own artificial or “simulated” defects. Artificial defects are typically made using drills (to simulate corrosion pitting), or saws or cutting wheels (to simulate crack growth.) While studying real service defects is more realistic, it also reduces control and increases variability, and data collection may take years depending on the defect growth rate. On the other hand, experiments with simulated defects can be well controlled and completed in relatively short periods of time. A compromise between the two approaches is to grow a “real” defect (similar to what would be seen in service) but use artificial means to increase the defect’s growth rate. An example of this would be growing a fatigue crack using a cyclic three point bend machine, or growing corrosion pitting using a salt water fog. However, these hybrid techniques do require special equipment and involve a higher level of complexity than simply growing an artificial defect using a drill or cutting wheel.

For the experiments relating to this thesis, a handheld Dremel tool with a right angle attachment and cutting wheel was chosen to create simulated crack growth. This method was chosen for simplicity, speed, and versatility – using a small, portable tool such as the Dremel allows cuts to easily be made anywhere on the pipe, even when the pipe is stored in a tight space.
in the lab. The downside of using a handheld tool is the loss of stability compared to a table saw or a drill press; precise and consistent cuts depend on the skill and steady hands of the operator.

Figure 4-4: The Dremel 4000 handheld rotary tool.

Figure 4-5: A right angle attachment was used to make precise cutting easier.
4.4.1 Area and Depth Calculations

Figure 4-6: Dremel cutting disc with 1.5” diameter.

Figure 4-7: Diagram of simulated crack growth.
A sketch of the cutting wheel and pipe is shown in Figure 4-7. The outer diameter of the pipe is 4.5” and the outer diameter of the cutting wheel is 1.5”. The sketch is not drawn exactly to scale; it is a conceptual rendering. Note that the shape is similar to the elliptical shape assumed in many LEFM calculations, such as in Chapter 1.5.3. Figure 4.8 shows a more detailed version of the cut with the dimensions used to calculate its area. To perform a quantifiable study of the defect growth, it is necessary to measure the area and depth of the defect. Measuring the area and depth of a thin crack directly is difficult, but measuring the length of the crack at the surface is simple. For this reason, the area and maximum depth of the cut were calculated based off the surface cut length as follows.

Figure 4-8: $R_o$ is the outer diameter of the pipe, $r$ is the diameter of the cutting wheel, and $L$ is the cut length at the surface (measured). $\Theta$ and $\alpha$ are the central angles from the centers of the pipe and cutting wheel, respectively.

The measurable variable is the cut length, $L$ – this is easily measured using calipers. The other two known variables are the outer radius of the pipe, $R_o$, and the radius of the cutting disc, $r$. From these variables, the area and depth of the cut can be calculated as follows.

From simple right triangle trigonometry, it is clear that the cut length $L$ (which is also a chord of the two circles) is related to the other dimensions as shown in equation 4.3:

Equation 4.3

$$L = 2R_o \sin(\theta) = 2r \sin(\alpha)$$
From this, the central angles theta and alpha can be solved for in terms of known variables:

Equation 4.4
$$\Theta = \arcsin \left( \frac{L}{2R_o} \right)$$

Equation 4.5
$$\alpha = \arcsin \left( \frac{L}{2r} \right)$$

Now that theta and alpha are known, the area of the “slice” of each circle can be found as a fractional part of the entire area. In geometry, these “slices” are more formally known as sectors.

The triangle outlined in black, along with the red shaded area labeled “b” is a sector of a circle with radius $R_o$ and central angle $2\Theta$. The triangle outlined in light blue and red shaded area labeled “a” is a sector of a circle with radius $r$ and central angle $2\alpha$. These will be referred to as “sector a” and “sector b”. The areas of sectors a and b are given in Equations 4.6 and 4.6, where alpha and theta are taken in radians.

Equation 4.6
$$sector\ a = \left( \frac{2\Theta}{2\pi} \right) \pi r^2 = ar^2$$

Equation 4.7
$$sector\ b = \left( \frac{2\alpha}{2\pi} \right) \pi R_o^2 = \Theta R_o^2$$

To find the area of the cut (the red shaded area), the area of the triangle outlined in black must be subtracted from sector b; and the triangle outlined in light blue must be subtracted from sector a. This gives the two halves of the cut, a and b.

Equation 4.8
$$a = sector\ a - blue\ triangle = ar^2 - \frac{L}{2} \cos(\alpha)$$

Equation 4.9
$$b = sector\ b - black\ triangle = \Theta R_o^2 - \frac{L}{2} R_o \cos(\Theta)$$

Recall that theta and alpha are known in terms of $L$, $R_o$, and $r$ as shown in Equations 4.4 and 4.5.

The total area of the cut, described entirely in terms of the known variables $r$, $R_o$, and $L$ is simply the sum of a and b.

Equation 4.10
$$total\ cut\ area = a + b$$
The maximum depth of the cut can also be found using geometry. The horizontal legs of the two triangles in Figure 4-7 simply need to be subtracted from the radii of the pipe and the cutting disc.

\[ \text{max depth} = (R_o - R_o \cos \theta) + (r - r \cos \alpha) \]

Equation 4.11

These calculations for total area and max depth can easily be written into a computer code such as MATLAB. This makes it very quick and easy to do the calculation repeatedly for different cut lengths. For completeness, the MATLAB code that was written and used by the author for this purpose is shown in Appendix B.

4.4.2 Accuracy of Cut Size

In order for the area and maximum depth calculations shown in Chapter 4.3.1 to remain valid as the size of the cut is increased, the cutting disc must be centered in the same spot during each cut. If the cutting disc moves off-center, the shape of the cut deviates from the circle-circle intersection that is assumed, and the actual area and depth begin to differ from the calculations. Of course, when using a hand-held tool such as the Dremel, it is impossible to keep each cut centered on exactly same location. Even when markings on the pipe were used to align the cutting disc at the beginning of each cut, the forces that arise between the pipe and the cutting disc during cutting tend to “kickback” the cutting disc and move it off center. This is similar to the kickback that can happen when using a chainsaw to cut wood; it happens very suddenly and forcefully. Kickback was not a problem with the Dremel tool when the cut was relatively small,
but it increased as the depth of the cut approached the wall thickness of the pipe (0.25") and the length of the cut became about 50% as great as the diameter of the cutting disc. The kickback caused the cut to become longer without much increase in depth. This deviation between the actual geometry of the cut and the geometry that was assumed in the area and maximum depth calculations means that the area and depth numbers are approximations. The approximations should be very accurate when the cut is relatively small, but become less accurate when the cut is larger, especially when \( L \geq 0.80" \) since this is when pronounced kickback began to occur.

Another assumption of the cut area and maximum depth calculations is that the cut has not yet breached the pipe wall, i.e. the maximum depth is \( \leq 0.25" \). Obviously, once the cut has gone all the way through the pipe wall, the shape of the cut area changes considerably. However, for preventative maintenance the goal is always to detect and locate cracks before they reach such an advanced stage that they become through-cracks. Keeping the ultimate goals of NDE and SHM for preventative maintenance in mind, testing with cracks that have not yet penetrated the entire pipe wall is realistic and reasonable.

### 4.5 Results

#### 4.5.1 \( L(m,2) \) mode group at 250 kHz

At a frequency of 250 kHz and an incident angle of about 28° from the normal (vertical), a phase velocity of approximately 5,700 m/s can be excited according to Snell’s law. This matches the \( L(m,2) \) mode group on the phase velocity dispersion curve, highlighted in yellow in Figure 4-8. From the group velocity dispersion curve, the modes of the \( L(m,2) \) group propagate at a range of velocities between roughly 3,500 and 5,500 m/s at 250 kHz, as shown in Figure 4-9.
Figure 4-9: Phase velocity dispersion curve showing \( L(m,2) \) group at 250 kHz\(^{13}\).

\[^{13}\text{Plot produced by the author using calculations from Li Zhang (FBS Inc.)}\]
Figure 4-10: Group velocity dispersion curve showing L(m,2) group at 250 kHz.
Figure 4-9: Half rectified A-scan at 250 kHz, 28° with 27 dB of gain. The cut is located 2 feet away from probe, the end-wall is 3 feet away, and the cut length is $L=0.58$ in. A bandpass filter of 100-300 kHz was used.

Data collected when the probe was located 3 feet from the end wall are shown in the A-scan in Figure 4-9. A bandpass filter of 100 to 300 kHz was used. The first noticeable feature in the A-scan is the main bang, which is noisy and extends out all of the way to 250 µs. This large main bang causes a significant “dead zone” or “blind spot” in front of the transducer, the length of which can be calculated quite easily. Consider that in between the transducer and the pipe there are approximately 87 mm of Plexiglas (77 mm thick wedge plus 10 mm thick shoe.) Given the bulk longitudinal wave speed in Plexiglas of 2,670 m/s, it takes the wave roughly 32.5 µs to travel from the transducer to the pipe, and another 32.5 µs for the echo to travel from the pipe to the transducer. If we subtract this from the main bang, that leaves 185 µs – half of this time is used to propagate away from the probe, and the other half is used for the echo to return.

Assuming a group velocity of 5,250 µs (this is the upper end of the possible group velocity range,
and thus gives a conservatively large estimate for dead zone length), 185 µs is enough time for the wave to travel 1.6 feet down the pipe and back – but the transducer cannot “see” anything in this range because the echoes from any reflectors within 1.6 feet (1 foot and 7.2 inches) of the transducer arrive back at the transducer before the main bang has ceased.

The second noticeable feature in Figure 4-9 is the large reflection arriving at approximately 430 µs. Considering that the wave takes approximately 65 µs to pulse and echo through the acrylic wedge and shoe, this means that 365 µs was spent in the pipe. Assuming that the reflection is from the end-wall (which it must be), then the group velocity is approximately 5,000 m/s. This agrees with what is theoretically possible from the group velocity dispersion curve. The double peak in the reflection may be from two different modes in the L(m,2) group travelling at slightly different velocities.

