



**EFFECTS OF MECHANICAL LOAD
HISTORY ON LAMB WAVE INTERACTIONS
WITH FATIGUE CRACKS IN ALUMINUM
PLATES**

DISSERTATION

C. Todd Owens, Lieutenant Colonel, USAF, Retired
AFIT-ENY-DS-17-S-061

**DEPARTMENT OF THE AIR FORCE
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DISSERTATION

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Degree of Doctor of Philosophy in Aeronautical Engineering

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Abstract

The average age of the USAF aircraft fleet is now more than 27 years and climbing. Currently, the USAF assesses the structural health of aircraft primarily using schedule-based inspections. The application of automated structural health monitoring (SHM) systems could enable a transition to condition-based maintenance, reducing maintenance costs per flight hour and increasing aircraft operational availability. A U.S. Army sponsored study on helicopter structures employing a commercial-off-the-shelf SHM system using elastic ultrasonic waves found that such systems may demonstrate reduced sensitivity to high-cycle fatigue cracks as compared to low-cycle fatigue cracks.

This dissertation reports on experiments to study the interaction of ultrasonic Lamb waves with both high- and low-cycle fatigue cracks in aluminum plates. Three similar crack specimens (one high-cycle, two low-cycle) were interrogated with broadband Lamb wave excitations generated via bonded piezoelectric transducers. The resulting wavefields were measured using a scanning laser Doppler vibrometer. The data was post-processed using chirp and frequency-wavenumber filtering to determine the structural response for symmetric and asymmetric Lamb wave modes at frequencies from 50 kHz to 500 kHz. Transmission and reflection coefficients were calculated representing the amount of wave energy that passed through or was reflected from each crack.

The experimental results demonstrated that for the crack specimens and excitation frequencies tested, there were quantifiable differences in the amount of Lamb wave energy transmitted through and reflected from high-cycle and low-cycle fatigue cracks.

For Tina, Nathan, Mother, Father, Phil, David, the PhD classmates who egged me on, and everyone who ever started a Ph.D. but never finished.

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EFFECTS OF MECHANICAL LOAD HISTORY ON LAMB WAVE INTERACTIONS WITH FATIGUE CRACKS IN ALUMINUM PLATES

I. Introduction

1.1 The Aging Aircraft Problem

The United States Department of Defense (DoD) maintains and operates a fleet of approximately 14,000 fixed and rotary wing airframes; of these, approximately 5,400 belong to the United States Air Force (USAF) [1]. The average age of the USAF fleet is now more than 27 years and climbing. “By automobile standards, 12 fleets [different types] of Air Force aircraft are authorized antique license plates in the state of Virginia” [2]. In a RAND study on the cost impacts of aging aircraft, Pyles found that in the 1970’s the USAF replaced airframes by around 20 years of service; however, in the intervening decades, the acquisition time and cost of new systems has increased dramatically. Development times of 15-20 years from program inception to initial operational capability (IOC) are now common for major weapon systems, and acquisition costs for new airframes can exceed 300% of the systems being replaced [3]. In addition, ongoing budgetary constraints (to include sequestration) have led to a decline in the USAF research, development, test, & evaluation (RDT&E) and procurement budget from approximately half the total service budget in the 1980’s to less than one-third in the late-90’s. Recent increases have brought these figures to approximately 44% of the total service budget [4]; however, the overall result has been a reduction in the overall rate of airframe acquisition from approximately 270 per year in the 1980’s to around 100 per year over the last 3 decades [1, 3]. Looking

specifically at fighter aircraft, the acquisition rate dropped from an average of 200 airframes per year prior to 1992 to less than 25 in the following years [5].

Furthermore, replacement weapon systems are not being procured in sufficient quantity to fully replace legacy capabilities. F-22A production was decreased from the initially planned 750 airframes to 187, thus requiring the F-15C fleet to remain operational much longer than originally planned [6]. Current plans call for production of only 179 KC 46 tankers, which, despite its improved capabilities, is insufficient to replace the more than 400 KC-135 airframes (average age greater than 53 years) in the current inventory [1, 4]. B-52H airframes already average over 53 years in service [4], but the replacement B-21 is not expected to reach IOC until sometime around 2030 [7]. In addition to the advancing age of the current fleet, the USAF has been engaged in continuous combat operations since the Persian Gulf War in 1991, resulting in airframes accumulating more flight hours and exposure to harsh environments than they would have under a peacetime operational tempo [8, 9].

Not unexpectedly, there are increased operations and maintenance (O&M) costs associated with operating an aircraft beyond its originally designed service life [10]. In addition to budgetary and manpower impacts, increased maintenance-related downtime combined with fewer airframes lead to reduced operational availability. Subsystem (avionics, sensors, propulsion, etc.) modifications and upgrades are often preplanned in the life-cycle of a weapon system and can be implemented to improve the capabilities of an aging platform to better meet current operational requirements. In comparison, it is much less practical to significantly modify or replace large and/or critical portions of the basic airframe. While examples such as the C-130 center wing box and A-10 wing replacement programs exist [11, 12, 13, 14], unlike most subsystem modification programs these efforts provide little in the way of increased operational capability.

All metallic airframes are subject to deterioration by fatigue, corrosion, stress-corrosion cracking, etc. These problems typically increase with increased airframe age and flight hours. If such deterioration is not found and remedied, it can eventually result in catastrophic failure. In order to maximize safety of flight, it is necessary to monitor the health of the airframe structure throughout its operational life.

The requirement for Structural Health Monitoring (SHM) is not unique to aircraft, since the same concerns apply to aging ships, bridges, skyscrapers, oil pipelines, etc. As such, SHM has been the subject of extensive research over the past few decades and many methodologies have been proposed [15, 16, 17]; however, operational implementation of automated SHM systems in aerospace structures remains an elusive goal.

1.2 Schedule-Based Maintenance

At present, the USAF assesses the structural health of aircraft using a combination of schedule-driven inspections and model-based engineering analysis. This combined approach is described in MIL-STD-1530D, The Aircraft Structural Integrity Program (ASIP) [18]. ASIP analysis begins with the assumption that every airframe contains structural flaws on the day it is delivered from the factory. Structural models are created and analyzed against the design loads/environment spectrum (expected flight duration, gross weight, maneuvers, thermal loads, etc.) to identify critical structures and estimate the time/flight hours required for a flaw to grow to a critical size. Inspection intervals are established (e.g., every 6 months or every 500 flight hours) to ensure a defect can be detected before it reaches a critical size. Various inspection techniques are used, ranging from a simple visual inspection to a variety of non-destructive evaluation (NDE) techniques as described in MIL-HDBK-6870B, Nondestructive Inspection Program Requirements for Aircraft and Missile Materials

and Parts [19]. These techniques include fluorescent penetrant, magnetic particle, eddy current, ultrasonic, and radiographic [20]. Probability of detection (POD) for the selected inspection type is considered when establishing the initial and repeat inspection intervals to help ensure a flaw is detected before it can cause a catastrophic failure.

Not surprisingly, aircraft which remain in service decades past their originally anticipated service life can see operating environments and usage spectra vastly different from those considered during initial system design, development, and testing. New munitions and sensors are developed and integrated onto existing platforms, new tactics are developed and employed, and operational tempo (number of flight hours per year and severity of maneuvering) may be higher than originally anticipated. In order to address this, a sample subset of airframes are instrumented with sensors (strain gages, accelerometers, corrosive environment sensors, etc. [15]) to gather real-world data on the operational loads/environment spectrum; these data, along with the results of prior inspections, are used to periodically update engineering models and the inspection schedule accordingly. Additionally, adjustments are made for individual aircraft taking into account possible modifications, repairs, or more severe usage that may be different from the average airframe in the fleet [21].

This schedule-based approach to airframe SHM has been successfully used since the 1950s and is still in wide use in both commercial and military aviation [20]. In the vast majority of cases, scheduled inspections find damage and trigger corrective maintenance action before it can become catastrophic, thus ensuring safety of flight. Unfortunately, while effective, this approach does have drawbacks. No two airframes in a fleet are truly identical. Small differences in materials and construction details, varying operational histories, prior repairs, etc. mean that corrosion or fatigue damage found on one airframe may take years to appear (or may never appear) on another.

Despite efforts to take individual aircraft history into account and tailor inspection intervals accordingly, inspections often find no problems.

In most cases, critical airframe structures are not easily accessible and require extensive preparation steps prior to the actual inspection. This includes procedures such as jacking the aircraft, draining fuel tanks, removing panels, removing/relocating wiring bundles, and preparing surfaces (removing sealant, paint, etc.). In some cases, original production jigs are required to maintain the alignment of key aircraft structures while load-bearing panels/components are removed to gain inspection access [22]. All of this leads to increased maintenance costs and reduced aircraft availability, especially when no structural flaw is found. According to a USAF Scientific Advisory Board (SAB) study in 2011, using a ten-year average across all major mission design series (MDS), scheduled inspections were among the top five reasons aircraft were categorized as not-mission-capable due to maintenance (NMCM) [10]. In addition, due to human error, foreign object damage (FOD), etc., every time an inspection is performed, there is a non-zero chance of actually causing damage where none previously existed.

1.3 Structural Health Monitoring and Condition-Based Maintenance

According to Gopalakrishnan, et al., the objective of SHM is to provide “tools for the constant or periodic monitoring of critical structural assets in order to determine the need for remedial action, and to prevent catastrophic failures” [23]. Viewed this way, the schedule-based and manpower-intensive maintenance paradigm described in the previous section is indeed a form of SHM. However, the vast majority of research, as it relates to SHM, has been focused on the development of sensors and algorithms to “provide the structure of interest with sensing and analysis capabilities to enable monitoring and evaluation to be carried out . . . autonomously” [23]. The widespread

application of such SHM capabilities would essentially bring the concept of the built-in test (BIT) functions commonly found in avionics systems to the airframe structure itself, and enable a transition from schedule-based inspections to a condition-based maintenance (CBM) paradigm in which such inspections are triggered only when the SHM system indicates there is a need. In the nearer term, this would have the effect of reducing maintenance costs per flight hour and increasing aircraft operational availability. According to Schmidt and Telgkamp, et al., onboard SHM systems may, in the long term, enable the use of lower structural margins during initial airframe design and manufacture [24, 25, 26]. This could, in turn, lead to reduced structural weight, improved performance, reduced fuel consumption, etc. However, these considerations are beyond the scope of this dissertation.

1.4 SHM Methodologies

A variety of damage detection techniques have been proposed in the literature, depending on the type of structure, construction materials, type of damage, etc. In general, all these techniques can be categorized as passive, active, or a mixture of the two. Passive methods make use of a variety of sensor types to ‘listen’ to the structure (e.g., acoustic emission) but not actively interact with it [27]. In contrast, active SHM techniques directly interrogate the structure. Commonly used NDE techniques such as ultrasonics and eddy current are active in nature; however, these methods generally require a human operator and are limited to small area or single-point measurements [20]. The majority of active SHM research has been focused on diagnostic methods such as vibration/modal, electro-mechanical impedance, and elastic wave propagation [28].

Vibration/Modal.

As outlined by Staszewski [20], damage such as cracks and corrosion can change the local mass, stiffness, and/or damping distribution in a structure and lead to a different modal/vibratory response from that of the undamaged state. It is possible to analyze changes in characteristic frequencies, modal shapes, and/or damping in order to detect the presence of damage. Much of the early SHM research was based on these techniques [29] and it appears regularly in the literature; however, its primary drawback is a lack of sensitivity. As a global method, it is effective in detecting large damage areas (flaw sizes greater than approximately 10% of structure), but is not generally useful for identifying defects such as short cracks [20]. Since the intent is to detect and locate damage long before it becomes critical, this approach is not as well suited for SHM of aircraft structures as the following two methods: electro-mechanical impedance (EMI) and elastic wave propagation.

Electro-Mechanical Impedance.

The electro-mechanical impedance (EMI) method is essentially another vibration technique, but it operates on a local rather than global scale [28]. According to research by Giurgiutiu and Zagrai, Park, et al. and Yan and Chen [30, 31, 32], this method is based on the principle that defects such as cracks and corrosion will cause changes in the local mechanical impedance of a structure. While mechanical impedance is difficult to measure, electrical impedance is not. Typically, small piezoelectric transducers are used to drive the structure with high-frequency vibrations while the electrical impedance of the transducer is measured directly with an analyzer. Because the transducer is bonded to the structure, changes in local mechanical impedance affect the measured electrical impedance of the transducer. Changes in this electro-mechanical impedance over time can be analyzed in order to detect struc-

tural damage. This technique is capable of detecting small damage sites due in part to the short wavelengths at the typical excitation frequencies of approximately 10 to 500 kHz or higher. However, similar to global vibration techniques, EMI frequency response data lack directionality and therefore EMI techniques can require a relatively high sensor count if the objective is not only to detect but also locate damage in a structure. Multiple statistical damage metrics appear in the literature, and several researchers have made use of transducer arrays and neural networks in an attempt to locate damage and/or estimate its severity, but the estimation of damage severity and location are not as straightforward using EMI as compared to wave propagation techniques [31, 32, 33].

Wave Propagation.

Wave propagation techniques are based on inducing elastic waves into a structure to ‘probe’ for damage. Elastic waves are a broad and complex subject; multiple types of waves and wave behaviors can exist, depending on materials, boundary conditions, and so on. Multiple books, such as those by Graff [34] and Rose [35], address the subject in depth; however, this dissertation will focus on a specific type of elastic waves very common in SHM research—Lamb waves. First defined by Lamb in 1917 [36], Lamb waves are guided elastic waves that propagate between two parallel surfaces, such as in a plate or pipe. An example of a propagating Lamb wave field can be seen in Figure 1. This example wave field was excited in an aluminum plate using a bonded piezoelectric transducer and measured using a three-dimensional (3D) scanning laser Doppler vibrometer (SLDV). A_0 mode waves are antisymmetric while S_0 mode waves are symmetric—this will be discussed in more detail in Chapter II

Many aircraft structures, such as wing skins, shear webs, and bulkheads can be characterized, at least in part, as flat or curved plates, which makes Lamb waves an

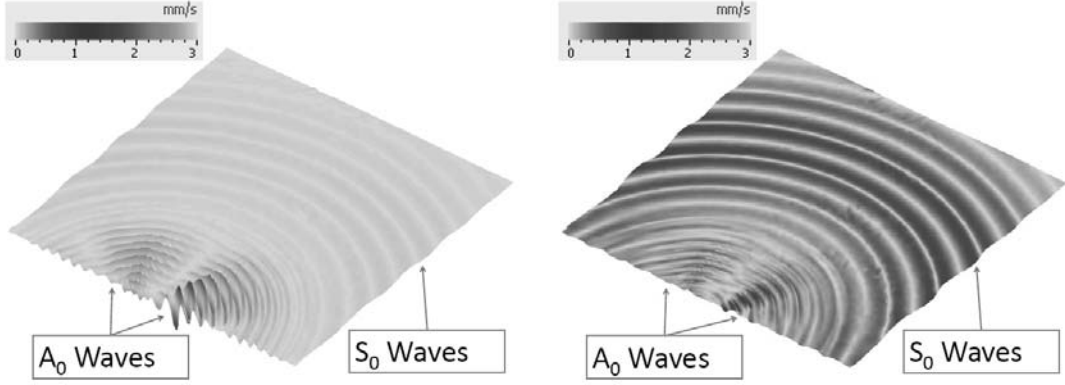


Figure 1. Propagating Lamb wave velocity fields as measured with a 3D-SLDV: left side is out-of-plane velocity (V_z), right side is in-plane velocity (V_x and V_y).

ideal interrogation technique. Significant SHM research has been conducted using Lamb waves to interrogate the structure of interest. These waves are most commonly excited via bonded piezoelectric transducers, though high-energy laser [37, 38, 39] and air-coupled transducer excitation [40] are also found in the literature. The primary disadvantage to laser-induced wave techniques is wide-band frequency content in the resulting wavefield which, for reasons that will be discussed in Chapter II, tend to complicate post-measurement analysis. The propagating waves can be measured using both contact and non-contact means. The most common contact techniques utilize multiple bonded transducers in a “pitch-catch” arrangement, where one or more transducers excite the waves, while other transducers sense the resulting wave energy (in the form of surface strain) as it passes their location [41]. The “pulse-echo” method uses the same transducer(s) for both excitation and response measurement [42].

The most common non-contact sensing methods are air-coupled transducers [43] and laser Doppler interferometry/vibrometry [44, 45], though at least one research team has investigated TV holography [46]. Compared to contact methods, when

combined with the appropriate scanning mechanisms these non-contact techniques are capable of measuring a dense field of thousands of points on the structure, enabling full-wavefield measurements and therefore potentially more robust analysis of the area of interest. Depending on the equipment used, this is true even for high excitation frequencies producing wavelengths of only a few millimeters [47, 48].

The majority of elastic wave analysis techniques are “baseline” methods, in which current measurements of the structure are compared to a baseline measurement of the undamaged structure. Changes between the current and baseline signals can be used to detect, locate, and quantify structural damage. However, elastic waves can be impacted by a variety of environmental effects (temperature, stress/strain, sensor degradation, etc.), potentially resulting in false or failed damage detection [49, 50, 51]. In response, “baseline-free” techniques are a growing area of research interest. These methods seek to detect, locate, and/or quantify structural damage without the need for a baseline measurement from the undamaged structure. Another approach taken by researchers is to attempt to characterize how common environmental factors affect the propagating waves so that these effects may be accounted for in baseline damage detection algorithms, thereby mitigating them [52]. This area is the primary focus of the research presented in this dissertation, as discussed in the next section.

1.5 Research Objective

In a U.S. Army Research, Development, & Engineering Command (RDECOM) sponsored study [53], researchers reported on the use of a commercial off-the-shelf (COTS) elastic wave propagation based SHM system to evaluate structural damage during fatigue testing of a representative helicopter fuselage structure. This system used bonded piezoelectric transducers to both excite and measure elastic waves as well as a damage detection and localization algorithm utilizing baseline measurements.

Two identical test structures were used, one subjected to higher loading (low-cycle fatigue) and one to lower loading (high-cycle). These differences in loading resulted from researchers' desire to speed crack formation and growth on one test article (thereby shortening the overall duration of the experiment) as opposed to a planned comparison between the different crack types. The researchers reported that in the case of high-cycle fatigue cracks, the "system performed below expectations, in terms of sensitivity, compared to observations made" on the test article with low-cycle cracks [53]. They hypothesized that the COTS system's built-in damage evaluation algorithm "may not be as sensitive to higher cycle fatigue" [53]. During the course of a cooperative experiment with Army Research Lab (ARL) in the summer of 2010, researchers from ARL proposed a detailed investigation of the phenomenology of elastic wave interaction with both high- and low-cycle fatigue cracks as a topic for this author's dissertation research.

An informal review of more than 50 SHM related conference papers and journal articles by this author showed that approximately 60% of experiments in the reviewed literature were conducted using simulated rather than realistic damage on the test article. Machined notches were often used to represent cracks, while partial depth holes and bonded masses were used to represent more general types of damage. Out of 16 papers reporting the use of real cracks grown under fatigue loading, 10 did not include enough information to clearly determine whether the crack was high- or low-cycle fatigue, 4 were high-cycle, and 1 was low-cycle. Only a single paper [54] was found that reported testing against both high- and low-cycle fatigue cracks; however, the experimental and analytical techniques used were significantly different from those presented in this dissertation and a direct comparison of wave behavior between the crack types was not an explicit objective.

The primary objective of this research was to investigate and characterize differ-

ences in Lamb wave interactions with fatigue cracks grown under different loading spectra (specifically low-cycle vs. high-cycle fatigue), as well as at different static loads. This was accomplished through the experimental excitation and measurement of Lamb wave velocity fields in aluminum plates containing fatigue cracks. Experimental data was used to calculate transmission (TC) and reflection coefficients (RC) along the length of each crack specimen. These coefficients represented the amount of incident Lamb wave energy that was either transmitted through or reflected from each crack. Comparison of TC and RC results indicated that, for the crack specimens and excitation frequencies tested, there were quantifiable differences in the amount of Lamb wave energy transmitted through and reflected from high-cycle and low-cycle fatigue cracks.

The primary differences between a low- and high-cycle fatigue crack of similar size and configuration are the size of the plastic zone surrounding the crack, the magnitude of plastic deformation and residual stresses in those zones, and the contact conditions and topology of crack contact faces. Additionally, under different loading conditions, cracks can open and close, producing significant changes in wave scattering behavior as the crack face contact conditions vary. Multiple researchers have examined the use of nonlinear Lamb waves for the detection of material nonlinearities such as local plasticity and fatigue [55, 56, 57]. However, virtually no work found in the literature examines differences in wave scattering behavior between high-cycle and low-cycle cracks. Both experimental and numerical investigations have been conducted on open and closed cracks [58, 59], but neither study made use of full-wavefield measurements, as presented in this research.

1.6 Dissertation Organization

This document contains five chapters. Chapter II presents background information on major engineering concepts related to SHM, including Lamb wave fundamentals, signal processing, and data analysis techniques present in the research literature.

Chapter III presents a detailed description of the procedures used to generate and analyze data, including experimental set up and data collection, signal processing, and data analysis. Techniques specifically used in this research are presented with sufficient detail so that the experimental and analytical procedures are both repeatable and verifiable.

Chapter IV presents the relevant results and analysis of the experiments described in Chapter III, while Chapter V provides a summary of the key research findings, potential applications of this work, and recommendations for future research.

II. Background and Literature Review

2.1 Lamb Wave Fundamentals: Basic Theory and Governing Equations

In elastic, isotropic, infinite media, mechanical disturbances propagate as bulk elastic waves [35]. Two basic types of bulk waves exist: longitudinal or pressure (P-waves) and transverse or shear (S-waves). As shown in Figure 2, material particles oscillate primarily along the wave propagation vector in P-waves and perpendicular to it in S-waves. Additionally, shear waves may be further described as vertical (SV-waves) or horizontal (SH-waves) depending on their orientation with respect to the structure, as shown in Figure 3 [60].

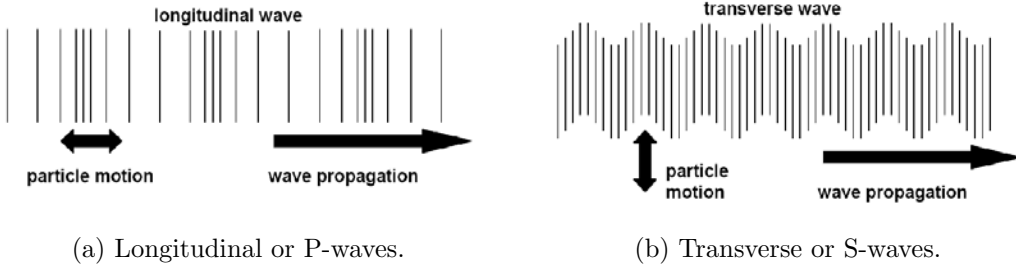


Figure 2. Particle motion in P- and S-waves [60].

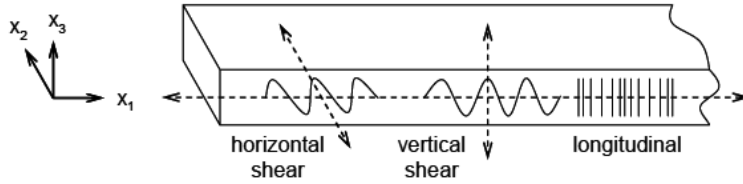


Figure 3. Wave propagation in finite media [60].

Beginning from the theory of elasticity and assuming a continuous isotropic medium, the partial differential equations of motion in Cartesian tensor notation are given by

$$\mu u_{i,jj} + (\lambda + \mu) u_{j,ji} + \rho f_i = \rho \ddot{u}_i \quad (1)$$

where u is displacement, λ and μ are the Lamé constants, ρ is the material density, and f is the applied force. After applying Helmholtz decomposition, longitudinal and shear waves can be uncoupled in unbounded isotropic media and their propagation can be described by the wave equations

$$\nabla^2 \phi = \frac{1}{c_L^2} \frac{\partial^2 \phi}{\partial t^2} \quad \text{for longitudinal waves} \quad (2)$$

$$\nabla^2 \psi = \frac{1}{c_T^2} \frac{\partial^2 \psi}{\partial t^2} \quad \text{for transverse/shear waves} \quad (3)$$

where

$$c_L^2 = \frac{\lambda + 2\mu}{\rho} \quad (4)$$

$$c_T^2 = \frac{\mu}{\rho}. \quad (5)$$

ϕ and ψ are the longitudinal and transverse displacement potentials, while c_L and c_T are the longitudinal and transverse wave speeds, respectively.

Unlike bulk waves, guided waves “arise due to the coupling between the longitudinal and vertical shear waves ... reflected and refracted at the” boundaries of finite media [60]. Rayleigh waves occur on the traction free surface of semi-infinite elastic solids and decay with depth [61]. Lamb waves, first described mathematically by

Horace Lamb in 1917 [36], are guided elastic waves of plane strain that propagate between two parallel, traction free surfaces such as in thin plates and cylindrical shells. The propagation of guided waves is governed by the same wave equations as bulk waves; however, the presence of boundary conditions (specifically, traction free upper and lower plate surfaces for Lamb waves) leads to different behavior. Unlike bulk waves, Lamb waves are dispersive, meaning their propagation speed and wavelength vary with frequency. In addition, Lamb waves have a theoretically infinite number of wave modes, and multiple wave modes can exist at a single frequency.

Applying plane-strain conditions, Equations (2) and (3) become

$$\frac{\partial^2 \phi}{\partial x_1^2} + \frac{\partial^2 \phi}{\partial x_3^2} = \frac{1}{c_L^2} \frac{\partial^2 \phi}{\partial t^2} \quad \text{for longitudinal waves} \quad (6)$$

$$\frac{\partial^2 \psi}{\partial x_1^2} + \frac{\partial^2 \psi}{\partial x_3^2} = \frac{1}{c_L^2} \frac{\partial^2 \psi}{\partial t^2} \quad \text{for transverse/shear waves} \quad (7)$$

and per the method of potentials solution presented in Rose [35], Equations (6) and (7) are assumed to have solutions of the form

$$\phi = \Phi(x_3) \exp [i(kx_1 - \omega t)] \quad (8)$$

$$\psi = \Psi(x_3) \exp [i(kx_1 - \omega t)] \quad (9)$$

where ω is the angular frequency, k is the circular wavenumber, and Φ and Ψ are unknown functions. These assumed solutions “represent traveling waves in the x_1 direction and standing waves in the x_3 direction” [35]. Substitution into Equations (6) and (7) and application of the complex exponential identity $e^{ix} = \cos x + i \sin x$ yields

$$\Phi(x_3) = A_1 \sin(px_3) + A_2 \cos(px_3) \quad (10)$$

$$\Psi(x_3) = B_1 \sin(qx_3) + B_2 \cos(qx_3) \quad (11)$$

where

$$p^2 = \frac{\omega^2}{c_L^2} - k^2 \quad (12)$$

$$q^2 = \frac{\omega^2}{c_T^2} - k^2. \quad (13)$$

Application of traction free plate boundary conditions and separation of the results into symmetric and antisymmetric modes produces the Rayleigh-Lamb frequency (or dispersion) relations

$$\frac{\tan(qh)}{\tan(ph)} = -\frac{4k^2pq}{(q^2 - k^2)^2} \quad \text{for symmetric modes} \quad (14)$$

$$\frac{\tan(qh)}{\tan(ph)} = -\frac{(q^2 - k^2)^2}{4k^2pq} \quad \text{for antisymmetric modes} \quad (15)$$

where $2h$ is the plate thickness. The terms symmetric and antisymmetric refer to the displacements of the top and bottom surfaces of a plate with respect to each other and the mid-plane of the plate. Symmetric modes are compressive, while antisymmetric modes are flexural in nature, as shown in Figure 4. These modes are referred to as $S_0, S_1, \dots S_n$ (symmetric) and $A_0, A_1, \dots A_n$ (antisymmetric).



Figure 4. Symmetric and antisymmetric wave modes [60].

Dispersion and Multi-mode Behavior.

Using numerical methods described by Rose [35] and MATLAB[®] code provided by AFRL, Equations (14) and (15) were solved to produce the theoretical phase velocity dispersion curves for Lamb waves, as presented in Figure 5. Phase velocity (c_p) describes the speed at which single frequency (sinusoidal) Lamb wave energy will propagate along a plate and is related to ω and k by

$$c_p = \frac{\omega}{k}. \quad (16)$$

Because wave speed is also affected by plate thickness, the frequency-thickness product fd is commonly used as the independent variable when plotting wave speed.

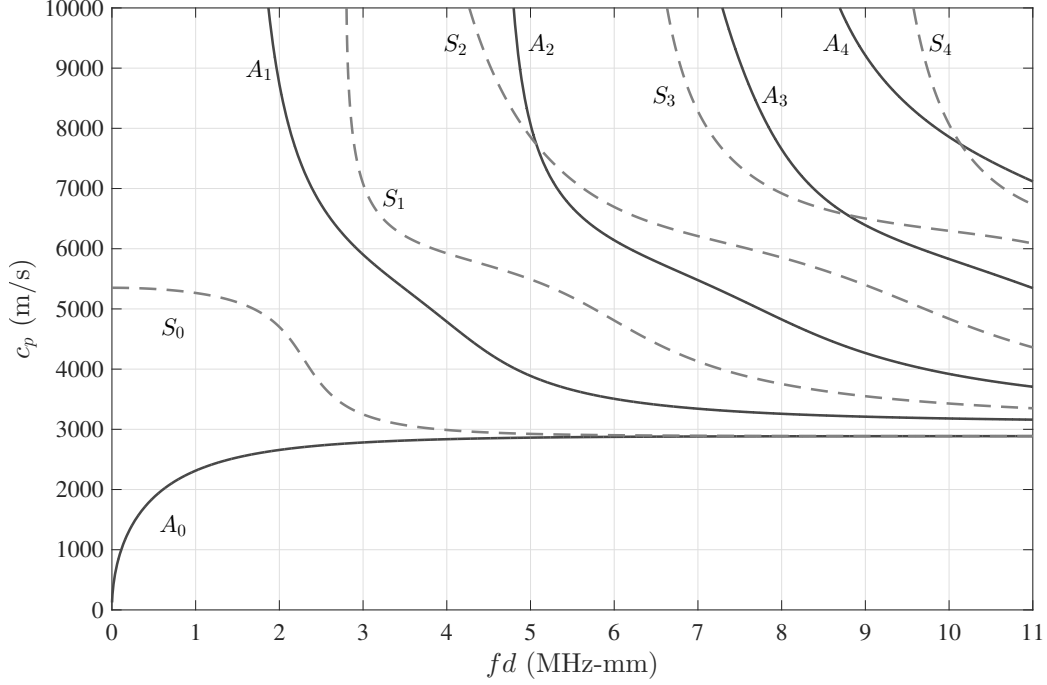


Figure 5. Phase velocity dispersion for an aluminum plate.

When wave energy is spread across a range of frequencies, as with finite duration signals such as impulses, chirps, and sine bursts, the different frequency components of the wave packet can have different propagation velocities. This can cause the wave packet to spread as it travels. The group velocity c_g is the speed at which the envelope of the wave packet propagates and is defined by

$$c_g = \frac{d\omega}{dk}. \quad (17)$$

Again, following numerical methods presented in Rose [35], the Lamb wave group velocity dispersion curves were calculated and are shown in Figure 6.

Dispersion and multi-mode behaviors of Lamb waves increase the complexity of signal processing and analysis operations required for SHM. Many researchers typically excite waves at or below approximately $1.8 \text{ MHz} \cdot \text{mm}$ in order to prevent the

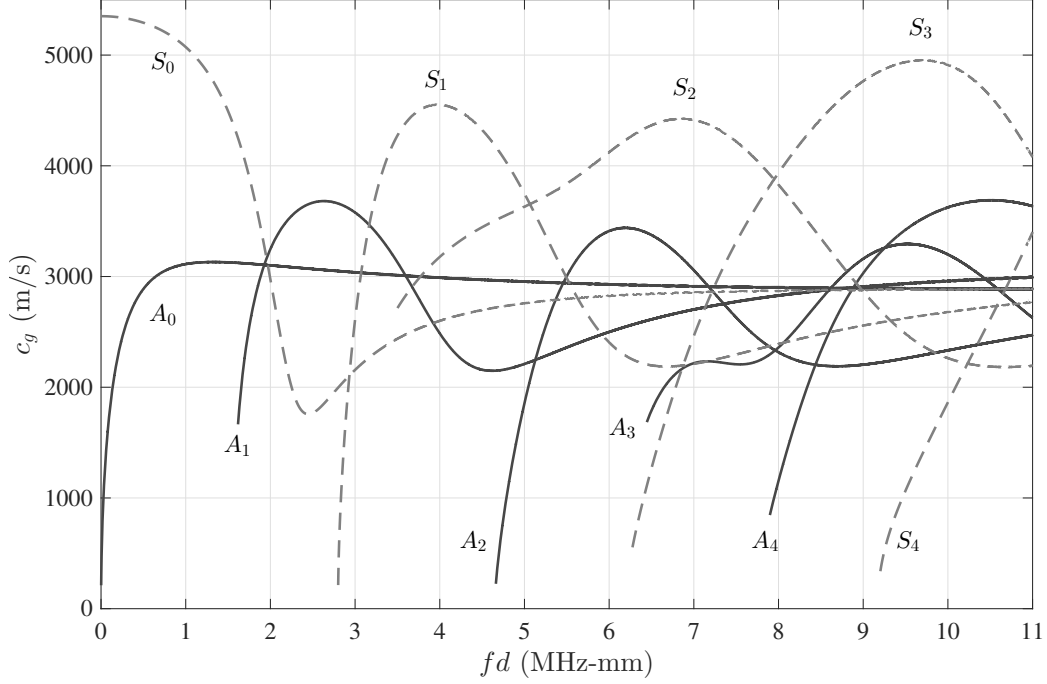


Figure 6. Group velocity dispersion for an aluminum plate.

appearance higher order modes; however, a number of more recent studies have been focused on the application of these higher order (nonlinear) wave modes for the detection of material nonlinearities such as fatigue damage [54, 55, 62, 63, 64, 65, 66, 67]. Additionally, frequency tuning can be used to minimize dispersion (lower frequencies for S_0 and higher frequencies for A_0) and at least partially isolate S_0 or A_0 due to variation in the amplitudes of each mode with frequency [68], as discussed in the next section.

2.2 Experimental Lamb Wave Techniques

Generation of Lamb Waves.

Excitation Methods.

There are a variety of ways to excite Lamb waves in a structure. Impact hammers, high-power lasers [37], and other short-duration or impulse-type excitation techniques

can be used but, as discussed in the previous section, the wideband frequency content and resulting wave dispersion make signal analysis more difficult. For these reasons, such techniques are less common in the literature. The most common techniques typically involve piezoelectric transducers such as those used in conventional NDE as well as piezoelectric patches bonded directly to the material.

Piezoelectric materials generate a voltage when subjected to strain and, conversely, strain when subjected to an applied voltage. Conventional ultrasonic NDE transducers are a category of (typically) piezoelectric devices that are specifically designed to excite and measure elastic waves; as such, they have been successfully used by a number of SHM researchers [55, 66, 69, 70]. These transducers are typically fixed-frequency, narrowband devices that are coupled to the structure via an angled wedge and a fluid medium [60]; however, non-contact, air-coupled transducers are also in use [40, 71, 72, 73]. While these transducers typically operate at a fixed frequency, the angle between the transducer and the test article can be varied in order to excite a preferred wave mode [69]. In comparison, directly bonded piezoelectric transducers are smaller, lighter, and less expensive. Due to these advantages, they are very common in wave propagation based SHM applications for both generation and sensing of Lamb waves.

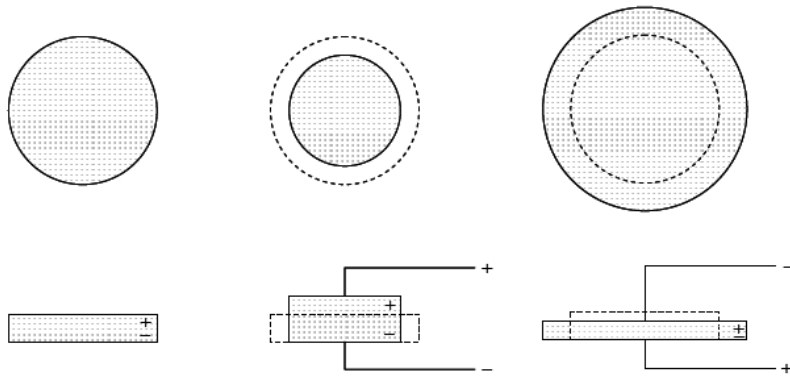


Figure 7. Behavior of piezoelectric disc subject to electric fields of different polarities [60].

In the case of thin, disc-shaped transducers electrically poled in the thickness direction, the dominant effect is radial expansion and contraction, as shown in Figure 7. When subjected to a time-varying voltage, strain energy from an adhesively bonded transducer is transmitted to the structure via the adhesive layer, producing elastic waves. Similarly, propagating Lamb waves cause localized strain in a structure; this strain energy is transmitted to the transducer via the adhesive layer, thus producing an output voltage proportional to the strain. One common piezoelectric material used in SHM research is lead zirconate titanate (PZT). Disks manufactured from this material were used to generate Lamb wave fields in this research, as will be discussed in Chapter III.

If desired, bonded transducers can be mounted in ways that allow for isolation of symmetric or antisymmetric Lamb wave modes. Installing two identical transducers opposite one another (one on the top and one on the bottom of a plate) enables the generation of symmetric or antisymmetric modes depending on the phasing of the two excitation signals. If the signals are in phase, the excitation will predominantly excite symmetric wave modes. If the two signals are 180° out-of-phase, the resulting waves will be predominantly antisymmetric. Hu et al. used this technique to isolate A_0 mode Lamb waves in a damage identification study [74].

Excitation Signals.

Due to the dispersive behavior of Lamb waves, windowed sine bursts, as shown in Figure 8, are often selected as excitation signals. Due to their relatively narrow frequency content, such excitation signals can also be used as a means to “tune” the induced wave to favor a specific wave mode. As shown by Giurgiutiu [68], calculated by Underwood [75], and presented in Figure 9, for a given plate thickness the amplitude of a given wave mode varies with frequency. By selecting the appropriate

frequency, researchers can emphasize the amplitude of one wave mode vs. another.

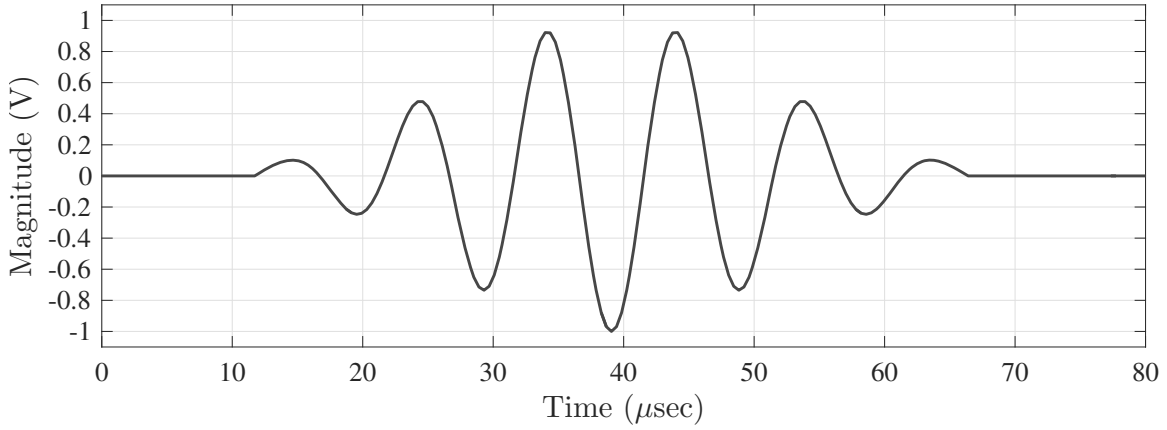


Figure 8. 5-1/2 cycle Hanning windowed sine burst excitation signal.

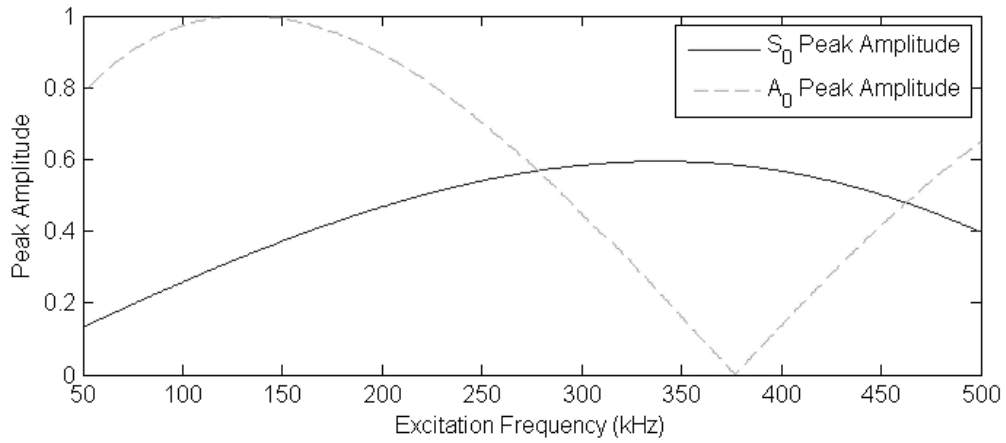


Figure 9. Theoretical normalized amplitude of A_0 and S_0 Lamb waves in a 3.175 mm thick aluminum plate using a 6.35 mm diameter PZT for excitation.[75]

While narrowband excitation signals are very common, broadband signals such as chirps and pseudorandom noise are also used, typically in combination with post-measurement signal processing techniques to account for dispersion and to separate wave modes [50, 59, 76, 77, 78]. These techniques will be discussed later in the chapter.

