

The Upcoming Revolution in Ultrasonic Guided Waves

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Introduction

This paper will include discussions on fundamental principles and market forces associated with the upcoming revolution in ultrasonic guided waves. A literature survey is also outlined covering some selected major developments this past decade. A few applications in pipe, rail, bonding and composites, imaging and tomography, ultrasonic vibration, de-icing, structural health monitoring, gas entrapment, and non-linear methods are treated to provide an idea of where we are heading with ultrasonic guided waves.

Market Forces:

Ultrasonic Guided Wave integration into NDE and SHM is growing rapidly for a variety of reasons. Quite often it is the only way to solve a problem because of limited access to a structure and the ability to inspect a large area from a sensor at only a single location on the structure. Ultrasonic guided waves are very different from the more standard ultrasonic bulk wave inspection where hundreds of test modes become possible, whereas for bulk waves only two modes of inspection are possible, longitudinal and shear. With the initiation of guided wave inspection taking off around 15 years ago, there was high expectations on use which was subsequently held back because of a lack of theoretical understanding and weakness in computational power required in modeling analysis. In technology transfer from laboratory to field, we often encountered many challenges of coatings, hidden, buried structures and geometrical intricacies in environment, etc. Many of their problems have now been overcome and technology transfer and product development are moving rapidly forward. Guided wave innovation is amazing in application, sensitivity and penetration power. Some of these advancements are discussed on these pages.

Taking place is a paradigm shift from bulk wave ultrasonics to guided waves because of reduced cost, less inspection time and greater coverage, and the ability to solve new problems with no prior solution potential.

There is also a paradigm shift from NDE to SHM because of improved reliability, continuous screening, and early warning of defect growth and structural failure. As a result, there is baked in potential for prefab sensor installation. There are also many cost and safety benefits associated with SHM.

Expectations for market growth are focused on new markets and not necessarily replacement in the bulk wave market. From discussions with many users, funded research, and number of publications, up to 20% of the current bulk wave market could be replaced with an expansion in new SHM and NDE markets which could expand by 35% over the next decades compared to the current ultrasonic bulk wave market. In fact, the anticipated growth rate for NDE, SHM and ultrasonic guided wave services could be about 10% per year starting in 2020. Reasons for growth can be associated with improvements in guided wave application and innovation in new product development programs with integration into wireless and energy harvesting systems. Instead of tens of specialized guided wave products, guided wave product trends are directed towards custom to configurable, easier to use, lightweight, speed, and improved coverage. More transparency is also becoming possible with improved software so that training becomes simpler and straight forward

The future looks bright for ultrasonic guided waves in NDE and SHM with applications in pipe, rail, bridge, aircraft, power plants, processing plants, highways, buildings, and in almost any government or industrial facility.

Literature Survey

Many textbooks are available on the subject of ultrasonic guided waves. For example, in 1975, Graff 's book covers waves in infinite media and in various waveguides [1]. Rose's book 1999 [2] covers fundamentals including dispersion curves, wave structure, source influence and excitability. Fundamentals of wave propagation are presented nicely by Achenbach (1973), Auld (1973), and Datta (2008) [3~5]. In Achenbach 2003, some interesting reciprocity concepts associated with guided and Lamb waves are treated [6]. A recent book that highlights some interesting aspects of guided waves in composite materials is presented by Rokhlin, Chimenti, and Nagy [7].

Zhu and Rose 1999 employs boundary element methods (BEM) and simulation [9] for guided wave analysis. Rose 1994 also covers wave mechanics principles [8] and Gao et al. 2010 [10] introduces the concept of goodness curves to assist in mode and frequency selection in studying such features as skew, a variety of wave structure variables, excitability, etc. Yan et al 2010 [11] uses ultrasonic guided wave mode and frequency selection for defect detection and characterization in a multilayer hybrid laminate. Fromme and Sayir 2002 studied the detection of cracks at rivet holes using guided waves [12]. Rizzo et al in 2009 studied fatigue crack detection in waveguides [13]. Ing and Fink in 1998 introduced time reversal techniques [14]. Wilcox in 2003 employed rapid signal processing techniques to remove the effect of dispersion from guided wave signals [15].