The third (and perhaps the most important) noticeable feature in Figure 4.9 is the noise level. The signal is so noisy that the amplitude of the reflection from the end wall of the pipe, at the relatively short distance of 3 feet, is only 3.5 times the amplitude of the noise floor. The level of noise makes it impossible to reliably identify small defects, which produce much weaker reflections than the end wall, because their reflections are indistinguishable from the noise. In fact, the A-scan in Figure 4.9 was taken when there was already a cut of surface length L = 0.58” 2 feet away from the transducer. Based on the wave velocities, we expect to see a reflection from this defect at approximately 300 µs. However in Figure 4.9, no reflection stands out at 300 µs, most likely because it is obscured by the noise. This issue continued as the cut was grown larger, leading to the conclusion that the high noise floor and (possibly) poor crack sensitivity observed with L(m,2) mode group ruled it out from further consideration.

One common way to improve the signal-to-noise ratio (SNR) is to increase the number of averages. By taking a set of identical measurements and averaging the results, the effects of random noise can be reduced. In the results shown in Figure 4.9, 10 averages were used.
However, increasing the number of averages beyond 10 did not appear to improve the SNR in this case. This suggests that some of the noise seen in the signal is not truly random, rather it is coherent. It’s possible that coherent noise could arise due to excessive echoes and vibrations inside of the acrylic wedge and shoe, or inside of the piezo transducer itself. Remember, 250 kHz is near the limit of this transducer’s intended frequency range (the fundamental resonant frequency is 500 kHz), so it’s possible that the transducer is not well damped at 250 kHz and thus produces excessive noise due to ringing at this frequency. Although a thorough discussion on the sources of noise in piezoelectric angle-beam transducers lies outside the scope of this thesis, a brief investigation of the sources of the noise seen in this transducer at 250 kHz is provided in Appendix A for completeness.

4.5.2 L(m,3) and L(m,4) mode groups at 500 kHz

At 500 kHz, the phase velocity dispersion curve (Figure 4-10) shows that both the L(m,3) and L(m,4) mode groups coexist at a phase velocity of approximately 7,000 m/s. Because these two mode groups are so close in both frequency and phase velocity, it is difficult to excite one without the other. By reducing the frequency to less than 450 kHz, it is possible to go below the cut-off frequency of L(m,4) group, which could possibly lead to better isolation of the L(0,3) group. However, because of source influence effects on the excitation spectrum, even then the L(0,4) group might still be excited.
Figure 4-10: Phase velocity dispersion curve with the L(m,3) and L(m,4) groups at 500 kHz highlighted in yellow.\textsuperscript{14}

We can see on the group velocity dispersion curve that, fortunately, the L(0,3) and L(0,4) groups do travel at roughly the same group velocity when the frequency is near 500 kHz. Because of this, simultaneous excitation of these two groups might not result in confusing signals since both wave packets are expected to arrive at about the same time. An angle of incidence of 28° was chosen because this gave the strongest excitation.

\textsuperscript{14} Plot produced by the author using calculations from Li Zhang.
Figure 4-11: Group velocity dispersion curve with the L(m,3) and L(m,4) groups at 500 kHz highlighted in yellow. Although there is visible error from the numerical derivatives (evident as choppiness in the lines), the practical usefulness from the plot is not diminished.\textsuperscript{15}
Figure 4-12: Baseline data (no cut) taken at 500 kHz and an incident angle of 28° with the probe located 3 feet away from the end wall.

Figure 4-12 shows initial baseline data, collected with a bandpass filter of 400 to 600 kHz. Notice that the signal has a much improved signal-to-noise ratio (SNR) compared to the 250 kHz test, and the end wall reflection is very strong. Given that the end-wall is 3 feet from the transducer, and keeping in mind that the waves take 65 µs to propagate through the Plexiglas, we can deduce that the group velocity is approximately 4,000 m/s – this matches with what we expect from the group velocity dispersion curve in Figure 4-11.

As the cut was made with the Dremel tool, and its size was increased, a reflection began to appear at 375µs as shown in Figure 4-13. Assuming this reflection is from the cut, this
indicates that the group velocity is approximately 4000 m/s. This matches the group velocity that was determined based off the end wall reflection and the dispersion curve. We can be confident that the reflection at 375 µs is from the cut.

![Defect begins to appear]

Figure 4-13: Defect reflection appears at 375µs. The defect is located 2 feet from the probe.

The size of the cut was increased from zero (baseline) to a length of 1”, at which point the middle of the cut began to breach the inside of the pipe wall, making a through-crack – the resulting A- scan is shown below in Figure 4-14. Notice the growth in the amplitude of the defect’s reflection, and the decrease in the end-wall reflection (due to the defect blocking energy
from reaching the end wall) compared to the baseline data in Figure 4-12. After each successive cut, the length of the cut was measured with calipers and recorded.

Figure 4-14 A-scan taken from 2 feet away from the cut when the cut measured L = 1” and just extended through the wall thickness. Notice that the reflection from the cut now dwarfs the end-wall reflection.
Figure 4-15: As the size of the defect was increased, the length was measured at each step. This length was used to compute the cut’s area and depth as described in Chapter 4.4.

For the first five cut sizes, data was collected once for each cut size from distances of 1 foot, 2 feet, and 3 feet from the cut. For the sixth cut, it was decided to begin collecting data three times after each time the size of the cut was increased. After each data collection, the probe was removed from the pipe and disassembled. The transducer was removed from the shoe and the shoe was separated from the wedge. For the next round of data collection, the probe was reassembled and recoupled with Ultragel. This process ensured that, at least in terms of coupling, position on the pipe, and incidence angle, each data collection was independent. The purpose of this very time-consuming procedure was to gauge the variability, mostly due to difference in coupling. By taking data multiple times, there is less chance that “flukes” or outliers will drastically affect the results, and the results are therefore more valid for drawing conclusions and making comparisons.
After the iterative process of collecting data and increasing the cut size was completed, the amplitude of the reflection from the defect was plotted vs the cut area and maximum cut depth as shown in the figures below. For transparency, no data have been omitted from these plots.

Figure 4-16: Plot showing defect reflection amplitude versus area. The transducer was located 1 foot away from the defect.
Figure 4-17: Plot showing defect reflection amplitude versus defect depth. The transducer was located 1 foot away from the defect.
Figure 4-18: Plot showing defect amplitude versus area. The transducer was located 2 feet away from the defect.
Figure 4-19: Plot showing defect amplitude versus depth. The transducer was located 2 feet away from the defect.
Figure 4-20: Plot showing defect amplitude versus area. The transducer was located 3 feet away from the defect.
The plots shown in figures 4-16 through 4-21 all show the same overall trend – the amplitude of the reflection from the defect increases with both the size and depth of the defect. This is as expected. The plots also show great variability, mostly between the different cut sizes, but also on individual cuts. For example, in Figure 4.17, the data that was taken when the depth of the cut was 0.2” was very closely grouped. However, these data differed drastically from the data taken when the cut depth was 0.175”. In this case the data appears precise (as indicated by the tight groupings for each cut), but not very accurate. However, the last data set that was taken, when the cut depth was 0.24”, shows a large spread in amplitude (from 0.3 V to 0.5 v) indicating lack of precision.
What is surprising about these results is that the way the amplitude of the reflection from the crack stays relatively constant when the area of the defect is between ~0.04 in.\(^2\) and ~0.13 in.\(^2\) and the maximum depth of the crack is between ~0.1 in. and ~0.2 in. This is highlighted below in Figure 4-22.

Figure 4-22: The amplitude of the reflection is not a good indicator of crack growth for the crack sizes in the yellow highlighted region.

The amplitude of the reflection increases with the size of the crack as expected when the crack is small, then levels off, and then increases drastically shortly before the crack becomes a through crack. Based on these results, the L(m,3) and L(m,4) mode groups at 500 kHz do not appear to be well-suited to tracking defect growth since large amounts of crack growth are not seen in the A-scan. If this had been the result in only a single one of the tests, it may have been reasonable to assume that it was the result of operator error or some kind of fluke.
However, this same result is shown in the data that was taken at distances of 1 foot, 2 feet, and 3 feet away from the defect. During data collection, the author noticed that the signal was remaining relatively constant over a wide range of crack growth, and took care to make sure that the equipment was set up correctly and that the coupling was acoustically adequate and consistent.