Measurement of Lamb Waves.

Contact Methods.

Due to the piezoelectric effect, the same transducers commonly used to excite wave fields can also be used to measure them. In fact, this is probably the most common experimental technique in the literature. One or more transducers can be bonded to the structure of interest and, combined with the appropriate signal generation and data acquisition equipment, be used to excite wave energy, measure it, or both. When separate transducers are used to excite and measure, it is called a “pitch-catch” arrangement, as exemplified by Ihn and Chang [41], Valdés and Soutis [42], Michaels et al. [43], and many others. When the same transducer(s) are used for both excitation and measurement, it is referred to as “pulse-echo,” as can be seen in work by Cuc et al. [79], Yu et al. [80] and Wang et al. [81].

In addition to piezoelectric transducers, other contact sensors such as optical fiber sensors (OFS) have been successfully used to measure propagating waves. The most common of these is the fiber Bragg grating (FBG), which was used by Pierce et al. [82] and Ling et al. [83]. The use of these sensors in SHM is discussed at length by Okabe and Wu [84]; however, as they were not used in the experiments presented in this dissertation, they will not be explored further.

Non-Contact Methods.

Bonded transducers create local stiffness discontinuities and can therefore affect the propagating waves. In addition, capturing densely spaced measurement points using bonded transducers typically requires custom design and manufacture, as demonstrated by Rguiti et al. [85]. Absent such specialized transducers, it can be difficult or impossible depending on the size of the sensors and geometry of the test article. For these and other reasons, multiple researchers have investigated non-contact

methods for measuring ultrasonic waves, including TV holography [46], air-coupled transducers [71, 72], and laser interferometry/vibrometry [44, 55, 86, 87]. These measurement methods were relatively rare in the literature prior to the last decade, but have become much more common.

When combined with an electro-mechanical x - y scanning apparatus, air-coupled transducers can be used to automatically measure a dense field of points, allowing for full wavefield visualization and the application of more advanced signal processing techniques [43]. The same is true for the most basic laser Doppler vibrometers (LDV). More advanced commercial vibrometers are equipped with steerable mirrors at the laser exit aperture that allow the laser beam to be redirected, or scanned. These scanning LDVs (SLDV) allow for automated data collection at thousands of individual points over a large area.

LDVs can measure displacement/velocity only along the axis of the laser beam. As such, one-dimensional (1D) LDVs are typically aligned to measure the out-of-plane component of guided waves. While antisymmetric wave modes have higher out-of-plane displacements than symmetric modes, numerous studies have shown that information on symmetric mode propagation can still be acquired from out-of-plane measurements. Staszewski et al. demonstrated that 1D-LDV measurement of Lamb wave propagation in an aluminum plate can produce results comparable to those obtained by discrete PZT transducers [45]. Koehler et al. used 1D-LDV measurements to characterize the dispersion behavior of symmetric and antisymmetric Lamb waves in both isotropic and anisotropic media [88]. Giridhara et al. used 1D-LDV data to validate a finite element simulation for guided wave based SHM of a turbine blade [89]. 1D-LDV based wave measurements have also been used to detect both simulated (notch) [90] and actual fatigue crack [91] damage in aluminum plates. Ayers et al. combined 1D-SLDV measurements taken from different angles with an algorithm to

determine the in-plane components of Lamb wave motion for use in a Lamb wave polarization study [92].

Three-dimensional (3D) SLDVs take simultaneous measurements using three separate (1D) sensor heads oriented at different angles to the test article. The vibration measurement and geometry data (laser angles and distances) from all three sensor heads are combined in software to produce both in-plane and out-of-plane displacement/velocity data. Swenson et al. compared Lamb wave measurements taken using both 1D- and 3D-SLDVs [93]. Ostachowicz et al. used 3D-SLDV measurements to detect and localize simulated damage (hole/notch) [94] and Staszewski et al. demonstrated the detection of a fatigue crack using a 3D-LDV [95] (both in aluminum plates). Ayers et al. used 3D-SLDV measurements to calculate the polarization of propagating Lamb waves for use as a damage location parameter [96].

While LDVs offer many benefits there are also disadvantages. First, they are expensive—advanced units like those used in this research can cost \$500,000 or more. This places them out-of-reach for many researchers not affiliated with a large university or government lab. Second, because they depend on reflected laser light to operate, LDVs are sensitive to the surface conditions of the test article and the incidence angle of the laser beam; because of these and other factors, LDVs often produce a lower signal-to-noise ratio (SNR) than other measurement methods. Finally, SLDVs are relatively slow. As discussed in the Chapter III, each data collection session for the experiments presented here took approximately 10 hours, which equates to a measurement speed (at the point density and scan settings used) of approximately $0.0003 \text{ m}^2/\text{min}$. For these reasons, existing commercial SLDV technology is not practical for application in a robust operational SHM system and use is best limited to laboratory work.

That being said, at least one researcher has developed experimental hardware and

wavenumber-based imaging techniques that allow for rapid SHM data acquisition and analysis using SLDV-based measurement. Using a modified commercial SLDV with a custom continuous motion scanning unit and continuous sinusoidal excitation from a bonded PZT, Flynn et al. demonstrated the capability to scan and image test articles including aluminum panels with corrosion damage and composite panels with impact damage (layer disbonds) [97, 98], as well as an aluminum panel with fatigue cracks [99]. The maximum scan rate of this system was reported as $4 \text{ m}^2/\text{min}$ —4 orders of magnitude faster than the SLDV used by this author!

2.3 Signal Processing and Analysis

Frequency Domain Filtering for Broadband Signals.

It is often desirable to investigate wave behavior across multiple excitation frequencies. When using narrowband excitation signals such as sine bursts, multiple data collections are required. This is not typically a problem when using piezoelectric transducers and a digital data acquisition system to measure wave data, as these systems operate relatively quickly. However, when using a mechanically scanned air-coupled ultrasound sensor or an SLDV, the time required can become impractical. As discussed briefly earlier in the chapter, broadband signals can be used in conjunction with post processing to create analytical response signals for the desired narrowband excitations.

The technique discussed in this section is not unique to SHM, and can be applied to any broadband signal, assuming the underlying system is linear. As presented by Michaels et al. [59, 78, 100, 101], a broadband response signal can be transformed to the frequency domain via the Fourier transform and then filtered to generate the frequency domain response to any desired input signal (provided the frequency of the desired input falls within the frequency range of the original broadband excitation).

After applying the inverse Fourier transform, the result is the time-domain response to the desired narrowband input signal. Using this technique, a single data collection using a broadband excitation can be post-processed to find the response to a theoretically infinite number of different input signals.

This technique was used in the course of this research and will be discussed further in Chapter III.

Separating Wave Modes.

The dispersive and multi-mode behavior of Lamb waves can complicate analysis of experimental data. Earlier in this chapter, several techniques to selectively emphasize the desired wave mode during experimental data collection were discussed. This section will present two common techniques for separating wave modes in post-processing.

Frequency-Wavenumber Domain Filtering.

Frequency-wavenumber (fk) domain analysis for use with multi-mode signals was introduced by Alleyne and Cawley [102] and it has been used and expanded on since then by many other researchers. The basis of the technique is that different wave modes have different wavelengths from each other, those wavelengths vary with frequency, and this can be used to separate modes for further analysis. The mathematical application requires the two-dimensional Fourier transform. Time domain signals are collected at a number of closely and equally spaced measurement points, this time-spatial data is arranged in a two dimensional array, and the 2D Fourier transform is applied. The time data is transformed to the frequency domain, while the spatial data is transformed to the wavenumber (k) domain. Wavenumber represents the spatial frequency of a propagating signal and is the inverse of the wavelength,

with units of cycles/distance or radians/distance. When analyzed in the fk domain, multi-mode signals can be separated based on frequency and/or wavenumber, filtered if desired, and then transformed back to the time-spatial domain by the inverse 2D Fourier transform.

Early applications related to SHM were limited, and did not include filtering to separate wave modes. Pierce et al. utilized laser-based excitation and measurement, coupled with fk analysis to compare experimental and analytical dispersion curves for Lamb waves in several materials, including aluminum [37]. Rguiti et al. performed similar work using a custom designed multi-electrode PZT transducer for multi-point wave measurements [85].

Originally developed and used in medical imaging, fk mode filtering was introduced to the SHM community by Ruzzene [103]. Since then, it has been used by many other researchers to separate Rayleigh [104] and Lamb wave [101, 105, 106, 107] modes for further analysis.

This technique was used in the course of the research presented in this dissertation and will be discussed in more detail in Chapter III.

Time-Frequency Analysis.

Where fk domain techniques leverage the difference in wavelength (and therefore wavenumber) between various wave modes, time-frequency (tf) analysis techniques make use of the variation in velocity between modes and across frequencies. One significant advantage tf analysis techniques is that they can be applied to single point or sparse data sets. In comparison, fk domain analysis requires a line of dense and evenly spaced measurement points.

There are several mathematical techniques for transforming experimental data to a tf representation: the short time Fourier transform (STFT) [28, 108, 109, 110],

pseudo Wigner-Ville distribution [111, 112], wavelet transform [113], Hilbert-Huang transform [114], and others. This section will briefly examine the STFT, but it is left to the reader to investigate the other techniques.

In basic terms, the STFT takes a single time domain signal, slices it into many overlapping segments, and performs a Fourier transform on each segment. This results in a time-varying “spectral amplitude” envelope of the original signal. The STFT is defined by

$$S(\omega, t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} e^{-i\omega\tau} s(\tau) h(\tau - t) d\tau \quad (18)$$

where $s(t)$ is the signal of interest and $h(t)$ is a window function (e.g., Hanning, Gaussian, etc.). When plotted in two-dimensions, the resulting data/image is called a spectrogram, an example of which is shown in Figure 10. As can be seen, the S_0 and A_0 modes are easily distinguished from each other, and various techniques can be applied to the transformed data in order to identify and/or separate wave modes as well as incident and reflected wave packets.

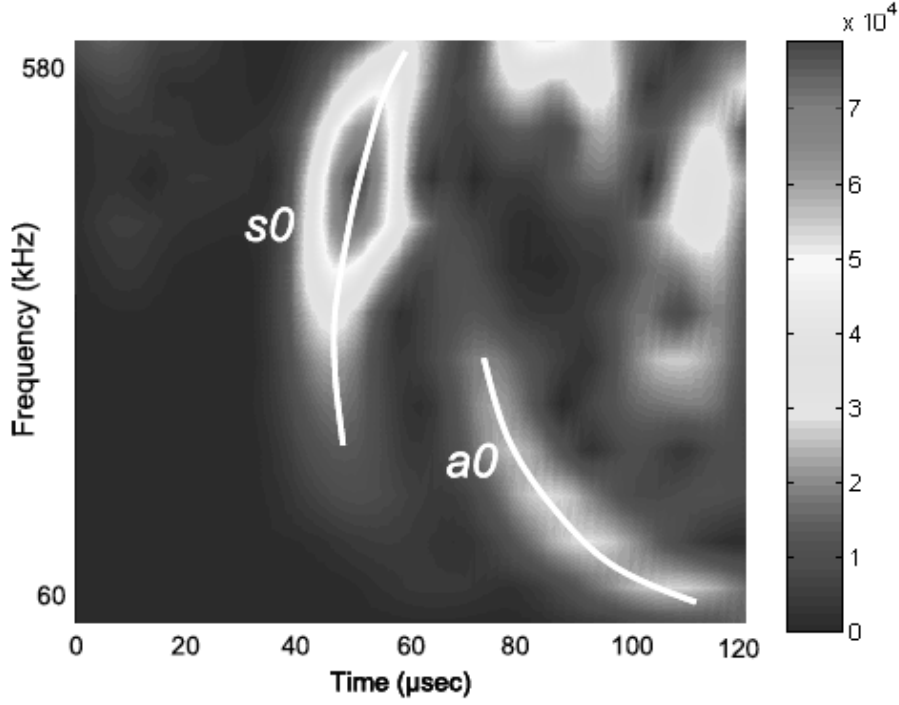


Figure 10. A wideband signal spectrogram [28].

Damage Detection and Characterization.

This section presents various Lamb wave based experimental and signal processing techniques for damage detection and characterization. A wide variety of such techniques exist, making a comprehensive review impossible. This summary presents a selection of those techniques commonly appearing in the literature.

Baseline vs. Baseline-Free.

The majority of techniques presented in the literature attempt to detect the appearance or growth of structural damage by comparing current data to a baseline (or reference) measurement collected at some time in the past. This approach has the advantage of being relatively simple to implement—when the difference between current and baseline data (typically in the form of a scalar damage metric) breaches a threshold, the presence of new damage is diagnosed. However, Lamb wave behavior can be

affected by changes in the operating environment (temperature, structural loading, etc.) and transducer performance can change over time due to micro-cracking, adhesive embrittlement, and so on. Some researchers have attempted to address these issues by accounting for temperature and other (non-damage) causes of signal variation in their algorithms. However, a growing number of papers are being published proposing baseline-free techniques, as seen in the following examples.

Anton et al. [115] used an array of transducers and, assuming the majority of pitch-catch paths would be undamaged, combined the signals from all paths to form an “instantaneous baseline.” The signals from each path were compared to this instantaneous baseline using statistical and eigenvalue techniques in order to successfully detect various types of simulated and real damage. Sohn et al. have published multiple studies on reference-free techniques, including time reversal [116], mode-conversion [50, 117], PZT polarization [118, 119], and transducer impedance [120].

Wave Time-of-Flight.

Time-of-flight (TOF) refers to the travel time of wave energy. Depending on the specific application, it can refer to the time between generation of a wave packet at one transducer and its reception at another (pitch-catch), the time it takes for reflected/scattered waves to return to a transducer (pulse-echo), and so on. The most common use for TOF data is damage localization—using group velocity and TOF data from multiple sensors, locating a source of wave scatter (damage) is reduced to a problem of geometric triangulation. However, because extraction of accurate TOF can be complicated by dispersion, fk or tf analysis methods are often applied. As shown in Figure 11, Ihn and Chang [28] used STFT generated spectrograms to find the peaks of various wave packets and used that as the basis for a TOF measurement.

Group velocity is related to TOF and distance (d) between transducers (or a

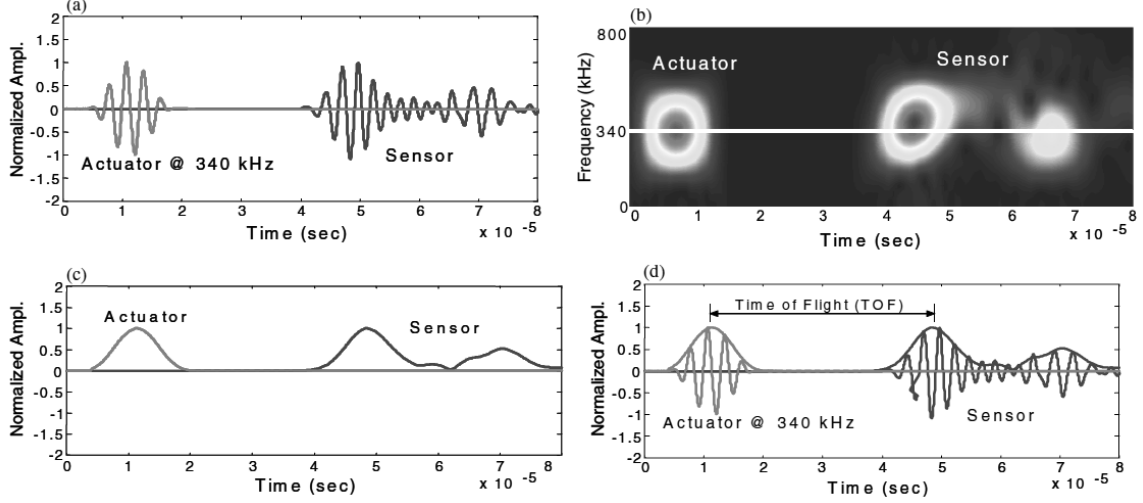


Figure 11. Time-of-flight extraction using the STFT [28]. Clockwise from top left: original actuator and sensor transducer signals, STFT calculated spectrogram of the original signals, original signals and magnitude envelope of the spectrogram at 340 kHz showing peak-to-peak TOF, magnitude envelope of the spectrogram at 340 kHz.

transducer and a boundary, damage, or other source of wave scatter) by

$$d = c_g(TOF). \quad (19)$$

If d is known (e.g., between two known transducer locations), c_g can be calculated using measured signals. Once c_g is known, the distance to any potential wave scattering source can be calculated. In the case of pitch-catch transducer pairs, the distance of the scatter source from each transducer will together describe an ellipse of possible damage locations, as shown in Figure 12(a). When multiple transducer pairs are used, the intersection of the various ellipses indicates the damage location with increased accuracy through triangulation, as shown in Figure 12(b)) [41, 74, 80]. For single transducer pulse-echo measurements, the TOF-derived distance will describe a circle instead of an ellipse, but otherwise the technique is the same.

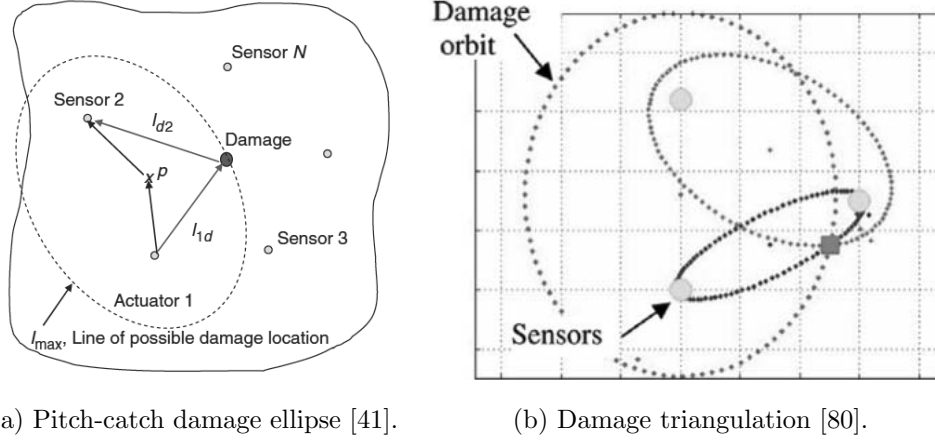


Figure 12. Determining damage location based on TOF data between transducer pairs.

Wave Amplitude/Energy.

Comparison of the amplitude or energy content of a measured transducer signal to a baseline or reference signal is a common technique. The amplitude of Lamb waves decrease due to geometric spread and damping; however, changes in the signal content of measurements taken at the same transducer locations at different times (neglecting changes in transducer performance as a cause) can indicate the presence of damage. A variety of damage indices proposed in the literature are based on this approach. The specific choice of amplitude/energy metric varies widely, including root-mean-squared [22, 75, 94], spectral amplitude (based on STFT [28, 41] or wavelet transformations [121]), power spectral density [115], strain energy [89], etc.

Using the distance between transducers (pitch-catch), the bandwidth of the excitation signal, and the group and phase velocities, specific time windows can be defined when the wave packet for a particular mode is expected to appear in the measurement data, as shown in Figure 13. Comparing current and reference signals only in these time windows can provide a more definitive indication of damage than attempting to analyze and compare the entire time history. This technique is the basis for the reflection and transmission coefficient calculations used in this research, and will be

discussed further in Chapter III.

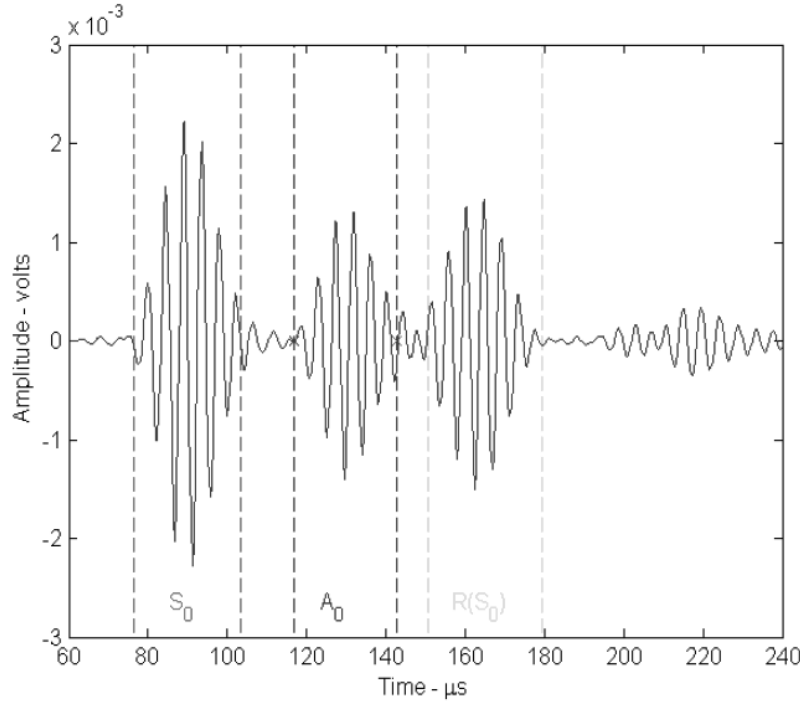


Figure 13. Time windows for calculating amplitude/energy of different wave modes [75].

Phased Arrays.

Attenuation of Lamb wave energy due to geometric spread and damping can increase the difficulty of successfully detecting damage, particularly at longer distances or in structural materials with significant damping, such as fiber-reinforced composites. One approach to increase the amount of wave energy input to a structure and/or increase the signal-to-noise ratio of wave measurements is the use of phased transducer arrays. These arrays can be used to both actively form a directional “beam” of wave energy (transmit arrays) and/or mathematically combine measurements from multiple transducers to form a beam in post-processing (receiving arrays) [60, 80, 122, 123].

Assuming a linear array of n omni-directional transducers, the beam forming technique works by applying a time delay to the signal of each transducer after the

first. The length of the time delay is related to the distance between the i -th and first transducers, l_i , the desired beam angle, θ , and the group velocity of the waves, c_g by

$$t_i = \frac{l_i \cos \theta}{c_g}. \quad (20)$$

Through constructive interference, the phase-shifted wavefronts combine to form a much higher amplitude signal along the desired beam angle, as shown in Figure 14. Note that the technique actually produces two beams, one at θ and one at $-\theta$. Data from multiple arrays installed at different angles can be combined to eliminate any location ambiguity caused by these symmetrical beam patterns [123]. In transmitting arrays the increased wave amplitude along the beam angle can be physical or mathematical (signals phase shifted and combined in post-processing), while in receiving arrays it is mathematical. Generally, physical transmitting arrays are more complicated to employ than receiving arrays, since they require the real-world implementation of transducer time delays. However, in thick or highly damped materials, the increased wave energy transmitted into the structure may justify their use. A 5 transducer array was used in this research; however, it was not steered and was created in post-processing by simply adding data sets collected using each of the transducers independently. This will be discussed more later.

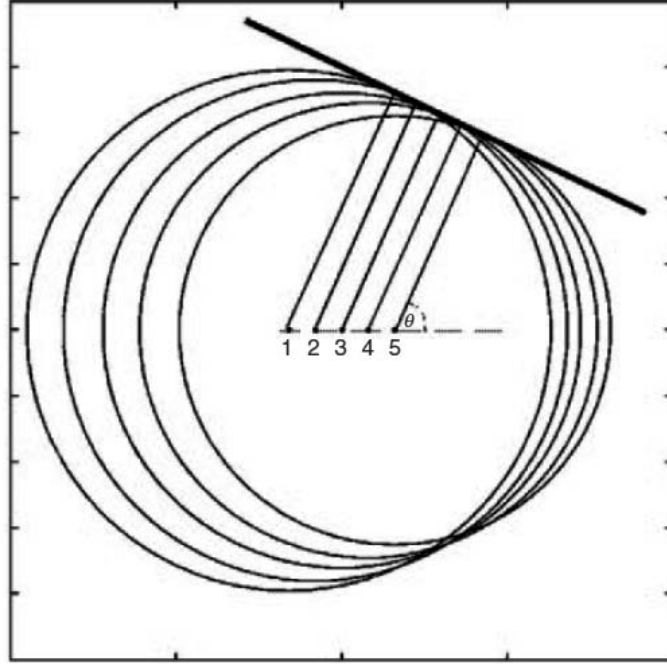


Figure 14. Beam formation using 5 transducers [123].

Time Reversal.

Time reversal is an analysis technique used to remove or minimize the effects of dispersion. In a linear elastic medium, due to “spatial reciprocity and time-reversal invariance of linear wave equations” [124], an input signal applied at location A can be recreated by taking an output signal from location B, reversing it in the time domain, and transmitting it from location B back to location A. This time reversibility “generally holds unless a non-linearity, such as damage, exists between” A and B [60].

Figure 15 depicts the propagation of an A_0 mode wave packet at a 200 kHz excitation frequency in a 1 mm thick aluminum plate [60]. At this frequency-thickness product, the phase velocity curve has a positive slope, as shown in Figure 16. This indicates that higher frequency content within the packet will have a higher phase velocity than lower frequencies. After propagating 200 mm, dispersion has caused the wave packet to spread, with higher frequency content shifted towards the leading edge

and lower frequency content trailing behind, as presented in Figure 15(a). When the response signal is time reversed and propagated back to the source, the lower frequency content is at the beginning of the pulse, with the high frequency components trailing. Over the same 200 mm propagation distance, the different phase velocities will, assuming the structure is undamaged, produce a reconstructed signal that is identical to the original input signal, as shown in Figure 15(b).

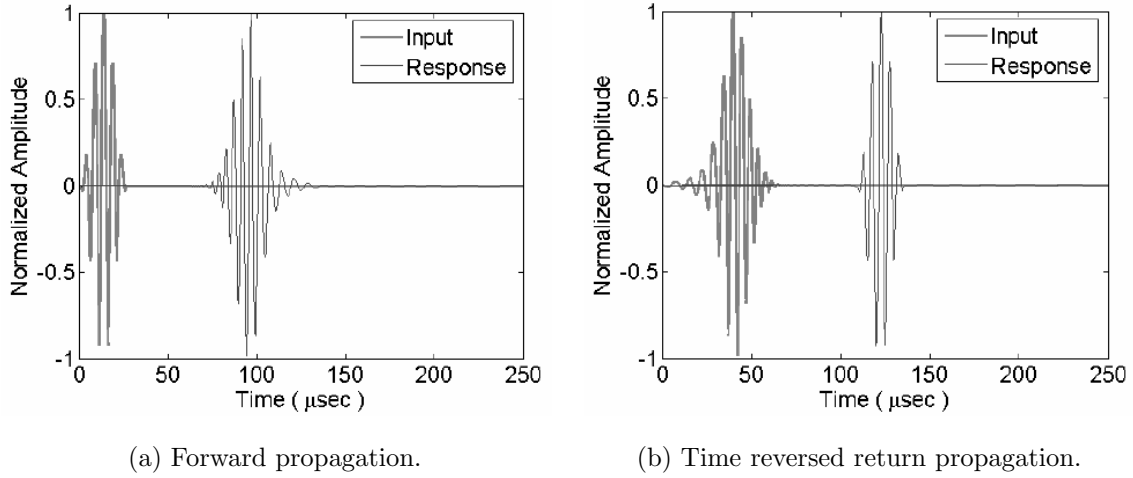


Figure 15. Time reversal of a 4-1/2 cycle, Hanning-windowed, 200 kHz sine burst in a 1 mm aluminum plate [60].

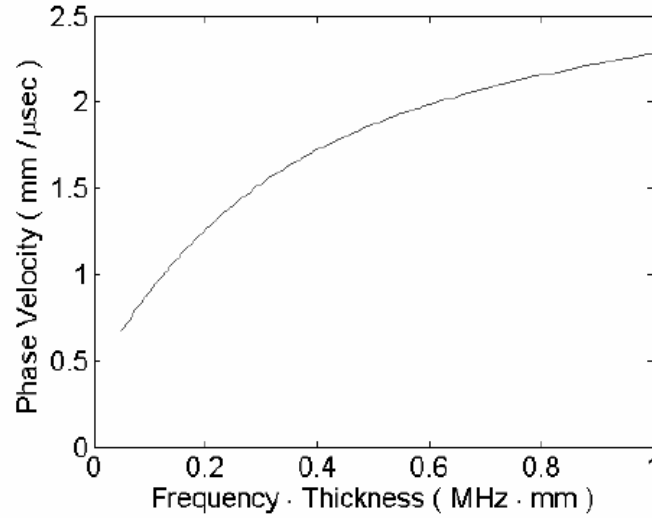


Figure 16. Phase velocity dispersion curve for A_0 Lamb wave mode in Aluminum [60].

Wang et al. developed a damage imaging method based on a time reversal technique using a sparse array of transducers and both pitch-catch and pulse-echo operating modes [81], while Sohn et al. have used the time reversal process in the development of a baseline-free damage detection technique [116]. Because the input signal is known and a reconstructed time reversed signal should be identical, no reference measurements are required. The reconstructed signal can be analyzed in comparison to the input signal in order to detect defects in the structure.

Transmission and Reflection Coefficients.

Multiple researchers have investigated Lamb wave interaction with various types of defects, including the calculation of transmission (TC) and/or reflection coefficients (RC). Diligent et al. performed both FEM and experimental work to characterize low-frequency ($100 \text{ kHz} \cdot \text{mm}$, equivalent to approximately 31.5 kHz excitation for the test articles used in this research) S_0 mode reflection and scattering from a hole in a plate and presented both time-domain and frequency domain approaches for calculating RCs. The time-domain technique was based on Hilbert transforms of the time-domain signals, and calculated by dividing the maximum amplitude of the reflected portion of the signal by the maximum amplitude of the incident portion. Similarly, the frequency domain technique involved “dividing the frequency spectra of the reflected part of the signal by that of the incident part” [125].

Fromme et al. conducted similar investigations focusing on scattering of A_0 mode waves from partial depth rectangular notches [126] and partial depth circular defects [127] in plates. The notch study presented RCs calculated in the frequency domain for both experimental and simulated (FEM) partial depth notches, as well as experimental and simulation based RCs for a partial depth fatigue crack (modeled as a zero width notch) in a steel plate. The experimental technique made use of a water-

coupled ultrasonic transducer in a pitch-catch arrangement. Results indicated that RC varied with both notch depth and frequency.

Fromme also reported on the scattering behavior of A_0 Lamb waves from a simulated crack (machined notch) in an aluminum plate [128]. This study used a non-scanning LDV to measure wave data in a circular pattern around the defect. The focus of the effort was directionality patterns of the notch scattered wavefield at several different wave incidence angles to the notch.

In one of the journal articles most directly relevant to the research presented in this dissertation, Lu et al. reported on an FEM and experimental investigation of S_0 mode Lamb wave scattering from through-thickness simulated cracks in aluminum plates, including the calculation of TC and RC via the maximum Hilbert amplitude method [129]. While this investigation had some similarities to the work presented in this dissertation, the experimental and signal processing techniques differed significantly from those applied in this research.

The test article contained a mechanically cut notch instead of a fatigue crack. This implies there could be no wave energy actually propagating *through* the notch, as illustrated by Figure 17. Instead, the transmission coefficients would represent wave energy diffracting around the notch and continuing on in the same direction. Signal excitation and measurement was conducted using 2 bonded excitation transducers (mounted on the top and bottom of the plate in order to allow for S_0 mode isolation, as described previously in this chapter), and 3 measurement transducers. The crack was offset from the excitation transducers resulting in a wave incidence angle of approximately 30° from normal to the notch. The measurement transducers were located such that one transducer was on the opposite side of the notch from the excitation source, one was at a location where the reflected wave packets would pass based on the incidence angle, and the last was placed as to provide an equidistant

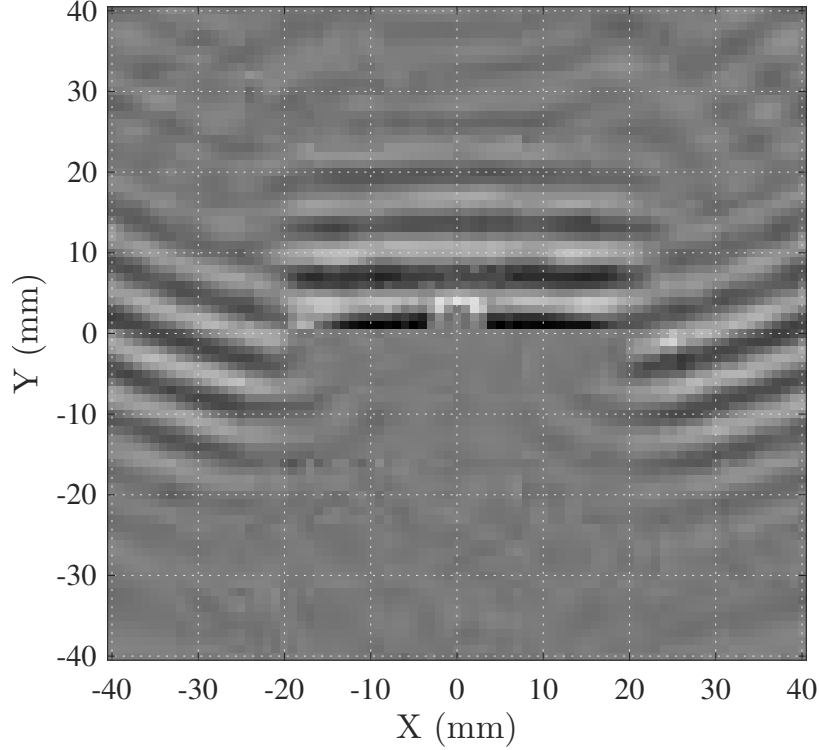


Figure 17. In-plane velocity field image of Lamb waves interacting with an EDM notch in an aluminum plate (400 kHz excitation, 51.2 μ s after excitation).

reference measurement away from the notch. The investigation was limited to fd of 1 MHz $\cdot$ mm and below, or approximately 60% of the maximum fd values tested in this research. Finally, while multiple notch lengths were investigated, only one wave mode was examined. However, despite these differences, the reported results are still likely to be of interest when analyzing the results of this research.

Relevant findings reported by Lu et al. included a reduction of TC across all investigated frequencies as notch length increased, with the exception of the two highest frequencies (500 kHz and 600 kHz) where TC increased from the baseline value of 1.0 (no notch) to a higher value before decreasing with increasing notch length. The opposite was true for RC up to a certain point, after which RC values decreased as notch length increased, only to increase again at an even longer notch length. The notch length at which these reversals occurred varied with excitation

frequency, implying a possible relationship between notch length, wavelength, and RC. Figure 18 presents the FEM based TC and RC results plotted against the ratio of crack length to wavelength of the excitation signal.

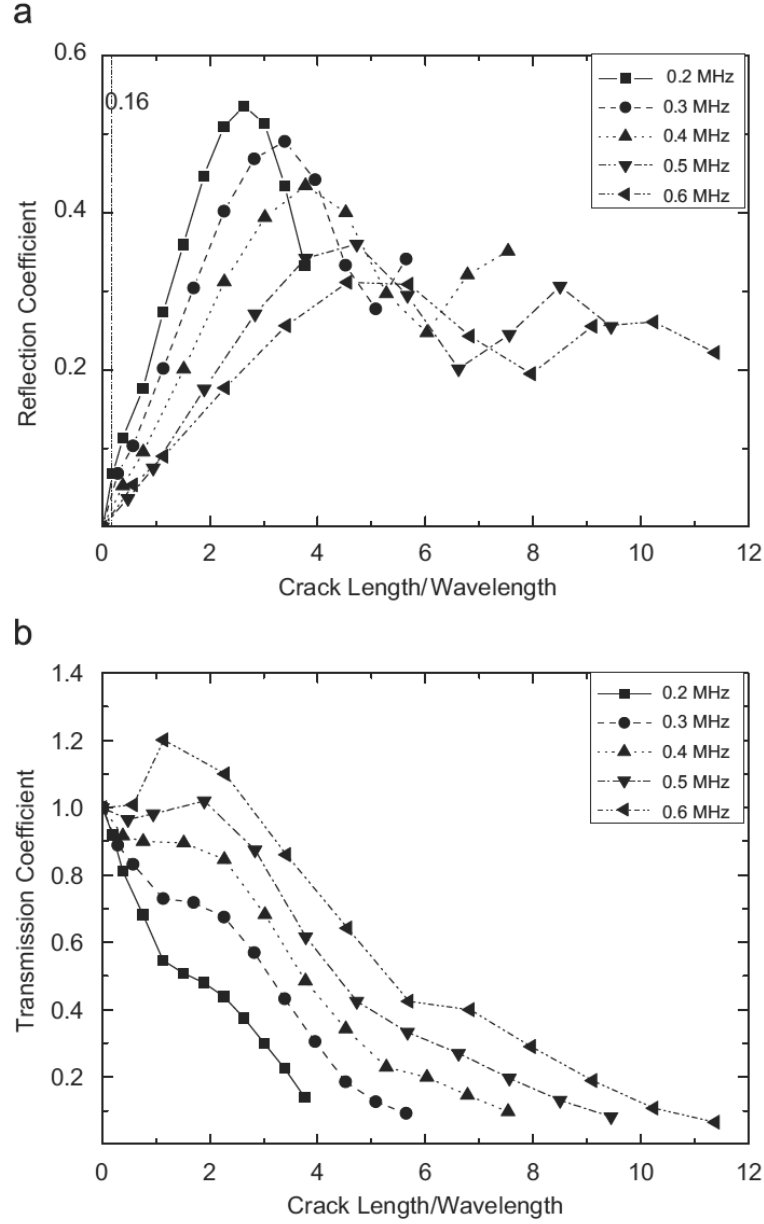


Figure 18. FEM generated RC and TC in terms of notch length normalized by wavelength: (a) RC, (b) TC [129].

III. Experimental Methodology

3.1 Test Articles

As stated in Chapter I, the overall objective of this research was to compare the interaction of Lamb waves with similar cracks grown under varying load spectra, specifically low-cycle vs. high-cycle fatigue. In order to increase confidence in the results and address lessons learned during initial experimental attempts [130], the first experimental objective was to produce test specimens with subjectively similar cracks.

As shown in Figure 19, each test specimen was a 610 mm long by 305 mm wide by 3.175 mm thick plate manufactured from 6061-T6 aluminum and cut into a “dogbone” shape via a computer numerically controlled (CNC) water jet cutting machine. The width of the center test section was 254 mm. The origin of the reference Cartesian coordinate system was established as the center of the front surface of the plate, with the x -axis running horizontally, y -axis running vertically, and the z -axis perpendicular to the surface of the plate. A 6.35 mm diameter hole (representing a typical fastener hole for a structural plate of this thickness) was made in the center of each specimen using electron discharge machining (EDM). EDM notches approximately 0.15 mm in length were placed on either side of this hole on the x -axis in order to produce local stress concentrations and facilitate fatigue crack growth from a predictable starting location.

Fatigue Cycling.

Three test specimens were prepared, each mounted in a set of mild steel grips using twenty two 12.7 mm diameter grade-8 bolts and loaded into a 500 kN capacity Material Test Systems (MTS) uniaxial fatigue test machine, as shown in Figure 20.

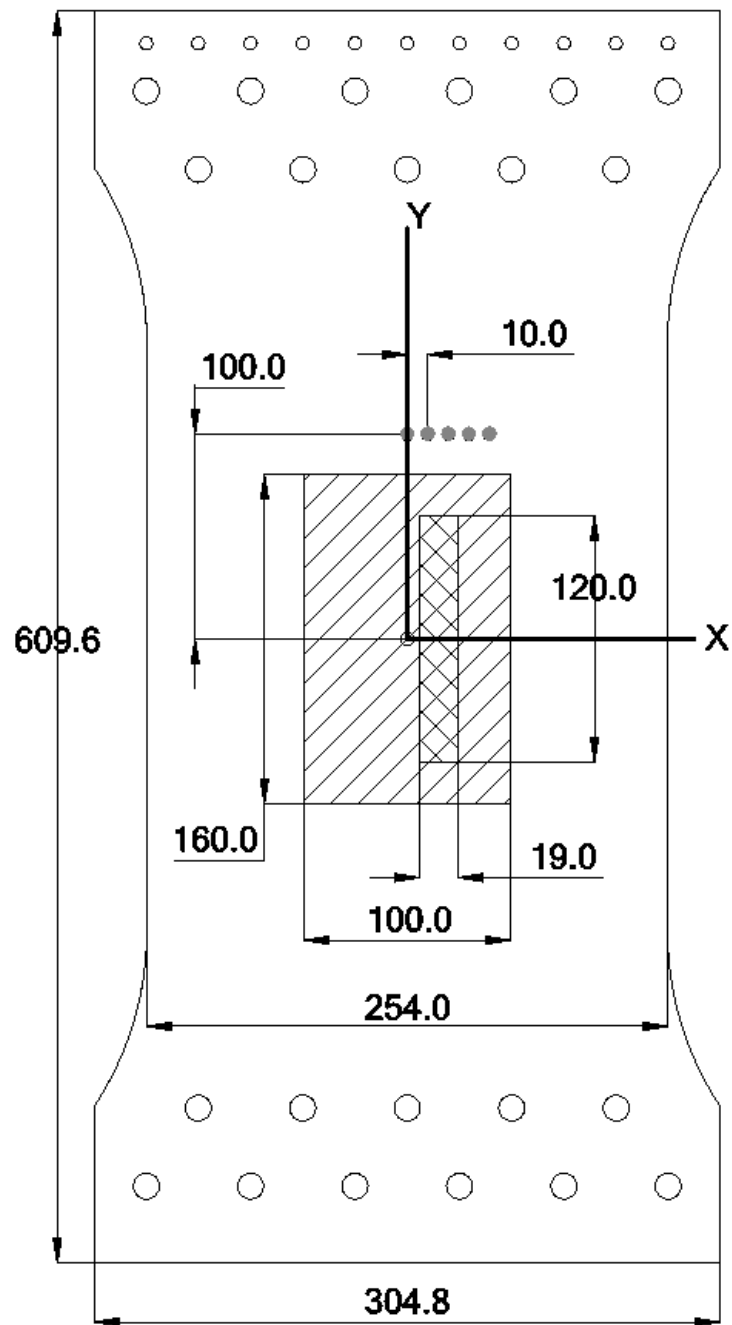


Figure 19. Aluminum "dogbone" test specimen (all dimensions in mm).