Pipe

Ultrasonic guided waves were first introduced to tubing inspection by Rose et al 1993 [16]. Following the research results of Ditri and Rose (1992) [17], Li and Rose developed an analytical method to simulate the angular profiles in hollow cylinders [18]. In 2002, Li and Rose presented the phased array focusing technique for longitudinal guided waves propagating in cylindrical shells [19]. Rose and Mudge introduced

a commercial application of the guided wave focusing technique with a pipeline inspection tool, the Teletest-focus instrument [20]. Sun et al. 2003 carried out the angular profile calculations and the phased array focusing technique for torsional guided wave propagation in hollow cylinders [21]. If the angular profiles show that ultrasonic energy is naturally concentrated at a circumferential location at a particular propagation distance, this phenomenon, which is called “natural focusing,” can be used to improve pipeline inspection [22, 23].

Circumferential waves were studied by Thompson, et al. who used Lamb waves for steel plate and pipe inspections in 1972 [24]. Van Velsor et al. 2009 developed enhanced coating disbond detection methods with guided wave physically based features [25].

Defect imaging and synthetic focusing methods were introduced by Hayashi et al. 2005 [26], Mu and Rose 2008 by focusing [27], and with coatings [28], Davies and Cawley 2009 [29], Mu et al. 2010 [30], and Velichko and Wilcox 2009 with post-processing [31].

Pavlakovic et al. in 1997 introduced a commercial software package for dispersion curve calculation: DISPERSE [32]. Demma et al. in 2001 studied mode conversion of longitudinal and torsional guided modes due to pipe bends [33]. Ma et al. in 2007 studied sludge and blockage detection inside pipes [34].

SAFEM efficient computational techniques were introduced for guided wave problems by Hayashi et al. 2002 [35]. Magnetostrictive methods were pioneered by Kwun et al. in 1998 covering guided wave inspection of pipe using magnetostrictive sensors [36]. Kim et al. in 2005 used magnetostrictive transducers with ferromagnetic strips 45° from the axis of a pipe [37].

Rail

Grewal 1996 used Rayleigh waves in rail [38]. Hayashi et al 2003 computed guided wave dispersion curves for a bar with an arbitrary cross-section with a rod and rail example [39]. Wilcox et al 2003 also introduced some interesting aspects of rail inspection [40]. Gunawan and Hirose in 2005 used boundary element analysis of guided waves in a bar with an arbitrary cross-section [41]. Bartoli et al. (including Lanza di Scalea) in 2006 employed modeling aspects of wave propagation in damped waveguides of arbitrary cross-section [42]. Lee et al. 2009 used a guided wave approach for defect detection under shelling in rail with wave structure selection examples for sensor design to achieve special effects [43].

Bonding & Composites

Mal et al. in 1988 and 1990 studied guided wave evaluation of adhesive bonds [44]. Chimenti et al. in 1988 made use of guided waves reflection and propagation in fluid-coupled composite laminates [45]. Datta et al. in 1990 studied edge and layering effects of guided waves in a multilayered composite plate [46]. Na (2002) researched ultrasonic guided waves for steel bar concrete interface testing [47]. Hosten and Castaings in 2005 employed finite elements method (FEM) for modeling the guided waves propagation in structures with weak interfaces [48]. Puthillath and Rose 2010 introduced higher order ultrasonic guided wave inspection of a titanium patch that was bonded to an aluminum aircraft skin [49].

Phased array for plates

Li and Rose (2001) implemented guided wave mode control by use of a phased transducer array [50]. Giurgiutiu et al. in 2002 invented a virtual beam steering technique by using PZT transducer arrays [51]. Wilcox in 2003 developed omni-directional guided wave transducer arrays for rapid inspections of large areas in plates [52]. Yan and Rose in 2007 used beam steering in composites [53] and in 2009 with a phased array time delay comb [54]. Salas and Cesnik in 2010 presented guided wave structural health monitoring (SHM) by using composite long-range variable-length emitting radar (CLOVER) transducers in composite materials [55]. Senesi et al. in 2010 developed guided wave frequency-steerable arrays for SHM [56].

Guided wave imaging and tomography

Hinders et al. in 1999 studied Lamb wave tomographic scanning [57] and Gao et al. in 2005 introduced guided wave mode and frequency selection for tomography for aircraft structures [58]. Breon et al. in 2007 did guided wave damage detection tomography for SHM in pipeline elbows [59] and Van Velsor et al. in 2007 studied pipe defects by employing guided wave tomography technique [60]. Yan et al. in 2010 also used ultrasonic guided wave imaging techniques in SHM [61].