In terms of mode selection for NDT and SHM, the L(m,3) and L(m,4) mode groups provide a poor result because the amplitude of the reflection does not change over a wide range of crack growth. However, for academic and illustrative purposes, this “failure” is actually quite an interesting result because it invites an intriguing question: Why does the amplitude increase with crack growth initially, then remain constant over a wide range of subsequent crack growth, and the begin increasing again once the crack is sufficiently deep? In the opinion of the author, the explanation likely lies in the wave structure. Wave structure refers to the particle displacement or energy profile of a wave across the thickness of the wave guide. Each specific guided wave mode and frequency combination has a unique wave structure, although the wave structures of modes from the same group are similar [30]. For waves in plates, wave structure can be calculated analytically from the displacement equations that arise from the method of potentials (see chapter 6 of Rose [30]) or numerically using a semi-analytic finite element method. The wave structure solutions, which depend on the frequency thickness (referred to as “fd”) product and phase velocity, can then be plotted for individual points on the dispersion curve. The coordinate system shown in Figure 4.25 is used to describe wave structure.
Longitudinal or Rayleigh-Lamb type wave modes have particle displacements primarily in the $x_1$ and $x_3$ directions, whereas shear horizontal (or torsional modes, in the case of pipe) have particle displacement in the $x_2$ direction (using the coordinate system of Figure 4-23). From both the theory and experimental evidence, it has been established that certain mode and frequency combinations have non-uniform wave structures; in some cases the wave structure may resemble a sine wave. These wave structures may concentrate acoustic energy at the surfaces of the wave guide, and leave the center of the wave guide relatively “untouched.” This type of wave structure could explain the results seen with the $L(m,3)$ and $L(m,4)$ at 500 kHz. Figures 4-24 and 4-25 show the normalized displacement of the A1 mode in a quarter inch thick steel plate at $f_d = 3.175$ MHz, which is the same $f_d$ value used in the experiments. Since Figures 4-24 and 4-25 are calculated based on plate geometry, they are approximations for a pipe, but they should be accurate approximations for the relatively short distances (several feet or less) used in this thesis.
Figure 4-24: Theoretical wave structure of A1 mode in a quarter inch thick steel plate at \( f_d = 3.175 \text{ MHz}\cdot\text{mm} \). Notice the displacement approaches zero at the center of the thickness.\textsuperscript{16}

\textsuperscript{16} Wave structure calculations done with assistance from Jason Philtron.
Figure 4-25: Theoretical power flow profile for A1 mode, calculated using the Poynting vector. Notice that the in-plane power flow is minimized at the center of the thickness.\textsuperscript{17}

Wave structures similar to the ones shown in Figures 4-24 and 4-25 may be responsible for the “strange” results seen with the L(m,3) and L(m,4) modes at 500 kHz. In fact, the input used to create Figures 4-24 and 4-25 is similar to the conditions of the experiment in this thesis: the assumed material properties are that of steel, the thickness is 0.25”, and the frequency is 500 kHz. Near to the outer edge of the pipe wall, there is significant displacement and power flow in-plane, which provides sensitivity to shallow defects. In the middle of the pipe wall, there is very little displacement, so there is no sensitivity to defect growth. Once the defect grows and begins to resemble a through-crack, there is an increase in the reflection because of the displacement and power flow on the inside of the pipe wall. This can be seen in the symmetry of the absolute value of the displacement profiles.

\textsuperscript{17} Wave structure calculations done with assistance from Jason Philtron.
One issue to note whenever using wave structure calculations is that wave structure is specific to a single mode and a frequency, but in practice a range of frequencies (and in many cases, a range of modes) are excited due to source influence. In this case, the true wave structure is a superposition of the wave structures of the various modes and frequencies which are excited. For more information on wave structure analysis or the effects that wave structure has on defect detection, see Chapters 6 and 10 of Rose [30] or the article by Ditri, Rose, and Chen [44].

4.5.3 L(m,5) mode group at 750 kHz

Using an incidence angle of 20°, a phase velocity of 7,800 m/s can be excited according to Snell’s law. At 750 kHz, this phase velocity is close to that of the L(m,5) mode group, as shown in Figure 4-26. There are practical reasons why the L(m,5) group at 750 kHz might be desirable. First of all, relatively high frequencies, such as 750 kHz, offer the potential to detect and resolve defects that are too small to detect at lower frequencies. This is because, in general, defect sensitivity and resolution both increase with frequency due to the accompanying decrease in wavelength [45]. As a rule of thumb, any defect which is dimensionally less than one half of the wavelength is undetectable [46]. From the dispersion curve, the L(m,5) group also appears to be fairly isolated at 750 kHz; it’s possible that modes in the L(m,5) group can be excited with little to no undesired excitation of modes from other groups.
Figure 4-26: Phase velocity dispersion curve with L(m,5) group near 750 kHz highlighted in yellow.\textsuperscript{18}

Of course, there are also drawbacks that may come with selecting a higher frequency, which should be mentioned. Waves with higher frequency and shorter wavelength generally experience stronger attenuation (and therefore offer reduced inspection range) compared to waves with lower frequency and greater wavelength. Attenuation is the decrease in amplitude of the wave due to both scattering and absorption. In addition to frequency dependence, attenuation rate also depends greatly on the material properties of the wave guide. For example, wrought and forged materials, such as the test pipe used in the experiments relating to this thesis, have refined grain structures which can typically be inspected effectively at relatively high frequencies [45]. However, cast materials may have coarse grain structures that cause excessive scattering (and

\textsuperscript{18} Plot produced by the author using calculations from Li Zhang (FBS Inc.)
thus attenuation) at higher frequencies; these materials may require lower frequencies in order to provide sufficient inspection range [45].

Figure 4-27: Group velocity dispersion curve with L(m,5) group near 750 kHz highlighted in yellow.19

The group velocity dispersion curve in Figure 4-27 shows the L(m,5) group near 750 kHz highlighted in yellow. From the dispersion curve, we can see that the expected group velocity is roughly 3500 m/s. Figure 4-28 shows baseline data collected with the probe located 3 feet from the end-wall, using a bandpass filter of 625 to 850 kHz. The end-wall reflection is clearly visible and arrives at roughly 550 µs. Recalling that that the wave spends 65 µs in the acrylic shoe and wedge during each pulse-echo, an arrival time of 550 µs from a reflection at a distance of 3 feet (0.914 meters) indicates a group velocity of 3,770 m/s. This matches what is expected from the group velocity dispersion curve, and confirms that the L(m,5) mode group is being excited.

19 Plot produced by the author.
Figure 4-28: A-scan showing baseline data at 750 kHz taken when the probe was located 3 feet from the end-wall.

As the size of the cut was increased, a reflection with an arrival time of approximately 400 µs began to appear, as shown in Figure 4-29. Figures 4-28 and 4-29 both show half-rectified A-scans that were taken when the probe was located 2 feet away from the defect and 3 feet away from the pipe wall. Assuming a group velocity of 3,770 m/s (as determined from the baseline data and the group velocity dispersion curve) the defect reflection is expected to arrive at 388 µs. Based on how closely this matches the observed arrival time (only a 3% difference between 388 µs and 400 µs) and the way that the reflection grows with the size of the cut, it is safe to assume that this reflection is indeed from the cut.
Figure 4-29: A-scan showing data taken when the cut measured L=0.66”. Notice defect reflection at ~400 µs and end-wall reflection at ~575 µs.

As the size of the cut was increased, the amplitude of the defect reflection also increased, as expected, this is shown in Figure 4-30. Notice that the defect and end-wall reflections have the same arrival times as in Figure 4-29, only their amplitudes have changed. This is as expected.
Figure 4-30: A-scan showing data taken when the cut measured L=0.80”. Notice the amplitude of the defect reflection at ~400 µs has increased significantly compared to when L=0.66”.

When the defect became very large and approached becoming a through-crack, the amplitude of the defect reflection continued to rise, as shown in Figure 4-31. Interestingly, the amplitude of the end-wall reflection also decreased dramatically. Presumably, this happened because the defect became so wide relative to the beam profile of the wave, that a significant portion of the wave’s energy was reflected by the defect before it could reach the end-wall. Practically, a consequence of this is that if there was a second smaller defect located behind the main cut, it could effectively be hidden in the cut’s “shadow.”
Figure 4-31: A-scan showing data taken when the cut measured L=0.92”. Notice the amplitude of the defect reflection at ~400 µs has increased significantly compared to when L=0.80” (the vertical axis scaling is even doubled in Figure 4.30 to prevent clipping) and the end-wall reflection amplitude is decreased.

Once all of the data were collected at distances of 1, 2, and 3 feet away from the defect for each cut size, the results were compiled and plotted to observe the trends.
Figure 4-32: Amplitude of defect reflection versus approximate area. Data collected with probe located 1 foot away from crack.
Figure 4-33: Amplitude of defect reflection versus approximate maximum depth. Data collected with probe located 1 foot away from crack.
Figure 4-34: Amplitude of defect reflection versus approximate area. Data collected with probe located 2 feet away from crack.
Figure 4-35: Amplitude of defect reflection versus approximate maximum depth. Data collected with probe located 2 feet away from crack.
Figure 4-36: Amplitude of defect reflection versus approximate area. Data collected with probe located 3 feet away from crack.
Compared to the data taken with the L(m,3) and L(m,4) groups at 500 kHz, the data taken with the L(m,5) group at 750 kHz appears to better track defect growth. At 500 kHz, when the area of the cut was between 0.04 and 0.14 in$^2$, the amplitude of the reflection did not show clear indication of defect growth. On the other hand, the data taken at 750 kHz shows a more monotonic relationship between the defect reflection amplitude and the size of the defect. Obviously, this monotonic relationship is very important for tracking defect growth.

The variability in the data makes it impossible to draw sound conclusions from comparing individual (or even small samples) of the data points. For this reason, the least-squares regression lines (which take the entire data set into account) are used to make comparisons. The best-fit line is described by two numbers, the slope and the intercept. The
slope is the response rate; it is a measure how rapidly the reflection increases in response to
defect size. The response rate could be useful for monitoring defect growth, since it shows how
much the signal is expected to increase for a given increase in defect size at a given distance. The
response rates for the L(m,5) mode at 750 kHz are shown below in Figure 4-38. Notice that for a
given increase in defect size, the amplitude of the reflection increases more when the probe is
located nearer to the defect. Intuitively, this makes sense because the defect reflections a larger
portion of the wave’s energy when it is closer to the source of the wave, and the transducer also
receives a larger portion of the reflection due to the reduced beam spreading over short distances.

Figure 4-38: Response rates for defect growth using the L(m,5) mode group at 750 kHz and 27
dB of gain. These rates describe how the amplitude of the defect’s reflection increases as the size
of the defect is increased. Data points are at 1 foot, 2 feet, and 3 feet on the horizontal axis. The
green line shows the relationship between the reflection amplitude response rate and the defect
area. The red line shows the relationship between the reflection amplitude response rate and the
maximum defect depth.