Figure 20. Example test specimen with retro-reflective film installed in MTS.

Each test specimen was marked with two vertical lines at $x=\pm 20$ mm and subjected to constant amplitude (100%/10%) sinusoidal tension loading at room temperature while being visually monitored for crack growth. Initially, attempts were made to use crack detection sensors to automatically stop fatigue cycling at a given crack length; however, the results demonstrated too much variation in the resulting crack lengths. Once a crack was observed to reach both marks on each specimen, cyclic loading was stopped. Specific loading and crack length data for two low- and one high-cycle fatigue crack specimens are shown in Table 1.

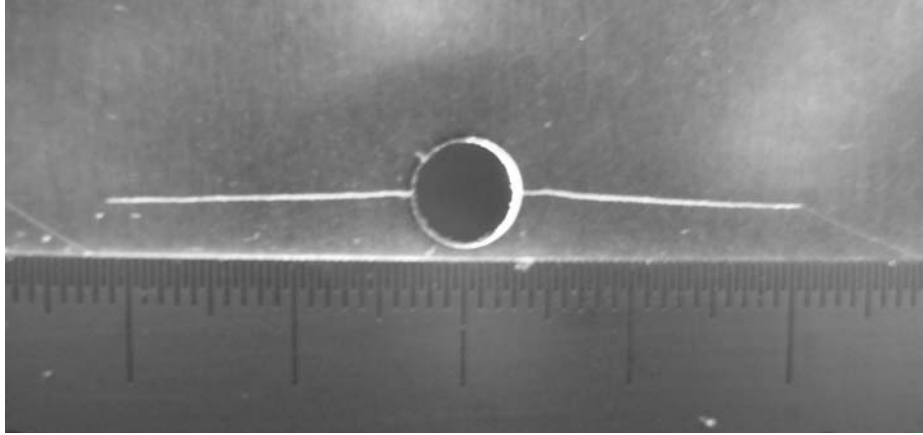
Table 1. Fatigue Loading and Crack Data

Test Specimen	Max/Min Load (kN)	Stress (% F_{ty})	Cycles (x1000)	Crack Length (mm)		
				- x	+ x	Total (incl. hole)
HCF	48.9/4.89	62.0	363	18.6	17.4	42.3
LCF1	89.0/8.90	112.7	55.7	18.7	18.6	43.6
LCF2	133.5/13.35	169.1	15.9	18.3	18.3	42.9

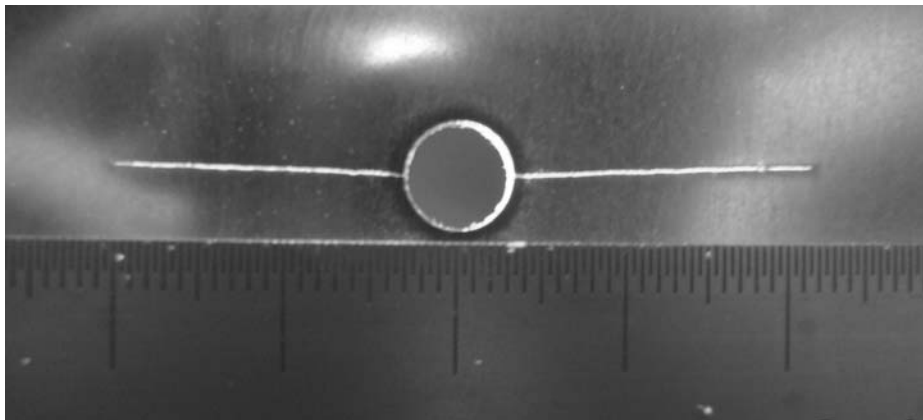
It should be noted that the generally accepted definition for low-cycle fatigue (LCF) is that the applied load is large enough that plastic deformation of the material is expected to take place during each loading cycle *and* that failure occurs at or before 10^4 cycles. This dissertation deviates somewhat from the traditional fracture mechanics definition in an attempt to meet the objective of comparing Lamb wave interaction between cracks as similar to one another as possible and, ideally, *closed* along their entire length (though achieving the latter under an LCF loading profile would prove to be difficult). Excessive plastic deformation (created either through increased mechanical loading or by allowing the crack to grow longer) would only increase the probability of a crack that was permanently open along a significant portion of its length (as was seen in initial experiments [130]). Based on finite element

modeling via SIMULIA Abaqus[®] and Al 6061-T6 material properties as listed in the Federal Aviation Administration (FAA) Metallic Materials Properties Development and Standardization report (AR-MMPDS-01) [131], both LCF specimens underwent loading large enough to exceed the tensile yield strength and cause plastic deformation beginning at the first cycle of loading. Though cracks had begun to form prior to 10^4 cycles, both specimens underwent more than 10^4 cycles to reach the desired crack length.

After cyclic loading was completed for all 3 test specimens, the resulting cracks were treated with fluorescent penetrant dye and photographed under ultra-violet light, as seen in Figures 21 to 23. The software tool SketchUp[®] was used to import the photos, scale them appropriately, and estimate the crack length measurements listed in Table 1.

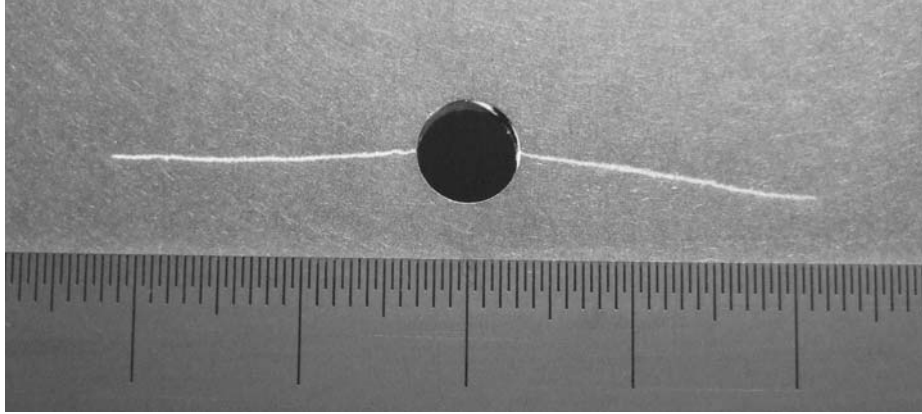


(a) HCF Crack Front Side.

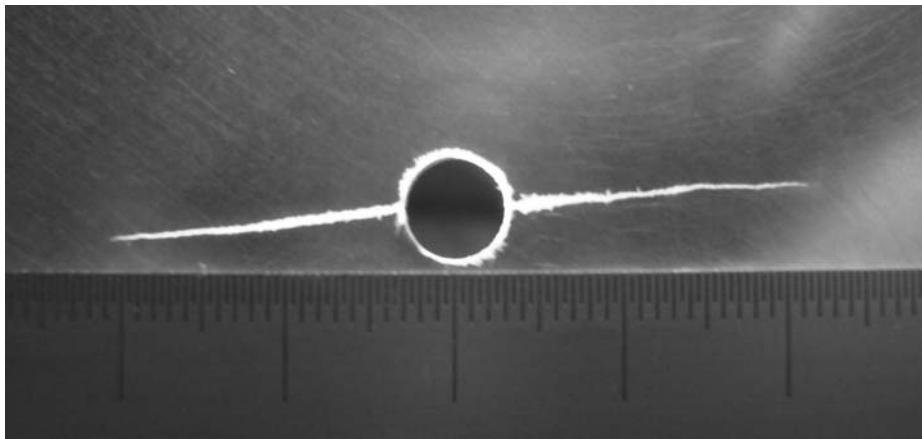


(b) HCF Crack Back Side.

Figure 21. High-Cycle Fatigue (HCF) Crack Images (ruler scale in mm).

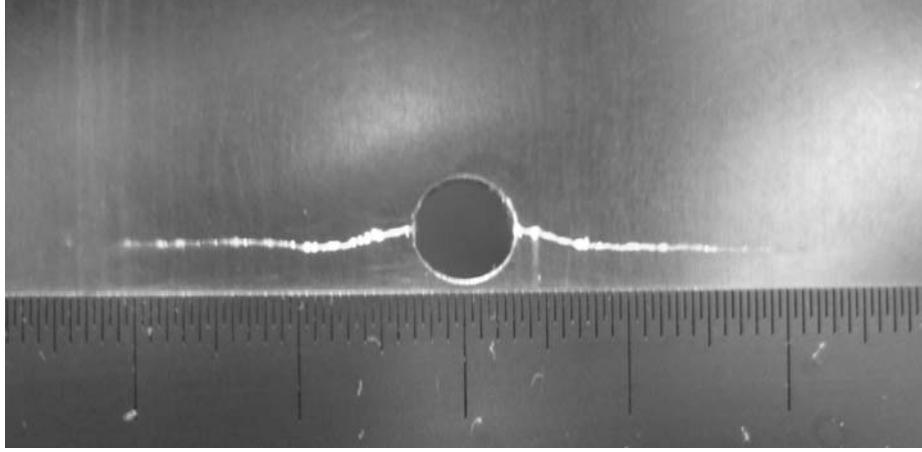


(a) LCF1 Crack Front Side.

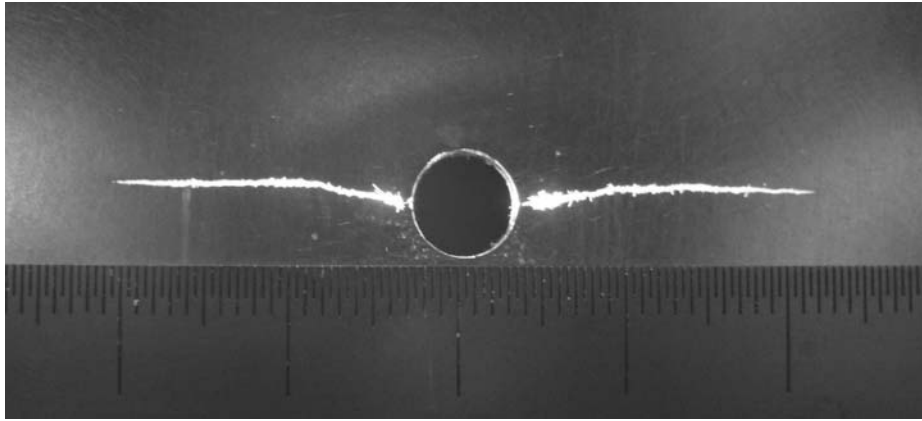


(b) LCF1 Crack Back Side.

Figure 22. Low-Cycle Fatigue Specimen 1 (LCF1) Crack Images (ruler scale in mm).



(a) LCF2 Crack Front Side.



(b) LCF2 Crack Back Side.

Figure 23. Low-Cycle Fatigue Specimen 2 (LCF2) Crack Images (ruler scale in mm).

3.2 Data Collection

Retro-Reflective Film.

Once each test article had been photographed, a square (approximately 180 mm in length per side) of retro-reflective film was applied to the front side of each test article. This material, a very thin adhesive film covered in microscopic glass beads, improves measurement signal to noise ratio (SNR) by increasing the amount of laser energy returned to the scanning laser Doppler vibrometer (SLDV), particularly when the incident laser beam is not perpendicular to the surface being measured (as is

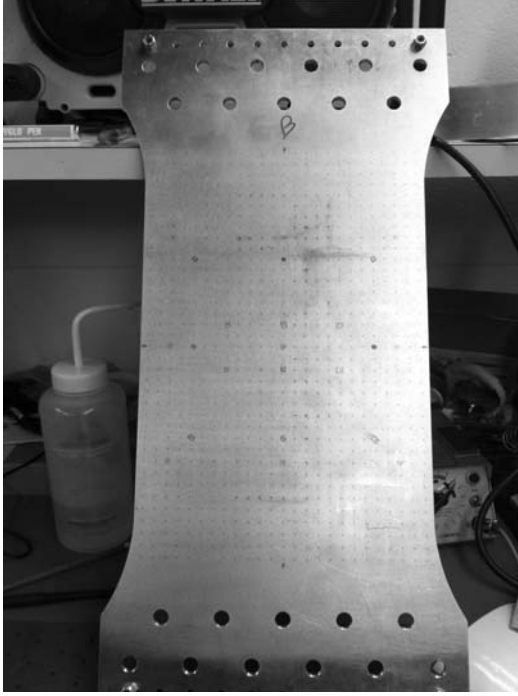
typically the case with a 3D-SLDV). Correct application of this material required practice and patience in order to ensure no wrinkles or air bubbles were present that might affect measurements. The best technique was found to be peeling only a small portion of the backing away on one edge, attaching that edge to the test article, then working slowly towards the opposite side of the film using a small squeegee while simultaneously peeling the backing away. Any small bubbles were removed by slicing a small slit in the film with a razor blade and then forcing out the air with the squeegee. Large bubbles or wrinkles typically required the film to be completely removed, the dogbone cleaned with acetone, and a new piece of film applied. An example test specimen with retro-reflective film installed can be seen in Figure 20.

Alignment Template.

In order to allow for precise and repeatable installation of transducers as well as geometric alignment of the SLDV for each test specimen and data collection session, a template was used to mark precise locations on each test article. This template was another 6061-T6 aluminum dogbone CNC machined with a regular grid of 1 mm diameter holes at 1 cm spacing in both the x and y -directions. As shown in Figure 24, the template and test specimen were bolted together and a mechanical pencil was used to place alignment marks at 8 separate locations around the perimeter of the retro-reflective film (outside the measurement area), as well as the transducer mounting locations.

Piezoelectric Transducers.

Five 6.35 mm diameter by 0.254 mm thick lead zirconate titanate (PZT) transducer disks were bonded to each dogbone using M-Bond 200 cyanoacrylate adhesive. The specific PZT material used was APC 850, manufactured by American Piezo



(a) Dogbone Marking Template.



(b) Marking an alignment point.

Figure 24. Use of geometric marking template.

Ceramics, Inc. As shown by the gray circles in Figure 19 and photographed in Figure 25, the transducers were designated PZT A through E and were centered at the coordinates listed in Table 2 (coordinate system shown in Figure 19).

Table 2. PZT Transducer Installation Coordinates

Transducer Label	Center Coordinates (x, y) (mm)
PZT A	(0,100)
PZT B	(10,100)
PZT C	(20,100)
PZT D	(30,100)
PZT E	(40,100)

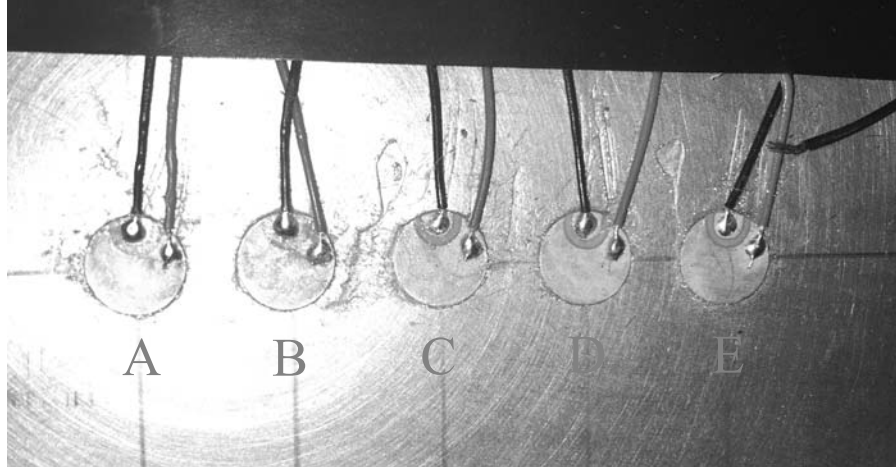


Figure 25. Installed PZT Transducer Array.

3.3 Data Collection

3D-SLDV Alignment.

After each specimen was prepared, installed in the MTS, and the MTS was set to the desired static load, the next step was to perform a geometric alignment of the 3D-SLDV. The specific SLDV used for these experiments was the Polytec® PSV-400-3D-M, as shown in Figures 26 and 27. This system was designed for full-field vibration measurements at excitation frequencies up to 1 MHz. The system made surface velocity measurements by evaluating the Doppler frequency shift of the laser energy reflected from the surface of the test article. The SLDV system included three PSV-I-400 scanning heads mounted on a stand with motorized elevation controls and a rack mount cabinet containing the scan head controllers, junction box, and data collection computer. The center/top scanning head was equipped with a geometry scan unit, used to measure the precise distance (± 1 mm) from the scan head to the test article. In addition, a high-definition video camera was mounted on the stand near the center of the three scan heads. The geometry scan unit and video camera worked together with the Polytec® Scanning Vibrometer (PSV) software suite to produce the



Figure 26. Polytec PSV-400-3D-M SLDV Scan Heads.

best geometric alignment possible for the system.

The alignment process was fairly straightforward. The user opened the 3D alignment dialog of the PSV software and, using a hand controller, moved the the laser spot for each scan head until it was at one of the pre-marked alignment points on the test article. Once all three heads' laser spots were on the target, the known coordinates for that calibration point were entered into the software. This process was repeated for anywhere from 3 to 7 calibration points. After at least 3 points were entered, the software would report its estimated alignment accuracy. The alignment accuracy goal for these experiments was less than or equal to 0.5 mm, which was typically achieved using 4 or 5 points. In some cases, the desired accuracy wasn't achieved even using 7 alignment points. In these cases, the alignment was started anew and a different combination of alignment points was tried. Detailed records on alignment accuracy weren't maintained (per the PSV software manual [132], the reported accuracy is an



Figure 27. Polytec PSV-400-3D-M SLDV Equipment Rack.

estimate and not guaranteed); however, a reported alignment accuracy of 0.3 mm to 0.5 mm was common throughout the experiments presented in this dissertation.

Lamb Wave Excitation and Measurement.

Data collection was performed 7 times for each test specimen, varying the excitation source and static load, as listed in Table 3.

Table 3. Test Conditions for Each Dogbone Specimen

Excitation Source	Static Load (kN)
PZT A	0
PZT A	22.2 (tension)
PZT A	2.22 (compression)
PZT B	2.22 (compression)
PZT C	2.22 (compression)
PZT D	2.22 (compression)
PZT E	2.22 (compression)

The tension load value was selected such that it would be expected to at least partially open each crack, but not be so large as to cause additional damage to the test specimens during data collection. A higher compression load value was initially desired; however, the 2.22 kN value was finally chosen in order to keep well away from the estimated buckling load for the plate. Even with this small load value, it was expected that the compression cases would demonstrate increased wave transmission and reduced reflection as compared to the zero load case.

An AGILENT® model 33120A arbitrary waveform generator was used to produce the excitation signal: a 200 μ s long, 0 kHz to 600 kHz linear chirp modified by a tapered cosine (Tukey) window, as shown in Figure 28. As discussed in Chapter II,

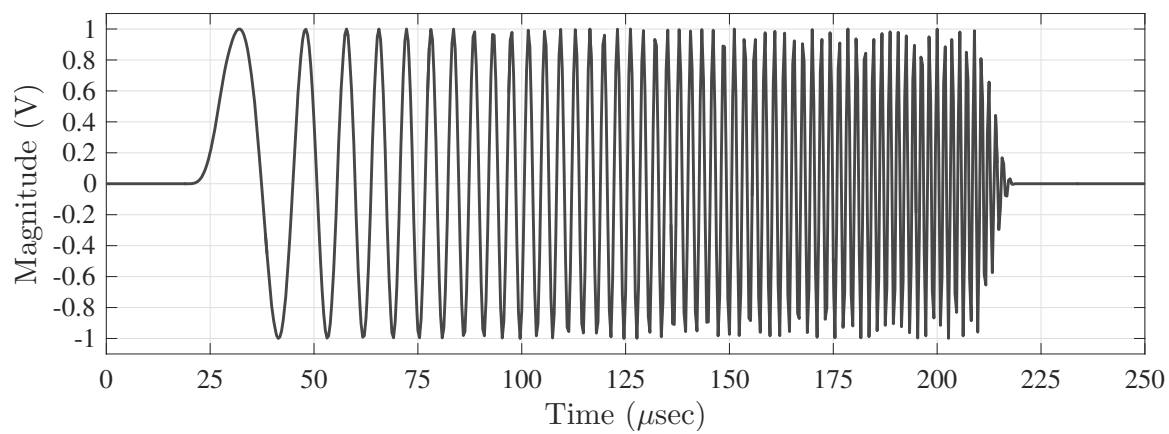


Figure 28. Excitation Chirp Signal.

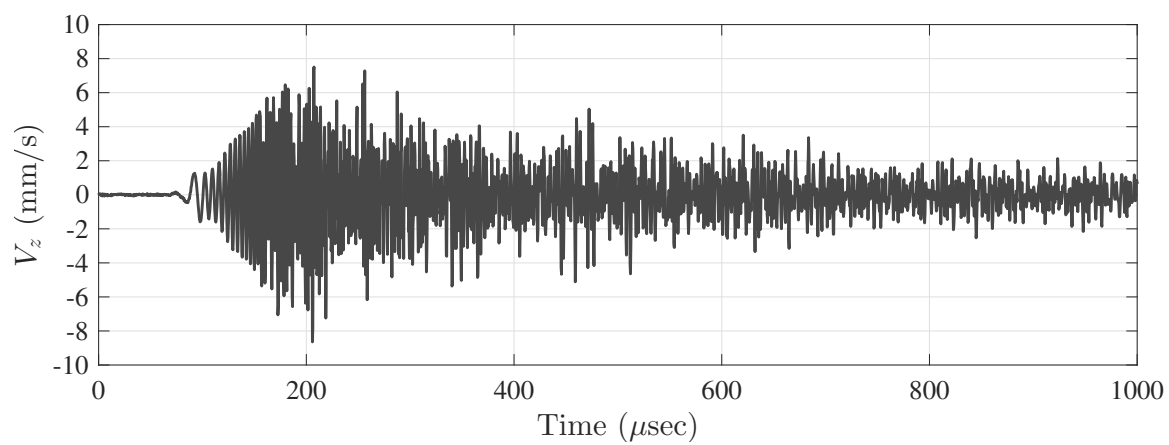


Figure 29. Example SLDV Measured Response to a Chirp Excitation.

chirp excitation signals enable simultaneous data collection across a wide frequency range, thereby increasing data collection efficiency by reducing the total number of required data collections by (in the case of these experiments) an order of 10. However, the response signals to a chirp excitation, an example of which can be seen in Figure 29, are difficult to interpret. For this reason, responses were manipulated in post-processing as will be described later in the chapter. Excitation signal and measurement timing were synchronized by a 120 Hz square wave generated by the SLDV's onboard waveform generator. The excitation signal from the AGILENT® was routed through a Krohn-Hite model 7500 wideband power amplifier, which boosted the signal to 100 V peak-to-peak (verified using an oscilloscope and 10:1 reducing probe). This amplified signal was used to excite a single PZT transducer, per the conditions listed in Table 3. Figure 30 includes a photo of the excitation signal equipment used in these experiments.

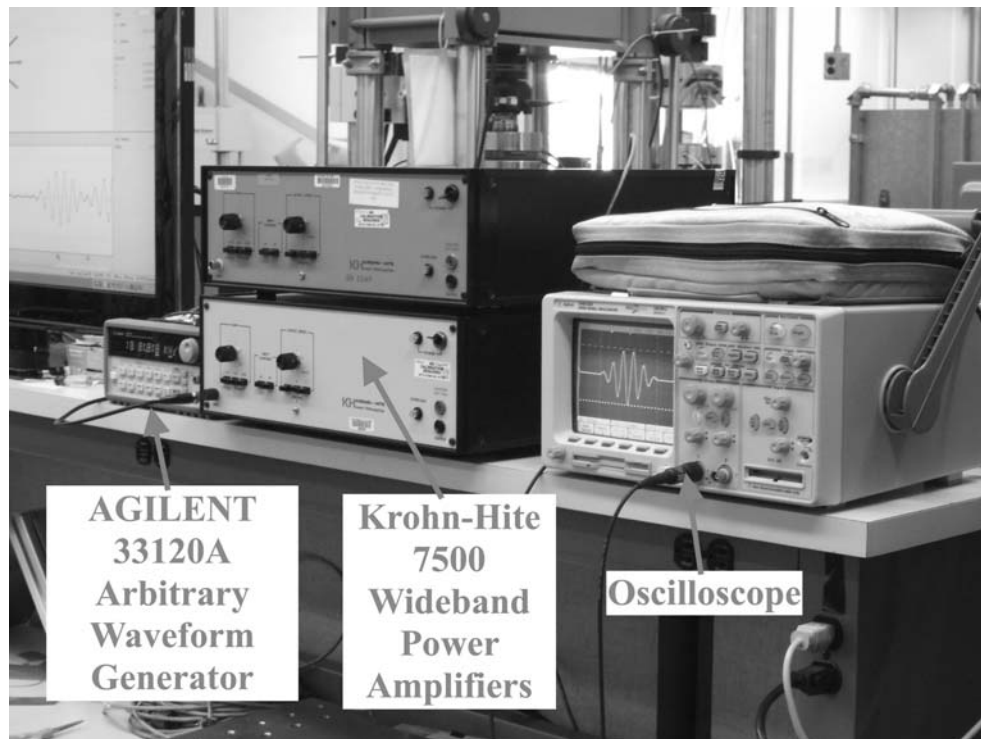


Figure 30. Equipment Used to Generate PZT Excitation Signal.

As depicted by the single-hatched area in Figure 19, the scan area measured 100 mm in x and 160 mm in y , with measurement points located on a 1 mm grid in both directions. This resulted in a total of 16,224 scan points. A sampling rate of 2.56 MHz was used (ensuring the maximum frequency content of the excitation signal fell below the Nyquist frequency of 1.28 MHz) for a duration of 1.6 ms, resulting in 4096 samples in each time history. Data for each point was averaged 60 times in order to reduce measurement noise. These parameters resulted in each data collection session taking approximately 10 hours. Following data collection, scan results files were converted from the proprietary Polytec[®] file format to a MATLAB[®] MAT file in order to facilitate signal processing and analysis.

In addition to the primary chirp responses, several scans were made using 100 kHz and 400 kHz 5-1/2 cycle, Hanning windowed sine bursts for PZT excitation. These results were used during the development of the chirp filtering MATLAB[®] code in order to verify proper function, as will be presented in the next section.

3.4 Signal Processing

The signal processing algorithms used in this project already existed in the literature; however, to the best of the author's knowledge (other than the author's initial trial experiments [130]) this is the first time they have been applied to this specific problem. Following experimental data collection, four additional processing steps were applied in order to produce the final results, transmission and reflection coefficients of both A_0 and S_0 Lamb wave modes at excitation frequencies from 50 kHz to 500 kHz. A flowchart of these steps is shown in Figure 31.

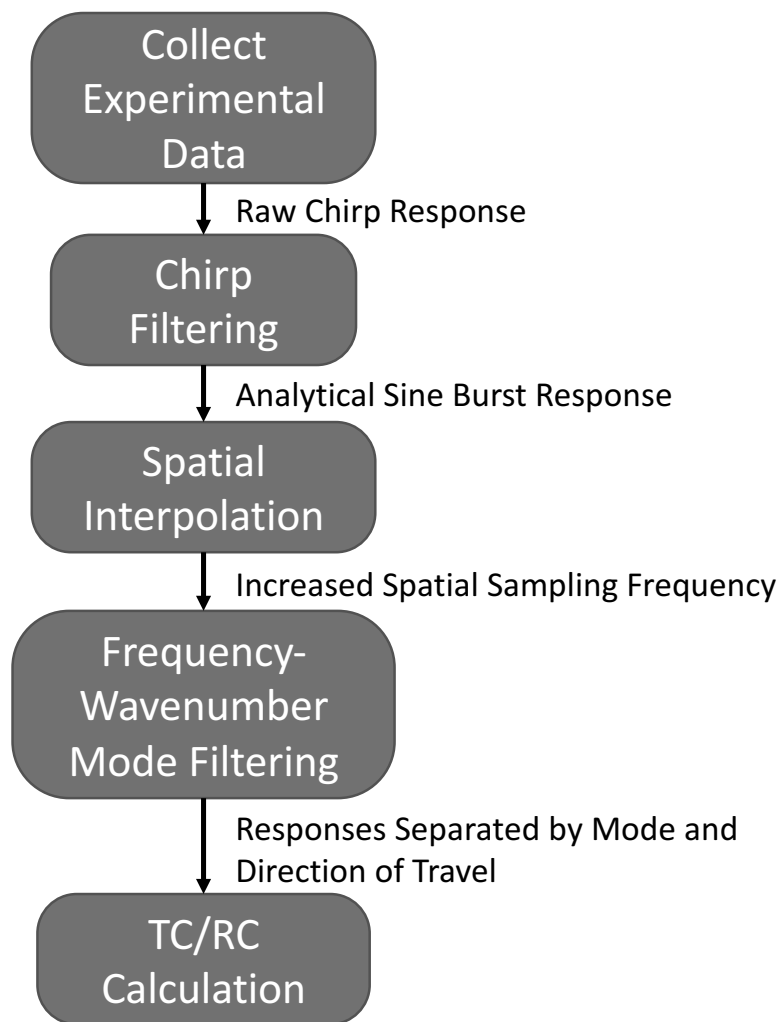


Figure 31. Flowchart of Major Signal Processing Steps.

High Performance Computing Center.

The signal processing steps described in the rest of this chapter were computationally demanding. Many thousands of fast Fourier transform (FFT) and inverse FFT operations were required to process a single data set. Due to the sheer volume of experimental data and based on the time to fully process a single data set, the total time necessary to complete all data reduction on a desktop computer was estimated at roughly four to six months. Because of this, the author modified the original MATLAB[®] code to run in parallel on several of the AFRL High Performance Computing (HPC) systems. While these modifications posed their own difficulties, in the end, use of massively parallel computing resources reduced total signal processing time for all data reduction steps from several months down to approximately six weeks, including the time required to modify and debug the code.

Chirp Filtering.

As discussed in Chapter II, Michaels, et al. have made extensive use of chirp filtering in their guided wave based research [43, 59, 78] in order to improve the efficiency of full-wavefield data collection, reduce measurement noise, etc. The application of this technique is limited to linear systems. While the experiments presented here do contain potential sources of non-linearity (crack tip singularities, plastic zones, etc.), these effects are minor and are primarily expected to affect higher-order Lamb wave modes outside the frequency range being investigated in this dissertation.

Following the development of the mathematics as presented by Michaels, et al. [78], if we assume a broadband time-domain input signal, $s_c(t)$ and the response to that signal, $r_c(t)$, they are related by

$$r_c(t) = h(t)s_c(t) \quad (21)$$

where $h(t)$ is the impulse response of the entire system, including excitation source and measurement system effects, etc. Taking the Fourier transform and looking at the frequency domain, this becomes

$$R_c(\omega) = H(\omega)S_c(\omega) \quad (22)$$

where $H(\omega)$ is the transfer function of the entire system from input to output. If $s_d(t)$ is the input signal of interest in the time domain, the response to that input in the frequency domain is given by

$$R_d(\omega) = H(\omega)S_d(\omega). \quad (23)$$

Because $s_c(t)$, $r_c(t)$, and $s_d(t)$ are all known, a frequency domain filter can be constructed. The time domain response to the desired input, $r_d(t)$ can be calculated by taking the inverse Fourier transform of

$$R_d(\omega) = R_c(\omega)G(\omega) \quad (24)$$

where $G(\omega)$ is a filter defined as

$$G(\omega) = \frac{S_d(\omega)}{S_c(\omega)}. \quad (25)$$

While the focus here is on chirp input signals, the same principles apply to other broadband excitation signals such as pseudo-random noise. As long as the desired excitation signal falls within the frequency range of the broadband excitation signal and the system is linear, the technique should work.

Figures 32 and 33 present the results of this chirp filtering technique for a single scan point. Figure 32 compares the analytical velocity response generated via chirp filtering to experimental data collected using a 100 kHz 5-1/2 cycle, Hanning windowed sine burst excitation. Figure 33 provides the same comparison for a 400 kHz sine burst excitation.

In both cases, it can be seen that the chirp filtered response is an excellent match to the experimentally measured response, particularly for the out-of-plane velocity (V_z). This is to be expected because V_z is typically a larger magnitude signal than the in-plane velocity components (V_x and V_y). In addition, as can be seen in both figures, out-of-plane 3D-SLDV measurements typically demonstrate a lower noise floor and therefore higher SNR than in-plane velocity measurements. An additional benefit of the chirp filtering technique can also be seen in both Figures: a reduction of high-frequency noise in the analytical signals as compared to experimental.

Spatial Interpolation.

After chirp filtering was completed on all 21 data sets (7 measurement sets as listed in Table 3 for each of the 3 test specimens), the next step was to increase the scan point density through spatial interpolation. At 500 kHz, the wavelength of the A_0 mode shrinks to approximately 5 mm. In order to increase the spatial sampling frequency

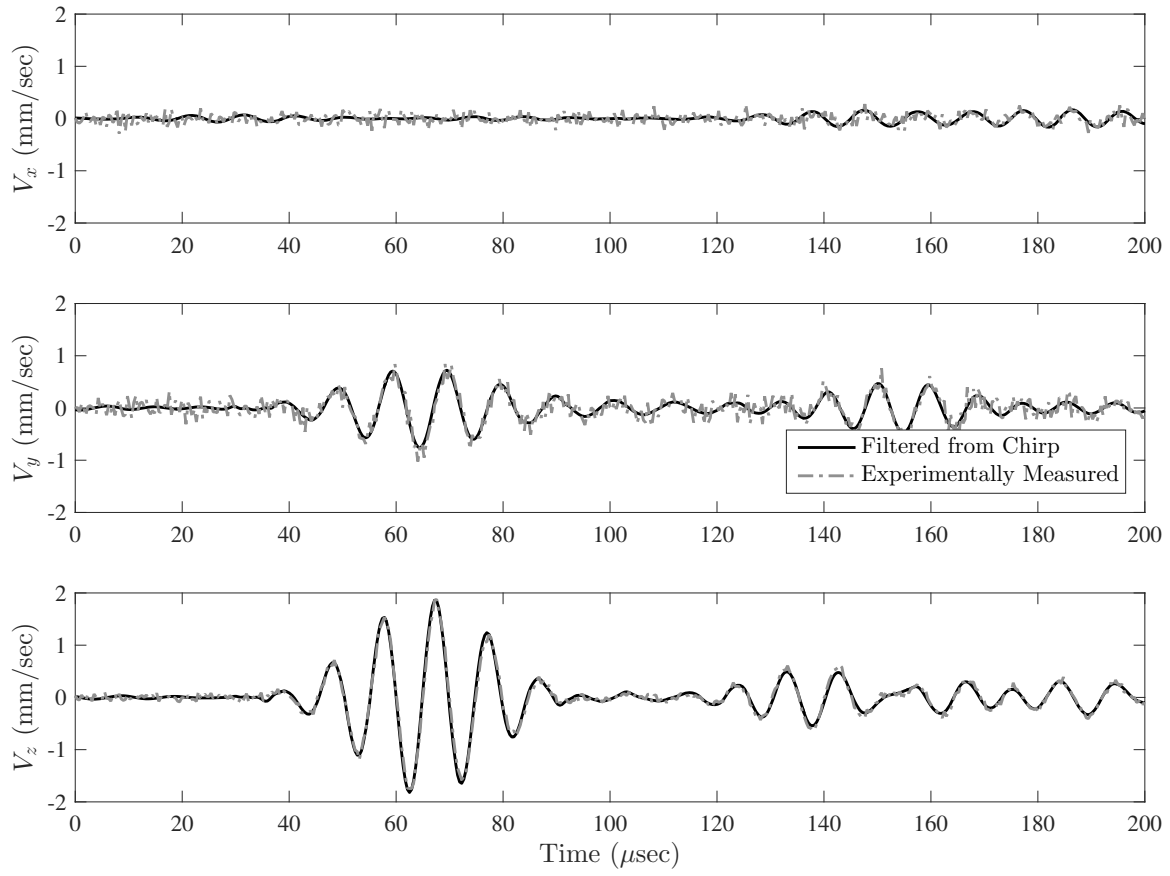


Figure 32. Comparison of Experimental and Chirp Filtered Responses at 100 kHz.

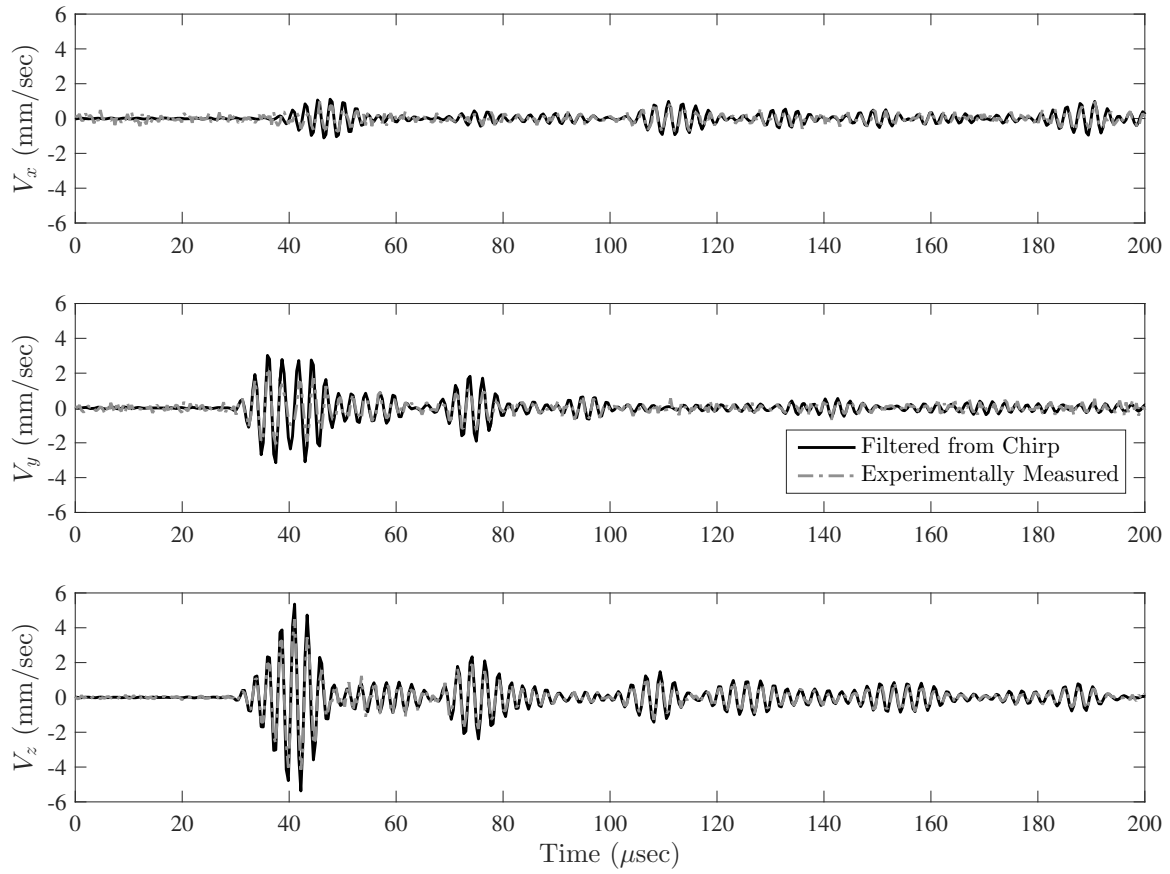


Figure 33. Comparison of Experimental and Chirp Filtered Responses at 400 kHz.

in the y -direction to approximately 10 samples per wavelength at 500 kHz, the two dimensional natural neighbor interpolation method was applied to generate additional points at 0.5 mm spacing in the y -direction, thereby doubling the spatial sampling frequency. This was performed after chirp filtering because the author felt the results would be more reliable and easier to evaluate than attempting to interpolate the broadband chirp response signals. As can be seen in Figure 34, the natural neighbor interpolation method (C1 continuous except at the original sample points, which are not changed during the procedure) produced results very close to a linear (C0 continuous) interpolation and did not extrapolate outside the envelope of the original signal. The cubic and biharmonic spline (both C2 continuous) interpolation methods available in MATLAB[®] had the potential to produce a better interpolation result, but the computational cost was considered too high given the number of data sets to be processed.

It should be noted that this step was not, strictly speaking, necessary. Even without interpolation, the spatial sampling frequency would have been above the Nyquist limit, and the final results would, in all likelihood, be the same.

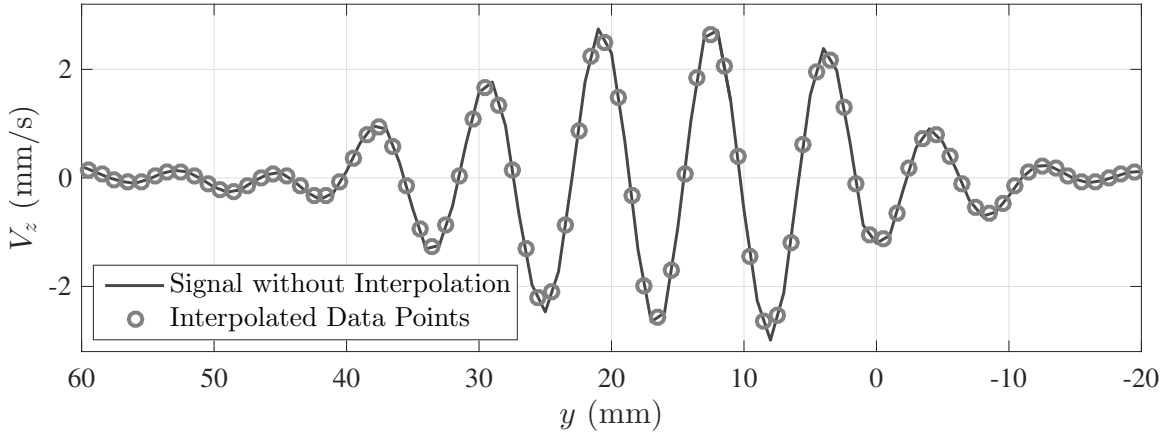


Figure 34. Original 250 kHz Sine Burst (Chirp Filtered) V_z Signal and Interpolated Points along a line at $x = 10$ mm (66 μ s after excitation).