Some research has been carried out to improve the guided wave imaging techniques. Ruzzene in 2007 employed frequency wave number domain filtering for improved damage visualization [62]. Hall and Michaels in 2011 studied computational efficiency of ultrasonic guided wave imaging algorithms [63].

Ultrasonic vibration

Rose et al. in 2010 introduced an ultrasonic guided wave modal analysis technique (UMAT) for defect detection [64], followed by work by Yan and Rose (2010) [65].

Deicing

Venna et al. 2007 [66], Zhu et al. 2008 [67], and Gao et al. 2009 [68] utilized ultrasonic guided waves for deicing experiments.

SHM

Michaels et al. in 2004 used feature-based classifiers for ultrasonic SHM [69]. Raghavan and Cesnik in 2004 modeled use of piezoelectric-based Lamb wave generation and sensing for SHM [70].

Nonlinear

Nonlinear methods are now finding applications in ultrasonic guided wave analysis. See Cantrell et al. 2001 [71], Kim et al. 2006 [72], and Pruell et al. 2009 [73].

Fundamentals

A comparison of ultrasonic bulk waves with ultrasonic guided waves is illustrated in figure 1. Note that bulk waves cover only a small localized section of a structure. Scanning is necessary to complete an inspection of a test part. The ultrasonic guided wave floods a large area from a single probe position. Two basic guided wave excitation examples includes angle-beam excitation and comb excitation as illustrated in figure 1. A more detailed comparison is presented in table 1.