Just as the poor results of the L(m,3) and L(m,4) mode groups at 500 kHz raised an
interesting question about wave structure, so do the more successful results of the L(m,5) mode at
750 kHz. Clearly, the amplitude of the reflection of the L(m,5) mode at 750 kHz tracks crack
growth well, over the entire range of size from initial surface crack to through crack. In the data, there is only one exception to this – a small, but noticeable deviation from the trend occurred when the transducer was located two feet from the crack, this is illustrated in Figures 4-39 and 4-40.

Figure 4-39: A deviation from the trend line exists when the area is \(~0.06\) in.\(^2\)
Figure 4-40: A deviation from the trend line exists when the maximum depth is ~0.12 in.

Based on the results, particularly when data was taken with the transducer located 1 foot or 3 feet away from the defect, the wave structure of the L(m,5) mode group at 750 kHz spreads energy across the entire thickness of the pipe wall. Otherwise, the amplitude of the defect reflection would not continue to grow linearly as the depth of the crack increased from zero to the wall thickness. An example of the type of wave structure that would track defect growth across the entire wall thickness is shown in Figure 4-43.
An explanation for the deviations from the trend line seen in Figure 4-39 and 4-40 is difficult. Peculiarly, this deviation is greatest in the data that was taken when the transducer was located 2 feet away from the defect. The deviation from the trend line is largely due to one cluster of three data points that were taken one after the other after the crack had been enlarged for the 8th time (3 data points were taken after each stage of crack growth.) In theory, each of these 3 data points is independent because the angle beam wedge was taken apart and couple between each. Nevertheless, it’s possible that some source of error, such as slightly inadequate couple, affected all three of the data points and resulted in lower amplitudes. Alternatively, it is also possible that this slight deviation from the linear trend is the result of wave structure, or natural focusing due to higher order modes spiraling around the pipe. Instead of being relatively constant across the thickness, perhaps the displacement profile of the wave structure concentrates energy at the

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20 Wave structure generated using MATLAB GWiP program developed by Jason Philtron for the E MCH/ACS 521 Stress Waves in Solids course (taught by Joseph Rose) at Penn State.
surfaces and the center of the wave guide, with a decrease in energy in between. An example of this type of wave structure is shown in Figure 4-42.

Figure 4-42: Example wave structure showing uneven distribution of displacement across thickness. This type of wave structure, which corresponds to the S2 mode in a steel plate at \( f_d = 5.9 \text{ MHz/mm} \), could be responsible for the deviation from the trend line seen in Figure 4-40.\textsuperscript{21} However, the \( f_d \) value used in this wave structure is not representative of what was used in the experiment.

The wave structure in Figure 4-42 is a general example of what is possible, rather than a direct approximation of the actual wave structure of \( L(m,5) \) mode group at 750 kHz. In fact, the mode structure in Figure 4-42 corresponds to \( f_d = 5.9 \text{ MHz/mm} \), whereas 750 kHz in the test pipe corresponds to \( f_d = 4.76 \text{ MHz/mm} \). Using the guided wave in plate program (GWiP) program to generate wave structures, the author did not find any wave structures at \( f_d = 4.76 \text{ MHz/mm} \) which explained the deviation from the trend line shown in Figure 4-40. In the future it would be beneficial to calculate (either analytically or numerically) the wave structure of the

\textsuperscript{21} Wave structure generated using MATLAB GWiP program developed by Jason Philtron for the E MCH/ACS 521 Stress Waves in Solids course (taught by Joseph Rose) at Penn State.
L(m,5) mode group in a 4” diameter pipe; this would help determine what role wave structure may play in the deviation from the trend line.

4.6 Comparison of Results and Conclusions

There are several lessons to be learned from Experiment 1, both from what worked well and what did not. Attempts to use the L(m,2) mode group at 250 kHz for inspection were unsuccessful due to excessive noise. The L(m,3) and L(m,4) groups at 500 kHz did detect the defect, but do not appear to be sensitive to defect growth. The L(m,5) mode group at 750 kHz offers a high signal-to-noise ratio (SNR) and shows a consistent, monotonic relationship between the amplitude of the defect’s reflection and the defect’s size. Out of the mode groups tested, the L(m,5) mode group clearly shows the most promise for NDE and SHM application.

Variability existed in the data, most likely due to variation in coupling, angle of incidence, and circumferential position of the transducer. Although steps were taken to be as consistent as possible between tests, there are practical limits on the precision of the variable angle beam set up. For example, the Ultragel couplant on the pipe is very slippery, which makes it difficult to keep the angle beam wedge in the exact same position (both axially and circumferentially) during repeated test. Variation in the circumferential position of the wedge has the greatest effect when the wedge is near the defect, due to reduced beam spreading, and is less significant at longer ranges. The variable angle beam wedge also up requires that three interfaces (transducer-shoe, shoe-wedge, and wedge-pipe) be coupled, and slight differences in the coupling of any one of these interfaces could change the signal. It is the author’s suspicion that variation in coupling was responsible for much of the variability in the results.
Chapter 5

Experiment 2: SHM of External Crack Growth in Pipe with Angle Beam Probe

5.1 Purpose

Experiment 1 showed the promise of the L(m,5) mode group at 750 kHz for detecting a crack-like defect and tracking its growth. However, there was also significant variability that occurred in the results of experiment 1; presumably this was due in large part to the variable angle beam set up. In practice, inspections that make use of oblique incidence typically use fixed angle beam wedges. Compared to variable angle beam wedges, fixed angle wedges can offer more consistent results because fewer interfaces need to be coupled (two instead of three) and the possibility of unwanted variation in the angle of incidence is eliminated. Despite the advantages of fixed beam wedges, angle beam wedges are still used for experimental purposes because they offer great versatility. As shown in Experiment 1, a single angle beam wedge can be used to excite many different modes at different phase velocities. The angle of incidence can also be fine-tuned to provide the greatest signal excitation of a given mode; in some cases miniscule changes in angle can produce a significant change in the excitation (as observed by the author). However, after an angle of incidence has been selected during the initial investigation or exploratory phase using a variable angle wedge, a fixed-angle wedge becomes preferable for subsequent testing because it allows for a more controlled experiment.

In this thesis, experiment 1 served as the initial investigation or exploratory phase. From the dispersion curve, several mode groups were chosen and tested. Out of these, the L(m,5) group at 750 kHz showed the most promise for detecting and tracking crack-like defects. Although the trends in the data were as expected (the amplitude of the reflection increased as the size of the defect grew), there was also significant scatter in the data. To build on these results,
the next step is to conduct a second, more controlled experiment to verify the results of experiment 1. This can be accomplished by leaving the wedge and transducer in place throughout the data collection (rather than dismantling and recoupling) and by using a fixed-angle type wedge. In theory, these two changes should make for a better controlled experiment with less scatter in the results. These changes make Experiment 2 more closely resemble a real structural health monitoring (SHM) application where the transducers are left fixed on the structure.

5.2 Set Up

To keep the angle of incidence constant, the variable angle wedge may still be used, provided that the shoe is tightened against the wedge and left unperturbed throughout the experiment. Once the shoe is sufficiently tightened, it is fixed in place, and the variable angle wedge effectively becomes a fixed angle wedge. If all three interfaces are coupled at the beginning of the experiment, and the experiment is done in a relatively short period of time (a few hours or less) while the wedge is not disturbed in any way, then the coupling can be assumed to be constant or nearly constant throughout the experiment. Tape can be used to hold the transducer and wedge in a fixed position on the pipe throughout the experiment. Light pressure from the tape also helps maintain coupling. Of course, if the experiment is repeated the next day with a different wedge, there could be differences in coupling compared to the previous day, but this method at least ensures constant coupling throughout a single experiment.

For Experiment 2, a new cut was initiated and grown in the pipe in the same manner as was done in Experiment 1. Care was taken to place the defect in a location where it could be studied without interference from the cut from Experiment 1 or from the pre-existing ground-out defect. The probe was placed at a distance of 24.5” inches from the new cut. The pulser and receiver settings were largely unchanged from experiment 1, except the filter was changed from
625-850 kHz to 600-850 kHz. This change improved the excitation slightly (based on the amplitude of the reflection from the end-wall during baseline testing) but did not appear to increase the noise. The rest of the pulser and receiver settings are listed below.

- 4 cycle tone burst
- 27 dB of gain
- Pulse voltage: 300V
- Sampling rate: 10 MHz
- Pulse repetition frequency (PRF): 10 Hz
- Averages: 10

5.3 Results

Just like Experiment 1, Experiment 2 began with collecting baseline data before crack growth was started. The baseline data in Figure 5 shows a signal with relatively low noise and no unwanted reflections that would interfere with the experiment. Since the pipe had several pre-existing defects at this point, it was important to check that none of these defects would produce reflections that would interfere with Experiment 2.
Figure 5-1: Baseline data shows the main bang lasting until 150 µs and the end-wall reflection at ~580 µs. The noise floor is relatively low.

After baseline data was collected, simulated crack growth using the Dremel tool began. The size of the crack was increased gradually in twenty increments. A representative sample of several of the A-scans is provided here to illustrate the general trend.
Figure 5-2: Data taken after cut 3 (L = 0.435") show a small spike at 460 µs. Based on the group velocity of the L(m,5) mode group, this is approximately the time-of-arrival expected for the crack reflection. However, the amplitude of this spike is less than 2x the noise floor, so this would not be flagged as a defect by most inspectors.

The first possible indication of a crack was seen in the signal when the length of the crack reached 0.435", which corresponds to an area of just 0.0124 in.\(^2\) and a depth of 0.043". At this point, a small spike began to protrude from the noise floor at the expected time of arrival (based on the group velocity.) However, this spike is less than 2x the noise floor in amplitude. In this experiment, we have the advantage of knowing where the crack is, and knowing that we expect a reflection at approximately 460 µs. In practice, an inspector would not have this knowledge, and a spike this small would most likely not be flagged as a potential defect.
Figure 5-3: Data taken after cut 5 ($L = 0.512''$) show growth in the spike at 460 µs compared to cut 3. This strongly suggests that the spike is indeed a reflection from the crack.