Frequency-Wavenumber Filtering.

Because the final data products for this research are focused on the positive x side of the three crack specimens and the large volume of experimental data collected, only a subset of the originally scanned data points was analyzed in this and subsequent signal processing steps. Specifically, as shown by the double cross-hatched area in Figure 19, the region from $x = 6$ mm to 25 mm and $y = -60$ mm to 60 mm was included.

As discussed in Chapter II, the application of frequency-wavenumber (fk) domain analysis for guided wave problems was introduced by Alleyne and Cawley in 1991 [102]. Frequency-wavenumber mode filtering was introduced later and has been used by numerous researchers [43, 85, 92, 104, 105, 130] as well as being addressed in at least one textbook [23].

The utility of frequency domain filtering techniques has already been demonstrated by the application of chirp filtering in a previous analysis step. Frequency-wavenumber domain techniques combine time to frequency domain Fourier transforms with spatial to wavenumber domain Fourier transforms. Wavenumber represents the spatial frequency of a propagating wavefield and is the inverse of the wavelength, with units of cycles/distance or radians/distance. Spatial data can be transformed along one or more axes, though in the case of experimental guided wave studies, the practical limit is two, as real-world techniques to measure through thickness displacement or velocity fields do not yet exist. When combined with the time to frequency domain transform, a two- or three-dimensional FFT operation is required. In the case of this research, the spatial direction of interest is parallel to the y -axis, since the geometry of the test articles produces a wavefield propagating predominantly in that direction. Therefore the frequency-wavenumber domain filtering techniques presented here require the 2D FFT.

The time-domain response at each data point and the spatial response along each

line of data points parallel to the y -axis are combined in a 2D array and the 2D FFT technique is applied. The resulting 2D array represents the combined fk response of a single line of scan points for the entire analyzed time history. Figure 35 presents a composite of the out-of-plane velocity (V_z) response in the fk -domain for three separate sine burst excitations at 100, 250, and 500 kHz. The dashed and solid lines are the A_0 and S_0 wave mode dispersion curves, respectively. Figure 36 presents a similar composite of the in-plane velocity (V_y) response. Both plots show a much stronger response at negative wavenumbers, indicating the majority of the wave energy is propagating in the negative y -direction, which is to be expected based on the geometry of the test articles.

fk -domain filters can be built by applying window functions along the fk dispersion curves, as shown in Figures 37 and 38. These filters are constructed using Hanning windows along the wavenumber direction and a tapered cosine window along the frequency direction. Figure 37 shows a filter to isolate the A_0 mode propagating in the positive y -direction, and Figure 38 shows the same for the S_0 mode. Filters for each mode propagating in the negative y -direction are achieved simply by inverting the positive wavenumber filters around the frequency axis (using the ‘flipud’ function in MATLAB®).

Figures 39 to 42 show the results of applying these filters to the composite responses in Figures 35 and 36. The figures clearly show that in each of the four cases, only the wave energy corresponding to the desired mode and direction of propagation is retained.

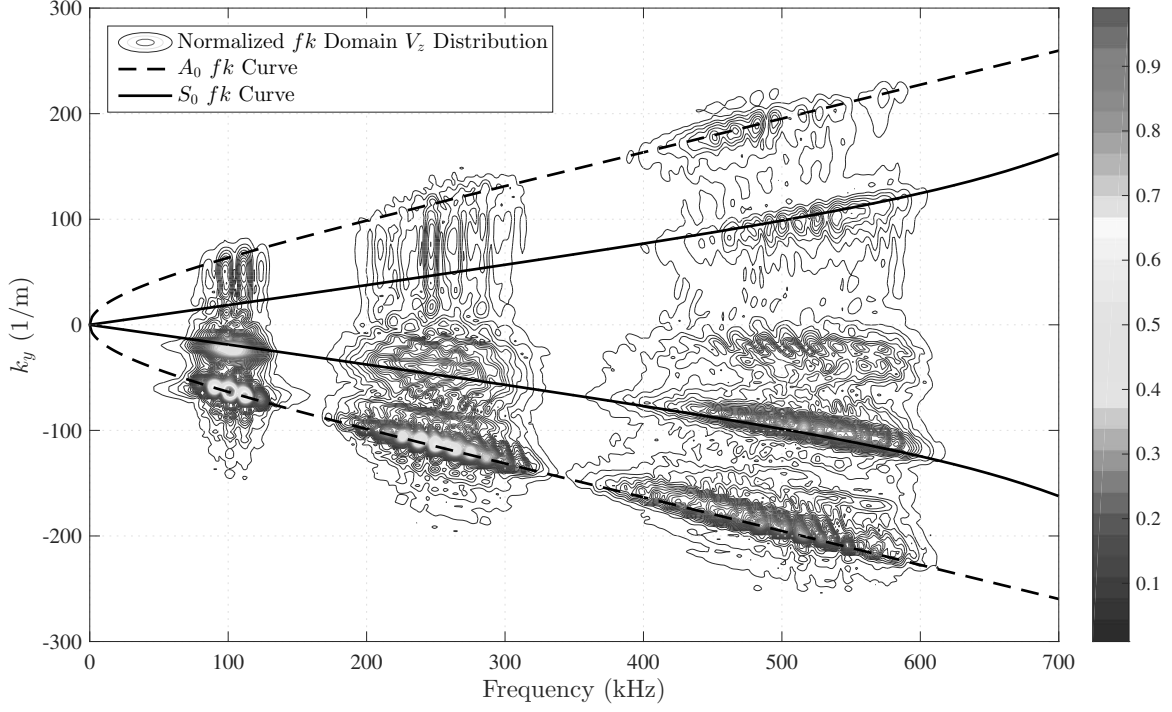


Figure 35. Composite Frequency-Wavenumber V_z Response for Sine Burst Excitations at 100, 250, and 500 kHz.

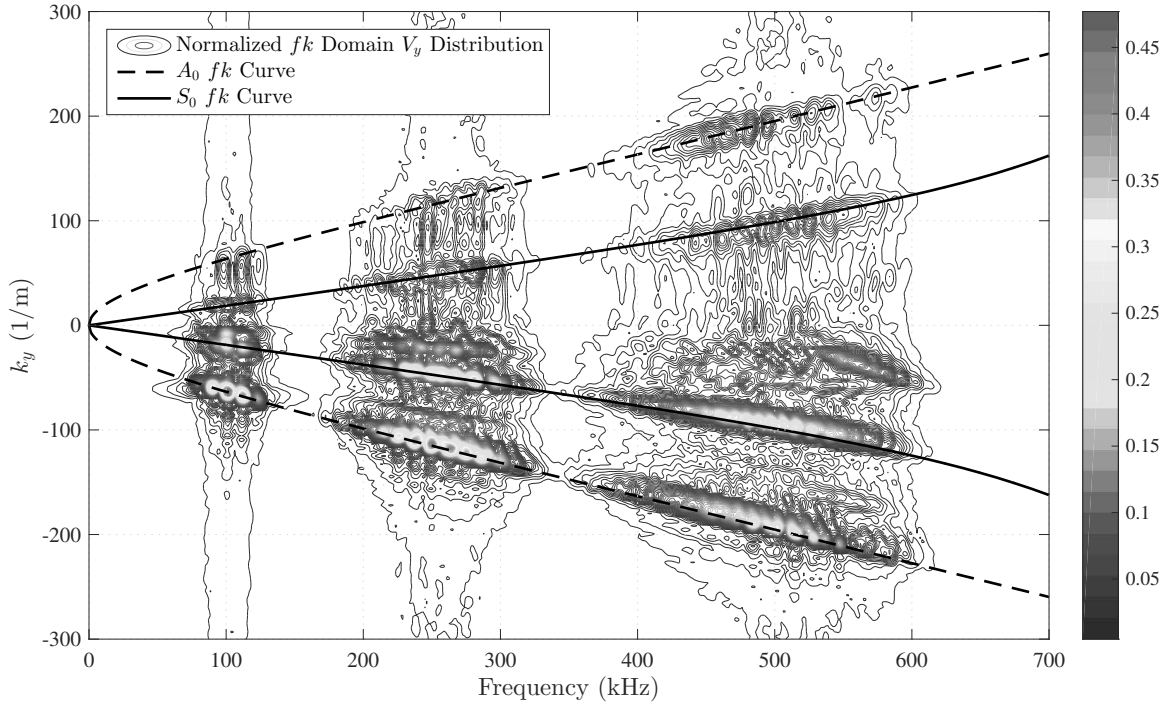


Figure 36. Composite Frequency-Wavenumber V_y Response for Sine Burst Excitations at 100, 250, and 500 kHz.

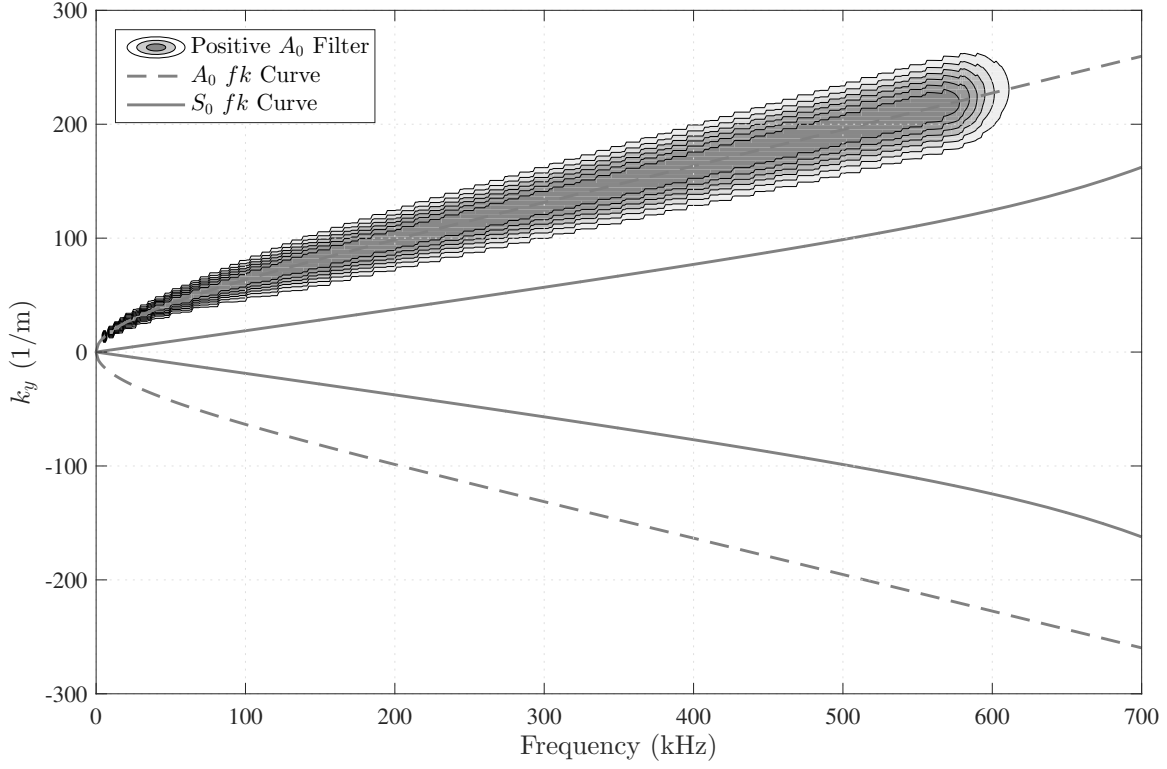


Figure 37. Positive k_y Mode Filter for A_0 .

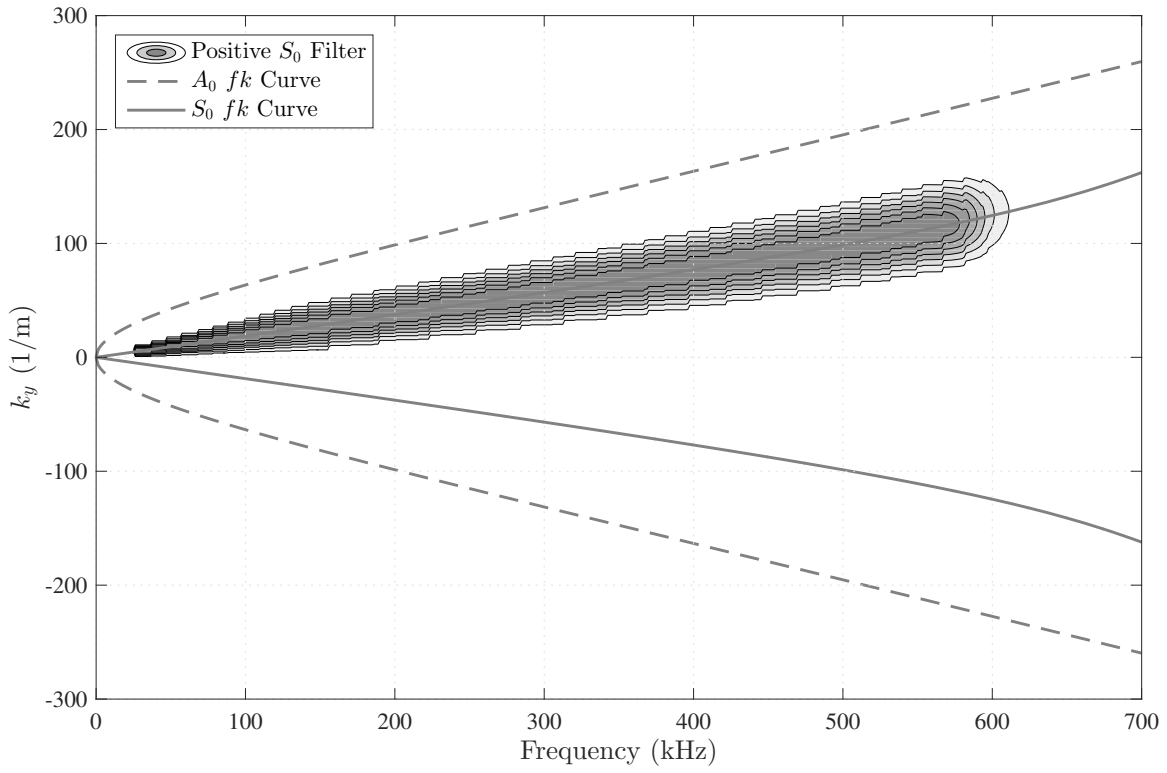


Figure 38. Positive k_y Mode Filter for S_0 .

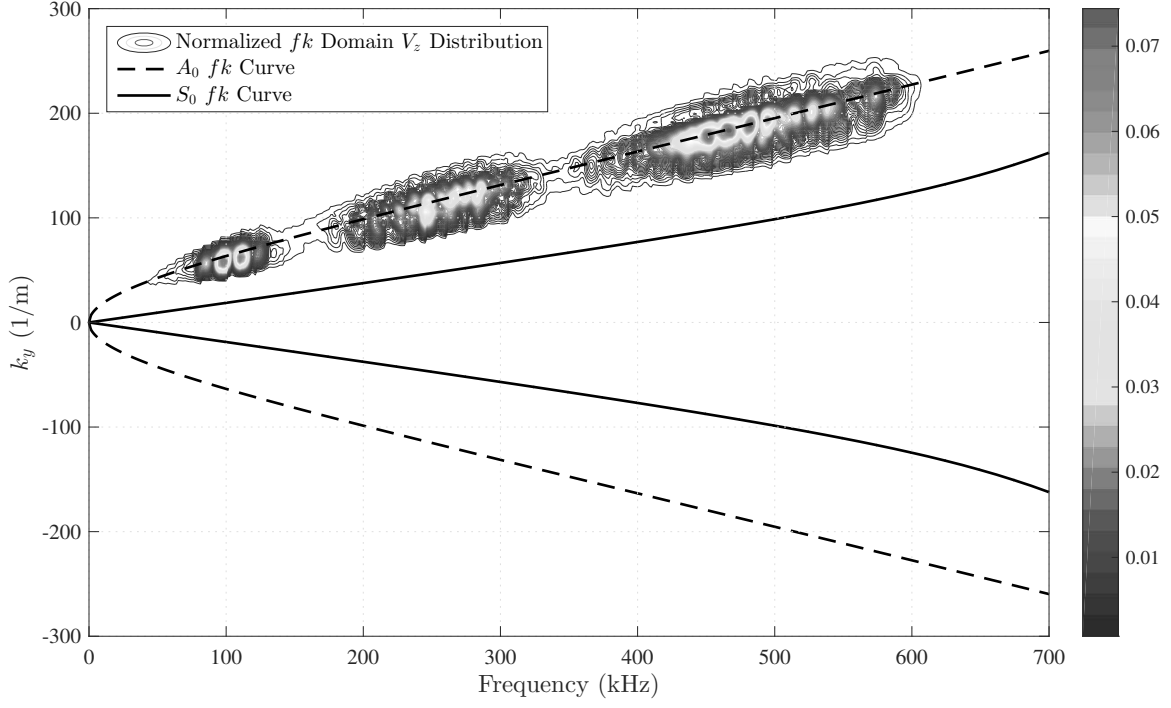


Figure 39. Positive k_y Filtered A_0 mode V_z response.

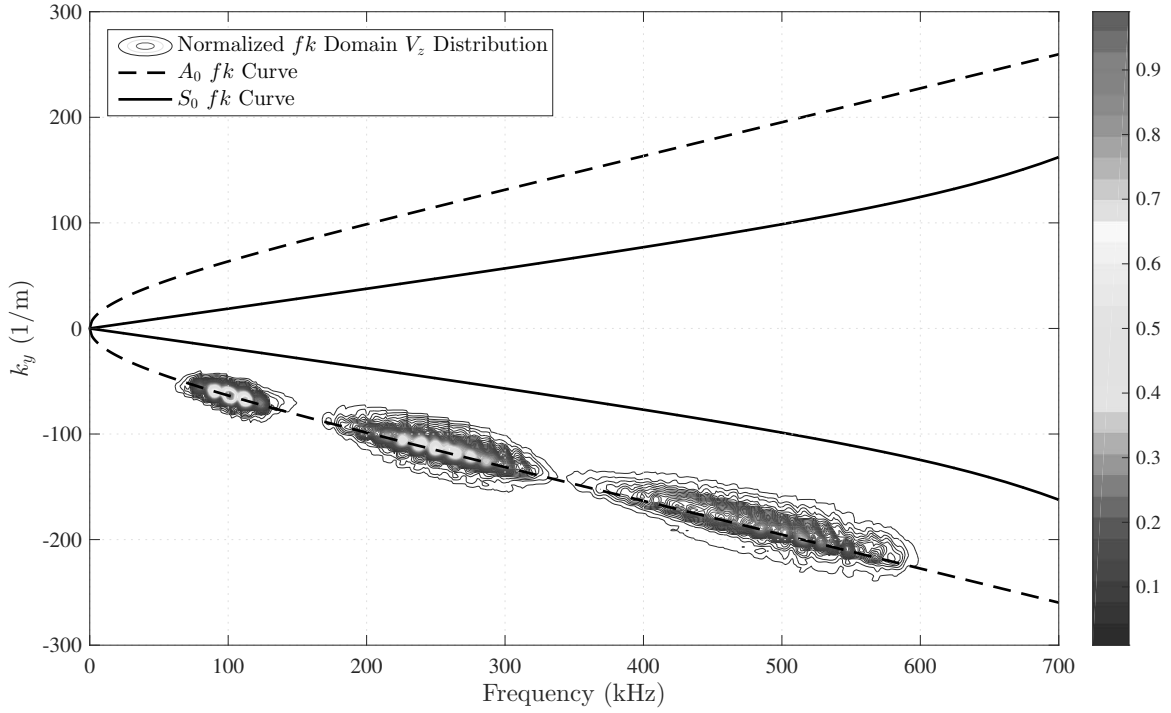


Figure 40. Negative k_y Filtered A_0 mode V_z response.

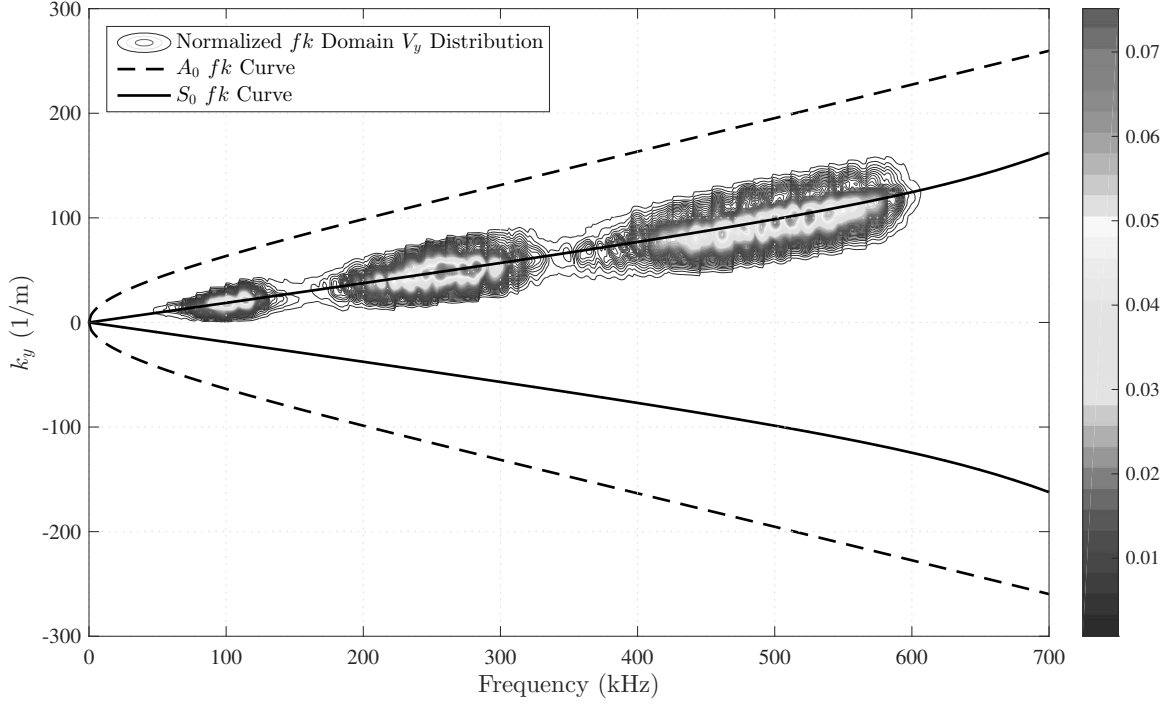


Figure 41. Positive k_y Filtered S_0 mode V_y response.

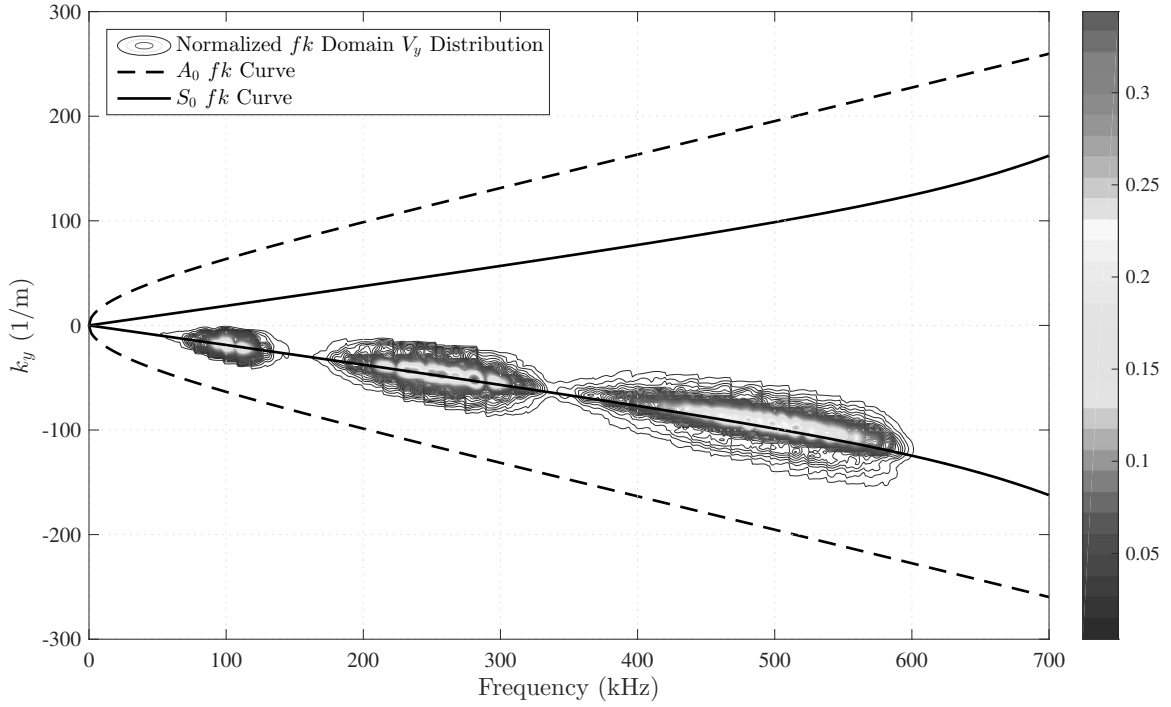


Figure 42. Negative k_y Filtered S_0 mode V_y response.

After filtering, the inverse 2D FFT is applied, resulting in four time domain signals for each analysis point, one for each combination of wave mode and direction of propagation. Figures 43 and 44 show the time histories of these four filtered response signals at a single scan point for both 150 kHz (V_z) and 400 kHz (V_y) sine burst excitations plotted against the original unfiltered time-domain signal. The bottom plot in each figure compares the original signal to the sum of all four filtered signals and clearly demonstrates both the effectiveness of this filtering technique and the relatively small loss of data during the process.

It should be noted that the sum of the filtered signals and the original unfiltered signal do begin to diverge from one another after the time period shown in the plots. The reason for this is straightforward—late in the time history, wave energy reflected off the positive x edge of the test article arrives in the scan area. Because it is propagating predominantly in the negative x -direction, it is filtered out.

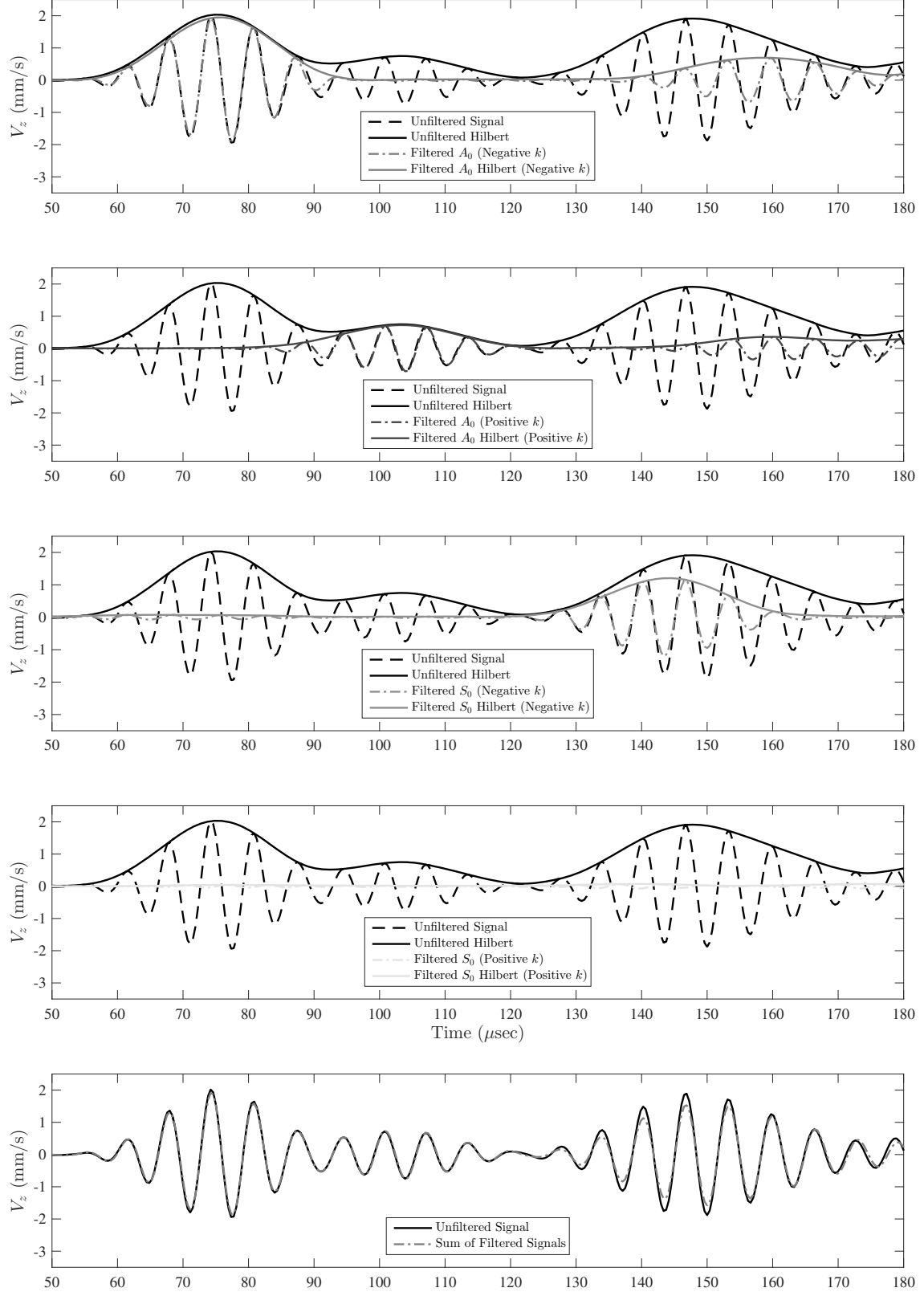


Figure 43. Unfiltered V_z Signal Compared with Mode Filtered Signals: from Top to Bottom, $-y$ Propagating A_0 , $+y$ Propagating A_0 , $-y$ Propagating S_0 , $+y$ Propagating S_0 , Sum of All 4 Mode Filtered Signals (150 kHz Excitation).

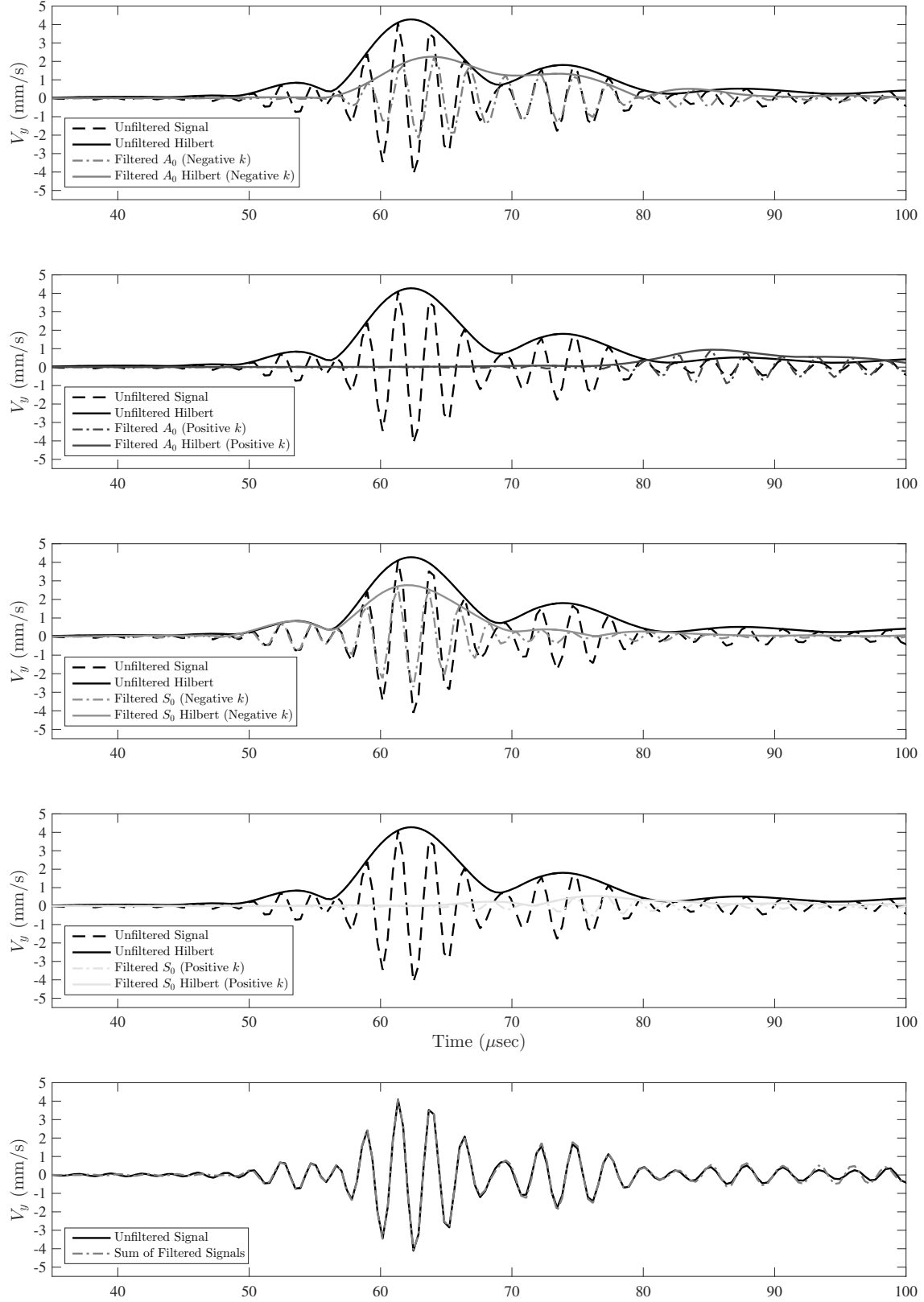


Figure 44. Unfiltered V_y Signal Compared with Mode Filtered Signals: from Top to Bottom, $-y$ Propagating A_0 , $+y$ Propagating A_0 , $-y$ Propagating S_0 , $+y$ Propagating S_0 , Sum of All 4 Mode Filtered Signals (400 kHz Excitation).

Determining Transmission and Reflection Coefficients.

Compared to the previous analysis steps, calculation of the transmission (TC) and reflection coefficients (RC) was relatively straightforward. The basic approach was to compare the incident wave packet for each mode at a point shortly before reaching the crack to either the same wave packet shortly after it passed the crack (TC) or to the corresponding wave packet reflected from the crack (RC). For each test specimen, coefficients were calculated at all x coordinates from 6 mm to 22 mm and two different y distances from the crack: ± 5 mm and ± 10 mm.

Three different calculation methods were used: maximum amplitude, assuming no wave packet dispersion, and assuming wave packet dispersion. In all cases, these calculations were made using the Hilbert transform of the signal, rather than the signal itself. As discussed in Chapter II, the maximum Hilbert amplitude was used by several other researchers to calculate coefficients, as well as during the initial attempts at these experiments [130] and was found to be satisfactory; however, this author chose to investigate several other methods to determine whether they produced significantly different results.

Figure 45 shows how the maximum amplitude and no wave dispersion TC/RC algorithms determine what values to use when calculating coefficients. Both methods begin by finding the maximum amplitude of the incident wave signal prior to the crack, then search within the appropriate time window for the maximum amplitudes of the transmitted (at a point past the crack) and reflected (at the same point as the incident wave) signals. In the case of the maximum amplitude method, the TC is then calculated as the ratio of the transmitted signal amplitude divided by the incident signal amplitude. The no dispersion method is slightly more complicated in that the time duration of the excitation signal is used to determine the start and stop times of each signal to use in the calculation. The area under the Hilbert envelope between

the start and stop time is calculated, and these values (shaded gray in the Figure) are used instead of the maximum amplitude value to calculate the coefficients.

The dispersion method is similar to the no dispersion method in that the area under the Hilbert envelope is used for the calculation; however, the time window is not based on the excitation signal, but determined using a threshold value. The procedure begins the same as the other two methods, finding the appropriate maximum of the Hilbert envelope of each signal. This maximum value is multiplied by a threshold, which determines a cutoff amplitude. The algorithm searches the signal both forward and backward in time from the maximum amplitude point until the value of the Hilbert amplitude reaches this threshold value, and sets the calculation start and stop times at these points in the time history.

Figure 46 illustrates how the method works and one of the potential problems with it—the results are sensitive to the chosen threshold value. As presented in the figure by the solid vertical lines and gray shaded area, too low a threshold value opens the possibility for the inclusion of smaller adjacent wave packets in the calculation. In contrast, the vertical dash-dot lines indicate the calculation time window using the no dispersion assumption, which effectively excludes the small secondary wave packet that arrives shortly after the main packet. Initially, a threshold value of 10% of the maximum amplitude was selected, but the results demonstrated large variations and the value was increased to 15%. While this was an improvement over a 10% threshold, in most cases the resulting coefficients were still significantly different from the other two methods. Increasing the threshold further and re-running the algorithm would likely have brought the results of the dispersion method in line with the other two methods, but (largely due to time constraints) it was decided to include the results using the 15% threshold.

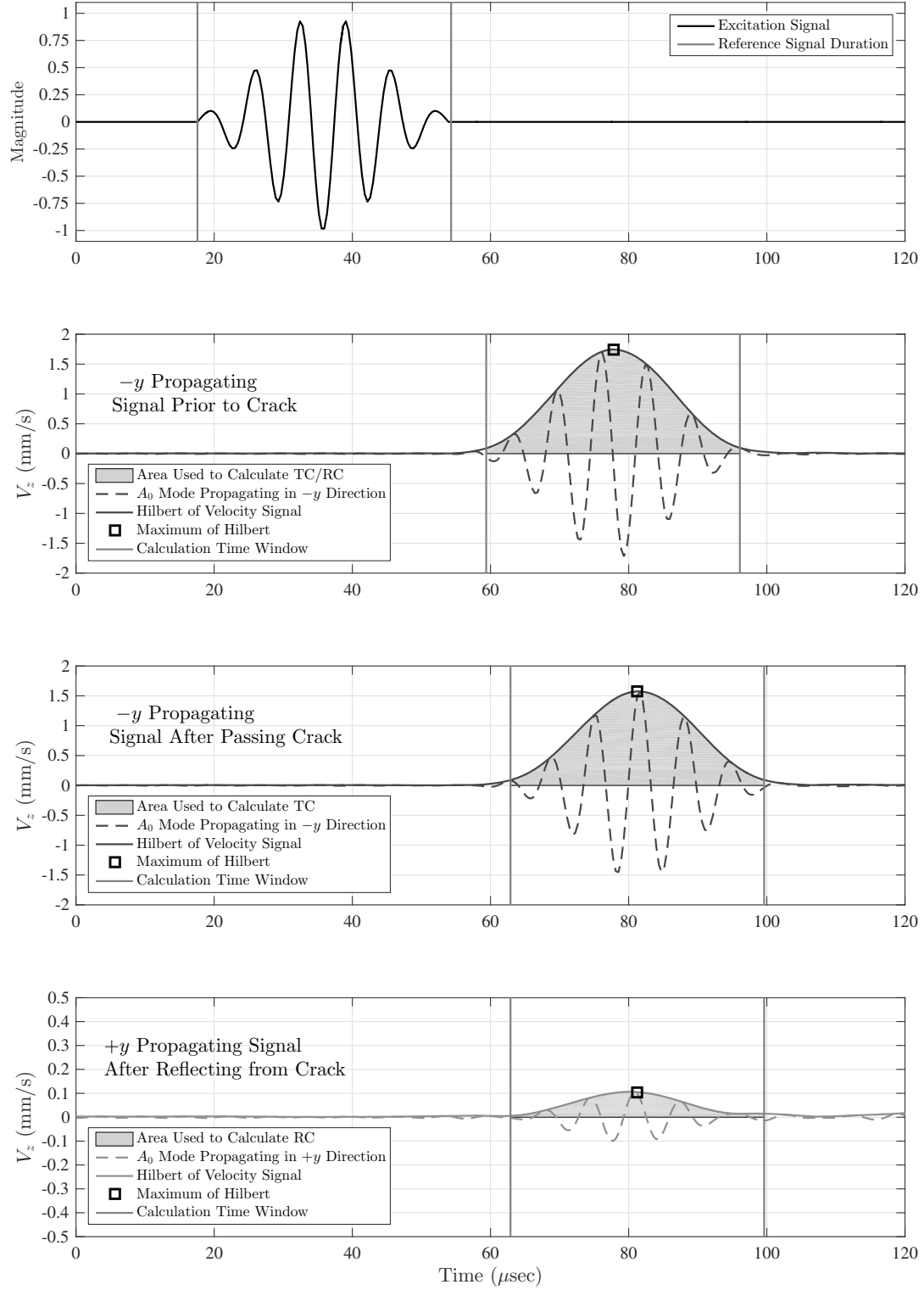


Figure 45. Selection of TC and RC calculation components for maximum amplitude and no dispersion methods (150 kHz Excitation). From top to bottom: excitation signal and reference signal duration, incident wave measured prior to reaching crack, wave transmitted through crack, wave reflected from crack

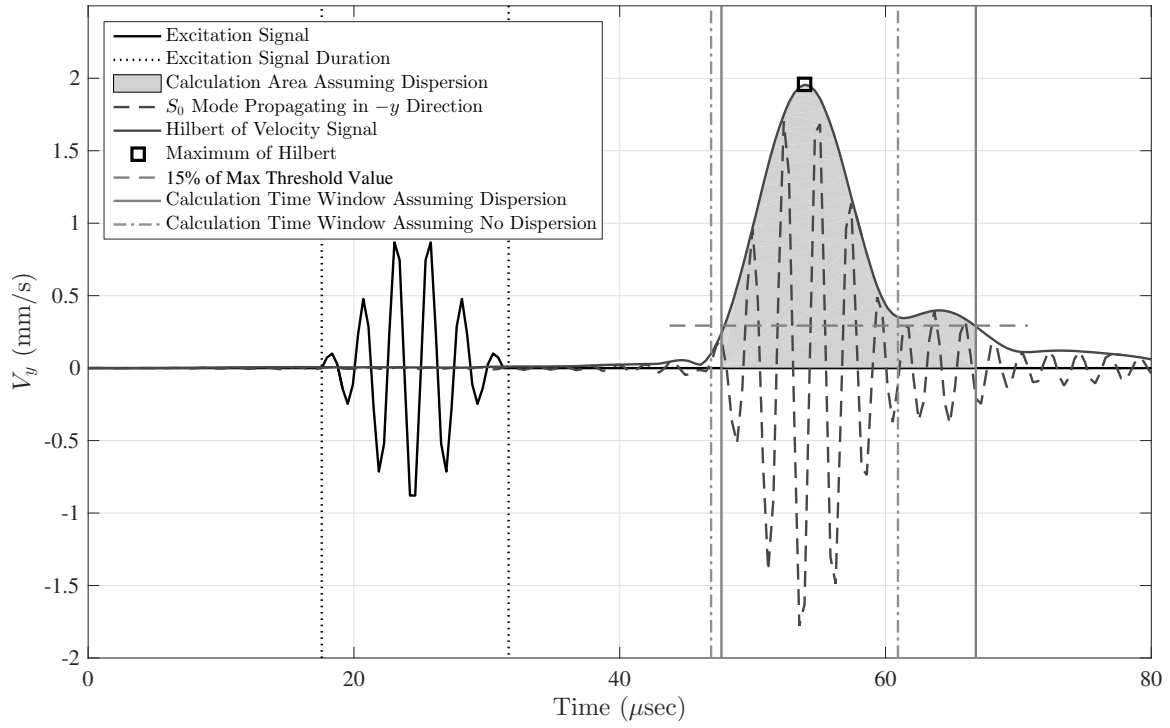


Figure 46. Selection of TC and RC calculation components for dispersion method (400 kHz Excitation).