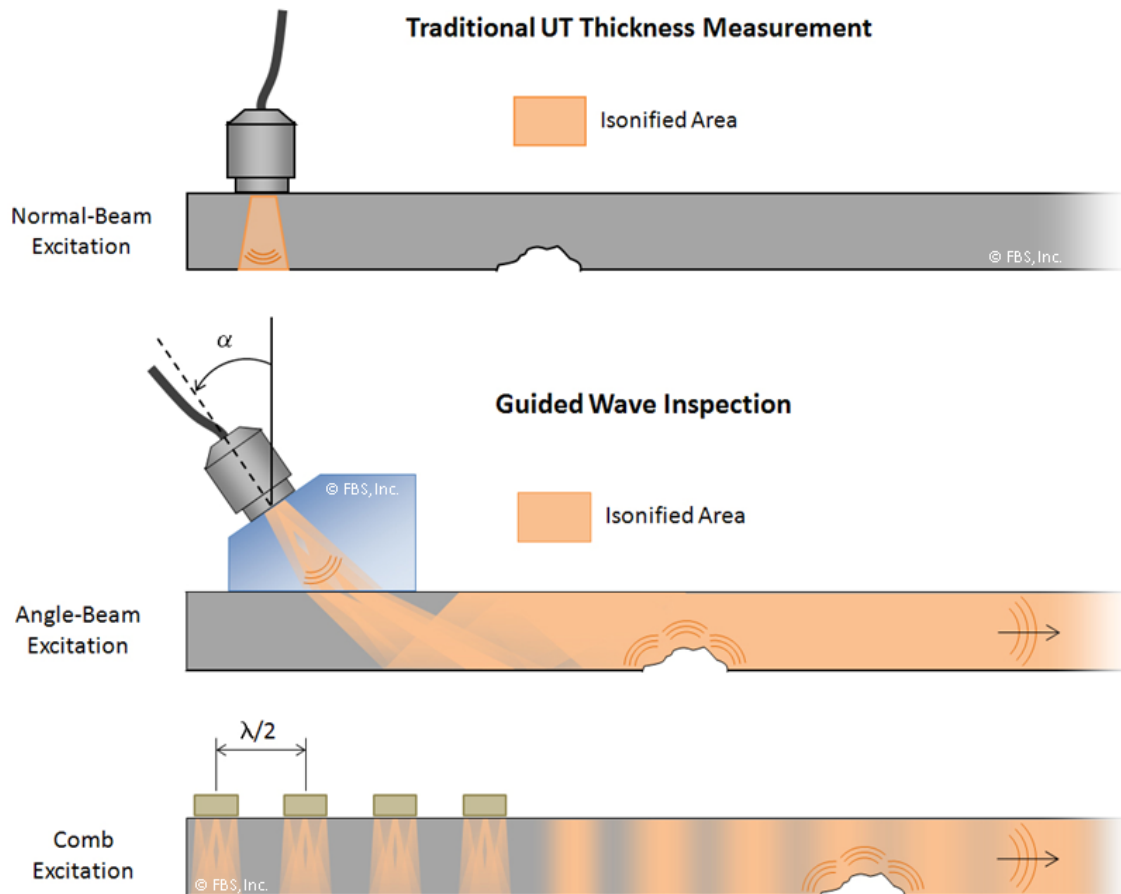


Figure 1
Comparison of Ultrasonic Bulk and Guided Waves

Ultrasonic guided waves can be used to inspect almost any structure since the structures fall into a class of natural wave guides. See table 2. Again, widespread adaptation of guided waves has just occurred because of improvements in understanding and in signal interpretation. A special challenge, however, is on thick sections, but even here, surface waves can be used to inspect regions close to the surface of a structure. Frequency changes can increase the depth of penetration and hence improve the examination of a structure.

Table 1

A Comparison of the Currently Used Ultrasonic Bulk Wave Technique and the Ultrasonic Guided Wave Inspection Procedure

Bulk Wave	Guided Wave
Tedious and time consuming	Fast
Point by point scan (accurate rectangular grid scan)	Global in nature (approximate line scan)
Unreliable (can miss points)	Reliable (volumetric coverage)
High level training required for inspection	Minimal training
Fixed distance from area of concern required	Any reasonable distance from defect acceptable
Defect must be accessible and area seen	Defect can be hidden

Table 2

Natural waveguides

- Plates (aircraft skin)
- Rods (cylindrical, square, rail, etc.)
- Hollow cylinder (pipes, tubing)
- Multi-layer structures
- Curved or flat surfaces on a half-space
- Layer or multiple layers on a half-space
- An interface

The many exciting benefits of ultrasonic guided waves are depicted in table 3. These reasons have propelled the development of guided waves forward. Site preparation for inspection is greatly reduced as a result of large coverage of hidden sections of a structure.

Table 3

Principal Engineering Benefits of Guided Waves

- **Inspection over long distances from a single probe position.**
- **Ability to inspect hidden structures and structures under water, coatings, soil, insulations, and concrete.**
- **Cost effectiveness because of inspection simplicity and speed**

Major differences between NDT and SHM are highlighted in table 4, the most crucial of which is the requirement of a baseline in SHM. Very complex structures can be studied with SHM that are not even approachable with NDT. Baseline information can change however, and such items as temperature and boundary condition compensation are being studied.

Table 4
The major differences between NDT and SHM

NDT	SHM