Data taken after cut number 5, when the area and depth of the crack had increased to 0.021 in.$^2$ and 0.06'', respectively, shows a small amount of growth in the spike at 460 µs. The spike is still very small (as would be expected for such a small crack), and therefore might go unnoticed in a normal NDE procedure. However, in this SHM scheme, we have the advantage of being able to compare to baseline data and data taken after previous cuts. The pattern of growth in this spike makes it reasonable to conclude that it is a reflection from a growing defect. This illustrates the power of the SHM strategy compared to conventional NDE.
Figure 5-4: Data taken after cut 9 (L = 0.653”) show continued growth in the spike at 460 µs. The amplitude of the reflection is now roughly 3x the magnitude of the noise floor; this would likely be flagged as a potential defect.

After cut number 9, when the area and depth of the crack had increased to 0.043 in.\(^2\) and 0.1”, respectively, the amplitude of the spike at 460 µs is significant – approximately 3x the noise floor. This would likely be flagged as a possible defect reflection by conventional NDE. Notice that the defect was “detected” by SHM as soon as cut number 5, but not detected by NDE until cut number 9.
Figure 5.5: Data taken after cut 10 (L = 0.705") show a second spike appearing at approximately 430 µs. This could be a reflection from a second mode in the L(m,5) group travelling at a slightly faster velocity. Notice the same double spike pattern is seen in the end wall reflection.

As the crack grew larger, a second reflection began to appear at approximately 430 µs. This could be a second mode in the L(m,5) group travelling at a slightly faster speed. Why this second reflection is only seen when the crack is large is not clear. It’s possible that the wave structure of the second mode causes little or no particle displacement near the surface, and therefore is only sensitive to defects beyond a certain depth. Data taken after cut number 13 shows a continuation of the double spike reflection, demonstrating that it is not a fluke.
Figure 5-6: Data taken after cut 13 (L = 0.8") show a large double spike reflection from the crack. Compared to cut 10, the crack reflection amplitude has approximately doubled.
Figure 5-7: Data taken after cut 17 ($L = 0.89"$) show a large reflection from the crack which closely resembles the shape of the end wall reflection.

Data taken after cut number 17, when the area and depth were $0.1165\text{ in.}^2$ and $0.19"$, respectively, show a resemblance between the reflections from the defect and end wall. Both exhibit the double spike. At this point, the cut was quite large relative to the size of the cutting blade, and kickback was becoming an issue. Therefore, the area and depth values are rough estimates. In reality, the defect is slightly wider and less deep than in the model described in Chapter 4.4.
Once the crack had been grown so large that it became a through-crack, data collection for Experiment 2 was finished. Further increase if the crack size would deviate drastically from the model used in Chapter 4.4 (since the shape of the crack would change) and a new method would be needed to calculate the area.

Figure 5-8: Amplitude of defect reflection versus cross sectional area of defect.

A plot of the crack reflection amplitude vs. the approximate area of the crack is shown in Figure 5-8. Compared to the data from Experiment 1, there is much less scatter and the data fits more closely with a linear fit. Figure 5-9 shows the same trend when the data is plotted against crack depth. One feature that is noticeable in both plots is the slight dip beneath the trend line seen when the crack area is between $\sim 0.05$ in.$^2$ and $\sim 0.1$ in.$^2$ and the crack depth is in the range of
~0.075 in. to ~0.16 in. This is similar to the deviation from the trend that occurs in the data taken with the L(m,5) mode at 750 kHz from a distance of 2 feet in Experiment 1. Note that in this case, the distance is also roughly 2 feet (24.5” to be exact.)

Figure 5-9: Amplitude of defect reflection versus maximum depth of defect.

The fact that a nearly identical deviation from trend line occurred under the same conditions occurred in both Experiment 1 and Experiment 2 suggests that it is not a fluke or statistical anomaly. However, the deviation from trend is quite small, and could be explained by sources of error such as the inaccuracy of the cutting method. For example, if the cut is actually slightly less deep than assumed by the calculation (which could occur due to kick-back from the Dremel tool human error), then that would shift the data points slightly to the left in Figure 5-9, which would put them in agreement with the trend line.
Another important observation from Experiment 2 is the reduction in scatter of the data points, which can be seen qualitatively in Figures 5-8 and 5-9. This was expected, and can be attributed to four changes that made for a more well-controlled experiment:

- Constant coupling throughout experiment
- Constant angle of incidence
- Constant circumferential position
- Unperturbed electrical connection between transducer and pulser

In order to accurately compare the variability of different sets of data, it is necessary to have a quantitative way to describe scatter. One simple way of doing this is by using the standard error of the estimate, which quantifies variability indirectly by measuring the accuracy of the regression line [47]. Clearly, a data set with no statistical variability could have a completely accurate regression line (assuming the correct regression shape e.g. linear, quadratic, cubic, etc. is chosen to fit to the data) and would therefore have zero standard error. As there is more scatter in the data, there are more data points that fall farther below or above the regression line, and the standard error increases. The formula for calculating standard error is given in Equation 5-1, where $\sigma_{est}$ is the standard error, $Y$ is the value of the dependent variable in the data, $Y'$ is the value predicted by the regression, and $N$ is the total number of data points in the set [47].

$$\sigma_{est} = \sqrt{\frac{\sum(Y - Y')^2}{N}}$$

Equation 5-1:

When applied to the data in Figures 5-9 and 5-10, $Y$ is the amplitude of the defect reflection, $Y'$ is the amplitude predicted by the regression line (the equation of the regression lines are provided in the figures for this purpose), and $N$ is simply the number of data points. Note that Equation 5-1 produces an output with the same units as the dependent variable $Y$, hence
in this case the units for the standard error are Volts. The standard errors for Figure 5-9 and 5-10 are 0.0012 Volts and 0.002 Volts, respectively.

5.4 Conclusions

The results of Experiment 2 verify the results of Experiment 1; that the L(m,5) mode group at 750 kHz is indeed effective for tracking crack growth. Further, Experiment 2 shows that the variability or scatter in the results of Experiment 1 was due to the experimental set-up (variable angle beam wedge) and procedure (disassembling and recoupling probe between each data collection) rather than any inherent variability in the L(m,5) mode group. Experiment 2 also reproduced the slight dip away from the trend line that was seen when the crack was mid-sized and the transducer was located two feet away.
Chapter 6

Experiment 3: SHM of External Crack Growth with Magnetostrictive Excited Torsional Modes

Experiments 1 and 2 showed that it is possible to track crack growth with certain longitudinal modes. In fact, the $L(m,5)$ mode group at 750 kHz was very successful. However, one inherent issue with using longitudinal modes is the difficulty in isolating specific mode groups. To work around this requires careful consideration of the dispersion curve and source influence. Another issue arises from the Plexiglas angle wedge and the piezoelectric transducer itself – both can cause ringing and noise in the signal.

An alternative approach that alleviates some of these issues is to use magnetostrictive transducers to excite torsional modes rather than longitudinal modes. In a sense, the flexible printed circuit board (FPCB) comb transducers used for magnetostrictive excitation are less versatile than the angle beam wedge because a given comb transducer can only excite a specific wavelength (the wavelength is directly determined by the comb spacing.) On the other hand, a custom FPCB can be produced with the correct spacing to generate whichever wavelength is desired. Additionally, FPCBs can also be made with various curvatures for natural focusing, and the edges of the comb can be designed to minimize unwanted excitation in the lateral direction.

Before going further, the nomenclature of transverse or shear waves in pipes should be reviewed. Similarly to the $L(m,n)$ designation used for longitudinal modes, each torsional mode is specified in the format $T(m,n)$ where $m$ is the mode order and $n$ is the group number. Axisymmetric modes, which are excited by axisymmetric loading (an even loading around the entire circumference), are designated $T(0,n)$. Hence, the first mode in each group is axisymmetric. Each axisymmetric mode is also accompanied by a “group” or “family” of non-axisymmetric modes which exist at slightly higher phase velocities. These are the $T(m,n)$ modes.
where \( m = 1, 2, 3, \text{ etc.} \). The axisymmetric and non-axisymmetric modes differ significantly in their particle displacement and propagation direction. The particle displacements of axisymmetric modes cause angular twist, or torsion, of the pipe about the neutral axis and are therefore sometimes referred to simply as “torsional modes”. The particle displacements of non-axisymmetric modes cause bending motion of the pipe, which is why these waves are commonly referred to as “flexural modes.” Whereas axisymmetric modes result in an even distribution of energy around the pipe, flexural modes concentrate energy in specific lobes, angular profile of which depends on the mode number, frequency, and axial position. When an entire mode group is excited, the overall angular profile can be determined by taking a weighted sum of the angular profiles of each individual mode [30]. When the loading area is only a small part of the circumference (as in this case), the amplitude of the higher order flexural modes is increased [30]. The fact that the angular position of the lobes depends on axial position is evidence that the flexural modes may in fact travel around the pipe in a spiral motion. For more detail information on guided wave propagation in pipe, see Chapter 10 of Rose [30].
In practical pipe inspection using shear waves, two approaches are commonly used. Both approaches involve using a collar transducer, which wraps around the entire circumference of the pipe. By pulsing the entire collar simultaneously, axisymmetric modes can be excited. Typically, the goal is to excite the T(0,1) axisymmetric mode because it is nondispersive i.e. the group velocity is independent of the wavelength and the thickness. The second approach involves pulsing individual segments at specific time delays to create interference patterns and focusing.