IV. Experimental Results and Analysis

This chapter will present the results of the experiments described in Chapter III. Based on all combinations of test article, excitation source, wave mode, coefficient calculation method/distance, excitation frequency, and static load, there were more than 3,000 individual test cases. As it would be impossible to present and adequately discuss such a large volume of data in this dissertation, a relevant subset of these cases will be presented.

The presentation will start with an examination of raw experimental data illustrating wave interactions with each crack under two different static loads and at two different frequencies. This examination will help establish basic expectations of the final results after signal processing and analysis. Following this, the chapter will continue with a comparison of transmission and reflection coefficient calculation methods and distances for both A_0 and S_0 wave modes at frequencies corresponding to the maximum theoretical amplitude of the mode in question (150 kHz for A_0 and 350 kHz for S_0). Based on these results, a single coefficient computation method and distance from the crack will be used to present all data in the remaining sections. The discussion will then continue with an examination of the effects of three different static loads and multiple excitation transducer locations on calculated transmission and reflection coefficients. Finally, averaged transmission and reflection coefficients will be presented and discussed for all three test articles, both fundamental wave modes, and across all examined frequencies.

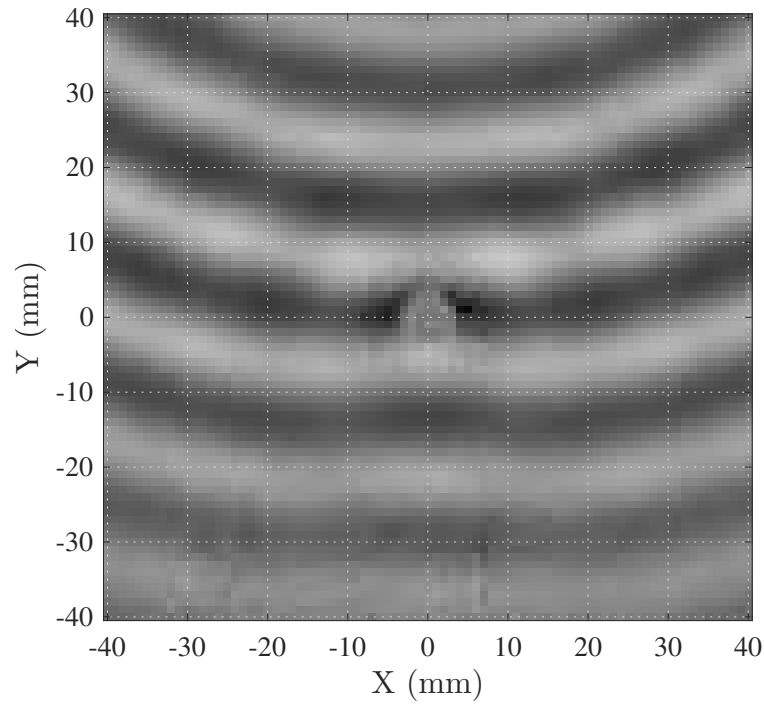
4.1 Wave Interactions with Cracks: Raw Data

In order to provide a rudimentary assessment of each test specimen and establish basic expectations for final results, normalized, but otherwise unprocessed experi-

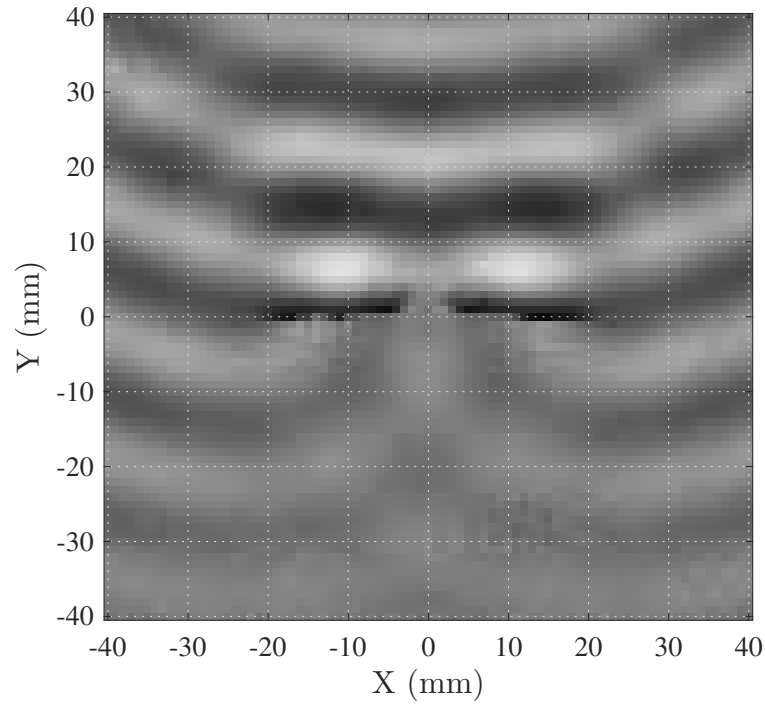
mental data based on 100 kHz and 400 kHz 5-1/2 cycle Hanning windowed excitation signals from PZT A (located at $x = 0$ mm) were plotted at both 0 kN and 22.2 kN static loads. Figures 47 to 52 present a 2-dimensional image of the velocity of the wave field at the moment the peak of the first wave packet is passing the crack front. In the case of the 100 kHz excitation, where the A_0 mode is expected to be dominant, the figures will present z -velocity data; for the 400 kHz excitation, the S_0 mode is expected to dominate, so y -velocity data will be used.

As was discussed briefly in Chapter III, the ideal situation would be for all three crack specimens to be closed along their full length under zero load. As Figure 47(a) shows, it appears the HCF specimen comes close to meeting this criteria. The darker region immediately surrounding the center hole appears to be predominantly caused by reflections from the hole itself. Strong reflections from the crack would tend to produce a more discernible linear pattern at the crack face, as seen in Figure 47(b), where the static load has opened the HCF crack across most of its length, producing a strong linear interference pattern and curling of the wave front as it diffracts around the open portion of the crack and continues to propagate in the negative y -direction.

In contrast, Figure 48(a) indicates that the LCF1 crack specimen is partially open even under zero load, particularly on the positive x side of the crack out to approximately $x = 9$ mm (which is the side on which the off-center excitation transducers are mounted and upon which all signal processing and analysis were performed). Like the HCF specimen, Figure 48(b) shows that application of a tension load opened the LCF1 crack even further; however, not to the same extent as the HCF specimen. This behavior is to be expected, as the residual stress in the plastically deformed areas surrounding an LCF crack are expected to result in reduced strain (compared to the HCF case with much less plastic deformation) when the same static load is applied.

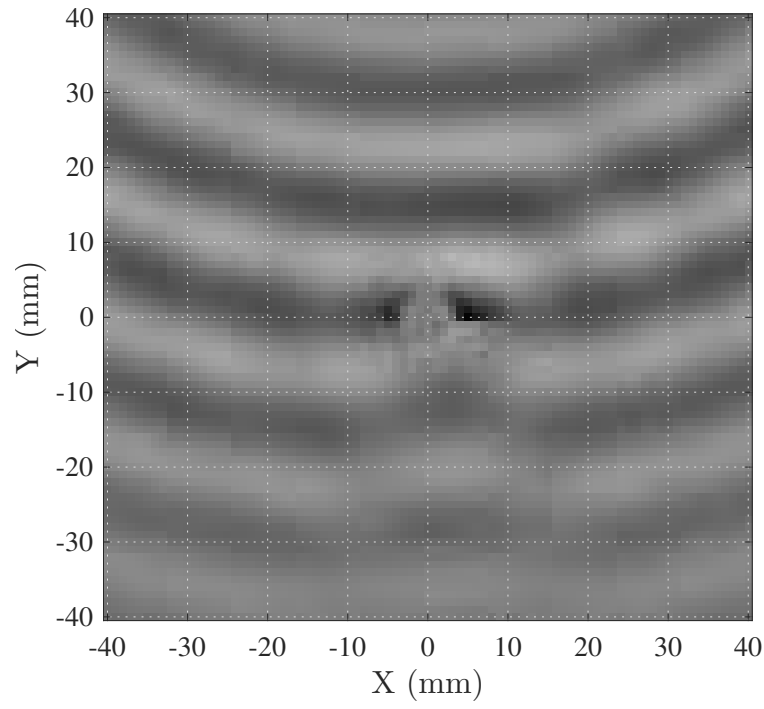


(a) 0 kN Load (74.6 μ s after excitation).

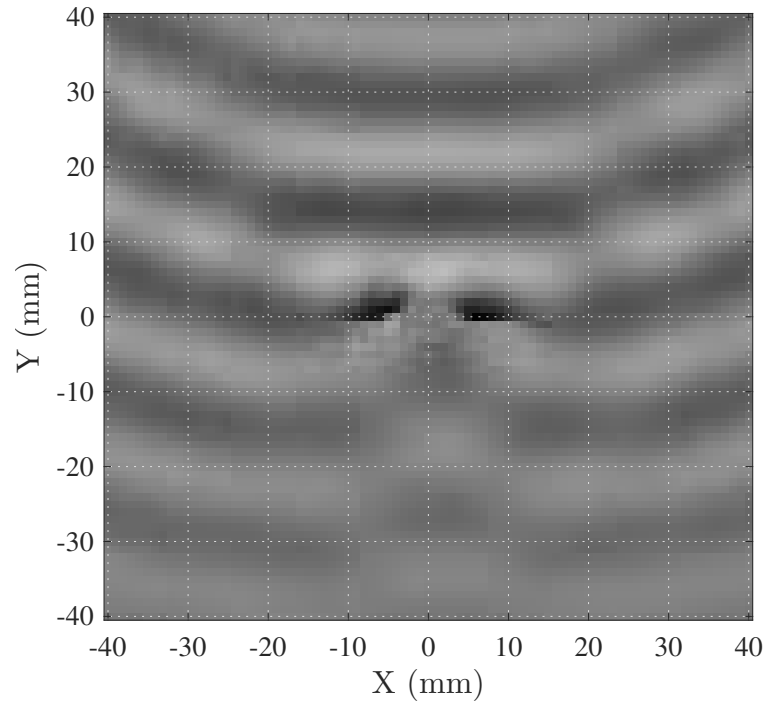


(b) 22.2 kN Load (75.8 μ s after excitation).

Figure 47. Normalized V_z of 100 kHz Lamb Wave Field Interacting with HCF crack specimen.

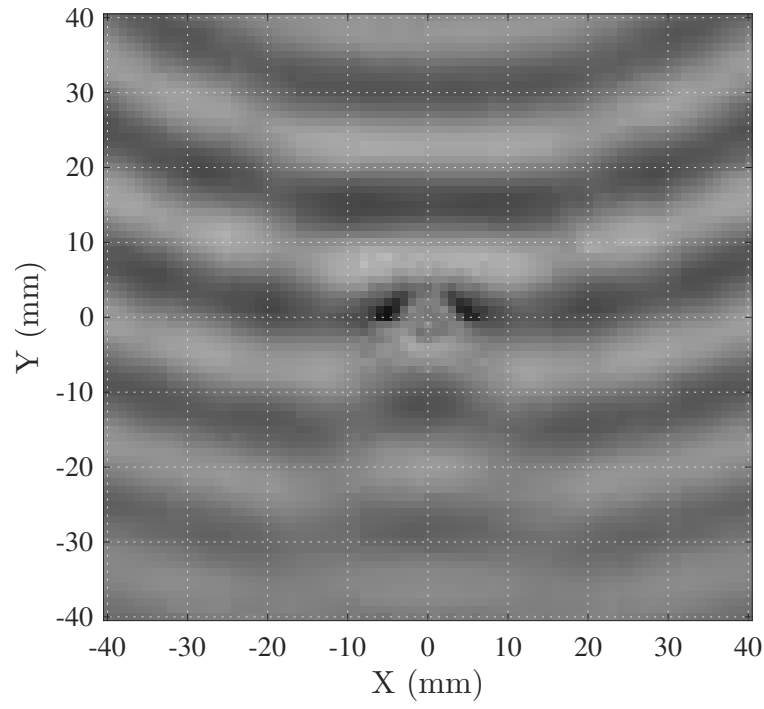


(a) 0 kN Load ($75.0 \mu\text{s}$ after excitation).

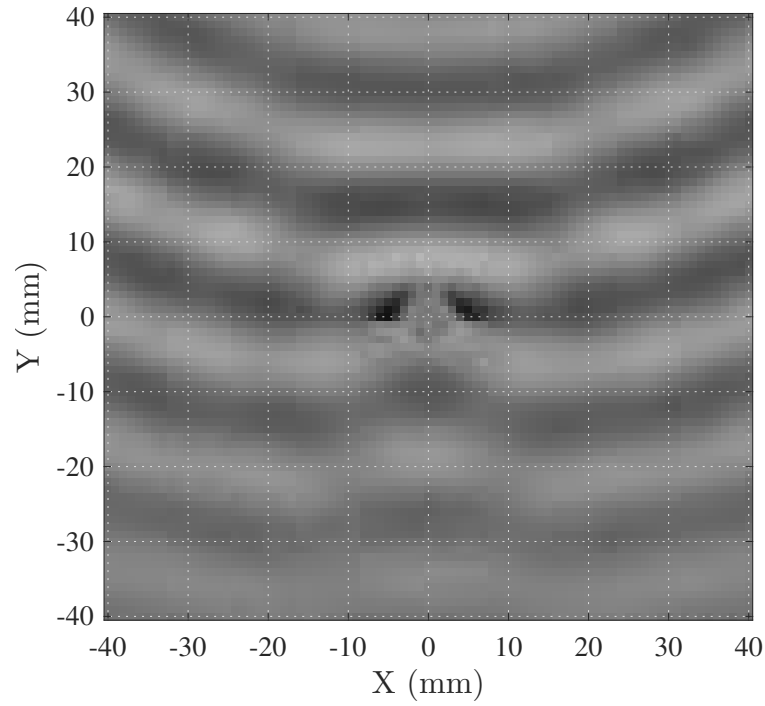


(b) 22.2 kN Load ($75.8 \mu\text{s}$ after excitation).

Figure 48. Normalized V_z of 100 kHz Lamb Wave Field Interacting with LCF1 crack specimen.



(a) 0 kN Load (76.1 μ s after excitation).



(b) 22.2 kN Load (76.1 μ s after excitation).

Figure 49. Normalized V_z of 100 kHz Lamb Wave Field Interacting with LCF2 crack specimen.

Somewhat surprisingly, Figure 49(a) appears to indicate that at zero load the LCF2 crack specimen, though subjected to higher amplitude fatigue loading, is open along a shorter length than LCF1, out to approximately $x = 7$ mm on the positive x side. As with LCF1, Figure 49(b) indicates that application of a tension load opens the LCF2 crack further, but not as far as either HCF or LCF1; once again, this is most likely due to greater plastic deformation of the material immediately surrounding the crack.

Analysis of the y -velocity data reveals similar results at 400 kHz. The shape of the inbound wavefield is generally maintained on the negative y side of the crack with minimal diffraction patterns, as shown in Figure 50. This indicates that the HCF specimen is closed across its entire length under zero load. There appears to be more reflection of the in-plane wave energy (V_y) than in the out-of-plane case (V_z) shown in Figure 47. This can likely be attributed to the different energy transfer mechanisms at play between in-plane and out-of-plane wave motion for a lightly closed crack. Under a tension load, the HCF crack opens across the majority of its length, as indicated by the large reflection signal and relative lack of wave energy on the negative y side of the crack.

Figure 51(a) again shows that under zero load, the LCF1 crack is partially open, particularly on the positive x side. The shape of the inbound wavefield is maintained towards the outboard edges of the crack, while a larger null area is present towards the center. Figure 51(b) indicates that application of a tension load opens the crack even further, though not as far as the HCF specimen. Finally, Figure 52(a) again shows the LCF2 crack to be open near the center at zero load, but for a shorter distance than LCF1. Examining Figure 52(b), it appears the wave reflection pattern under a tension load is not as strong for the LCF2 specimen; however, the larger null area on the leeward side of the crack does indicate that the crack has opened further

under load. Due to the less intense reflection pattern it is difficult to determine a clear difference in open crack length compared to the LCF1 specimen under the same tension load.

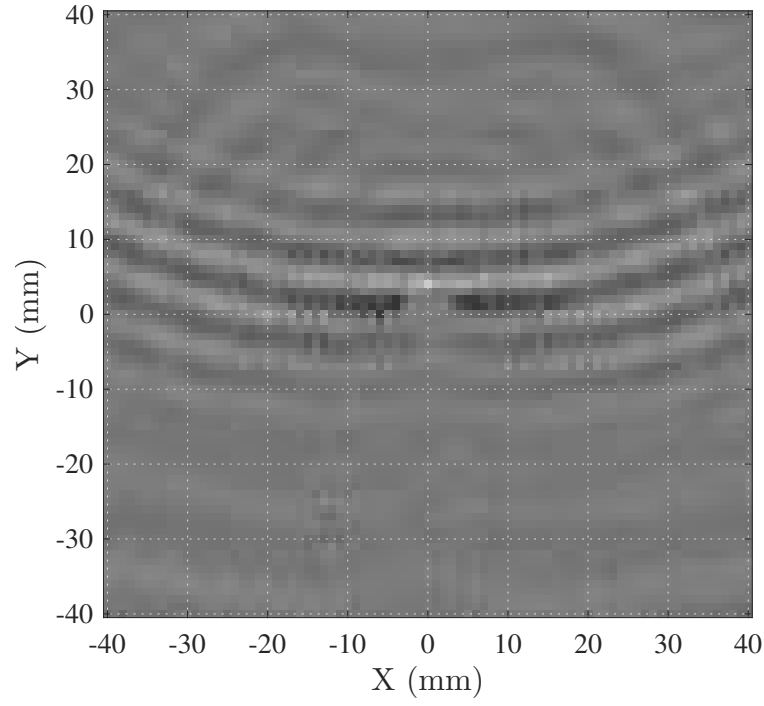
Based on these observations, general expectations for the final results can be established. Under zero or compressive static loads, the HCF crack is expected to demonstrate higher TC and lower RC than either of the LCF specimens, especially near the center of the crack. This is particularly true for in-plane motion (V_y) most associated with the S_0 mode. However, the LCF1 specimen is likely to demonstrate lower transmission and higher reflection than the LCF2 specimen, especially near the center of the crack due to LCF1 being open a longer distance at zero load.

4.2 Comparison of TC/RC Calculation Methods and Locations

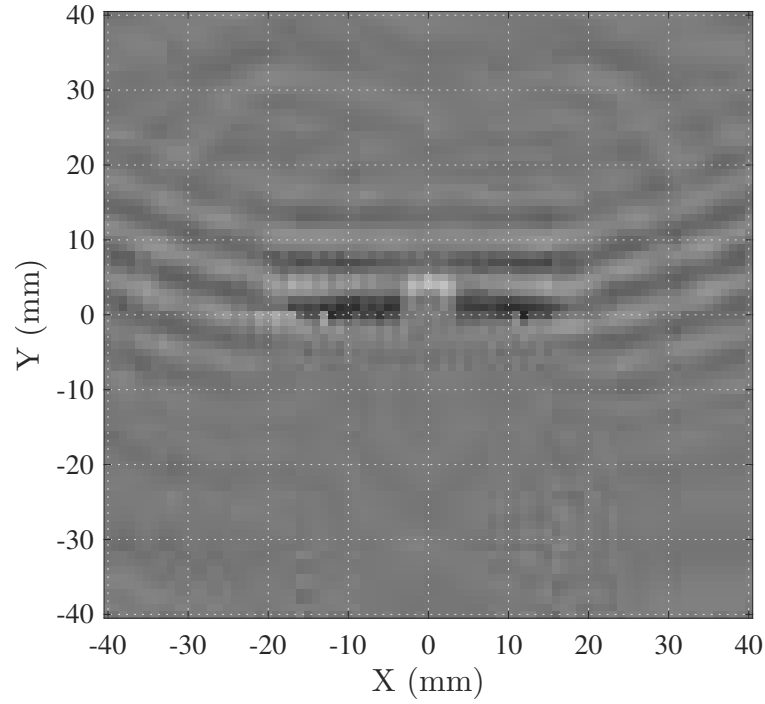
As described in Chapter III, transmission and reflection coefficients were calculated using three different methods: maximum amplitude, assuming wave packet dispersion, and assuming no wave packet dispersion. In addition, for each of these methods, TC and RC were calculated using data from points at two different y -distances from each crack front (5 mm and 10 mm).

As shown in Figure 9, the theoretical maximum amplitude for A_0 mode waves in a 3.175 mm thick aluminum plate occurs between 100 kHz and 150 kHz (but closer to the latter), while for S_0 mode waves, it occurs at approximately 350 kHz. As such, those are the frequencies used to generate the data presented in this section. In addition, results were generated using a single excitation source at $x = 0$ mm (PZT A) and zero static load. All A_0 coefficient calculations are based on out-of-plane velocity (V_z) and all S_0 results are based on in-plane velocity (V_y).

All plots include coefficients calculated along the crack front from $x = 6$ mm to 22 mm. Based on the estimated crack lengths presented in Table 1, the tip of the

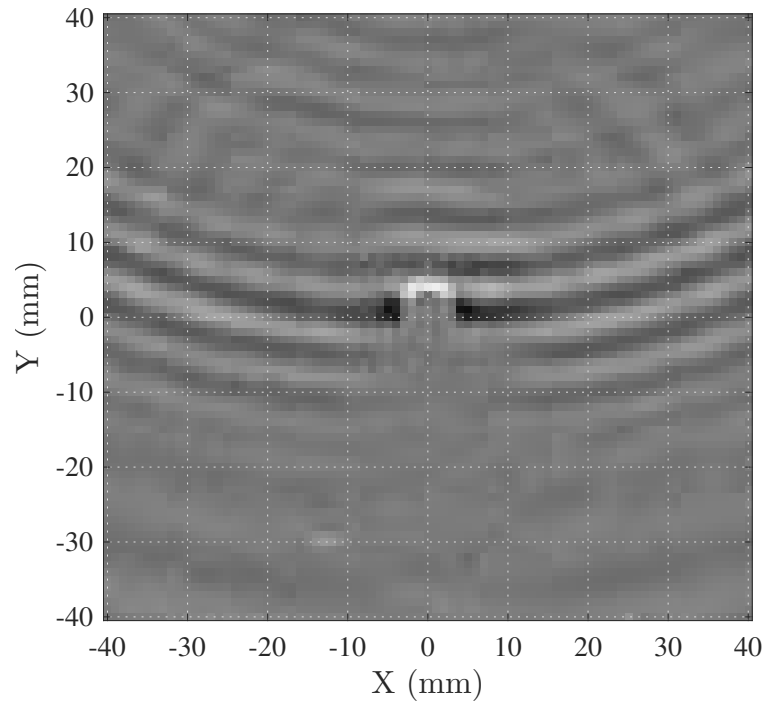


(a) 0 kN Load (48.4 μ s after excitation).

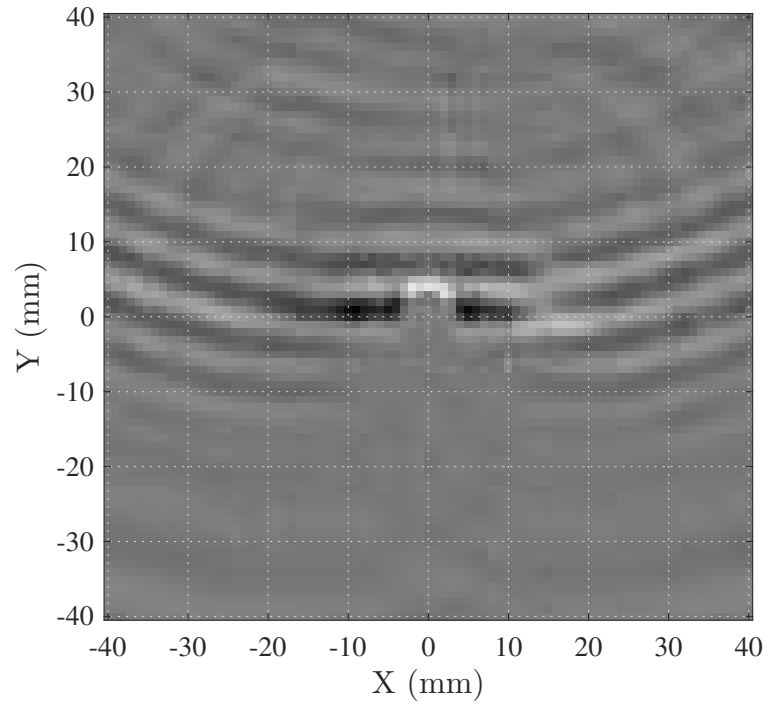


(b) 22.2 kN Load (48.8 μ s after excitation).

Figure 50. Normalized V_y of 400 kHz Lamb Wave Field Interacting with HCF crack specimen.

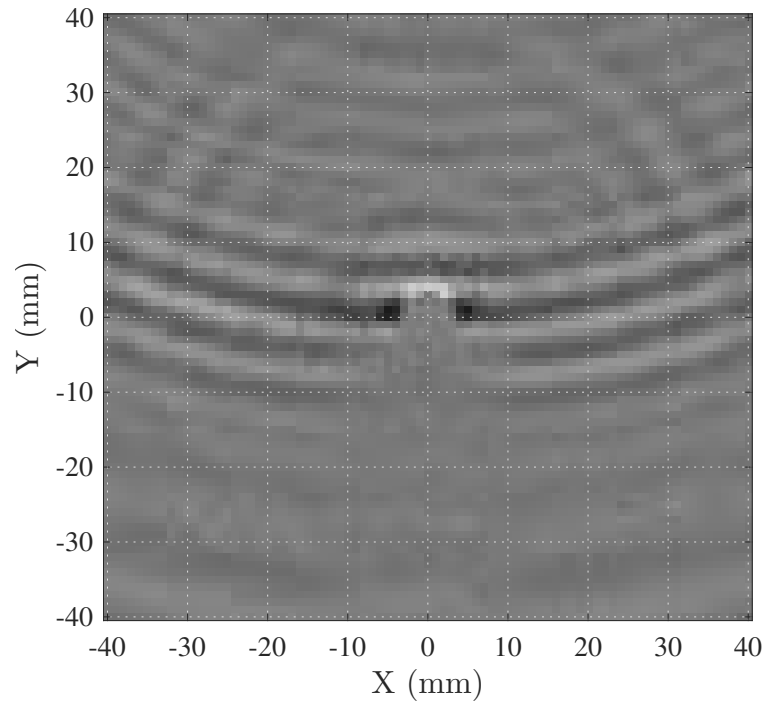


(a) 0 kN Load (48.8 μ s after excitation).

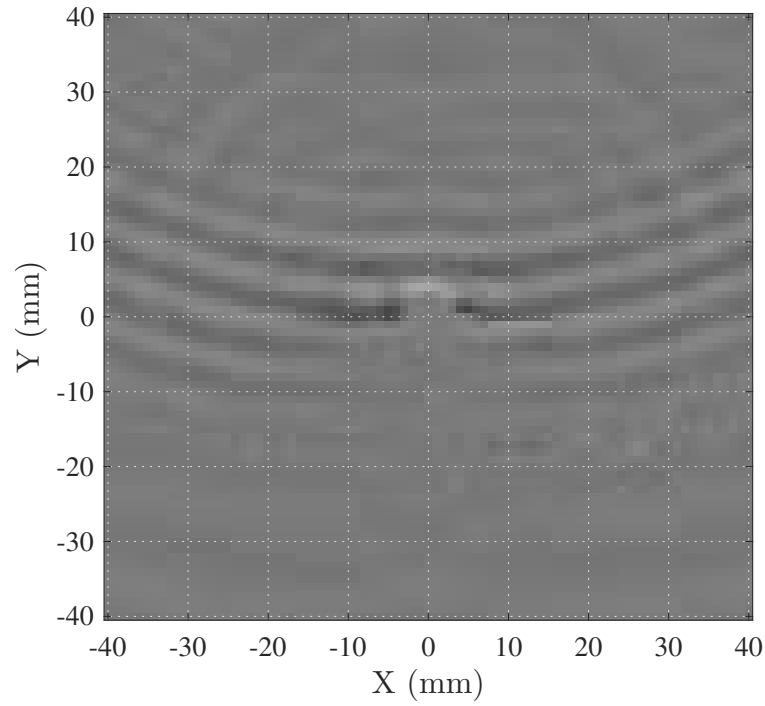


(b) 22.2 kN Load (48.8 μ s after excitation).

Figure 51. Normalized V_y of 400 kHz Lamb Wave Field Interacting with LCF1 crack specimen.



(a) 0 kN Load (49.9 μ s after excitation).



(b) 22.2 kN Load (49.9 μ s after excitation).

Figure 52. Normalized V_y of 400 kHz Lamb Wave Field Interacting with LCF2 crack specimen.

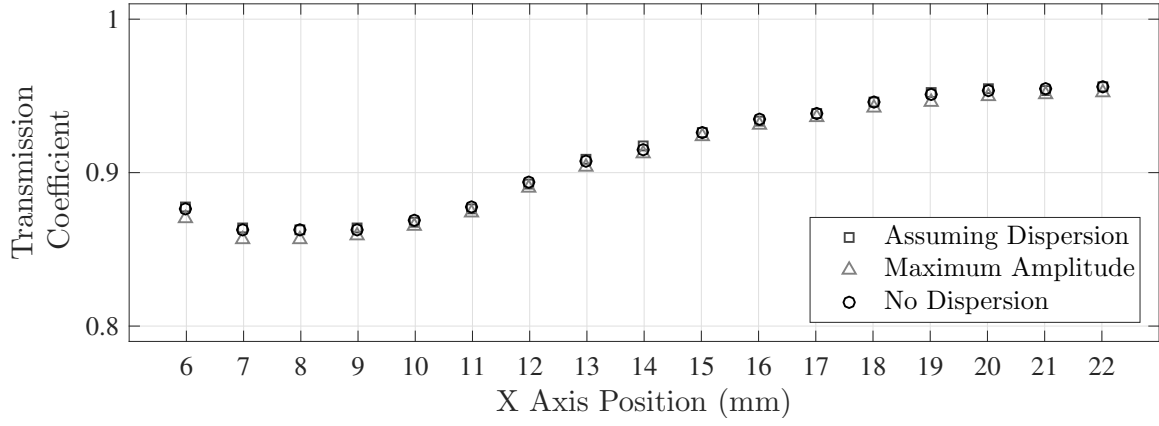
HCF crack is estimated to lie at $x = 20.5$ mm, while the tips of both LCF cracks are estimated to lie between $x = 21$ mm to 22 mm.

Coefficient Calculation Methods.

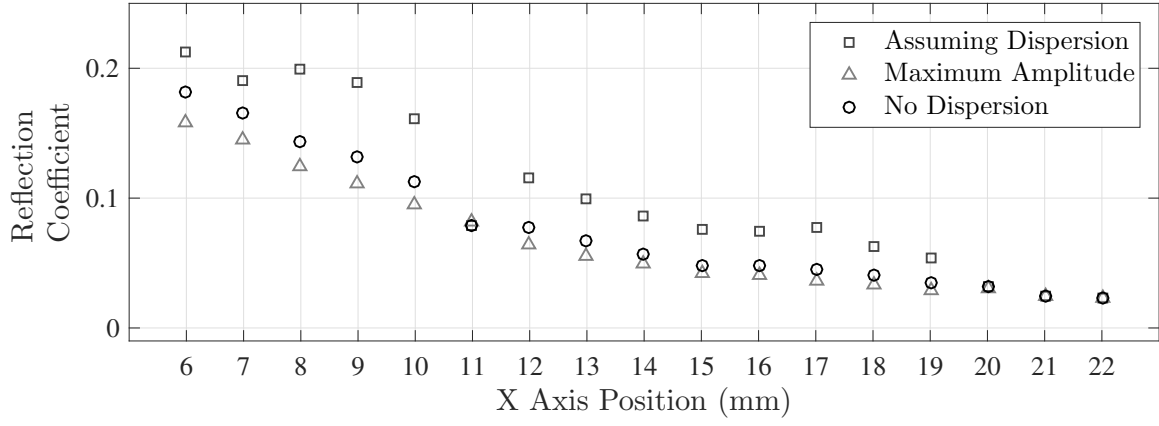
Figures 53 to 58 show the TC and RC calculated for each test specimen using all three methods at a y -distance of 5 mm from the crack.

Examining the A_0 mode for the HCF specimen in Figure 53, TC results vary little between the three calculation methods across the entire crack length, and demonstrate a pattern of lower TC near the center of the crack and higher towards the tip. However, the different methods demonstrate greater variation for RC calculations, except at the location $x = 11$ mm and the three most outboard points. RC calculations assuming wave dispersion tended to produce higher values, followed by the no dispersion and maximum amplitude methods. In general, the trends are as expected, with lower TC associated with higher RC, and vice-versa.

Figure 54 again shows that all three calculation methods produce similar TC results for the S_0 mode, with the exception of the two points nearest the center hole. Similar to the A_0 results, TC for the S_0 mode is generally lower near the center of the crack and increases towards the crack tip. RC results vary significantly across the length of the crack, with RC values greater than 1.1 near the center and middle of the crack, and values near 0.1 at the crack tip. TC and RC trends do not follow the expected behavior across the entire length of the crack, with RC and TC both increasing from $x = 9$ mm to approximately 15 mm. As with the A_0 results, the method assuming wave packet dispersion generally produced higher RC values across the majority of the crack and demonstrated the greatest variation compared to the other two methods.

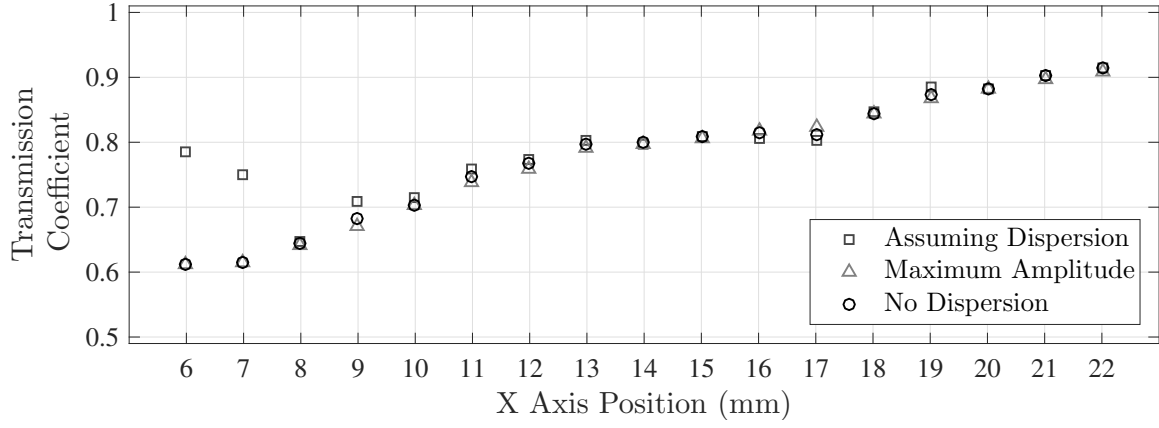


(a) TC for A_0 mode.

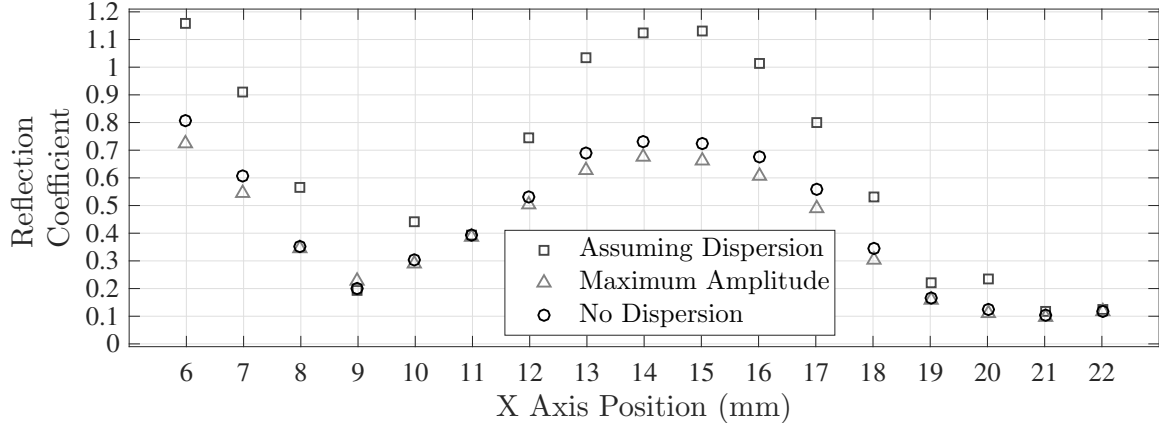


(b) RC for A_0 mode.

Figure 53. TC and RC for HCF crack, A_0 mode (150 kHz), calculated at 5 mm from crack.

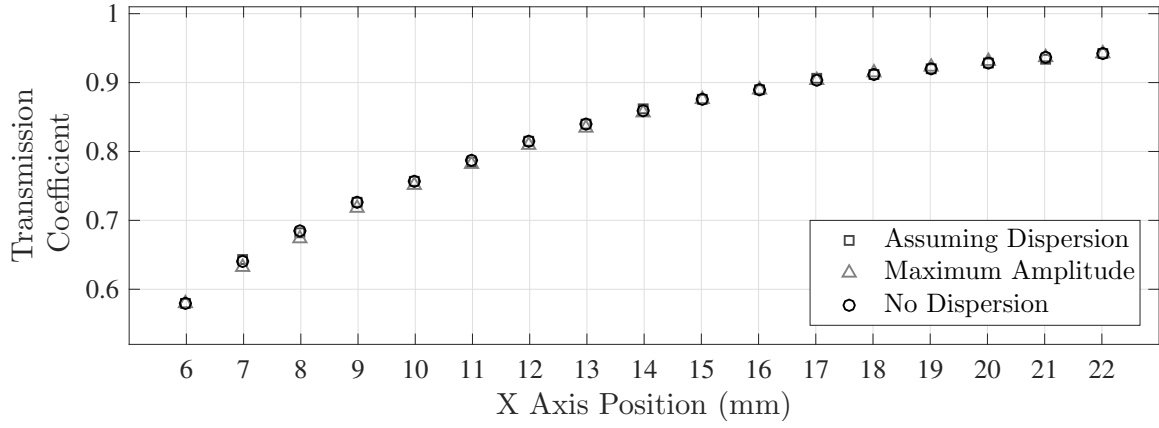


(a) TC for S_0 mode.

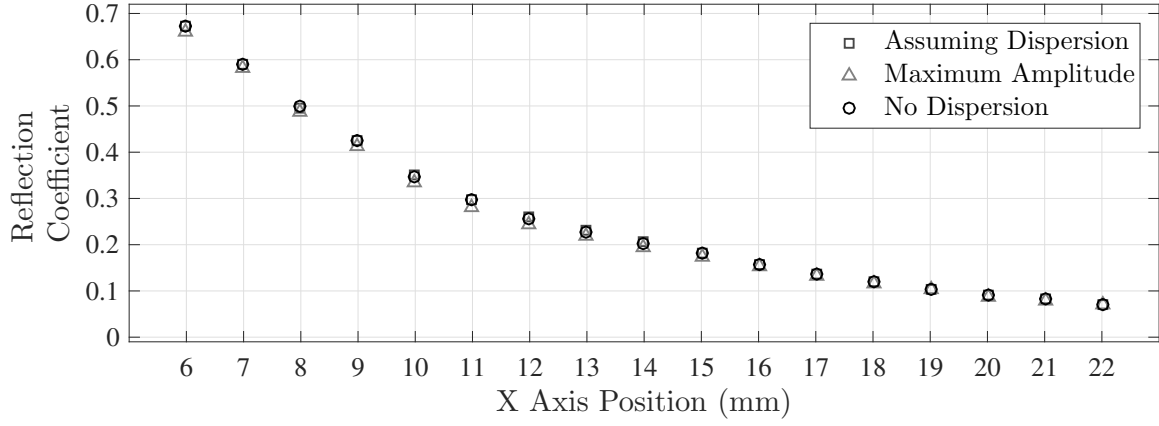


(b) RC for S_0 mode.