<ul style="list-style-type: none"> • Off-line evaluation • Time based maintenance • Find existing damage • Baseline generally not available 	<ul style="list-style-type: none"> • On-line evaluation • Condition based maintenance • Determine fitness-for-service and remaining useful time • Starts with a Baseline on initial data collection

Let us now consider some aspects of wave mechanics associated with guided waves. For every wave guide there is a unique set of phase velocity dispersion curves as shown in a sample problem for a plate. Group velocity dispersion curves can be calculated from the phase velocity dispersion curves. Attenuation dispersion curves can be calculated from computed complex roots in the eigen value problem. See Rose [2] for example. For every point on the dispersion curve there is a corresponding wave structure that is a special distribution across the thickness of the structure of such variables as in-plane displacement and out of plane displacement, as shown in a sample result in figure 2. Note for example, that if the outer surface has dominant out of plane displacement, a water loaded plate would lead to ultrasonic energy leakage into the fluid. On the other hand, if the outer surface had only in plane displacement, the ultrasonic guided wave energy propagating in the plate would not see the fluid. Other variables like shear stress, normal stress, or energy could also be considered. In fact, the key to success in ultrasonic guided wave experiments is associated with a wise choice of mode and frequency on the dispersion curve. The experimental ability to get onto a dispersion curve is possible by using a comb activation line or angle beam activation line as demonstrated in figure 2. To do this, of course, sufficient frequency bandwidth is required to be successful. A further challenge is trying to select a proper mode and frequency is delineated in figures 3 and 4. Because of the excitation transducer's source influence (size and vibration pattern) there will be a

phase velocity spectrum along with the frequency spectrum. The activation region in the phase velocity dispersion curve space is quite large; hence many modes and frequencies are generated at the same time. See [2]. Note in figure 4, the presence of side lobes in the phase velocity spectrum. Hence propagation of a single mode is difficult, often including other nodes possibly with different group velocities. The noisy signals are of a coherent variety and not random, often leading to difficulties for the inspector. Proper sensor design and narrow band frequency content can improve the result.