A practical advantage of shear horizontal and torsional waves over longitudinal waves, which should be briefly mentioned for completeness, involves energy leakage. Longitudinal wave modes may “leak” energy from the wave guide to a surrounding liquid if there is out-of-plane displacement at the surface. For pipe inspection, this can pose a problem if the pipe is filled with liquid or submerged in liquid. Since shear horizontal and torsional modes have little or no out-of-plane displacement, and since non-viscous fluids cannot support shear stress, there is little to no energy leakage from the wave guide to fluid surroundings.

Plot produced by Li Zhang (FBS Inc.) and used with permission.
6.1 Set-Up

For Experiment 3, a third simulated crack was grown in the pipe. In order to use the FPCB comb transducers, a strip of iron cobalt (FeCo) was bonded to the pipe. The FeCo used is the commercially available Hiperco® 50A, which is an iron-cobalt-vanadium alloy that is designed and processed specifically to achieve the desired magnetic properties [48]. Because this specialty FeCo alloy is very expensive, it is common (at least at FBS) to reuse a single strip for multiple pipe tests, provided the FeCo can be removed from the first pipe without sustaining damage. The markings from dried up epoxy and/or paint on the inside of the FeCo rolls in Figure 6-2 indicate that they have already been applied to and removed from at least one pipe.

![FeCo rolls ready to be reused]

Figure 6-2: Rolls of Hiperco® 50A alloy ready to be reused.

To bond the FeCo to the pipe, a standard procedure developed by FBS, Inc. was followed. Although there are multiple ways to successfully bond FeCo using various adhesives, this procedure has been used successfully by FBS tens (if not hundreds) of times. The procedure is as follows:
• Roughen bond surface of FeCo with sandpaper (increases surface area and grip which promotes adhesion)
• Remove any rust from the surface of the pipe with orbital sander
• Clean FeCo bond surface and pipe bond surface with acetone to remove any dust, grease, or oil
• Apply Loctite® E-30Cl Hysol® epoxy to FeCo bond surface liberally, use cotton-swab stick or similar tool to spread.
• Attach FeCo strip to pipe with electrical tape. Wrap the electrical tape around multiple times to hold the FeCo tightly and squeeze out excess epoxy.
• Let the epoxy to cure overnight before removing the electrical tape

Once the FeCo was bonded, the next step was to choose which frequency and comb spacing to use. The other equipment (pulser/receiver and laptop with Guided Wave Workstation software) was the same as in experiments 1 and 2, although some settings were changed to match the FPCB transducer.

6.2 Frequency Selection

Frequency selection was guided by the dispersion curve (Figure 6.1), the comb spacing (wavelength) of the available FPCBs, and by Equation 3.4, which is shown again below.

Equation 3.4 \[ c_p = f \cdot \lambda \]

For this experiment, only a small transducer was used (rather than a collar), which provided a partial loading over a small portion of the circumference. With only a partial loading, it is not possible to excite axisymmetric modes such as the dispersionless T(0,1). However, other
modes in the T(m,1) group can potentially be excited, and these modes are also nondispersive except at very low frequencies. Like the T(0,1) mode, the higher order modes T(m,1) (shown in Figure 6-3) also propagate at the bulk transverse wave speed, which is ~3,230 m/s in steel. Since these modes are dispersionless, the phase velocity is equal to the group velocity. By measuring the comb spacing of the FPCB transducer with calipers, the wavelength it will produce can be determined. From this, the appropriate frequency to reach a phase velocity of 3,230 m/s is determined by Equation 3.4.

Figure 6-3: Dispersion curve with the target flexural T(m,1) modes highlighted in light blue.  

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Plot produced by Li Zhang (FBS Inc.) and used with permission.
Four different FPCBs were chosen for preliminary testing. The wavelength and necessary frequency to achieve \( c_p = 3,230 \) m/s are summarized in Table 6-1.

<table>
<thead>
<tr>
<th>FPCB number</th>
<th>Wavelength (m)</th>
<th>Required frequency for 3,230 m/s (kHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.0127</td>
<td>254</td>
</tr>
<tr>
<td>2</td>
<td>0.00753</td>
<td>429</td>
</tr>
<tr>
<td>3</td>
<td>0.00534</td>
<td>605</td>
</tr>
<tr>
<td>4</td>
<td>0.00376</td>
<td>859</td>
</tr>
</tbody>
</table>

In theory, any of the FPCBs in Table 6-1 can excite the non-axisymmetric modes in the \( T(m,1) \) group if pulsed at the required frequency. By choosing a high frequency, such as in FPCB 3 or 4, it may be possible to increase sensitivity to small defects, but this would also likely result in greater attenuation and shorter range. Exactly how well each frequency will perform is dependent on the wave guide and the material, and needs to be determined by testing.

Fortunately, it is easy to test multiple FPCBs because they can be stacked on top of the FeCo strip as shown in Figure 6-4.

Figure 6-4: The four FPCB options are stacked on the FeCo strip for preliminary testing.
Before a new defect was made with the Dremel tool, each of the four FPCBs was tested in the baseline state. The frequency, bandpass filter, and gain were adjusted to optimize the performance of each FPCB to achieve the greatest signal-to-noise ratio (SNR) based on the end wall reflection. Based on this initial testing, FPCBs number 1 and 2 performed the best. Interestingly, FPCB 2 gave the greatest signal at $f = 420$ kHz rather than at the predicted value of $f = 429$ kHz. FPCBs number 3 and 4 were not chosen for further testing because their SNRs were significantly lower than those of FPCBs 1 and 2. Based on the preliminary baseline testing, the pulser/receiver settings shown in Table 6-2 were chosen.

Table 6-2: Pulser and receiver settings

<table>
<thead>
<tr>
<th></th>
<th>FPCB 1</th>
<th>FPCB 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gain (dB)</td>
<td>16</td>
<td>24</td>
</tr>
<tr>
<td>Pulse Voltage (V)</td>
<td>120</td>
<td>120</td>
</tr>
<tr>
<td>Cycles</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Frequency (kHz)</td>
<td>254</td>
<td>420</td>
</tr>
<tr>
<td>PRF (Hz)</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Sampling Rate (MHz)</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Bandpass Range (kHz)</td>
<td>200-350</td>
<td>350-490</td>
</tr>
</tbody>
</table>

The baseline data from FPCB 1 at 254 kHz in Figure 6-5 shows a short main bang, an extremely strong and clean reflection from the end-wall, and a low noise floor. The small reflection at ~290 µs is believed to be from the pre-existing ground-out defect that was offset 90 degrees from the transducer. Interestingly, the baseline data taken with FPCB 2 at 420 kHz does not show this same reflection. Presumably, this is because the signal is noisier at 420 kHz and...
possibly because there is less beam spreading, or a different wave structure that is less sensitive to shallow defects.

Figure 6-5: Baseline data taken with FPCB 1 at 254 kHz.

The baseline data taken with FPCB 2 at 420 kHz, shown in Figure 6-5, is significantly noisier than the data taken with FPCB 1, but the SNR is still high compared to any of the data taken with angle beam transducer in Experiment 1 or Experiment 2.

Figure 6-6: Baseline data taken with FPCB 2 at 420 kHz.
6.3 Procedure

After baseline data was taken, a new simulated-crack was made with the Dremel tool. The crack was located 18” away from the transducer with no offset circumferentially. The pre-existing ground-out defect was also located at this distance, but was off-set 90 degrees circumferentially from the transducer and from the new defect site. Having the pre-existing defect located in close proximity to the test defect was not ideal, but the pipe was crowded with three defects at this point, so there was no way to completely work around them without switching to a new pipe. Because the magnetostrictive system used lack directional control, it sends and receives waves in both directions along the axis of the pipe, so reflections from prior defects the reverse direction can also interfere with an experiment. Since the epoxy used to bond the FeCo takes hours to fully cure, and the FeCo is expensive difficult to remove once it has been bonded, it is important to take care to place the FeCo in an appropriate the location the first time.

Figure 6-7: Schematic of test pipe showing location of transducer, defects, and relevant dimensions.

The new simulated crack was “grown” in ten increments, with data collected after each. This was the same procedure followed in Experiments 1 and 2. Since the only mechanical
coupling is the bond between the FeCo and the pipe, the coupling is constant throughout the experiment. The FPCBs were held in place on the FeCo with tape throughout the experiment.

6.4 Results

6.4.1 FPCB 1 at 254 kHz

The first signs of crack growth (compared to the baseline data) were seen with FPCB 1 after the third cut, when the crack area and depth were 0.0227 in.$^2$ and 0.064 in., respectively. This is shown by the slight increase in the amplitude of the reflection at ~280 $\mu$s.

![Increase compared to baseline: possible defect](image)

Figure 6-8: A-scan of data taken with FPCB 1 at 254 kHz after cut 3.

By cut number 5, when the crack area and depth were 0.0502 in.$^2$ and 0.109 in., respectively, the amplitude of the reflection at ~280 $\mu$s had increased substantially and was clearly a marker of crack growth. This is shown in Figure 6-9.
After each of the remaining cuts, the amplitude of the reflection at ~280 µs continued to grow. There was also some decrease in the amplitude of the end-wall reflection, presumably due to energy blockage from the defect. The data in Figure 6-10, which were taken after cut number 10 when the area and depth of the cut were 0.16 in.² and 0.24 in., respectively, show these changes. Note that the depth of the crack after cut number 10 was only 0.01 in. away from being a through-crack (the wall thickness of 4” schedule 40 pipe is 0.25”).