Figure 54. TC and RC for HCF crack, S_0 mode (350 kHz), calculated at 5 mm from crack.



(a) TC for A_0 mode.



(b) RC for A_0 mode.

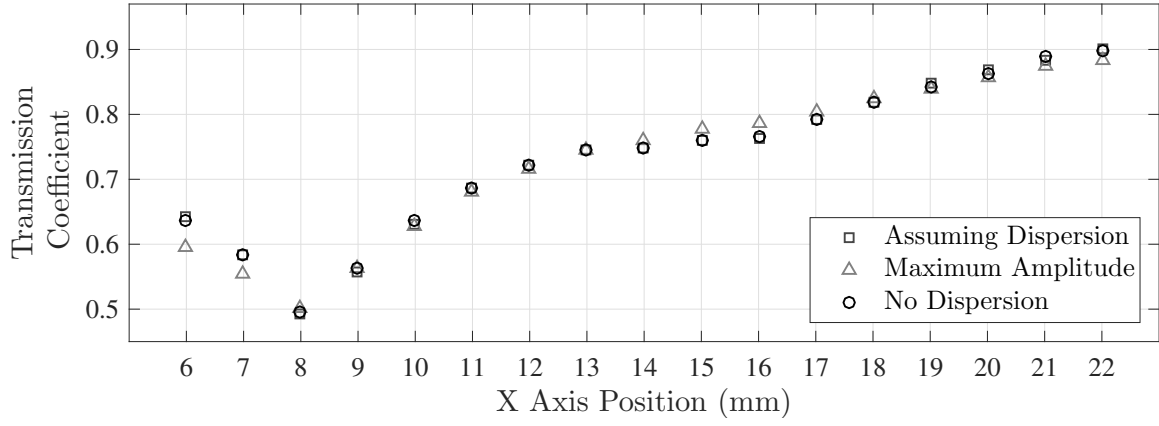
Figure 55. TC and RC for LCF1 crack, A_0 mode (150 kHz), calculated at 5 mm from crack.

Examining the results for A_0 mode for the LCF1 specimen, Figure 55 shows little variation in either TC or RC results based on the calculation method. The overall trend is as expected, with TC lower near the center of the crack and increasing towards the tip, and RC behaving opposite.

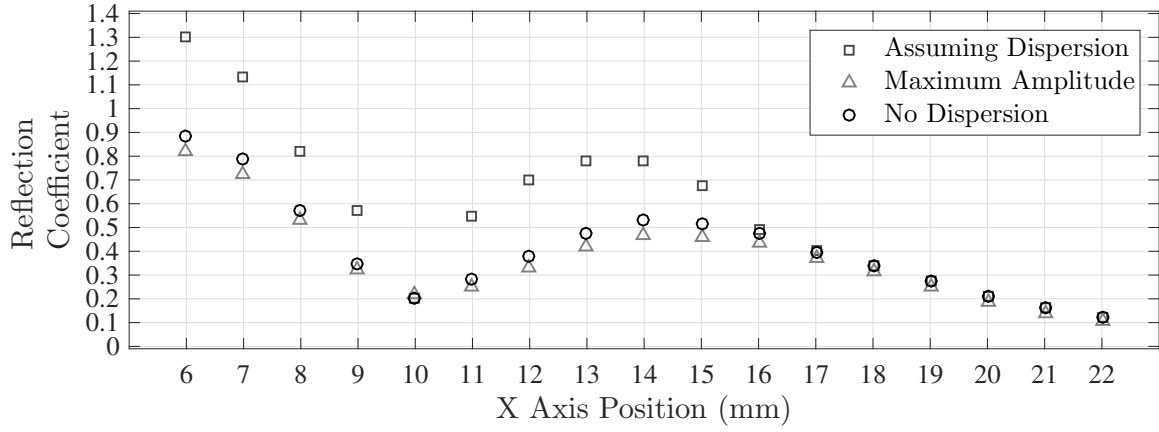
TC and RC results for LCF1 and the S_0 mode are similar to those for the HCF specimen S_0 mode. All three calculation methods produced largely similar results for TC, but the method assuming dispersion produced higher RC results across the majority of the crack. RC again demonstrated significant variation, ranging from approximately 1.3 at the center of the crack down to approximately 0.1 at the tip. The TC trend across the crack front is as expected with the exception of the two points nearest the center hole. As discussed previously, the LCF1 crack appeared to be partially open towards the center, which would be expected to produce lower TC, not higher. As with the HCF crack, the RC vs TC trend again showed areas where both TC and RC were increasing from point to point rather than moving in opposite directions.

Figure 57 shows similar results between the LCF2 and LCF1 cracks for the A_0 mode. All three calculation methods produced similar results for both TC and RC along the length of the crack, and TC/RC trends were as expected.

Results for the S_0 mode and the LCF2 crack are presented in Figure 58 and demonstrate similar trends to the S_0 mode results for both of the other test specimens. With the exception of the point at $x = 6$ mm, which appears anomalous, TC results were similar for all three calculation methods. RC results again showed more variation; however, the method assuming wave packet dispersion did not produce results differing from the other two methods to the same degree as seen in the HCF and LCF1 cracks. TC trends are generally as expected; however, similar to the other S_0 mode results, RC varied widely along the length of the crack (from a high of approximately

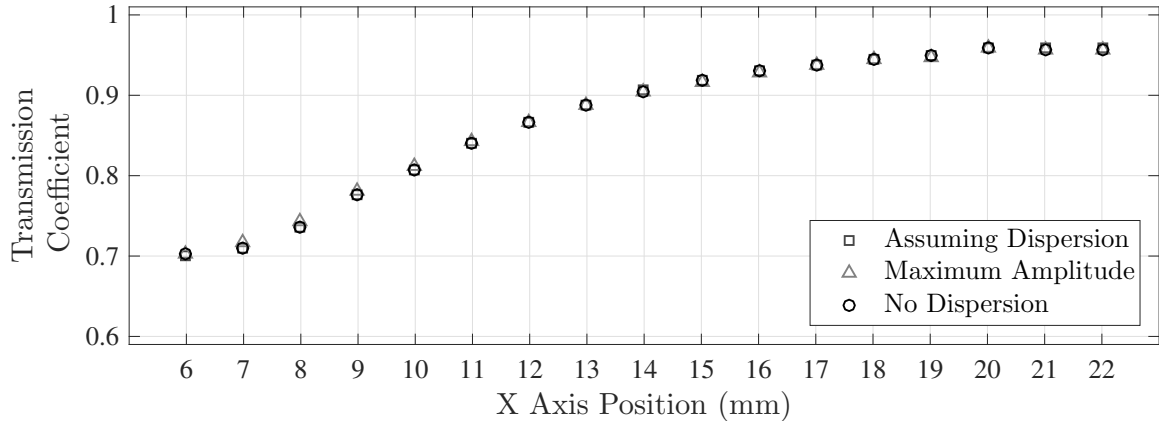


(a) TC for S_0 mode.

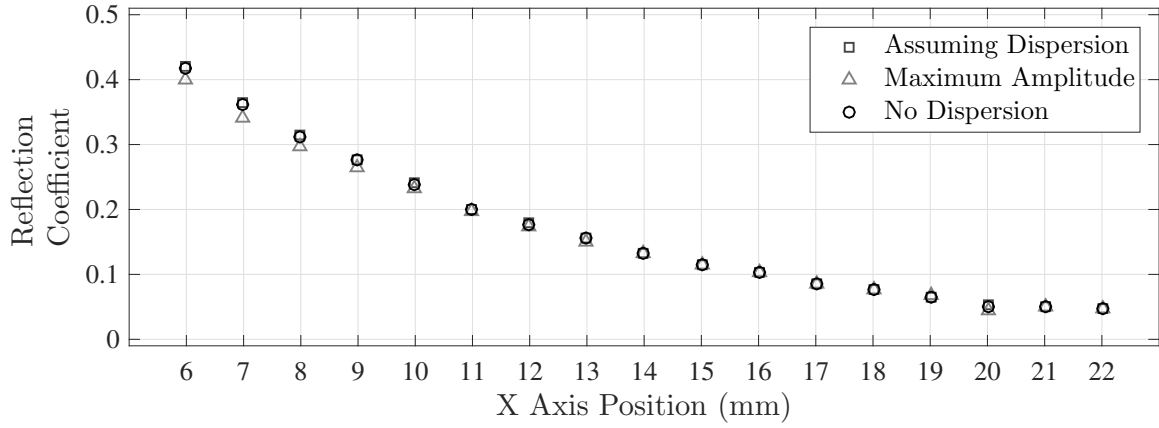


(b) RC for S_0 mode.

Figure 56. TC and RC for LCF1 crack, S_0 mode (350 kHz), calculated at 5 mm from crack.

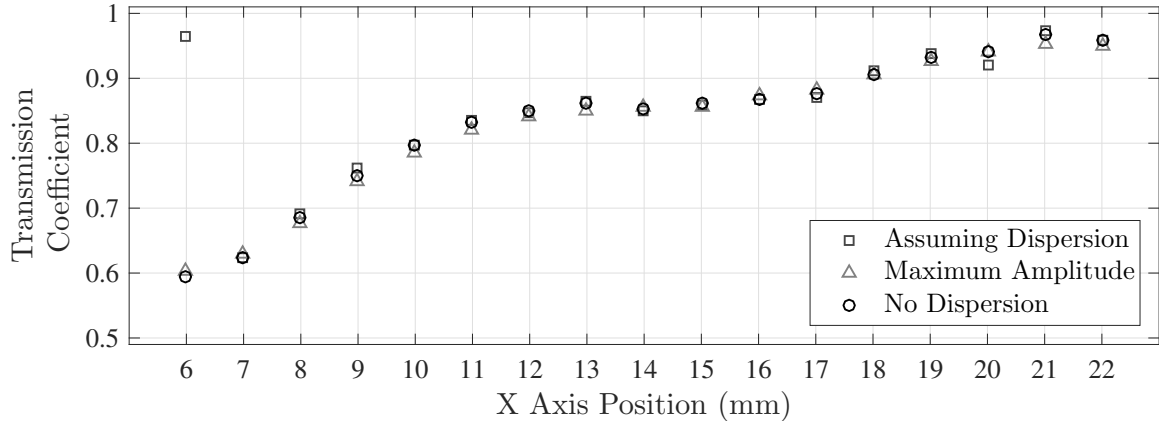


(a) TC for A_0 mode.

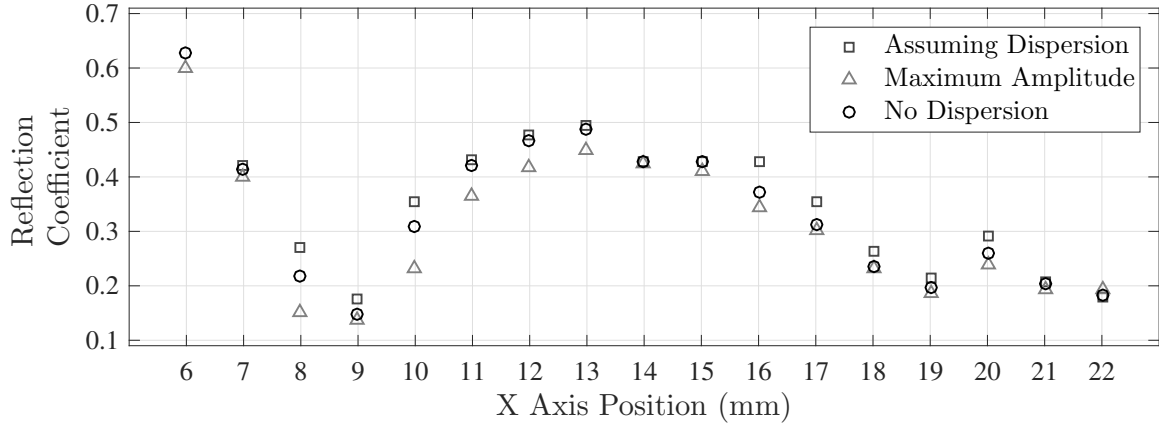


(b) RC for A_0 mode.

Figure 57. TC and RC for LCF2 crack, A_0 mode (150 kHz), calculated at 5 mm from crack.



(a) TC for S_0 mode.



(b) RC for S_0 mode.

Figure 58. TC and RC for LCF2 crack, S_0 mode (350 kHz), calculated at 5 mm from crack.

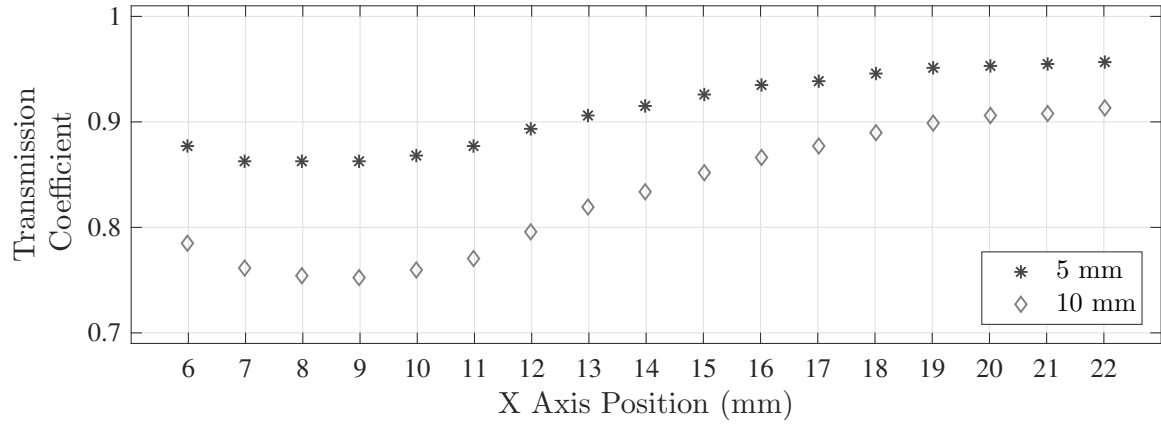
0.63 near the center to a low of 0.13 at $x = 9$ mm). While the spread of RC results was not as large as was seen for the HCF and LCF1 cracks, the LCF2 results again demonstrated regions where both TC and RC were increasing at the same locations along the crack front.

Overall, RC calculated assuming wave packet dispersion demonstrated larger variation from point to point along the crack front as well as greater variation from RC values calculated using the other two methods. As was discussed in Section 3.4, this method is sensitive to selection of an appropriate threshold value for determining the appropriate time range of the signal to include in the coefficient calculation. Given that all tone burst excitations were narrow band signals and the demonstrated variation in coefficient results calculated using the dispersion assumption, TC and RC calculated using the assumption of no wave packet dispersion will be presented throughout the rest of the chapter.

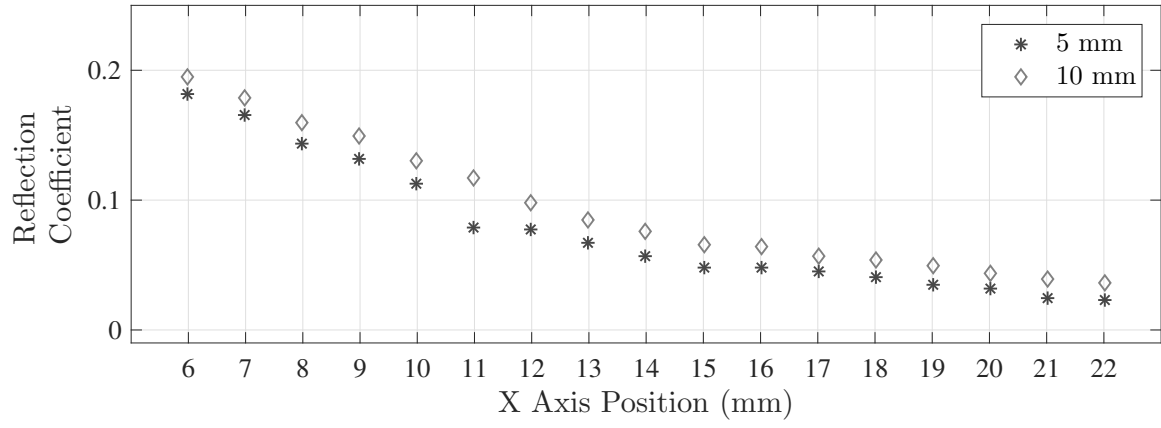
Coefficient Calculation Distance.

Figures 59 to 64 show the calculated TC and RC (assuming no wave packet dispersion) at y -distances of both 5 mm and 10 mm from the crack.

Overall trends were similar across all three test specimens and both wave modes. TC calculated using data points at a y -distance of 10 mm from the crack face were consistently lower than those calculated at 5 mm separation. This behavior is expected in that the increased distance (20 mm total) between calculation points results in lower wave energy at the calculation point on the leeward side of the crack due to geometric spreading and damping. RC results did not vary as significantly as TC, despite the greater travel distance. This is likely due to the fact that wave energy reflected from any point along the crack would spread laterally to adjacent measurement points, thereby increasing the strength of the measured reflected signals.

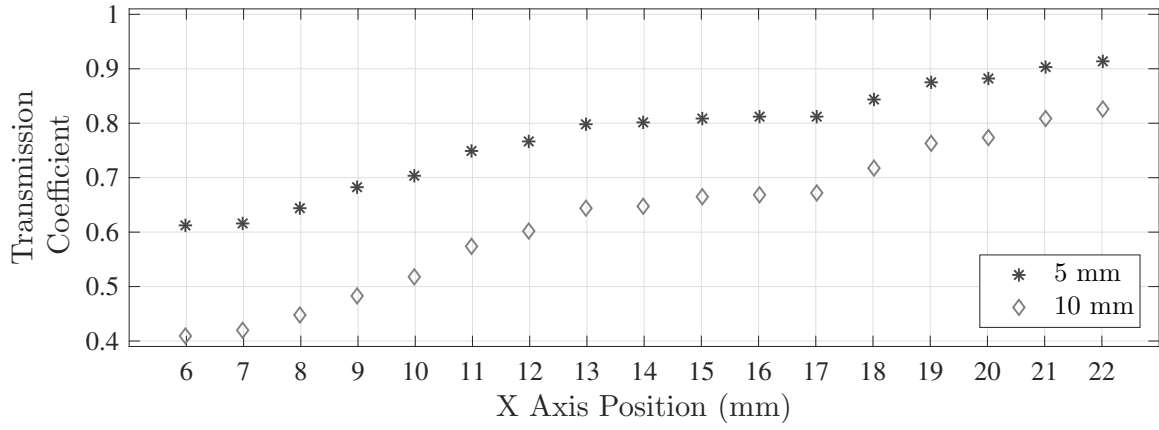


(a) TC for A_0 mode.

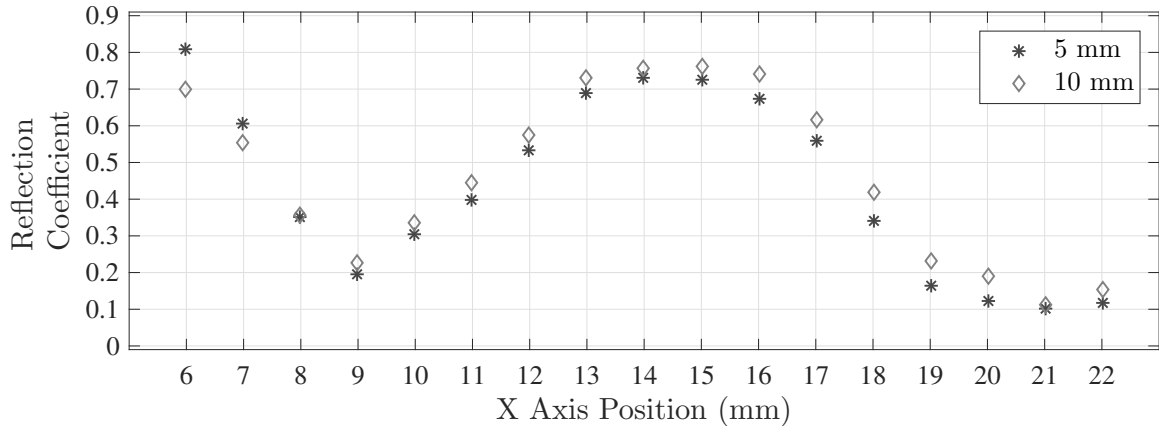


(b) RC for A_0 mode.

Figure 59. TC and RC for HCF crack, A_0 mode (150 kHz), calculated at 5 mm and 10 mm from crack front.

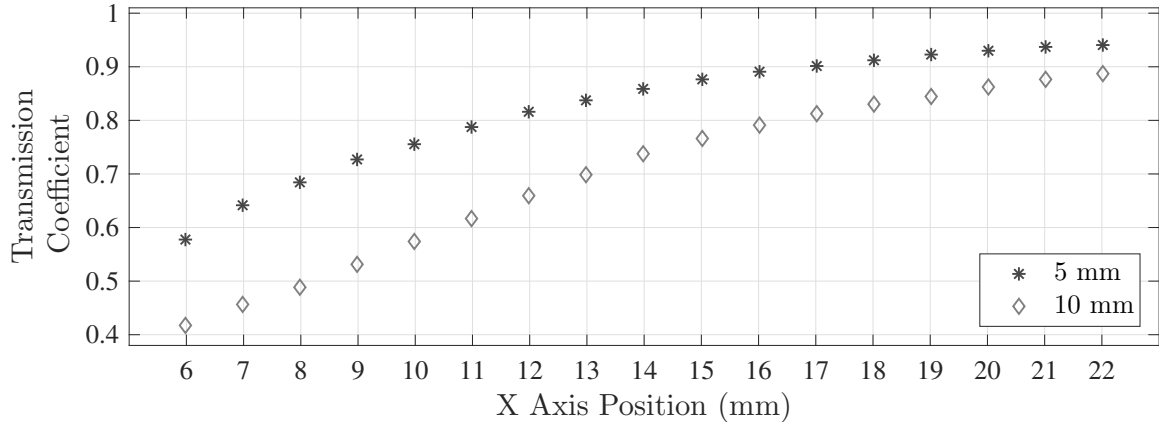


(a) TC for S_0 mode.

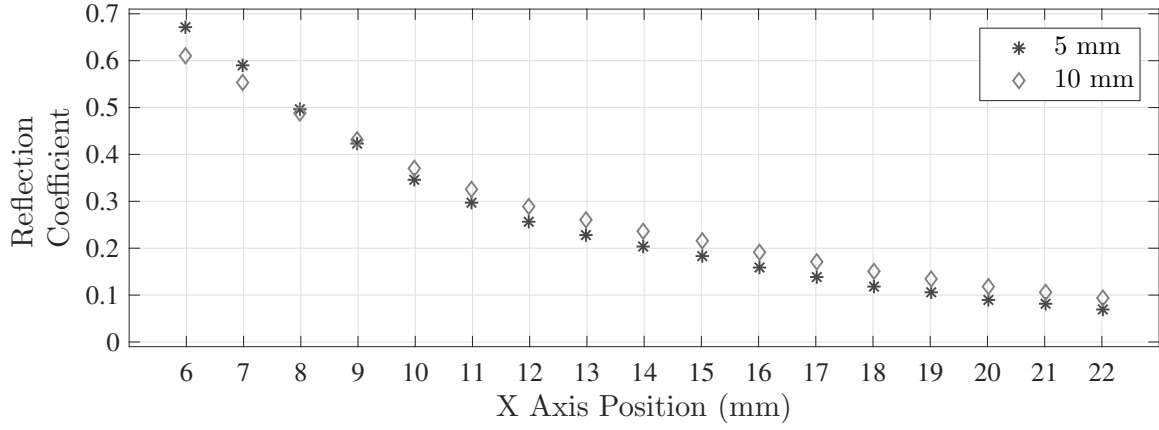


(b) RC for S_0 mode.

Figure 60. TC and RC for HCF crack, S_0 mode (350 kHz), calculated at 5 mm and 10 mm from crack front.

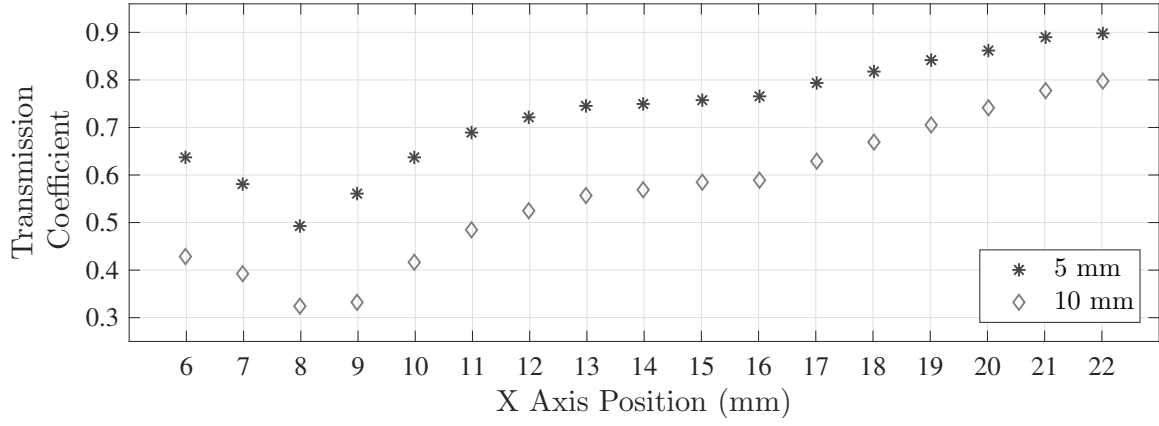


(a) TC for A_0 mode.

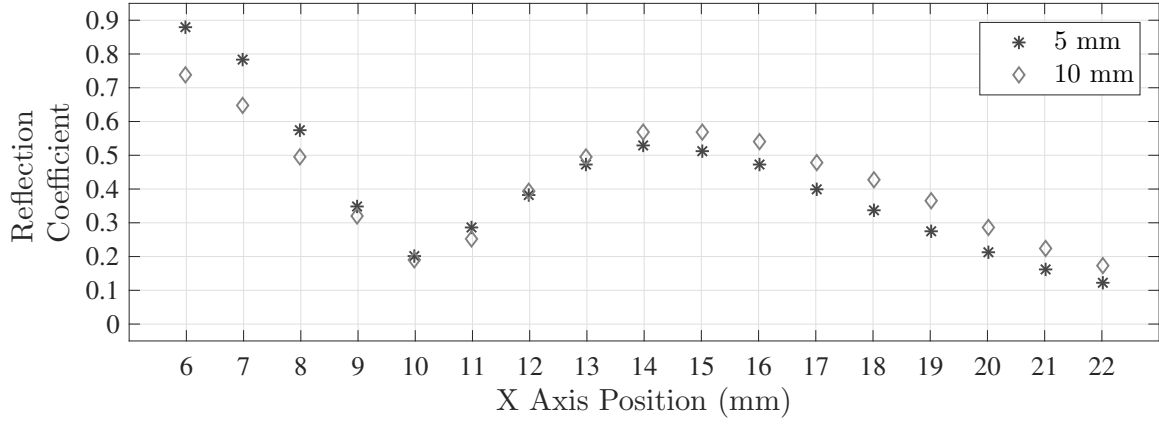


(b) RC for A_0 mode.

Figure 61. TC and RC for LCF1 crack, A_0 mode (150 kHz), calculated at 5 mm and 10 mm from crack front.

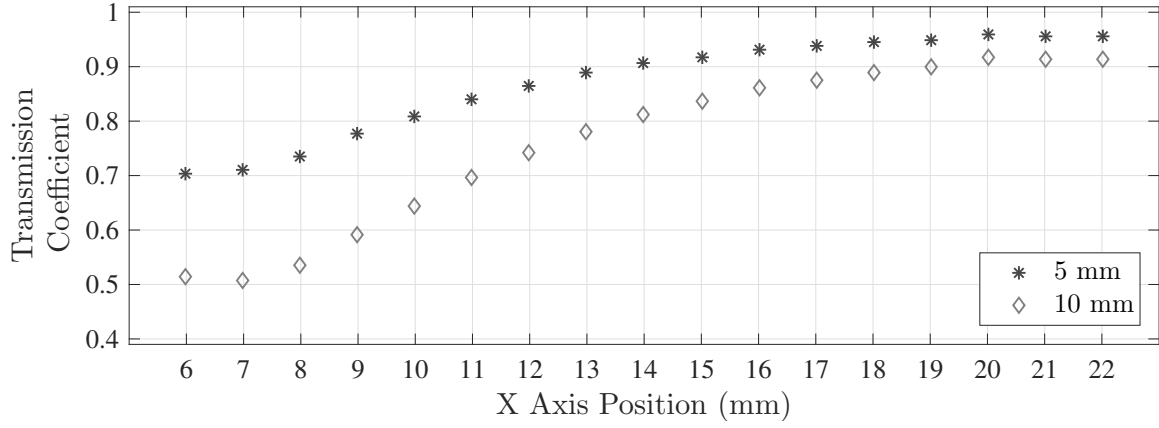


(a) TC for S_0 mode.

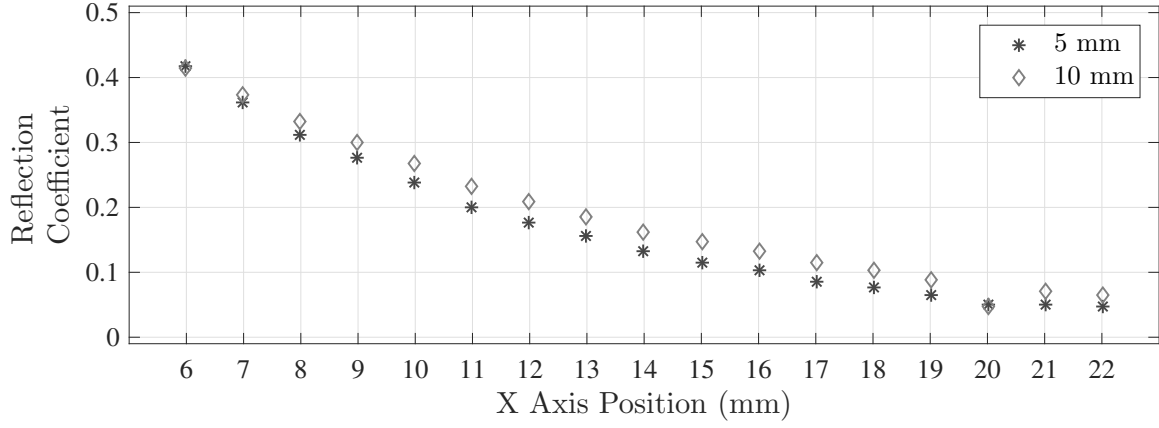


(b) RC for S_0 mode.

Figure 62. TC and RC for LCF1 crack, S_0 mode (350 kHz), calculated at 5 mm and 10 mm from crack front.

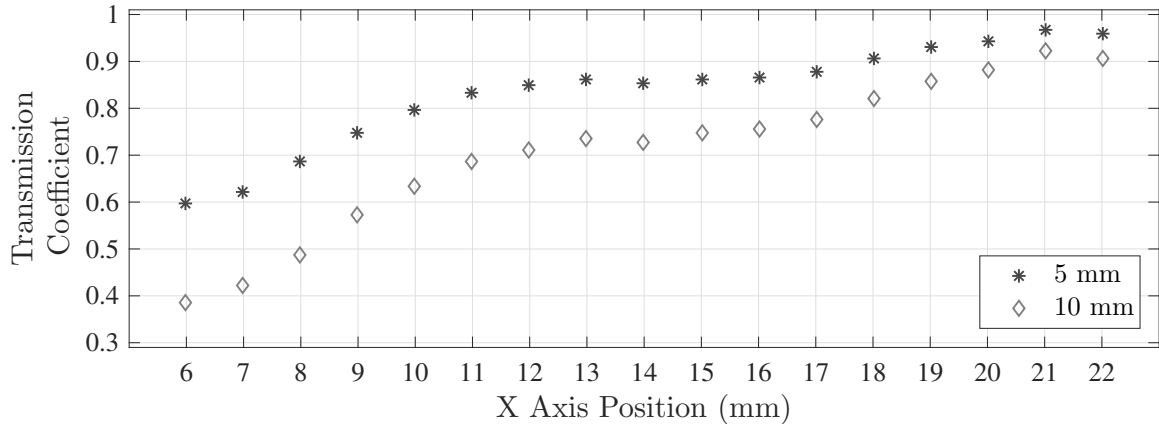


(a) TC for A_0 mode.

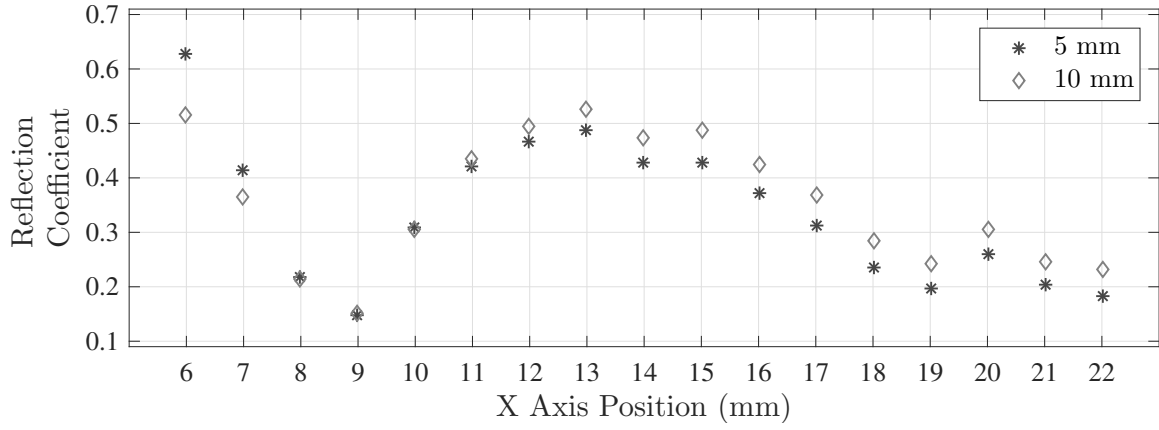


(b) RC for A_0 mode.

Figure 63. TC and RC for LCF2 crack, A_0 mode (150 kHz), calculated at 5 mm and 10 mm from crack front.



(a) TC for S_0 mode.



(b) RC for S_0 mode.

Figure 64. TC and RC for LCF2 crack, S_0 mode (350 kHz), calculated at 5 mm and 10 mm from crack front.

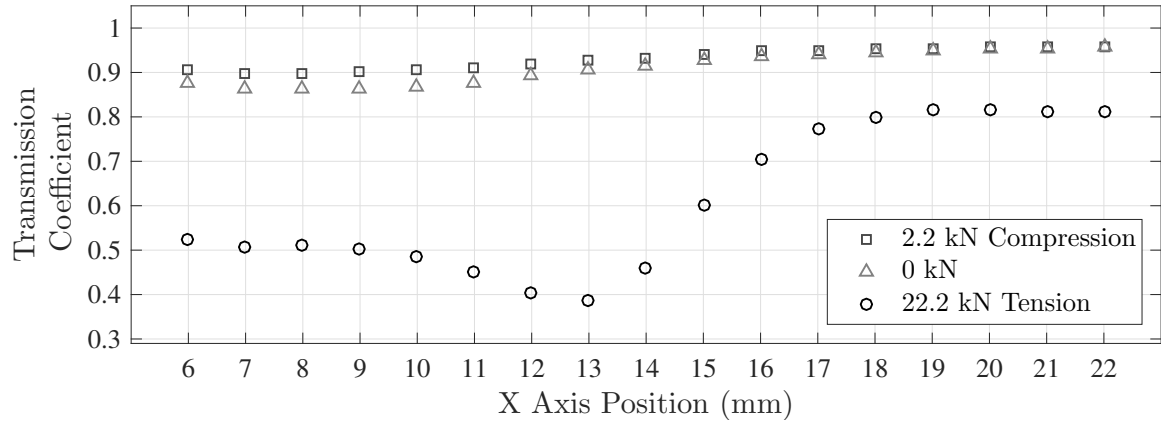
Based on these results, TC and RC calculated at a distance of 5 mm from the cracks will be presented throughout the rest of the chapter.

4.3 Effects of Static Loads on Wave Interaction with Cracks

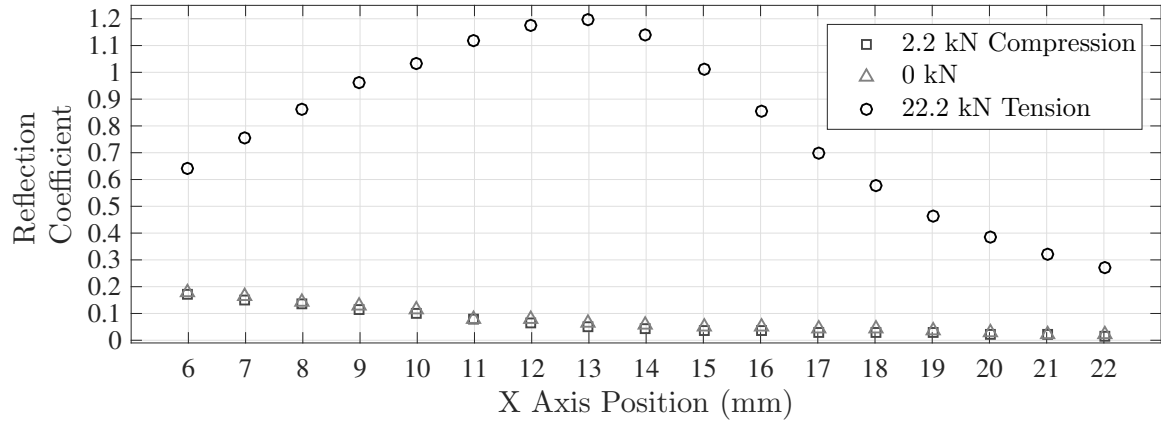
As described in Chapter III, full wavefield measurements were taken for each test specimen at three different static loads: zero load (MTS maintained 0 kN), 22.2 kN tension, and 2.22 kN compression. Figures 65 to 70 show the calculated TC and RC (assuming no wave packet dispersion and calculated at a y distance of 5 mm from the crack front). As with the previous section, results are based on excitation from PZT A (located at $x = 0$ mm). A_0 mode results are based on V_z and S_0 results are based on V_y .

As shown in Figure 65, TC and RC results for the A_0 mode and HCF crack were largely as expected. TC was highest when the crack was being forced closed under a compression load. This effect was strongest near the center of the crack. RC results showed the opposite trend, with lower values under compression, though the differences between RC values for the compression and zero load cases were very small. As predicted at the beginning of the chapter, the HCF crack appears to open significantly under the tension load, resulting in a dramatic decrease in TC and increase in RC, particularly from the center hole to the middle region of the crack.

Figure 66 shows that S_0 mode results for the HCF specimen under tension were also as expected, though the results for the compression and zero load cases were mixed along small sections of the crack. Under tension, TC was lower and RC was higher across the entire length of the crack. TC and RC values for the zero and compression load cases were similar along the majority of the crack front. Near the center hole, the compression load resulted in higher TC and lower RC, as expected; however, from $x = 11$ mm to 12 mm and $x = 19$ mm to 22 mm, TC values for the

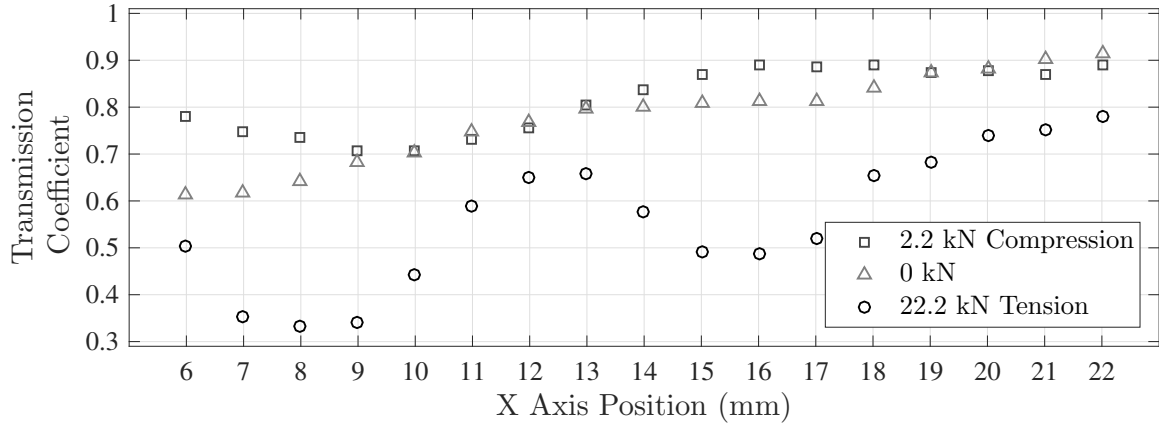


(a) TC for A_0 mode.