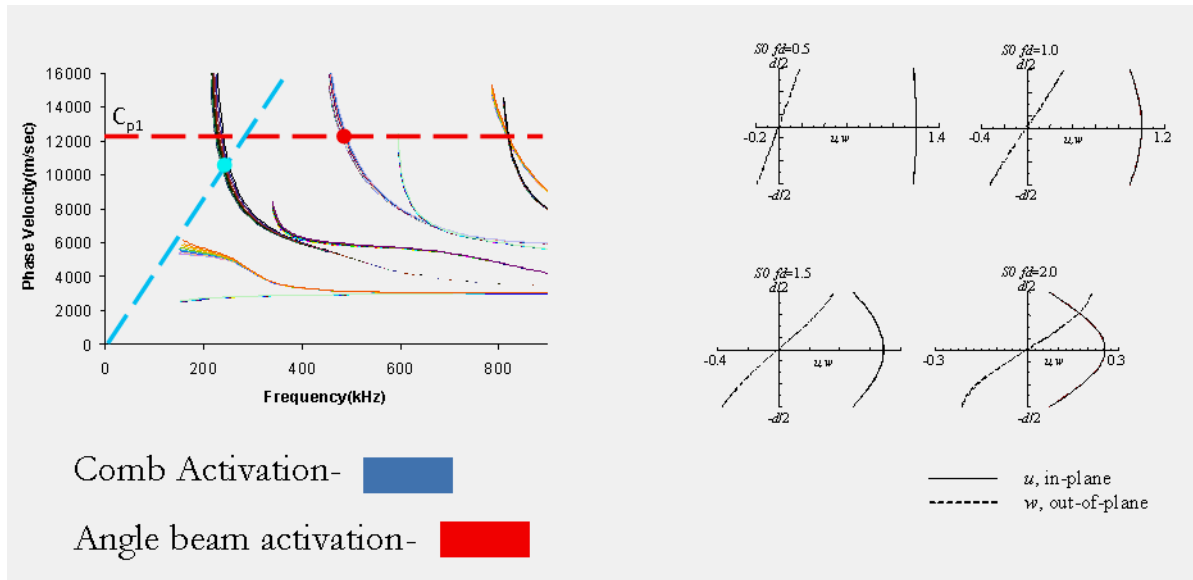


Figure 2
Activation and wave structures

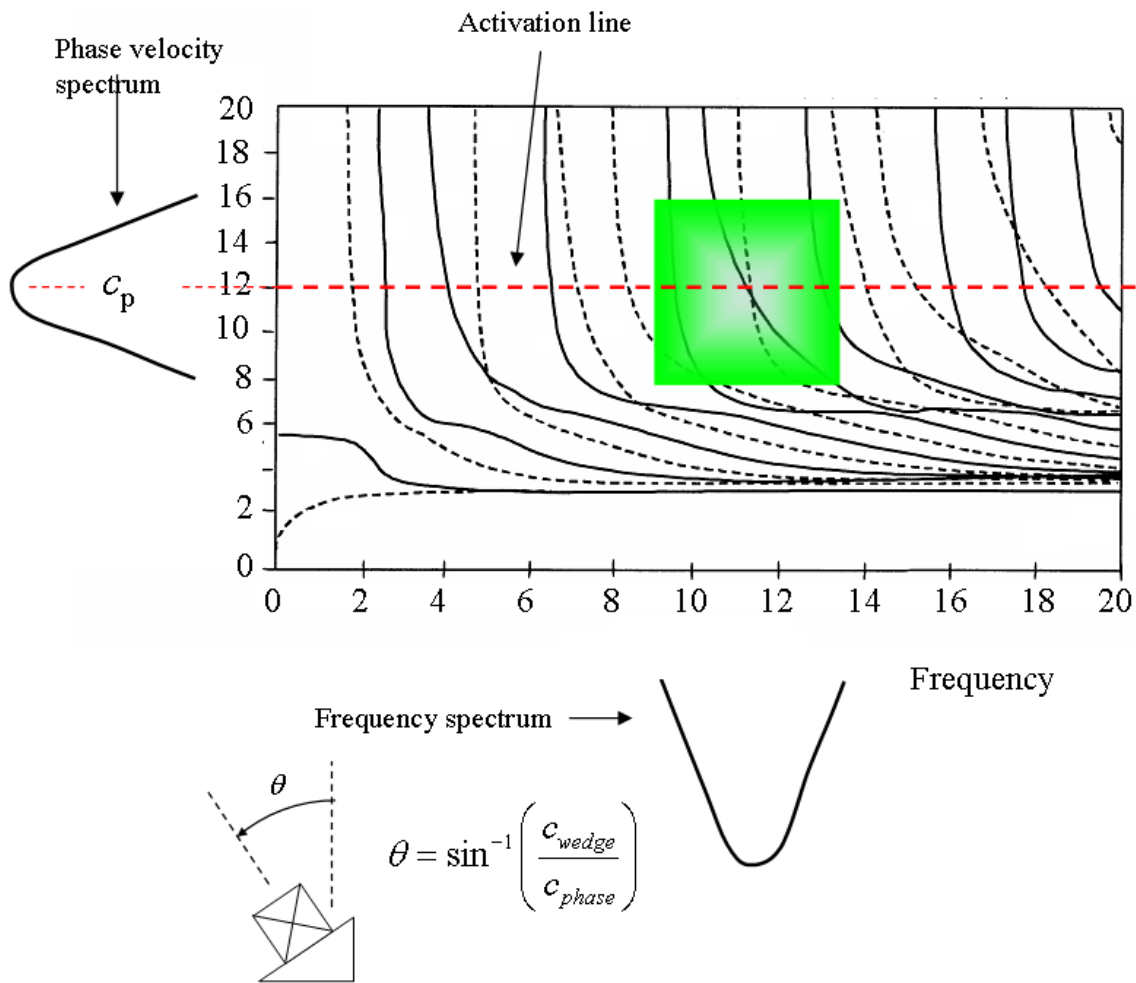


Figure 3
Source influence for a typical angle beam excitation or an
ability to generate a specific mode and frequency

We will now consider the modeling analysis component associated with the understanding of ultrasonic guided waves. The approach makes use of a hybrid analytical FEM computation as exhibited in figure 5. The FEM computation process is useless unless proper boundary conditions are considered in a simulation of an ultrasonic guided wave inspection. The boundary condition comes from a sensor design that comes from a choice of appropriate wave structure from the phase velocity dispersion curve space, hence an appropriate mode and frequency choice to solve a particular problem is NDE or SHM.