Figure 6-9: A-scan of data taken with FPCB 1 at 254 kHz after cut 5.
After cut number 10, data collection was completed since the crack could not be grown any further without losing the shape used in the area calculation; further cuts would create a through crack of increasing width. The amplitude data from baseline through cut 10 is plotted vs. crack area and maximum depth in Figures 6-11 and 6-12 respectively.
Figure 6-11: Defect amplitude vs. approximate crack area using FPCB 1 at 254 kHz.
The plots in Figures 6-11 and 12 both show that the defect reflection amplitude increases monotonically and linearly with both the area and depth of the crack. The standard error Figures 6-11 and 6-12 are both 0.0037 Volts. This should not be compared directly to the standard error from Experiment 2, because the amplification (gain) is different in these two experiments. Unlike some of the results with longitudinal modes in Experiment 1, the T(m,1) mode group at 254 kHz appears to be sensitive to crack growth over its full range, from tiny surface crack to through crack. In practice, the simplicity of being able to detect and monitor a wide range of crack sizes with a single nondispersive mode and frequency is valuable.

More generally, several comparisons can be drawn between the characteristics of the signals generated by the magnetostrictive system and the angle-beam wedge system. Since these
two systems rely on a completely different method of transduction, and are generating fundamentally different wave modes (shear and longitudinal), this is not an “apples-to-apples” comparison. Nonetheless, both of these systems can be used to accomplish the same goal, such as tracking crack growth, so it is natural to draw comparisons.

Figure 6-13: Baseline data collected using angle-beam excitation to generate L(m,5) at 750 kHz.

Figure 6-14: Baseline data collected using FPCB to generate T(m,1) at 254 kHz.
By comparing Figures 6-13 and 14, it is easy to see that the magnetostrictive system offers a shorter main bang and an improved SNR, at least in this case. The practical benefit of a shorter main bang is a reduced dead zone; this allows for inspection from close range. A high SNR helps with identifying small defects, since weak reflections are more likely to stand out from the noise floor if the SNR is high. These experimental observations, namely that magnetostrictive systems offer a high SNR and short main bang, generally match the impressions of Engineers at FBS, Inc. who have experience with both systems.

6.4.2 FPCB 2 at 420 kHz

![A-scan data](image)

Figure 6-15: A-scan of data taken with FPCB 2 at 420 kHz after cut number 2.

The first sign of the crack was seen after the second cut, when the area and maximum depth of the crack were approximately 0.015 in.² and 0.05 in., respectively. This is shown in
Figure 6-15. Notice that even though there is only a single defect, there are three different peaks in the reflection.

Figure 6-16: A-scan of data taken with FPCB 2 at 420 kHz after cut number 4.

The reflections seen after subsequent cuts, shown in Figures 6-16 and 17, are similar to what was seen after cut 2. The amplitude of the reflection from the defect is clearly growing, and it continues to have three distinct peaks.
Figure 6-17: A-scan of data taken with FPCB 2 at 420 kHz after cut number 8.

Why the defect reflection contains three peaks is an interesting question; the defect is only a single crack, and is only expected to produce one peak. At first glance, one might assume that the three peaks are the result of three different modes, each travelling at slightly different velocities. However, at 420 kHz the T(m,1) group is non-dispersive and each mode in the group travels at the same velocity, so this theory does not hold water. A second theory is that the multiple peaks are the result of simultaneous excitation of the T(m,1) and T(m,2) groups. At 420 kHz, these two modes are very close together, as shown in Figure 6-18. This could explain why this phenomenon was not observed at 254 kHz, since that is below the cut-off frequency of all torsional modes except the T(m,1) group.
Figure 6-18: Phase velocity dispersion curve showing excitation region highlighted in blue.

Figure 6-19: Defect amplitude vs. approximate crack area using FPCB 2 at 420 kHz.
The overall results for FPCB 2 at 420 kHz are shown in Figures 6-19 and 20. Defect growth is tracked excellently at both 254 kHz and 420 kHz, as indicated by the monotonic, linear relationship between defect reflection amplitude and crack area or maximum depth. The explanation for why the T(m,1) mode works also has to do with wave structure. Although there are some differences due to the curvature of the pipe, non-axisymmetric (or flexural) modes in pipe are essentially shear horizontal (SH) modes, as found in plate. The wave structure of SH modes in plate has a close-formed solution; the solution for symmetric modes (n = 0, 2, 4, ...) is given in chapter 14 of Rose [30]:

Figure 6-20: Defect amplitude vs. approximate crack depth using FPCB 2 at 420 kHz.
Equation 6.1

\[ u_3^x(x_1, x_2, t) = B \cos \left( \frac{n \pi x_2}{d} \right) \cos(k x_1 - \omega t) \]

Where the argument of the first cosine term includes the position across the thickness of the plate, \( x_2 \). For the SH\(_0\) mode, \( n = 0 \), and so \( x_2 \) has no influence on the wave structure. The T(m,1) group is similar to SH\(_0\), and the same effect occurs. For equation 6.1, the coordinate system shown in Figure 6-21 is used.

6.5 Conclusions

Experiment 3 demonstrated the T(m,1) group is effective at tracking crack growth when excited by a partial loading at 254 or 420 kHz. At both frequencies, the defect reflection increased linearly and monotonically across the full range of crack size, from tiny surface crack to through crack. At 420 kHz, multiple reflections were seen from both the defect and the end-wall,
possibly due to simultaneous excitation of the T(m,1) and T(m,2) groups. This, along with the fact that the signal was slightly less noisy at 254 kHz, makes 254 kHz the preferable frequency out of the options tested. More generally, Experiment 3 also demonstrated that the torsional waves excited by FPCB magnetostrictive transducers have relatively short dead zones and high SNR compared to piezoelectric excitation.
Chapter 7

Summary and Conclusions

The experiments carried out as part of this thesis served as evidence of both the importance of guided wave theory and of practical considerations. It was demonstrated that the ability to track defect growth with guided waves depends on both mode and frequency selection due to the differences in wave structure. For example, Experiment 1 showed that just because a longitudinal mode can be excited, does not mean it will have the appropriate wave structure to track defect growth all the way across the thickness of the wave guide. Experiment 1 also showed the variability that occurs, primarily due to differences in coupling, when using a variable angle beam transducer. Unless large samples of data are collected, this variability makes it difficult to compare results with confidence.

Experiment 2 verified the results of experiment 1 by showing that the $L(m,5)$ at 750 kHz was excellent for tracking crack growth in this case. Also, Experiment 2 confirmed the hypothesis that differences in coupling and perturbation of the angle beam wedge were the primary sources of variability in Experiment 1.

Experiment 3 served as a direct comparison between using oblique incidence to excite longitudinal modes and using magnetostrictive comb transducer to generate torsional modes to track the same defect. While both approaches can be used to effectively track crack growth, the results showed that the magnetostrictive system offered a shorter main bang and a higher signal-to-noise ratio. Experiment 3 also demonstrated that when the same mode is excited at different frequencies, the results can be very different.
7.1 Contributions

The experiments in this thesis clearly demonstrate the value of both mode and frequency selection for effective guided wave inspection. Hopefully, this will help dispel the misconception that any mode and frequency will work well, as long as it can be excited. When attempting to track a defect which grows from the surface through the entire thickness, mode and frequency selection is especially crucial since the wave structure must contain energy throughout the thickness. This thesis illustrates this concept well by providing results from mode and frequency combinations that were effective for tracking defect growth, as well as other mode and frequency combinations that were ineffective.

This thesis also contains an overview of many topics that are relevant to ultrasonic NDE such as maintenance philosophies, defect growth, transducer technology (magnetostrictive and composite piezoelectric), source influence, sources of noise, dispersion principles, and variability in test results. Many of these topics were addressed because they were issues that needed to be taken into account to design, understand, and explain the experiments and results of this thesis; thus these topics are described in a practical context. Hopefully, these discussions will help future students of ultrasonic guided waves to both understand the theoretical background and to design practical, effective experiments.

7.2 Directions for Future Work

This thesis used three experiments to demonstrate the hypothesis that certain guided wave mode and frequency combinations are effective for tracking defect growth, while others are not. The primary reason for this is that each mode and frequency combination has a unique wave
structure. Hence, a thorough explanation of why a mode and frequency is sensitive or insensitive to defect growth requires an understanding of the wave structure. In this thesis, wave structure was explained qualitatively, and approximations from a plate solution were used to speculate about the wave structures in a hollow cylinder. In the future, the discussion of wave structure could be strengthened by solving (analytically, numerically, or by a hybrid approach) for the wave structures in a hollow cylinder. These solutions would provide theoretical backing to reinforce the conclusions drawn in this thesis, and would also help guide mode and frequency selection in future experiments.

Another way to build on this thesis would be to run similar tests but with different methods of simulated crack growth. In this thesis, a hand-held Dremel tool was used to grow “cracks” because it was quick and easy, reasonably well controlled, and produced the elliptical shape often used in fracture mechanics and crack propagation studies. Instead of using a Dremel tool, two possible alternatives are two grow simulated cracks using a table mounted saw, or to grow real fatigue cracks via cyclic loading from a three point bend machine or similar apparatus. Using a table mounted saw would remove most of the human error from the cutting process and would result in a more well-controlled experiment. Growing a real fatigue crack would provide a more realistic representation of a service defect, but could also cause other challenges; controlling the rate of crack growth and accurately calculating the area and depth of the crack would not be trivial. A sound understanding of fatigue crack growth, and access to specialized equipment, would be required for this method.

In this thesis, the experimental focus was on pipe inspection, but the same principles could be readily adapted to study other structures such as plates and beams. In fact, since partial circumferential loadings were used, the axisymmetric torsional T(0,m) modes that are often used in pipe inspection were not excited. This thesis could be built upon by testing for defect growth
in structures other than pipes, or if the focus is to be kept on pipes, transducer collars which load the entire circumference could be used to excite the axisymmetric torsional modes.
Appendix A: Investigation of Noise in Composite Piezoelectric Transducer at 250 kHz

During Experiment 1 of this thesis, the broadband composite piezoelectric transducer with a center frequency of 500 kHz was used at 250 kHz in attempt to excite the L(m,2) mode group (see Chapter 4.5.1.) This resulted in extremely noisy signal. By determining the source of the noise, there is a possibility that it can be removed from the system thus improving the quality of the data. However, pinpointing the exact source of noise is not an easy task. After all, the apparatus being used to excite and receive guided waves is a complicated system consisting of the laptop, the pulser, multiple cables and pin connections, the piezoelectric transducer, the angle beam shoe and wedge, the test pipe, and the receiver. Although we may not be able to easily determine exactly where the noise is coming from, there are ways to make educated guesses. One quick and easy way to get an idea of which part of the system is introducing noise is to look at the signal while the system is in various stages of disconnect.