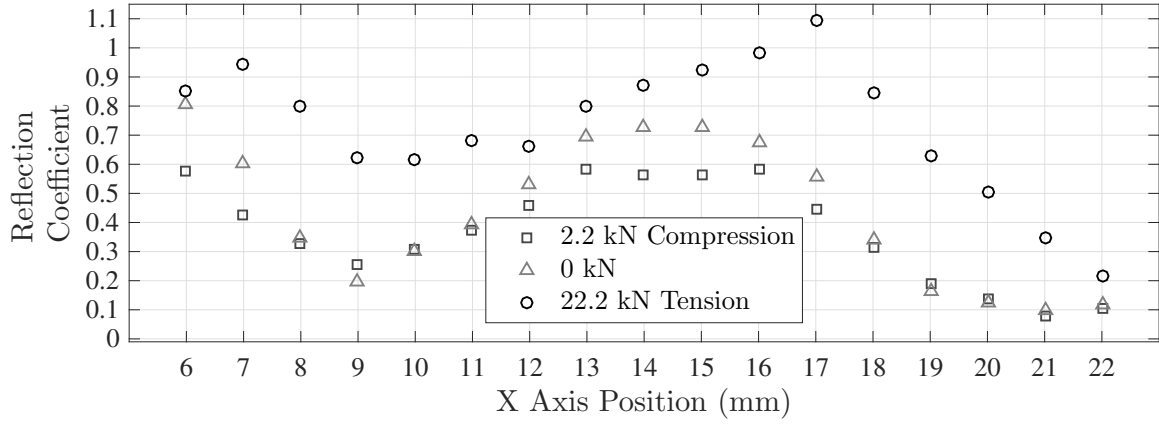


(b) RC for A_0 mode.

Figure 65. TC and RC for HCF crack, A_0 mode (150 kHz), calculated at three different static load conditions.



(a) TC for S_0 mode.



(b) RC for S_0 mode.

Figure 66. TC and RC for HCF crack, S_0 mode (350 kHz), calculated at three different static load conditions.

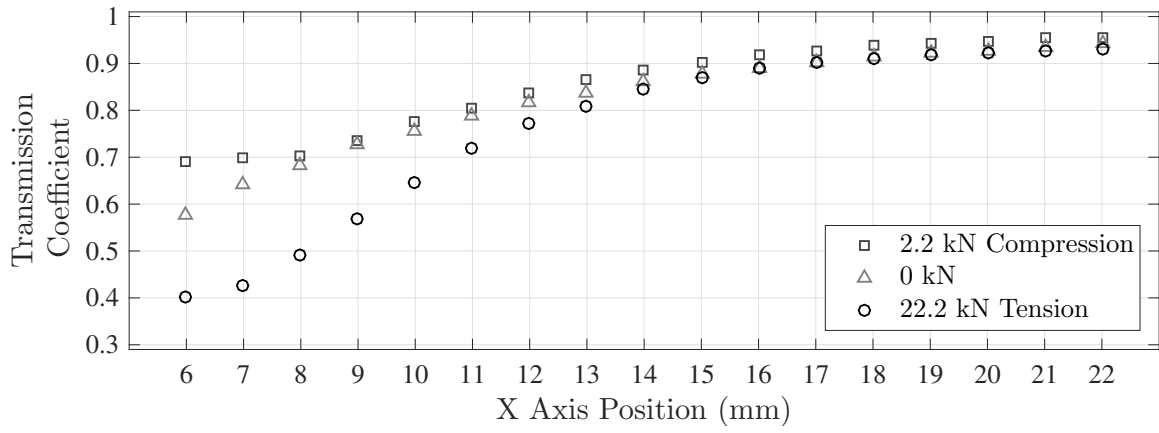
zero load case were slightly higher than the compression case. RC results were also the opposite of the expected trend at $x = 9$ mm to 10 mm and $x = 19$ mm to 20 mm. That being said, for both TC and RC, the difference in zero load and compression TC and RC magnitudes in these areas was very small.

Examining the A_0 mode results for the LCF1 specimen in Figure 67, TC and RC results were as expected. TC was highest and RC was lowest for the compression case, followed by the zero load and tension cases. Additionally, these effects were most prominent near the center hole and decreased progressing towards the tip. As was discussed at the beginning of the chapter, under a tension load, the LCF1 crack does not appear to open across as much of its length as the HCF crack, and these results support that observation.

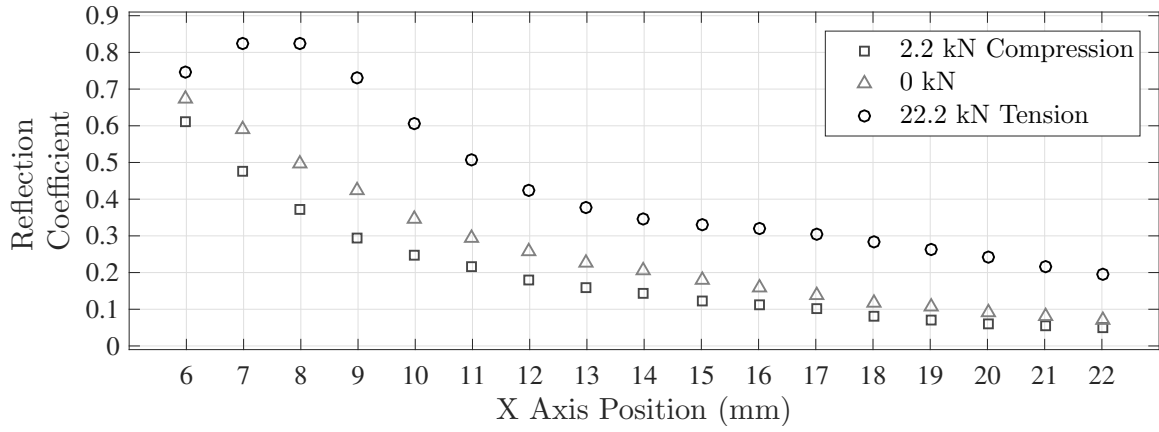
Figure 68 presents the S_0 mode results for LCF1. As with the S_0 mode results for HCF, the overall trends are as expected, with lower TC and higher RC across the majority of the crack when a tension load is applied. Results for the zero and compression load cases are also similar, with higher TC and lower RC for the compression case at most calculation points. As with the HCF case, differences between the zero and compression load results were generally closer than the tension load case.

A_0 mode results for the LCF2 crack are presented in Figure 69. RC results were as expected: higher values under a tension load, followed by the zero and compression load cases. As with the LCF1 specimen, these effects were strongest near the center hole and middle of the crack, and decreased significantly towards the crack tip, indicating that the LCF2 crack does not open as far along its length compared to the HCF specimen when under a tension load. Other than at the two calculation points nearest the crack center (which showed the expected trend), TC results for all three static load cases were similar across the majority of the crack.

Figure 70 displays the results for the S_0 mode and LCF2. Out of the six cases

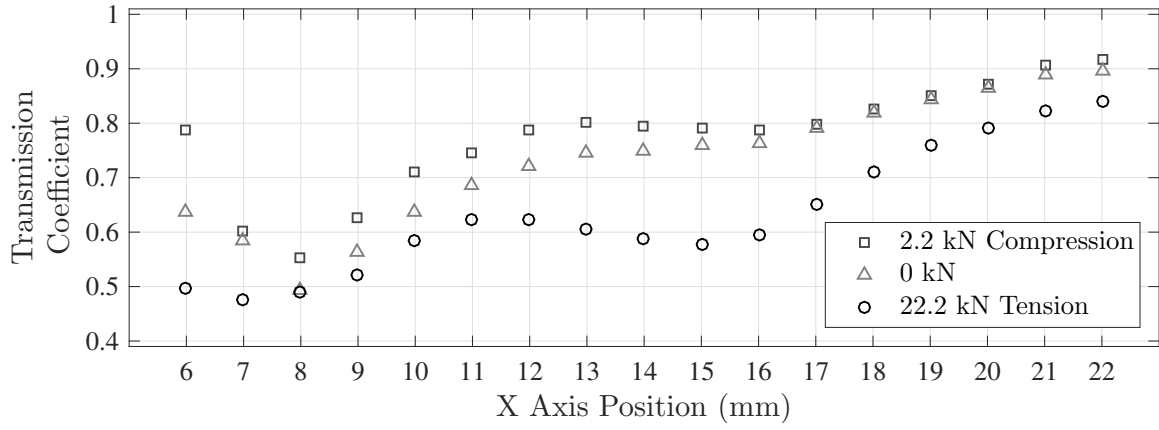


(a) TC for A_0 mode.

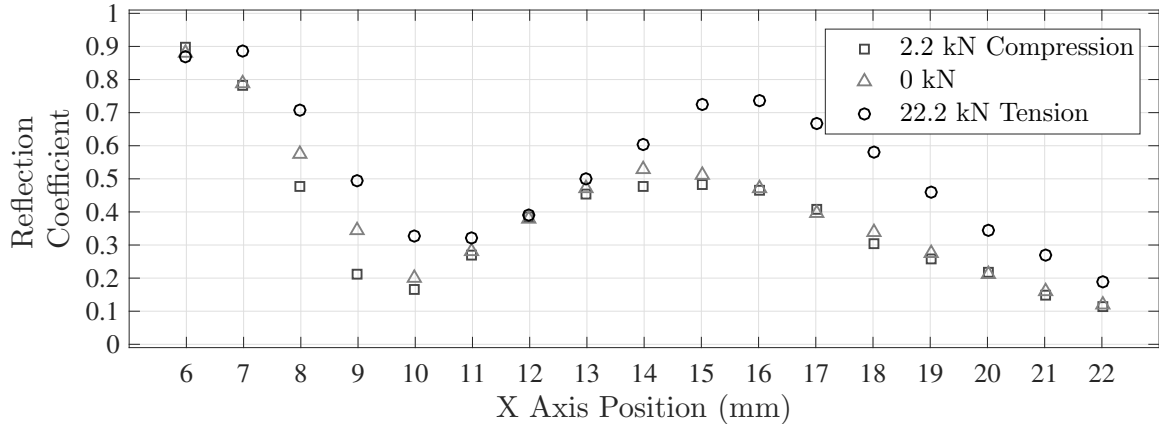


(b) RC for A_0 mode.

Figure 67. TC and RC for LCF1 crack, A_0 mode (150 kHz), calculated at three different static load conditions.

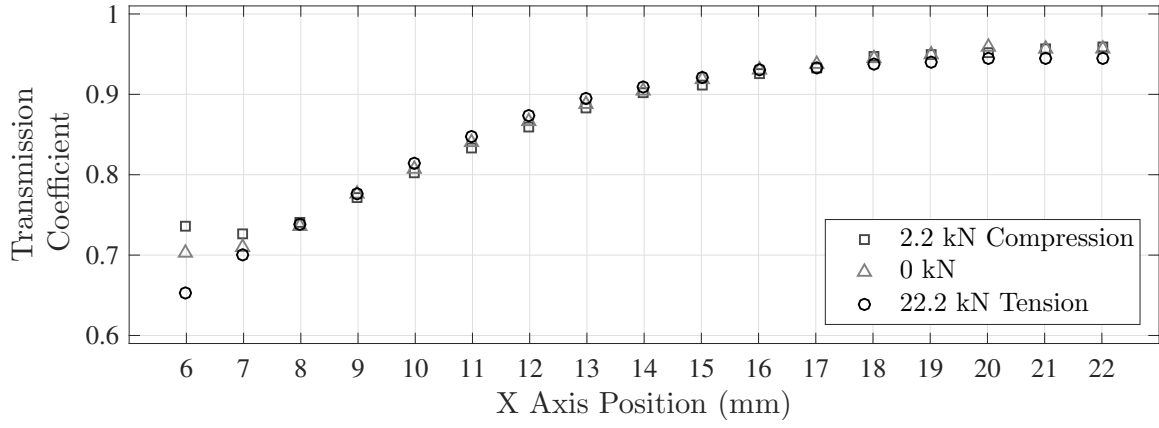


(a) TC for S_0 mode.

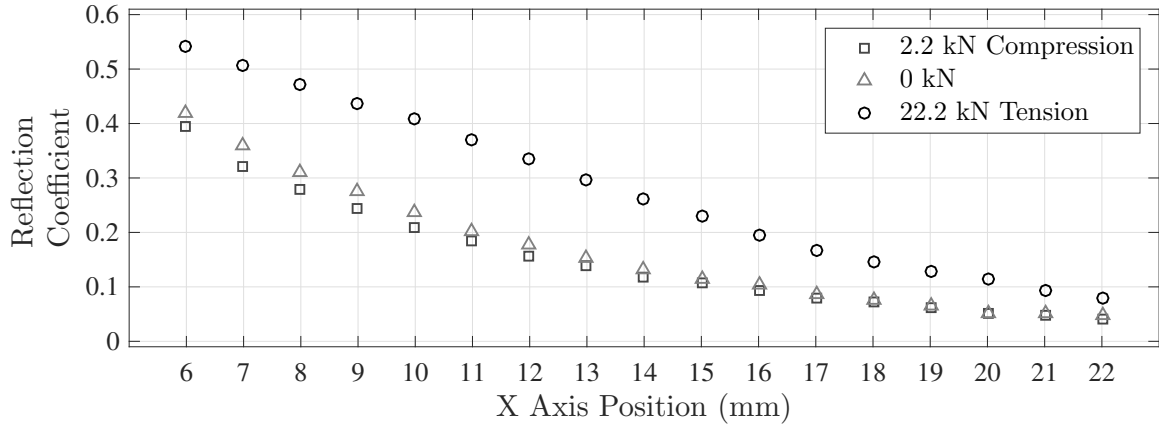


(b) RC for S_0 mode.

Figure 68. TC and RC for LCF1 crack, S_0 mode (350 kHz), calculated at three different static load conditions.

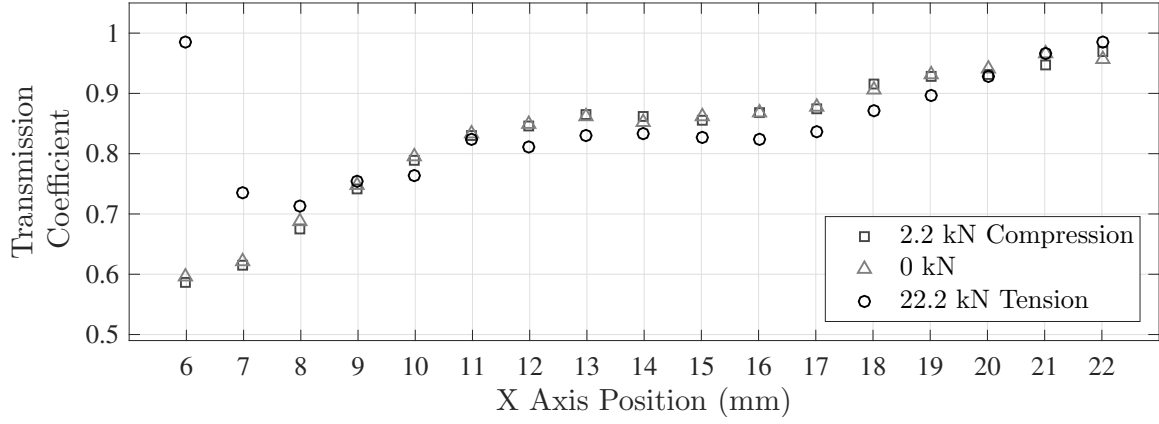


(a) TC for A_0 mode.

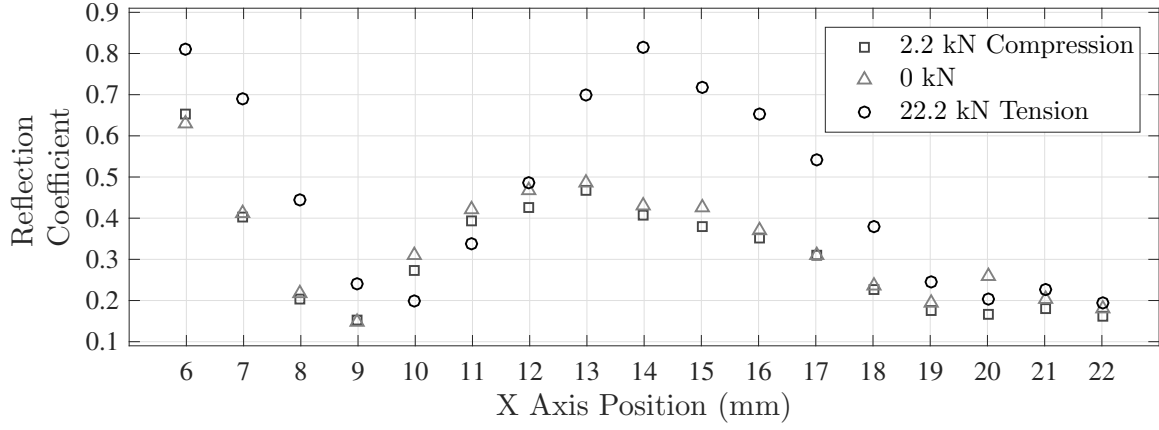


(b) RC for A_0 mode.

Figure 69. TC and RC for LCF2 crack, A_0 mode (150 kHz), calculated at three different static load conditions.



(a) TC for S_0 mode.



(b) RC for S_0 mode.

Figure 70. TC and RC for LCF2 crack, S_0 mode (350 kHz), calculated at three different static load conditions.

presented in this section, these results demonstrated greater variation and were not entirely in line with the expectations laid out at the beginning of the chapter. TC results for the compression and zero load cases were very close along the entire length of the crack; however, at multiple calculation points, the zero load cases actually demonstrated a higher value than the compression case. This was most notable in the large values of TC indicated for the tension load case at $x = 6$ mm to 7 mm. RC results were again similar for the compression and zero load cases, with the zero load cases showing slightly higher values across the majority of calculation points. RC results for the tension case were higher (as expected) at most points; however, at $x = 10$ mm to 11 mm and $x = 20$ mm the RC values were lower than one or both of the other load cases.

Data collected while specimens were under a 2.22 kN compression load are presented throughout the remainder of the chapter.

4.4 Effects of Excitation Transducer Location

As shown in Figure 71(a), a single disk transducer applied to an isotropic material produces a circular crested wavefield, resulting in energy propagating in all directions; however, frequency-wavenumber mode filtering is inherently directional. In the case of the experiments presented here, filtering for waves propagating predominantly in the y -direction. As the x -distance from the transducer increases, the angle between the y -axis and the direction of wave propagation at the analysis location increases, resulting in more wave energy propagating in the x -direction. As this angle increases, it results in a shift in the y -direction wavenumber, which gradually reduces the amount of the original wave energy that passes the filter. Because of this, mode filtering conducted on data points at or near the same x -coordinate as the transducer will capture more of the original wave energy than those further away. There are several ways to minimize

this effect. If using a single transducer, attempt to maximize the y -distance between the transducer and the area of interest in order to reduce the maximum angle between the wave propagation direction at the farthest edges of the area of interest and the selected direction of the filter. Another option is to select an excitation point at the center x -position of the area of interest (assuming the area is not too wide). Finally, the experiment designer can either use a larger and/or differently shaped transducer, or combine multiple transducers into an array in order to produce a more linearly crested wavefield. As shown in Figure 71(b), the array technique is effective at linearizing the wavefield and can effectively maximize the wave energy propagating in the direction of interest.

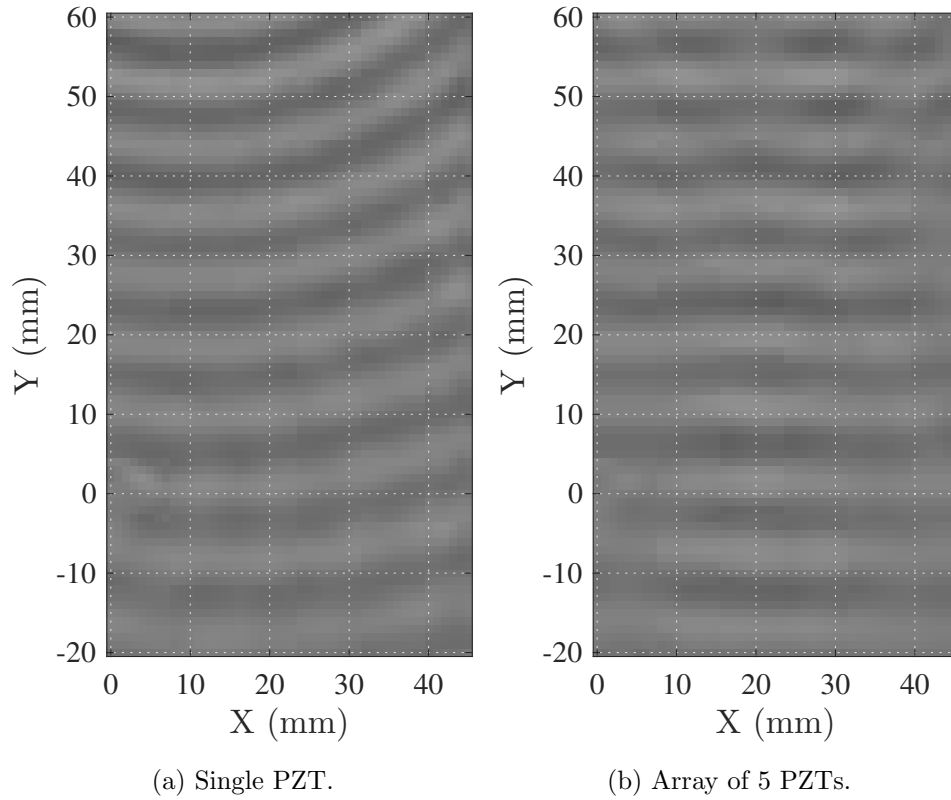


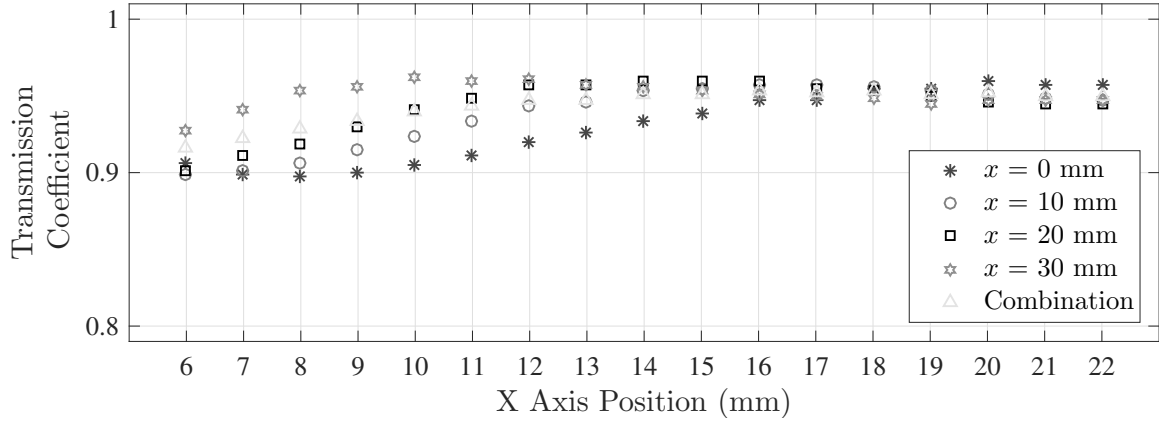
Figure 71. V_z Wavefield Images from a Single PZT and a 5 PZT Array based on Chirp Excitation (118 μ s after start of excitation).

Changing the point of excitation for a circular crested wavefield will change the arrival time and propagation angle of the wave packet at each point of analysis. When using PZT A at $x = 0$ mm, a given wave packet will reach the center hole first and the tip of the crack last. Using PZT D at $x = 30$ mm, the opposite is true. This variation in wave arrival times and angles can impact TC and RC calculations across the crack length because the amount and direction of reflected energy at each calculation point changes based on arrival time and angle.

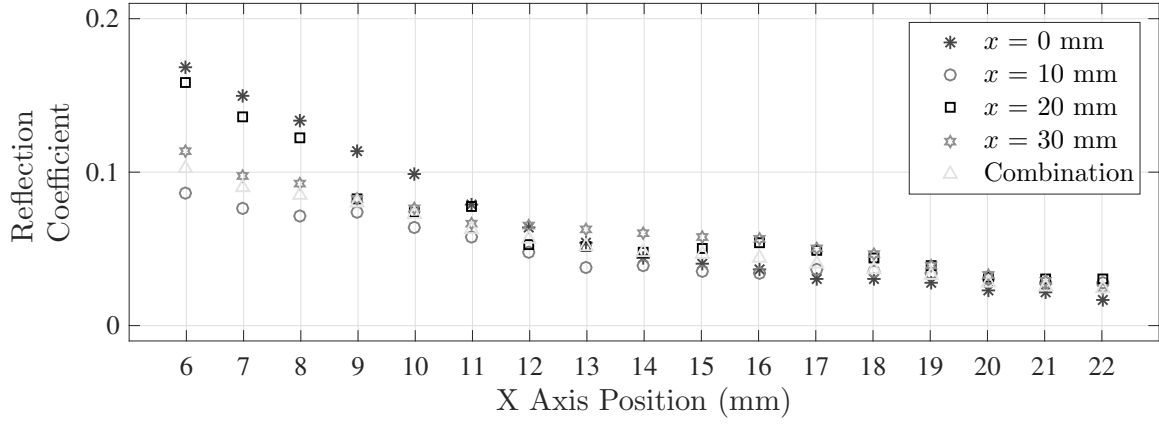
For the 0 kN and 22.2 kN tension static load cases, each test specimen was measured only once using PZT A. However, each specimen was measured five separate times under the 2.2 kN compression load—once for each excitation transducer location. This section will present the TC and RC results for each specimen using 4 single transducer excitations (PZTs A, B, C, and D), as well as a combined excitation using all five transducers in an array. Figures 72 to 77 show the effects of varying excitation source locations.

Examining Figure 72, different PZT locations demonstrate the largest spread of results for the A_0 mode and HCF specimen along the inboard portions of the crack. In general, TC increases as the excitation source moves further away from the center hole. Towards the middle of the crack and continuing outboard, the results cluster into a smaller range, until the order of TC results is essentially reversed approaching the crack tip. The RC results demonstrate a larger spread near the center hole, decreasing as the analysis point approaches the tip. However, the pattern is not the same as TC, with PZT A producing the highest RC at the center, followed in order by PZTs C, D, and B in decreasing order. The combined excitation results, while not technically an average, do fall generally in within the bounds of the individual PZT results across the crack length for both TC and RC.

Figure 73 presents the S_0 mode results for the HCF crack. The TC results follow



(a) TC for A_0 mode.



(b) RC for A_0 mode.

Figure 72. TC and RC for HCF crack, A_0 mode (150 kHz) compared across five different excitation sources.

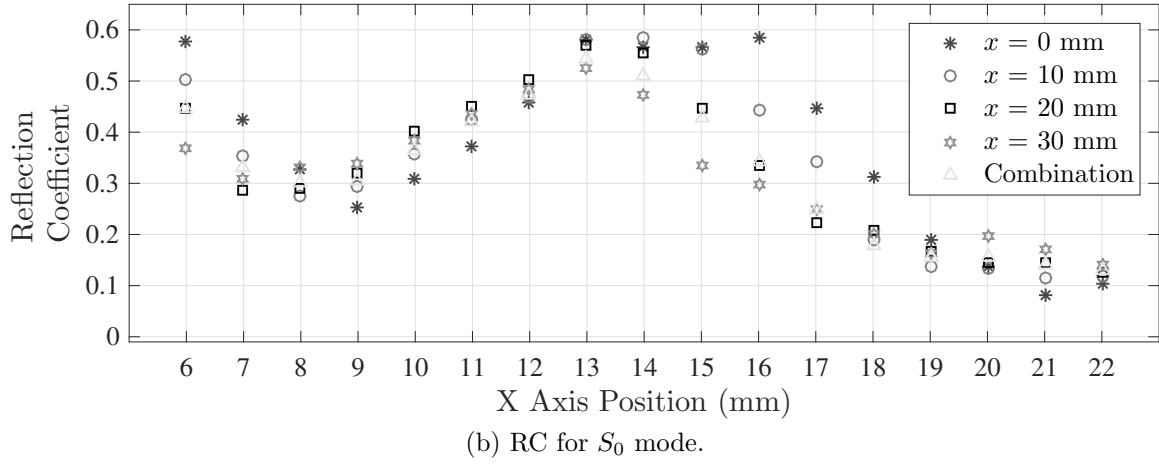
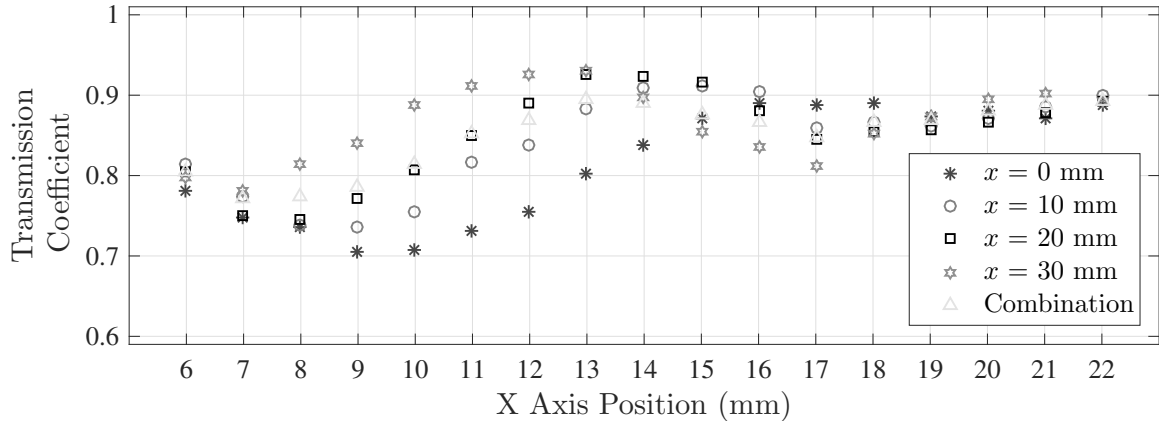


Figure 73. TC and RC for HCF crack, S_0 mode (350 kHz) compared across five different excitation sources.

the same general spreading pattern as those for the A_0 mode from the center hole out to the middle of the crack, but the trend does not clearly continue out to the crack tip. The results across all excitation sources are clustered together and do not maintain the same order near the tip. RC results show much more variation across the length of the crack, with no consistent pattern.

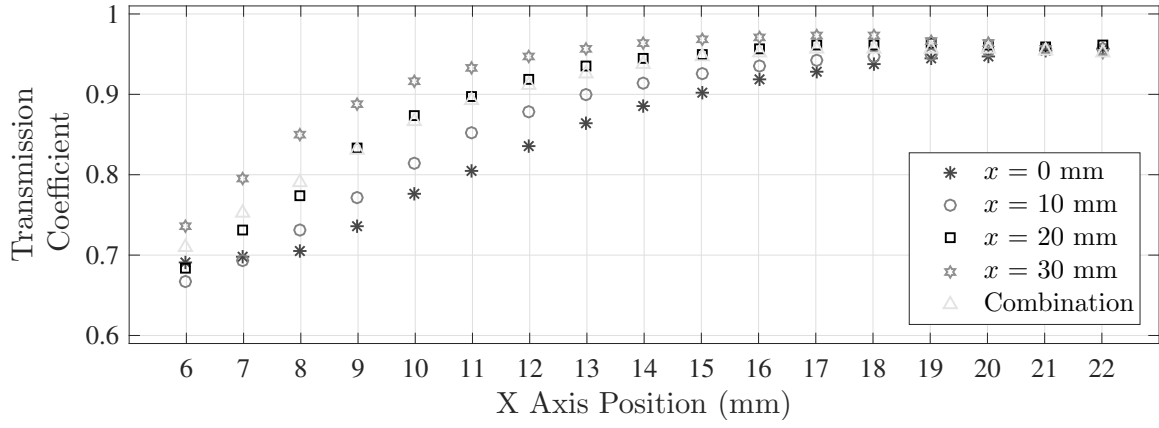
TC results for the A_0 mode on LCF1 are shown in Figure 74 and display a pattern very similar to the A_0 mode results from HCF; however, the RC results show little variation, regardless of the excitation source.

Figure 75 demonstrates similar S_0 mode results for the LCF1 specimen as were seen with the HCF crack. TC and RC results for the single PZT excitation sources vary along the length of the crack, without a consistent order based on excitation source. As was seen with the previous results, coefficients generated using the 5 PZT array mostly fall somewhere in the middle of the single PZT results.

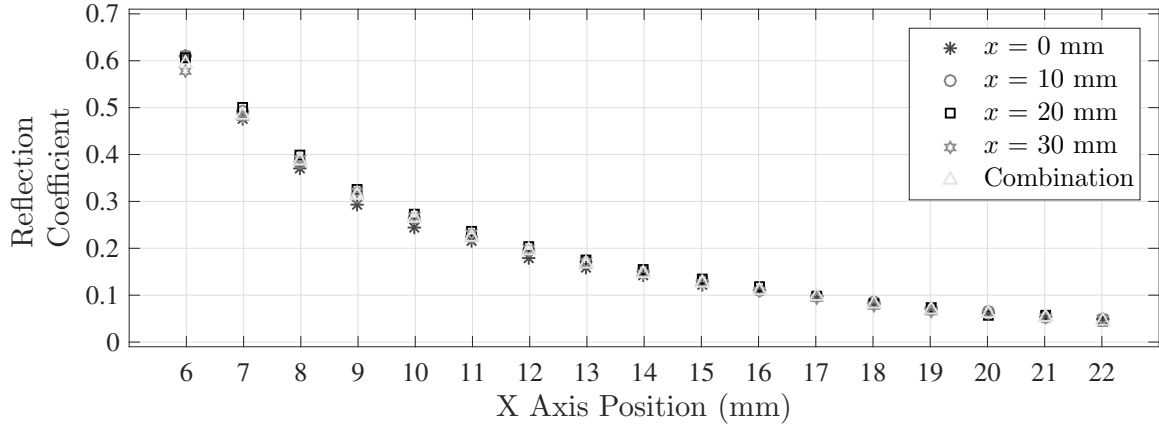
As shown by Figure 76, A_0 mode TC and RC for LCF2 follow a similar pattern to those of HCF and LCF1, though the RC results demonstrate a larger spread than LCF1 near the center hole.

The S_0 mode results for the LCF2 specimen are similar to those from LCF1, as shown by Figure 77 and will not be explored in further detail.

As discussed at the beginning of this section, a linear wavefront is desirable due to the directionality of frequency-wavenumber filtering. Because of this, all results presented in the final section of this chapter were generated using all five PZTs as an array.

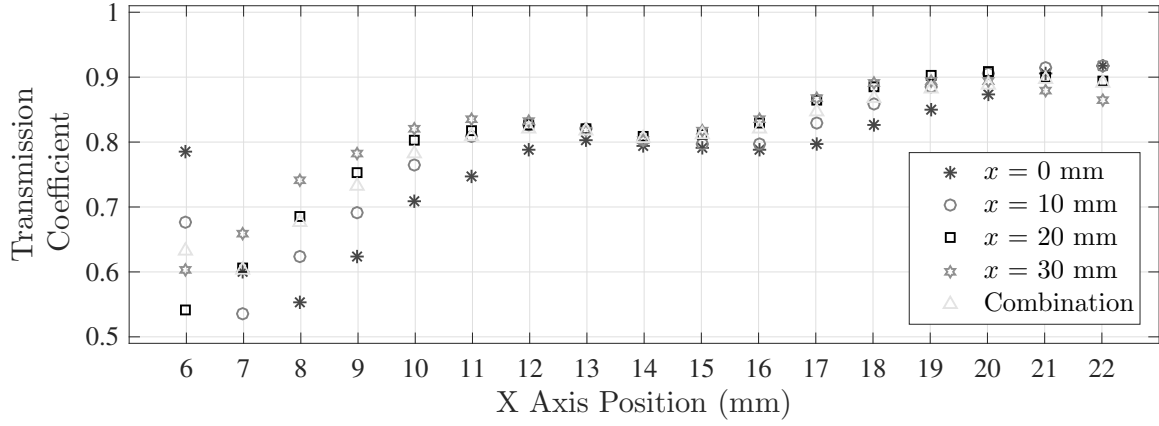


(a) TC for A_0 mode.

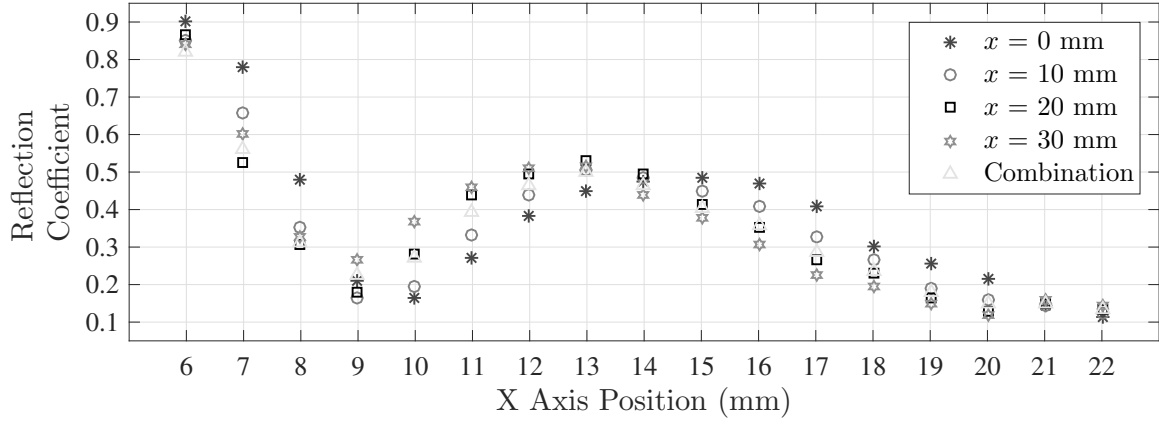


(b) RC for A_0 mode.

Figure 74. TC and RC for LCF1 crack, A_0 mode (150 kHz) compared across five different excitation sources.

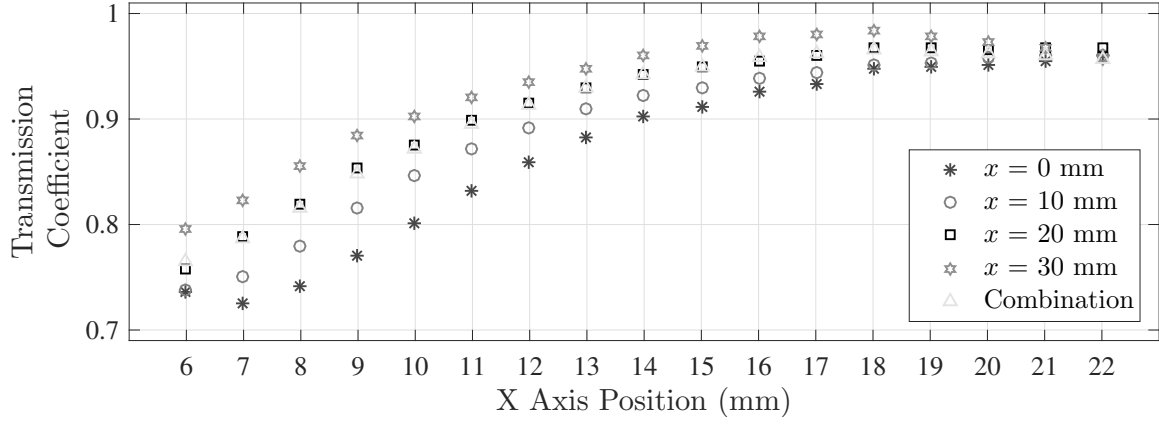


(a) TC for S_0 mode.

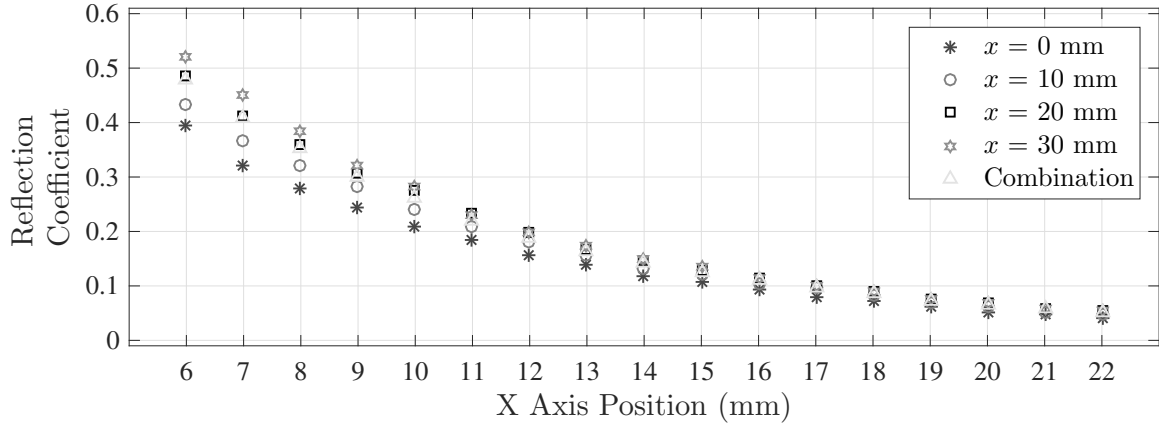


(b) RC for S_0 mode.

Figure 75. TC and RC for LCF1 crack, S_0 mode (350 kHz) compared across five different excitation sources.

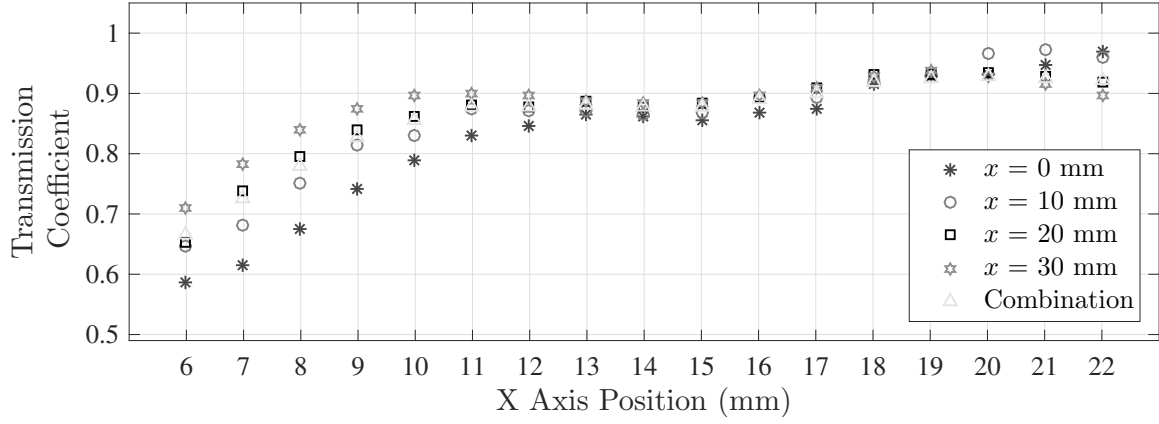


(a) TC for A_0 mode.