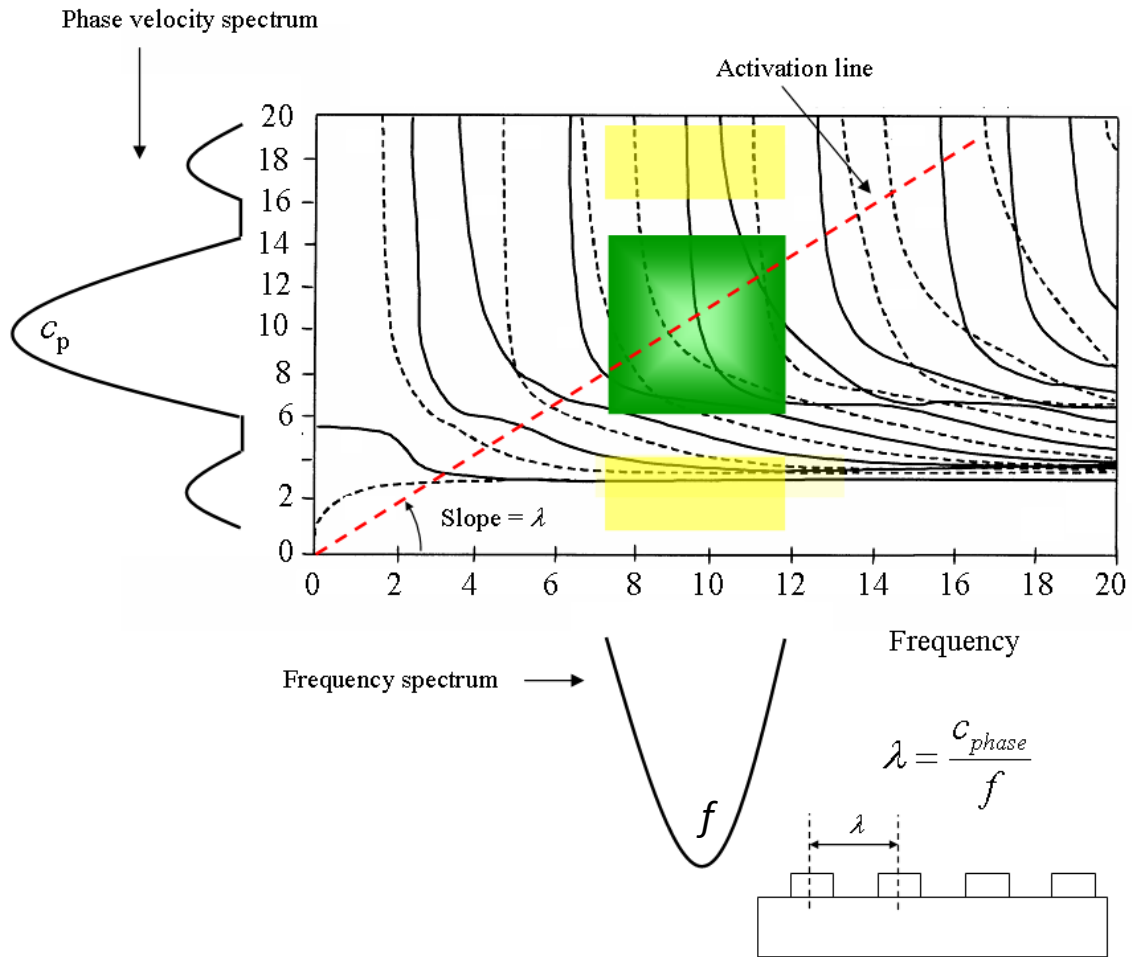


Figure 4
Source influence of a typical comb transducer excitation or
an ability to generate a specific mode and frequency

A few sample problems that have been solved using the hybrid analytical FEM computation are listed in table 5 along with appropriate references.

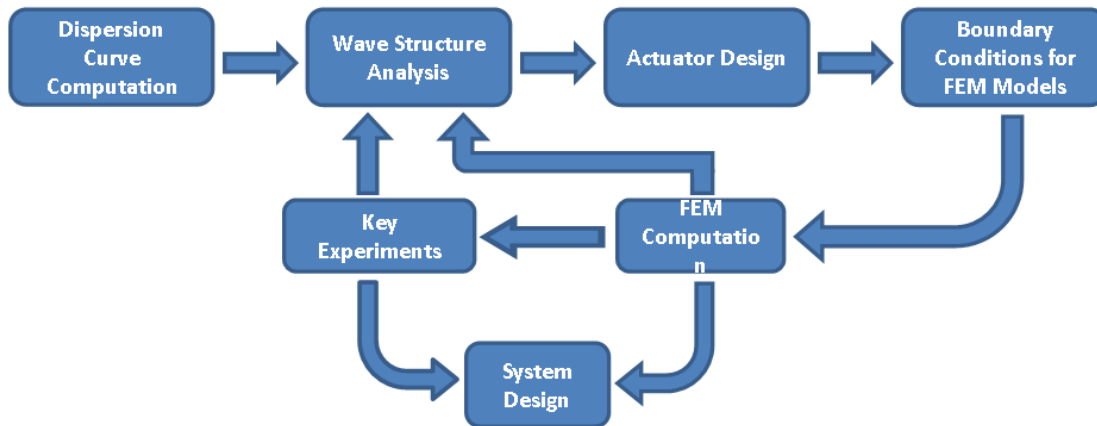


Figure 5
The Hybrid Analytical FEM Approach for Solving Guided Wave Problems

Table 5
Examples of the use of the Hybrid Analytical FEM
Approach for solving guided wave problems

- Rail – transverse cracking under shelling, defect in base (Lee et al [43])
- Adhesive Bonding – weak interface (Puthillath, [49])
- Water Loaded Structure – to avoid false alarms (Gao et al [58])
- Gas Entrapment – leaky and non leaky waves (Rose [2])
- De-icing – maximum shear stress at the interface (Zhu et al [67])
- Piping – flexural mode best selection for focusing (Sun et al [22])

Phased array systems have risen to ecstatic heights in the NDT field for ultrasonic bulk waves because of electronic beam scanning with one transducer array compared to manual scanning with many different angle beam probes. Laid out in figure 6 is the historical progression of phased array development from the 70's to current day developments. Just recently, phased arrays for real time and synthetic focusing in practical pipe inspection applications have been introduced by Rose and Mudge [20]. Even more recently phased arrays for plate inspection were introduced by Li and Rose [50] and Giurgiutiu and Bao [51].