Figure A-1: A-scan taken while the pulser/receiver box was disconnected from the transducer. The cable which normally connects the “pulse out” terminal of the box to the transducer was disconnected from the box.

Figure A-1 shows the signal when the cable that connects the transducer to the pulser/receiver box is unplugged from the box. There is still a short main bang period from the
pulse within the first 50 µs, but after that the signal goes quiet, as expected. There is some noise in the signal, but it is very slight. This noise must be originating somewhere in the pulser/receiver box, in the laptop, or in the connection in between the two.

Figure A-2: A-scan taken while the pulser/receiver box was connected to the BNC cable, but the BNC cable was unplugged from the transducer.

Figure A-2 shows the A-scan when the pulser receiver/box was connected to the cable, but the cable was disconnected from the piezo transducer. Compared to Figure A-1, the system has been expanded to include the cable, but the signal looks almost identical. It appears that the cable which connects the box and the transducer is responsible for very little (if any) noise.
Figure A-3: A-scan taken while the pulser/receiver box was connected to the piezo transducer via the BNC cable, but the piezo transducer was not connected to the acrylic glass shoe/wedge.

Compared to Figure A-2, there is clearly a drastic increase in noise. The simplest (and in the author’s opinion, most likely) explanation for this is that the noise is being generated inside the piezo element, possibly due to poor damping at this frequency (250 kHz is well below the recommended frequency of 500 kHz, but then again this is a broadband transducer.) However, this figure does not necessarily prove that the noise is being generated inside the transducer; rather it demonstrates that the noise is introduced when the transducer is connected to the pulser/receiver box and the laptop. It’s possible that the interaction between the transducer and the pulser/receiver is causing noise to be produced in some other part of the system.
Appendix B

MATLAB code

B.1 Computing Crack Area and Depth

Calculating Percent CSA of Circular Saw Cuts in Pipe

% Geometric Basis of Calculations
% Calculations are based on subtracting the area of right
triangles from the
% area of the "slice" of the circle to find the areas of the
curved circular
% segments which make up the cut.

Dimensions of the schedule 40 4" project pipe

L=[0,.407,.5,.54,.58,.62,.66,.7,.75,.8,.85,.92,1];
r=0.75;
Ro=2.25;
Ri=2.0;

w=size(L,2);
% L is the measured length of the cut (chord length), r is the
radius of the
% saw blade, and Ro and Ri are the outer and inner radii of the
pipe,
% respectively. All in inches.
theta=zeros(w(1),1);
alpha=zeros(w(1),1);
a=zeros(w(1),1);
b=zeros(w(1),1);
a_cut=zeros(w(1),1);
MaxDepth=zeros(w(1),1);

Calculation of the central angles of the pipe and blade

for i=1:w
theta(i)=2*asin(L(i)/(2*Ro)); % central angle in pipe, in radians
alpha(i)=2*asin(L(i)/(2*r)); % central angle in blade

% Theta and alpha are the central angles in the pipe and cutting blade,
% respectively, with respect to the cut. Both in radians.

% We can derive the areas of the two halves of the cut using trigonometry, and then use the half-angle identity to simplify

a(i)=(Ro*Ro/2)*(theta(i)-sin(theta(i)));
b(i)=(r*r/2)*(alpha(i)-sin(alpha(i)));
% a is the circular segment nearest the blade and b is the circular segment
% nearest the pipe

a_cut(i)=a(i)+b(i);
% The total area of the cut is the sum of the two halves

MaxDepth(i)=Ro*(1-cos(theta(i)/2))+r*(1-cos(alpha(i)/2));
% max depth of the cut is the sum of both sagittas

end
figure
subplot(1,2,1);
plot(L,a_cut,'s');
xlabel('Cut Length L, in.');
ylabel('Area of Cut, square in.');

subplot(1,2,2);
plot(L,MaxDepth,'o');
xlabel('Cut Length L, in.');
ylabel('Max. Depth, in.');
B.2 Relating Incidence Angle and Phase Velocity for Angle Beam Excitation

Define variables

```matlab
v1=2670; % longitudinal wave speed in plexiglass, m/s
v2=linspace(1500,16000,100); % range of possible phase velocities in steel, m/s
theta2=90; % Angle of refracted guided wave is 90 degrees
theta1=zeros(1,100); % Preallocate space for angle of incidence, theta 1
```

Calculation of required angle of incidence (theta1) for each phase velocity V2

```matlab
for i=1:100
    theta1(i)=asind(v1/v2(i)); % Snell's Law for refraction
end
```

Plot

```matlab
plot(theta1,v2);
xlabel('angle of incidence (measured from vertical), degrees');
ylabel('phase velocity of refracted wave, m/s');
title('Phase Velocity vs. Input Angle')
```

Warning: Imaginary parts of complex X and/or Y arguments ignored
Appendix C: Supplementary A-Scans

Many half-rectified A-scans were taken for the experiments of this thesis. Although the amplitudes from all of these A-scans are shown in the main chapters of the thesis in the plots of amplitude vs. defect area and amplitude vs. defect depth, only sample A-scans were included due to space constraints. For completeness, the entire sequence of A-scans for two of the best results – L(m,5) at 750 kHz from experiment 2, and T(m,1) at 254 kHz from experiment 3 - are included in this appendix.

Appendix C.1: Experiment 2 Cut Dimensions

Table A.C.1: Cut dimensions of Experiment 2.

<table>
<thead>
<tr>
<th>Cut number</th>
<th>Cut length L, in.</th>
<th>Cut area, in.²</th>
<th>Max. cut depth, in.</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 (baseline)</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>0.395</td>
<td>0.0093</td>
<td>0.0352</td>
</tr>
<tr>
<td>2</td>
<td>0.435</td>
<td>0.0124</td>
<td>0.0428</td>
</tr>
<tr>
<td>3</td>
<td>0.495</td>
<td>0.0185</td>
<td>0.0557</td>
</tr>
<tr>
<td>4</td>
<td>0.512</td>
<td>0.0205</td>
<td>0.0597</td>
</tr>
<tr>
<td>5</td>
<td>0.558</td>
<td>0.0266</td>
<td>0.0712</td>
</tr>
<tr>
<td>6</td>
<td>0.59</td>
<td>0.0316</td>
<td>0.08</td>
</tr>
<tr>
<td>7</td>
<td>0.615</td>
<td>0.0359</td>
<td>0.087</td>
</tr>
<tr>
<td>8</td>
<td>0.653</td>
<td>0.0433</td>
<td>0.099</td>
</tr>
<tr>
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<td>0.0549</td>
<td>0.116</td>
</tr>
<tr>
<td>10</td>
<td>0.725</td>
<td>0.060</td>
<td>0.123</td>
</tr>
<tr>
<td>11</td>
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<td>0.068</td>
<td>0.1338</td>
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<tr>
<td></td>
<td>0.80</td>
<td>0.08</td>
<td>0.1514</td>
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<td>------</td>
<td>------</td>
<td>--------</td>
</tr>
<tr>
<td>12</td>
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<td></td>
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<tr>
<td>13</td>
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<td>0.0875</td>
<td>0.1584</td>
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<tr>
<td>14</td>
<td>0.843</td>
<td>0.097</td>
<td>0.1695</td>
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<tr>
<td>15</td>
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<td>0.106</td>
<td>0.1806</td>
</tr>
<tr>
<td>16</td>
<td>0.894</td>
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<td>0.1926</td>
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<tr>
<td>17</td>
<td>0.9225</td>
<td>0.1293</td>
<td>0.2064</td>
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<tr>
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<td>0.2177</td>
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<td>19</td>
<td>0.97</td>
<td>0.1524</td>
<td>0.2308</td>
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</table>
Appendix C.1.1: Experiment 2 Sequence of Half-Rectified A-Scans

Figure A.C.1: baseline (vertical axis to 0.05V)

Figure A.C.2: cut 1 (vertical axis to 0.025V)

Figure A.C.3: cut 2

Figure A.C.4: cut 3

Figure A.C.5: cut 4

Figure A.C.6: cut 5
### Appendix C.2: Experiment 3 Cut Dimensions

Table A.C.2: Cut dimensions of Experiment 3

<table>
<thead>
<tr>
<th>Cut number</th>
<th>Cut length, in.</th>
<th>Cut area, in.²</th>
<th>Max. cut depth, in.</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 (baseline)</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>0.354</td>
<td>0.0067</td>
<td>0.0282</td>
</tr>
<tr>
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<td>0.46</td>
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<tr>
<td>3</td>
<td>0.53</td>
<td>0.0227</td>
<td>0.0640</td>
</tr>
<tr>
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<td>0.60</td>
<td>0.0333</td>
<td>0.0827</td>
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<td>0.0502</td>
<td>0.1090</td>
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<tr>
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<td>0.726</td>
<td>0.0602</td>
<td>0.1232</td>
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<td>0.0956</td>
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<tr>
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<td>0.93</td>
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<td>0.2362</td>
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</table>
Appendix C.2.1: Experiment 3, 254 kHz
Sequence of Half-Rectified A-Scan

Figure A.C.21: baseline

Figure A.C.22: cut 1

Figure A.C.22: cut 2

Figure A.C.23: cut 3

Figure A.C.24: cut 4

Figure A.C.25: cut 5
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