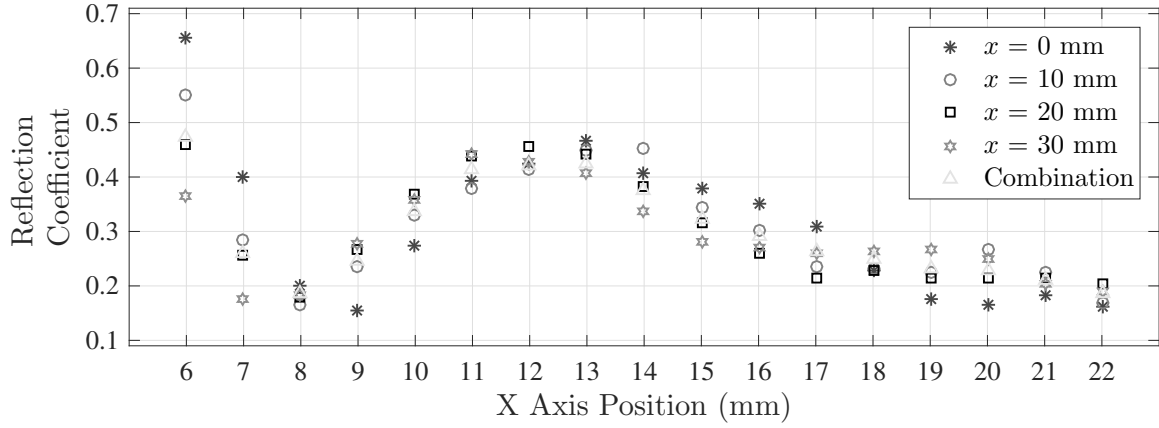


(b) RC for A_0 mode.

Figure 76. TC and RC for LCF2 crack, A_0 mode (150 kHz) compared across five different excitation sources.



(a) TC for S_0 mode.



(b) RC for S_0 mode.

Figure 77. TC and RC for LCF2 crack, S_0 mode (350 kHz) compared across five different excitation sources.

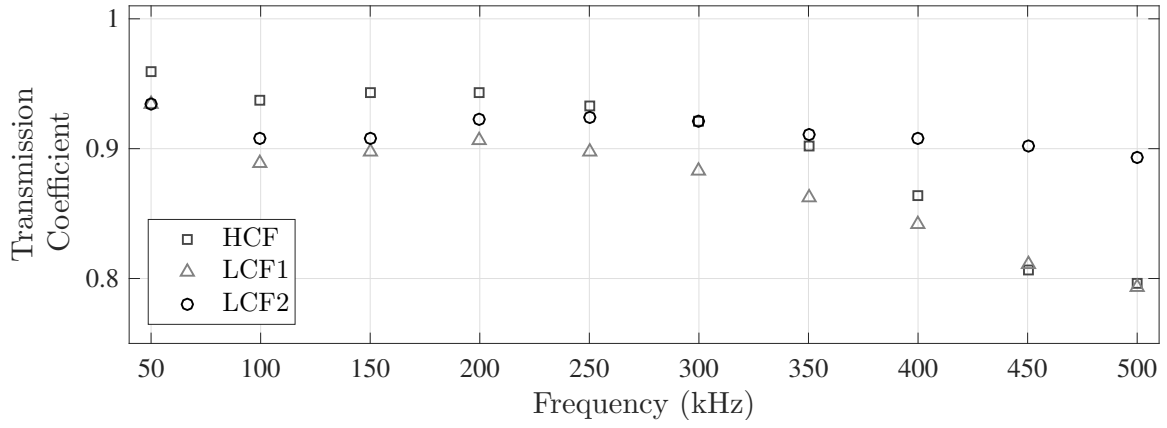
4.5 Effects of Mechanical Load History and Frequency

As presented in Chapter III, chirp filtering was conducted for each test specimen and excitation source based on an analytical 5-1/2 cycle sine burst excitation signal at 10 discrete frequencies from 50 kHz to 500 kHz in 50 kHz increments. Using the combined excitation from all five transducers, a 2.22 kN compressive load, and assuming no wave dispersion, the transmission and reflection coefficients (calculated at a y -distance of 5 mm from the crack front) were averaged across x locations from 6 mm to 22 mm for each test specimen, wave mode, and excitation frequency. Plots of the results are presented in Figures 78 and 79, and percent differences are shown in Tables 4 through 7. In addition, in order to minimize the effects of wave reflections from open crack sections near the center hole in the two LCF crack specimens, a second average was made across x locations from 10 mm to 22 mm. These results are presented in Figures 80 and 81, while percent differences are included in Tables 8 through 11.

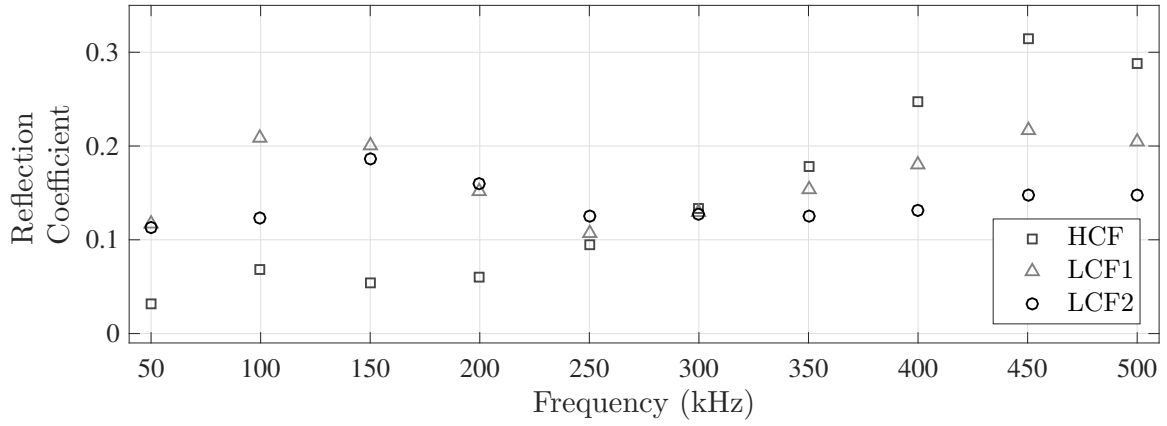
Percent difference values are labeled in the tables as “HCF to LCF1,” “HCF to LCF2,” and “LCF1 to LCF2.” In each case, these values were calculated using

$$A \text{ to } B = \frac{(A - B)}{A}. \quad (26)$$

It should be noted that TC and RC values *generally* fall between 0 and 1. As such, this calculation method can produce very large percent differences, particularly when including values close to 0 in the denominator. The percent differences presented below are intended only to show relationships and trends and should not be given too much quantitative significance by the reader.



(a) TC for A_0 mode.



(b) RC for A_0 mode.

Figure 78. Averaged TC and RC for A_0 mode from $x = 6$ mm to 22 mm and 50 kHz to 500 kHz excitation signals.

Figure 78 and Tables 4 and 5 show the A_0 mode TC and RC results for all three crack specimens at all examined frequencies, averaged from $x = 6$ mm to 22 mm. The HCF and LCF1 cracks demonstrated higher TC at lower frequencies decreasing as frequency increased. TC for HCF was higher than LCF1 at all frequencies except 450 kHz, with a maximum difference of +5.3% at 100 kHz. TC values for the LCF2 crack demonstrated the same overall trend as both other specimens; however, the reduction with increasing frequency was significantly less. As a result, TC for HCF were greater than LCF2 at low frequencies (maximum difference of +3.7% at 150 kHz), but lower at and above 350 kHz, reaching -12.1% at 500 kHz. LCF1 demonstrated lower TC than LCF2 at and above 100 kHz, with a maximum difference of -12.6% at 500 kHz.

Table 4. Percent Difference in TC (Averaged from $x = 6$ mm to 22 mm) for A_0 Mode and All Three Test Specimens

Specimen Comparison	Excitation Frequency (kHz)									
	50	100	150	200	250	300	350	400	450	500
HCF to LCF1	2.6	5.3	4.9	4.0	3.8	4.2	4.4	2.5	-0.6	0.4
HCF to LCF2	2.6	3.2	3.7	2.2	1.0	0.1	-1.0	-5.2	-11.7	-12.1
LCF1 to LCF2	0.0	-2.2	-1.3	-1.8	-2.9	-4.3	-5.7	-7.8	-11.1	-12.6

Table 5. Percent Difference in RC (Averaged from $x = 6$ mm to 22 mm) for A_0 Mode and All Three Test Specimens

Specimen Comparison	Excitation Frequency (kHz)									
	50	100	150	200	250	300	350	400	450	500
HCF to LCF1	-267.6	-200.5	-269.9	-151.2	-12.8	1.7	14.3	27.6	30.9	29.3
HCF to LCF2	-252.5	-78.9	-243.7	-165.1	-30.4	4.2	29.4	46.6	52.8	48.8
LCF1 to LCF2	4.1	40.5	7.1	-5.5	-15.5	2.5	17.6	26.3	31.8	27.6

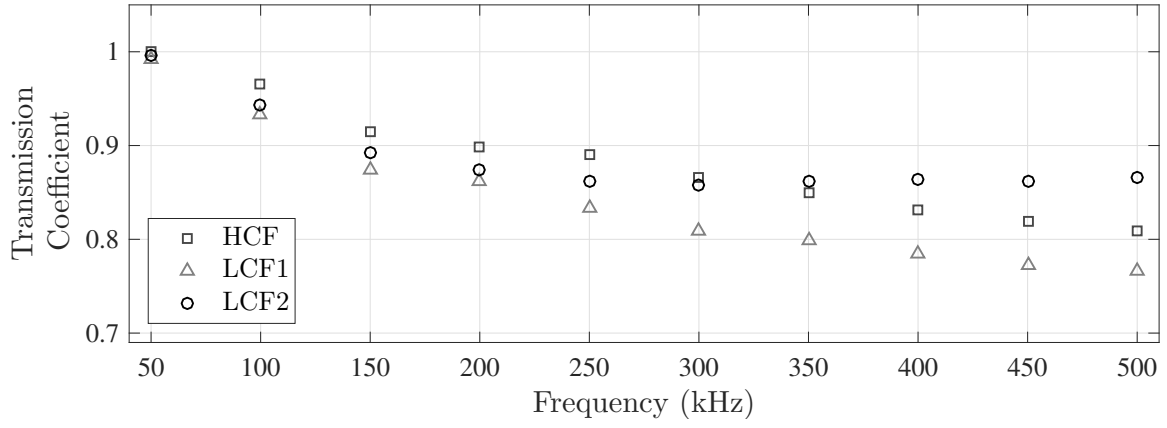
Examining the A_0 mode RC results, the trends are similar to those seen for TC, but in reverse. HCF has a lower RC than both LCF1 and LCF2 at 250 kHz and below, and greater RC than both at higher frequencies. These differences were greatest at 50 kHz, where the RC for HCF was -267.6% and -252.5% less than LCF1 and LCF2, respectively. At 450 kHz, HCF RC values were +30.9% higher than LCF1 and +52.8% higher than LCF2. LCF1 demonstrated a higher RC than LCF2 at all frequencies except 200 kHz to 250 kHz, with a maximum difference of +40.5% at 100 kHz.

The variations in TC and RC across the frequency range for all three test specimens appear consistently throughout the results presented in this section. While this behavior was not specifically predicted, several possible explanations will be presented at the end of the chapter.

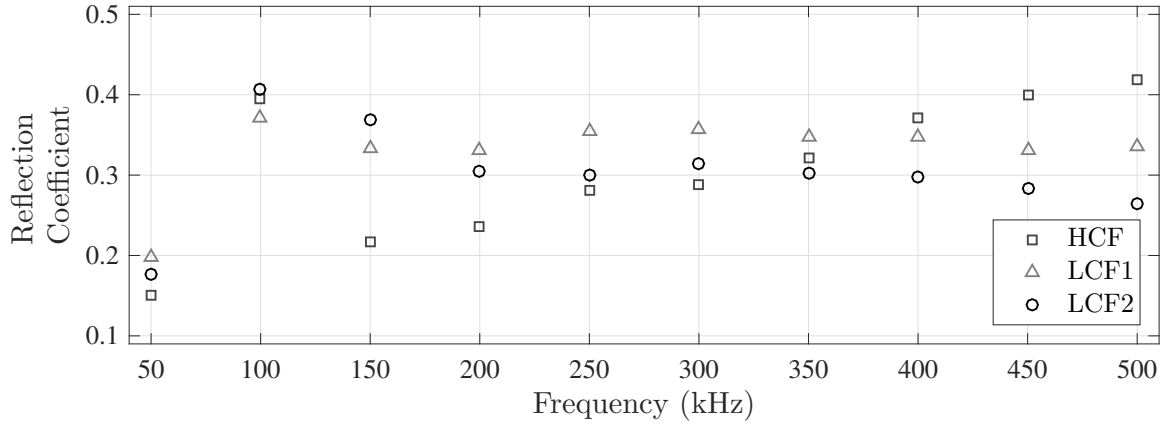
As presented in Figure 79 and Tables 6 and 7, TC and RC results for the S_0 mode averaged from $x = 6$ mm to 22 mm along the crack front demonstrate similar trends to those for the A_0 mode. The HCF crack had higher TC than LCF1 across all frequencies, with a maximum difference of +6.5% at 300 kHz. Compared to LCF2, the HCF specimen had higher TC at and below 300 kHz (maximum difference of +3.1% at 250 kHz), and lower TC with increasing frequency up to a -7.0% difference at 500 kHz. LCF1 had a lower TC than LCF2 across all frequencies, with a difference of -0.4% at 50 kHz increasing to -12.9% at 500 kHz.

Table 6. Percent Difference in TC (Averaged from $x = 6$ mm to 22 mm) for S_0 Mode and All Three Test Specimens

Specimen Comparison	Excitation Frequency (kHz)									
	50	100	150	200	250	300	350	400	450	500
HCF to LCF1	0.7	3.2	4.3	4.0	6.3	6.5	6.0	5.8	5.8	5.3
HCF to LCF2	0.3	2.2	2.5	2.7	3.1	0.9	-1.4	-3.9	-5.2	-7.0
LCF1 to LCF2	-0.4	-1.0	-2.0	-1.4	-3.4	-6.0	-7.8	-10.3	-11.7	-12.9



(a) TC for S_0 mode.



(b) RC for S_0 mode.

Figure 79. Averaged TC and RC for S_0 mode from $x = 6$ mm to 22 mm and 50 kHz to 500 kHz excitation signals.

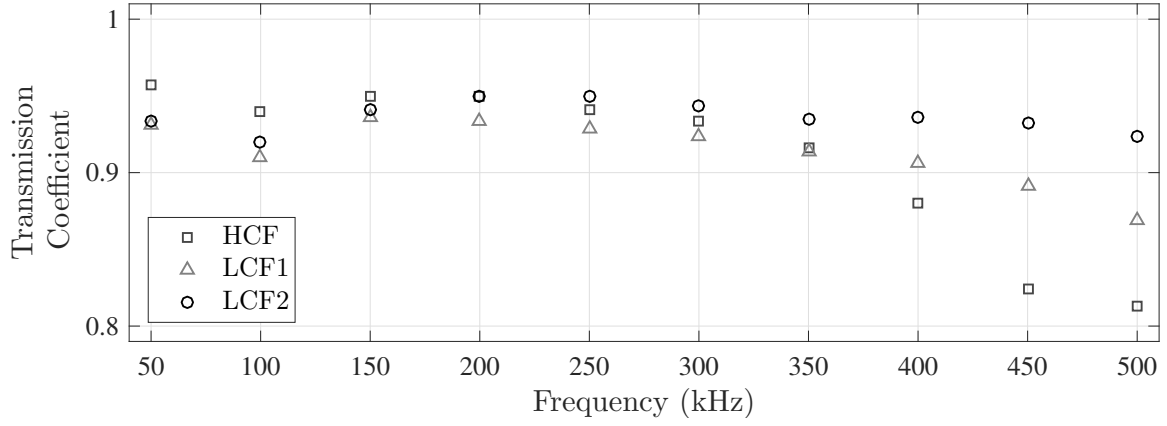
Table 7. Percent Difference in RC (Averaged from $x = 6$ mm to 22 mm) for S_0 Mode and All Three Test Specimens

Specimen	Excitation Frequency (kHz)									
Comparison	50	100	150	200	250	300	350	400	450	500
HCF to LCF1	-31.2	6.3	-52.5	-39.5	-26.6	-23.4	-7.8	6.6	17.3	19.9
HCF to LCF2	-17.0	-3.1	-69.4	-28.2	-6.9	-9.2	6.5	19.9	29.4	36.7
LCF1 to LCF2	10.8	-10.1	-11.1	8.1	15.5	11.5	13.3	14.3	14.6	20.9

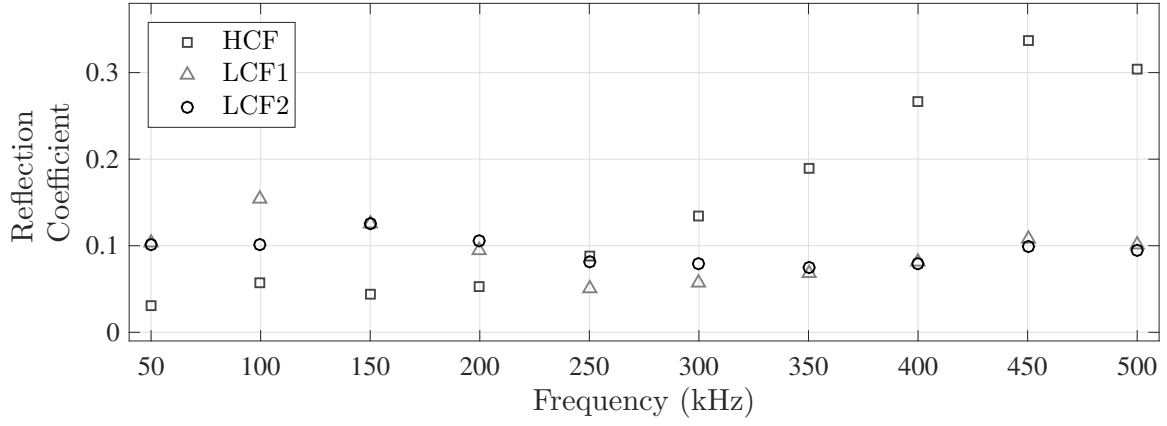
The HCF specimen demonstrated lower RC than LCF1 at most frequencies, with a maximum difference of -52.5% at 150 kHz. At 100 kHz as well as at and above 400 kHz, RC for HCF was higher than LCF1, with a maximum difference of +19.9% at 500 kHz. Compared to LCF2, HCF had a lower RC up to and including 300 kHz, with a maximum difference of -69.4% at 150 kHz. At 500 kHz, RC for HCF increased to +36.7% greater than LCF2. LCF1 demonstrated a higher RC than LCF2 at all frequencies except 100 kHz to 150 kHz, with a maximum difference of +20.9% at 500 kHz.

As was discussed at the beginning of this section, in order to minimize the possible effects of the partially open sections of the LCF1 and LCF2 crack specimens, TC and RC data were also averaged from $x = 10$ mm to 22 mm, thereby excluding the data points nearest the center hole. In general (and as may be expected), this change in calculation method affected the LCF1 and LCF2 results more than those for the HCF specimen.

Figure 80 and Tables 8 and 9 present these partial length average TC and RC results for the A_0 mode for all three cracks across all frequencies. Overall trends are similar to those presented earlier in the section, but percent differences between the HCF and both LCF cracks are generally lower with this calculation method. TC for HCF was higher than LCF1 at and below 350 kHz, with the greatest difference of



(a) TC for A_0 mode.



(b) RC for A_0 mode.

Figure 80. Averaged TC and RC for A_0 mode from $x = 10$ mm to 22 mm and 50 kHz to 500 kHz excitation signals.

+3.2% at 100 kHz. At 450 kHz, TC for the HCF crack was lower than LCF1 with a difference of -8.1%. HCF demonstrated greater TC than LCF2 from 50 kHz to 150 kHz (greatest difference was +2.5% at 50 kHz) and lower TC from 250 kHz to 500 kHz, with a maximum difference of -13.6% at 500 kHz. LCF1 had a lower TC than LCF2 across all frequencies, with a maximum difference of -6.3% at 500 kHz decreasing to -0.3% at 50 kHz.

Table 8. Percent Difference in TC (Averaged from $x = 10$ mm to 22 mm) for A_0 Mode and All Three Test Specimens

Specimen	Excitation Frequency (kHz)									
Comparison	50	100	150	200	250	300	350	400	450	500
HCF to LCF1	2.8	3.2	1.4	1.6	1.3	1.1	0.3	-3.0	-8.1	-6.8
HCF to LCF2	2.5	2.0	0.9	0.0	-0.9	-1.1	-2.1	-6.3	-13.2	-13.6
LCF1 to LCF2	-0.3	-1.2	-0.5	-1.6	-2.3	-2.2	-2.4	-3.3	-4.7	-6.3

Table 9. Percent Difference in RC (Averaged from $x = 10$ mm to 22 mm) for A_0 Mode and All Three Test Specimens

Specimen	Excitation Frequency (kHz)									
Comparison	50	100	150	200	250	300	350	400	450	500
HCF to LCF1	-232.7	-166.2	-189.8	-76.0	44.0	57.6	63.4	69.2	67.9	66.5
HCF to LCF2	-228.9	-76.2	-189.3	-97.7	8.6	40.8	60.3	70.2	70.4	69.1
LCF1 to LCF2	1.1	33.8	0.2	-12.3	-63.3	-39.8	-8.4	3.4	8.0	7.7

Examining the RC results, HCF was lower than both LCF1 and LCF2 at and below 200 kHz, with the maximum difference in both comparisons occurring at 50 kHz (-232.7% versus LCF1 and -228.9% versus LCF2). At higher frequencies, both LCF1 and LCF2 had lower RC than HCF, with the maximum difference occurring at 450 kHz (+67.9% for LCF1 and +70.4% for LCF2). LCF1 had a higher RC than LCF2 at

both the lowest and highest frequencies investigated, but was lower from 200 kHz to 350 kHz, with a maximum difference of -63.3% at 250 kHz.

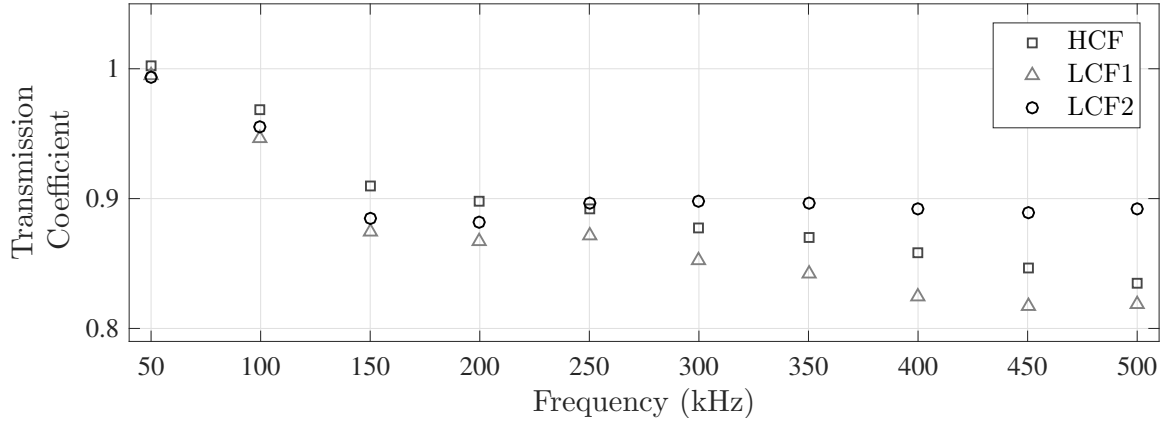
Table 10. Percent Difference in TC (Averaged from $x = 10$ mm to 22 mm) for S_0 Mode and All Three Test Specimens

Specimen	Excitation Frequency (kHz)									
Comparison	50	100	150	200	250	300	350	400	450	500
HCF to LCF1	0.8	2.3	3.8	3.5	2.2	2.9	3.3	3.8	3.4	2.0
HCF to LCF2	0.9	1.4	2.8	1.8	-0.5	-2.4	-3.0	-4.1	-5.0	-6.9
LCF1 to LCF2	0.1	-0.9	-1.1	-1.7	-2.9	-5.5	-6.5	-8.2	-8.8	-9.0

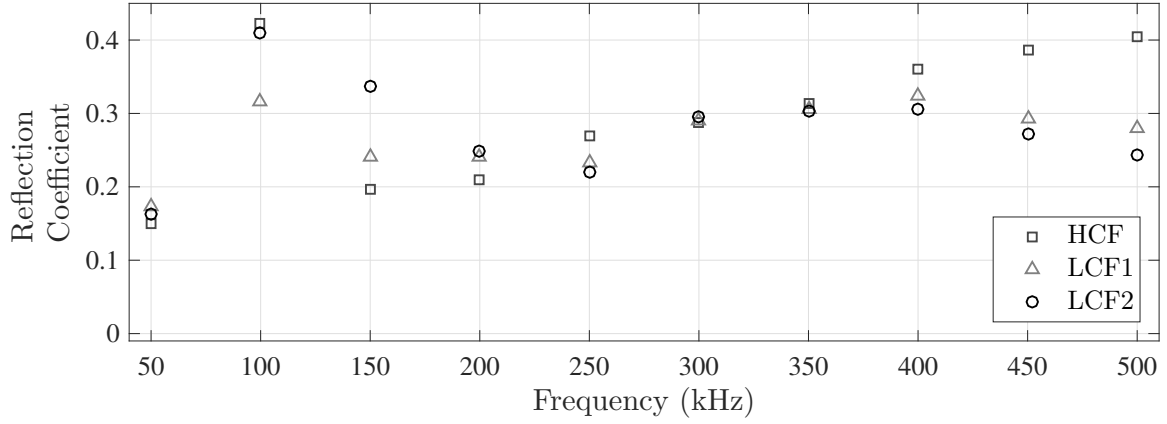
Table 11. Percent Difference in RC (Averaged from $x = 10$ mm to 22 mm) for S_0 Mode and All Three Test Specimens

Specimen	Excitation Frequency (kHz)									
Comparison	50	100	150	200	250	300	350	400	450	500
HCF to LCF1	-13.8	25.1	-23.0	-15.8	13.4	-0.5	2.7	10.0	24.0	31.1
HCF to LCF2	-8.4	2.7	-72.2	-19.0	18.6	-2.7	3.4	14.9	29.7	40.1
LCF1 to LCF2	4.8	-29.9	-40.0	-2.8	6.0	-2.1	0.7	5.5	7.5	13.1

Examining Figure 81 and Tables 10 and 11, the results for the S_0 mode excluding the data points nearest the center hole demonstrate similar overall trends to those averaged across the entire crack front. The TC of the HCF specimen is greater than LCF1 at all frequencies, with the smallest difference of +0.8% coming at 50 kHz and the largest, +3.8%, at 400 kHz. HCF TC is greater than LCF2 at and below 200 kHz, with a maximum of +2.8% difference at 150 kHz. At 250 kHz and above, TC for the HCF specimen is lower than LCF2, and the difference between the two increases to a maximum of -6.9% at 500 kHz. The TC values for LCF1 are lower than LCF2 at all



(a) TC for S_0 mode.



(b) RC for S_0 mode.

Figure 81. Averaged TC and RC for S_0 mode from $x = 10$ mm to 22 mm and 50 kHz to 500 kHz excitation signals.

frequencies except 50 kHz, where the difference is only +0.1%. The difference between LCF1 and LCF2 increases with frequency to a maximum of -9.0% at 500 kHz.

The RC results for the S_0 mode are similar to those seen earlier, with HCF lower than both LCF1 and LCF2 at 50 kHz, 150 kHz to 200 kHz, and 300 kHz and higher than both at all other frequencies. The maximum negative difference occurred at 150 kHz, where HCF is -23.0% lower than LCF1 and -72.2% lower than LCF2. The maximum positive difference in each case was at 500 kHz, with +31.1% compared LCF1 and +40.1% compared to LCF2. Comparing RC values for LCF1 to LCF2, LCF1 RC was lower at 100 kHz to 200 kHz and 300 kHz, and higher at all other frequencies. The maximum overall difference was -40.0% at 150 kHz, while the difference at 500 kHz was +13.1%.

General Observations and Discussion.

As was discussed at the beginning of the chapter, expectations were that the HCF crack specimen would demonstrate higher TC and lower RC than the two LCF crack specimens. It was additionally hypothesized that the LCF1 crack specimen was likely to demonstrate lower TC and higher RC than the LCF2 specimen due to the crack being open a longer distance near the center hole.

Comparing HCF to LCF1 and LCF2, below approximately 200 kHz to 250 kHz, the initial expectations were generally proven true; however, at higher frequencies, HCF specimen TC decreased and RC increased to the point where HCF demonstrated lower TC and higher RC than one or both of the LCF crack specimens.

A thorough analysis of the observed TC and RC changes with frequency will be included in future research; however, there are several possible causes that can be hypothesized, the first of which is mode conversion. When Lamb waves encounter discontinuities such as cracks, plasticity, delaminations, material interfaces, edges,

etc., wave energy can and does convert from one mode to another. At high enough frequency-thickness (fd) products (above approximately $1.8 \text{ MHz} \cdot \text{mm}$ in aluminum), energy can convert between the linear modes (A_0 and S_0) and nonlinear modes (A_1 , S_1 , A_2 , S_2 , and so on), as well as shear-horizontal wave modes (which are not technically Lamb waves). As discussed in Chapter II, this phenomenon is used by some researchers as a means to detect damage; wave energy can convert to non-linear wave modes at higher harmonics of the incident wave frequency when encountering material nonlinearities, such as those caused by fatigue damage. Because the maximum fd in these experiments was $1.6 \text{ MHz} \cdot \text{mm}$, the only conversions possible were between A_0 , S_0 , and shear horizontal waves. The algorithm developed in the course of this research was not robust enough to detect mode conversions. It is possible that mode conversion behavior changed significantly with frequency for one or more of the test specimens, leading to unexpected changes on the calculated TC and RC values.

Another possible hypothesis for the changes in TC and RC with frequency is the change in wavelength of both the A_0 and S_0 modes with increasing frequency. Considering the 3.175 mm thick aluminum plates used in this research, at 50 kHz A_0 waves have a wavelength of approximately 23 mm , while at 500 kHz the wavelength is only 5 mm . Similarly, S_0 mode wavelength decreases from approximately 105 mm at 50 kHz down to 10 mm at 500 kHz . The sensitivity of an elastic wave to a defect can vary based on the ratio of the defect size to the wavelength, as demonstrated by Lu et al. [129] and discussed in Chapter II; this may be a significant factor in the observed TC and RC changes with frequency.

A final potential source of the observed behavior is energy loss via friction and heating due to crack face fretting or other nonlinear behaviors. Klepka et al. [133], used an infrared camera to measure temperature changes at a fatigue crack in an aluminum plate subjected to vibro-acoustic (modal) excitation via a shaker and found

that crack opening and closing (crack mode I) action at very low strain levels produced a temperature rise and affected the vibro-acoustic modulations of the plate. While that was a modal study and not a Lamb wave study, based on the low strains produced by propagating Lamb waves, the results may be relevant to this work. As excitation frequency increases, wave induced acceleration of the plate particles also increases. At higher frequencies, this would logically increase the speed at which the crack faces would contact or rub against one another as a wave packet passes. When coupled with the fact that the HCF specimen should have lower residual stresses in the plastic zone surrounding the crack (and therefore potentially higher wave displacements in the vicinity of the crack), it is possible that these sorts of losses may be more significant in the case of the HCF crack than for the two LCF specimens.

V. Conclusions and Recommended Future Work

5.1 Research Motivation and Objective

Chapter I presented an overview of the aging aircraft challenges the USAF presently faces, the current schedule-based maintenance paradigm, and the significant potential for automated SHM systems to positively impact maintenance costs and aircraft availability by enabling a shift to a condition-based maintenance paradigm. Section 1.4 provided a brief overview of the most common categories of SHM methodologies and research areas. These include both passive and active SHM techniques; however, the majority of recent research has been focused on active techniques, with vibration/modal, electro-mechanical impedance, and elastic wave propagation based approaches being most common.

An RDECOM-sponsored experiment using a COTS SHM system based on bonded piezoelectric transducers and elastic wave propagation indicated that the system performed better against a low-cycle fatigue crack than a similar high-cycle crack, each grown in identical aerospace test structures. Based on this finding and the sparsity of existing research on the subject, the principal objective of this research effort was to investigate and characterize the differences in Lamb wave interaction with fatigue cracks grown under different loading spectra (specifically low-cycle vs. high-cycle fatigue) and at different static loads.

5.2 Conclusions based on Results and Analysis

Chapter IV presents data to support specific conclusions concerning the effectiveness of the data-reduction and analysis techniques used in these experiments as well as the effects of both the fatigue loading spectrum and static loads on Lamb wave interaction with fatigue cracks in aluminum plates.

Conclusion 1: *All three methods of calculating TC and RC produced similar results.* Section 4.2 and Figures 53 to 58 show that all three TC and RC calculation methods used (dispersion, no dispersion, and maximum amplitude) had similar results, particularly for the A_0 wave mode. In the cases where there was significant variation, the method assuming dispersion was typically the outlier, largely for reasons discussed in Section 3.4. Despite the larger variation produced using the dispersion method, overall trends of TC and RC along the length of the crack front were similar across all three methods.

Conclusion 2: *TC and RC magnitudes can vary based on the distance of calculation data points from the crack front.* Section 4.2 and Figures 59 to 64 demonstrate that TC calculated at 10 mm from the crack were lower in magnitude than those calculated at 5 mm from the crack; this effect was generally larger towards the center hole and decreased moving towards the crack tip. A similar (but opposite) effect was seen for RC; however, the magnitude of the difference between calculation distances was significantly smaller for RC.

Conclusion 3: *Increasing static load caused all cracks to open along at least a portion of their length, resulting in reduced TC and increased RC for both A_0 and S_0 wave modes.* Section 4.3 and Figures 65 to 70 show that as the static load transitions from compression to zero load, and then to a tension load, TC values decrease and RC values increase across virtually the entire length of the crack front. The magnitude of these changes was most significant for the HCF crack, which opened along the majority of its length under a tension static load. Both LCF specimens exhibited similar behavior, but with reduced magnitudes and more variation along the length of the crack.

Conclusion 4: *Position of the excitation transducer relative to the crack can affect calculated TC and RC values.* Section 4.4 and Figures 72 to 77 illustrate the variation

produced by changing the location of the excitation transducer. In general, these variations were largest near the center hole and/or middle region of each crack, and decreased towards the tip. However, in the majority of cases, the overall trend of TC and RC along the crack length was similar. Due to the geometry of the test articles, these effects were not considered large, and final results using a single transducer would likely not have varied significantly from those using all five transducers in an array. In virtually all cases, the results using the five transducer array fell near the center of the spread of results using individual excitation sources.

Conclusion 5: *At lower frequencies, the HCF crack demonstrated higher average TC and lower average RC than either of the LCF crack specimens; however, this trend generally reversed itself at higher frequencies.* Section 4.5, Figures 78 to 81 and Tables 4 to 11 show that the crossover frequency was typically between 250 kHz to 350 kHz when TC and RC were averaged from $x = 6$ mm to 22 mm, and 200 kHz to 250 kHz when averaged from $x = 10$ mm to 22 mm.

Using partial length averages, A_0 mode TC for the HCF crack was 3.2% greater than LCF1 at 100 kHz and 8.1% lower at 450 kHz. Compared against the LCF2 specimen, HCF demonstrated an A_0 mode TC 2.5% greater at 50 kHz and 13.6% lower at 500 kHz. A_0 mode RC for the HCF crack at 50 kHz were 232.7% and 228.9% lower than LCF1 and LCF2, respectively. However, at 400 kHz HCF RC was 69.2% greater than LCF1 and at 450 kHz, it was 70.4% greater than LCF2.

Again, based on partial length averages, S_0 mode TC for the HCF crack were larger than those of the LCF1 crack at all frequencies, with the largest difference of 3.8% occurring at both 150 kHz and 400 kHz. Compared against LCF2, the S_0 mode TC for HCF was 2.8% greater at 150 kHz and 6.9% lower at 500 kHz. RC results for the S_0 mode demonstrated greater variation across frequencies, but RC for HCF was 23.0% lower than LCF1 at 150 kHz and 31.1% higher at 500 kHz. Compared

against LCF2, RC for the HCF crack was 72.2% lower at 150 kHz and 40.1% greater at 500 kHz.

The crack samples tested during these experiments demonstrated quantifiable differences in Lamb wave interactions between high- and low-cycle fatigue cracks. In addition, differences in wave interaction with high- and low-cycle cracks under a tension static load were obvious; due to lower plastic deformation and residual stress/strain around the crack, the high-cycle crack opened along almost its entire length, acting more like a notch to Lamb waves and reflecting significantly more energy than either low-cycle crack. In comparison, both low-cycle crack specimens opened much less under the same static load, producing smaller changes in TC and RC than those seen for the high-cycle crack.

5.3 Recommendations for Application of this Work

The most obvious immediate application for the algorithms developed in the course of this work as well as the experimental results, is to the tuning of numerical models. As described in Chapters II and III, experimental data collection for this research required equipment unavailable to many researchers and that is not practical for use in an operational SHM system. The data generated through full-wavefield measurement and analysis of Lamb waves interacting with different crack types can be used to tune FEM and other numerical models to more accurately simulate how wave energy is transmitted and reflected from different types of cracks, thereby improving researchers' ability to develop and test more robust damage detection algorithms entirely in simulation.

Another possible benefit of this research is awareness for the SHM research community. As discussed in Chapter I, an informal survey conducted by this author revealed that approximately 60% of experiments reported in the reviewed literature

made use of simulated rather than real damage. As shown in Figure 17, a machined notch does not behave the same way as a real fatigue crack. Also, as made clear by the results presented in Chapter IV, waves can interact differently with cracks grown under different levels of fatigue loading, even when they are otherwise similar in size, orientation, etc. Because of this, as implied by the RDECOM experiment described in Chapter I, an algorithm that works well when tested against a notch or LCF crack may not perform as well or at all when applied to an HCF crack. While many researchers may be subjectively aware of this, the objective and quantitative demonstration presented in this dissertation may motivate more researchers to conduct experiments with real cracks of varying types earlier in the development of their SHM techniques.

5.4 Recommendations for Future Research

Recommendation 1: *Investigate the variations in TC and RC for the three test specimens across the examined frequency range.* Section 4.5 presented three possible explanations for the variation in TC and RC results across the examined frequency range: absence of a capability to detect wave mode conversion in the algorithm used, sensitivity effects due to changes in A_0 and S_0 mode wavelengths across frequencies, and nonlinear effects related to friction and heat loss at the crack face. The first step in this investigation should be improvement of the TC/RC calculation algorithm to detect mode conversions and calculate mode conversion coefficients in addition to the existing same-mode TC/RC. Assuming this did not explain the observed behavior, the presence of significant friction/heating effects could be investigated using a thermal imaging sensor or similar instrumentation during a SLDV data collection experiment. Finally, wavelength related sensitivity effects could be investigated by performing similar experiments on cracks of different lengths and analyzing whether the change

in behavior shifted to different frequencies than those observed in this work.

Recommendation 2: *Repeat these experiments on a statistically significant number of test articles.* As mentioned in a previous section, the experiments presented in this dissertation did not use enough sample crack specimens to support a statistically significant conclusion. This was largely due to the time required for both data collection and analysis. Adjusting the data collection parameters of the SLDV (less total area scanned, fewer averages, etc.) could reduce data collection time, while combining the various signal processing modules used into a unified program would reduce the workload necessary to go from raw experimental data to final results. After making these adjustments, additional experiments could be conducted to produce a statistically significant comparison of Lamb wave interaction with high- and low-cycle fatigue cracks in aluminum.

Recommendation 3: *Expand the capabilities of the existing algorithm in order to examine wave transmission and reflection coefficients at various angles of incidence to and distances from the crack.* The analysis reported in this dissertation was limited to wave energy traveling parallel to the y -axis of the test articles and in close proximity to the crack; however, as presented in Figure 71, wave energy excited from a single disk-shaped transducer propagates in all directions. It is expected that an operational SHM system would have to account for damage at a variety of distances and orientations from the transducer(s). Determining how wave signals vary with incidence angle and distance could help researchers to design better sensor placement and/or adjust their algorithms for better performance.

Recommendation 4: *Investigate whether the signal processing and analysis techniques used in these experiments can be expanded to create damage detection and prognostics algorithms.* The work presented in this dissertation has been focused on the phenomenology of Lamb wave interaction with fatigue cracks grown under differ-

ent loading spectra. While this work has value, even greater value lies in expanding it to include the ability to detect and potentially characterize the type and severity of damage. Currently available commercial SLDVs are impractical (expensive, large, and slow) for application to an operational SHM system; however, that could change in the future. If such techniques can be successfully developed, they could find immediate application in a lab environment and, should appropriate measurement technologies emerge, be applied operationally in the future.

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