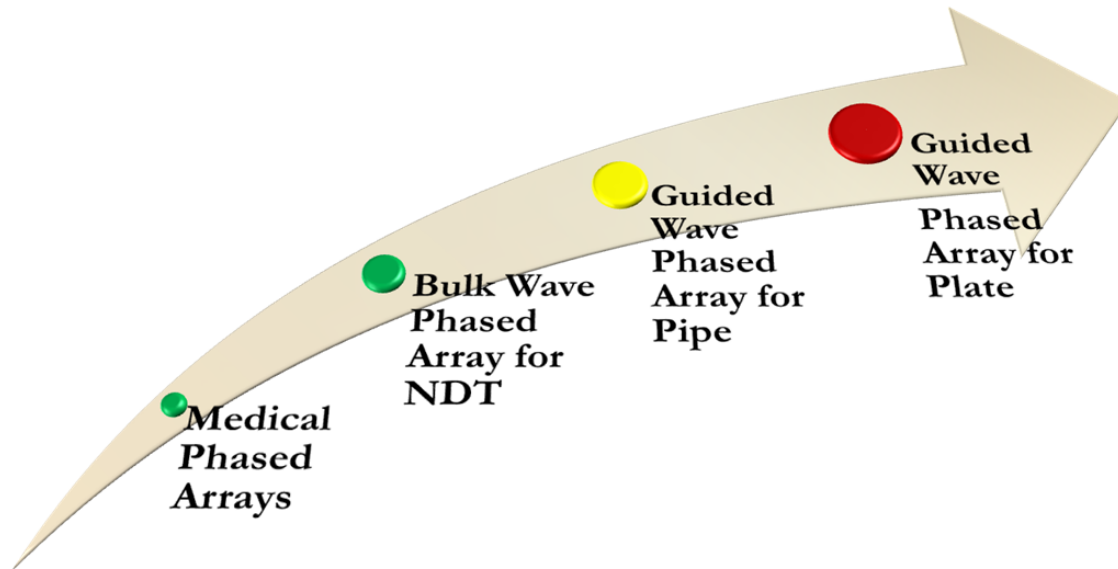


Figure 6
Guided wave phased array technologies

Applications

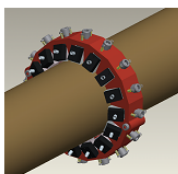
Pipe

Static shot FEM simulations, at different times of an axisymmetric guided wave propagation in a pipe are demonstrated in figure 7. To go beyond the axisymmetric wave to focusing considerations, the methods of focusing are listed in table 6. A static shot example of a real time phased array result is illustrated in figure 8. Notice the achievement of the focal spot in the 5th frame. The focal spot can be changed in size by changing the probe and instrument design parameters. The focal spot can then be moved anywhere axially and circumferentially in the pipe. The benefits of focusing are described in table 7.

A sample experiment is presented here in figures 9 and 10 where all three of the defects shown in figure 9 are found and presented in figure 10. The upper diagram shows an FFA plot over a frequency range from 20 to 80 KHZ showing that defect detection sensibility is a function of frequency. The FFA plot shows the best frequency to see each defect. Each defect could have a different preferred frequency in its reflection characteristics. The second trace is a video envelope of the RF waveform clearly showing the defects and welds in the structure. The third trace shows a pipe laid out flat with an image of the defect locations both axially and circumferentially. Excellent results were obtained.

To illustrate the focusing principle in a practical sense, consider the partial loaded field natural focusing result as calculated in figure 11. The loading transducer is centered at zero degrees. With the pipe laid out flat it can be seen that the natural focal spot in this example occurs at the opposite side of the pipe at 180 degrees at an axial location of around 10 meters. If we were to have an angular profile due to some partial loading around the circumference at some axial position as shown in figure 12a, and if we were to arrange a series of partial loadings around the circumference and phase them properly, we could end up with a superimposed result at the same axial distance with a strong focal point as plotted in figure 12b. Two focused experimental results are diagrammed in figure 13. These profiles provide confidence in a call that a defect is indeed there and its' circumferential position can be clearly determined.

Wave propagation into a pipe elbow and beyond can create blind spots at a specific frequency due to mode conversion. Pipe coating and buried pipes can also seriously reduce penetration distances. See Rose [74] for successes and challenges in pipe inspection.



Transducer array located at pipe end
Axisymmetric loading, no time delay applied

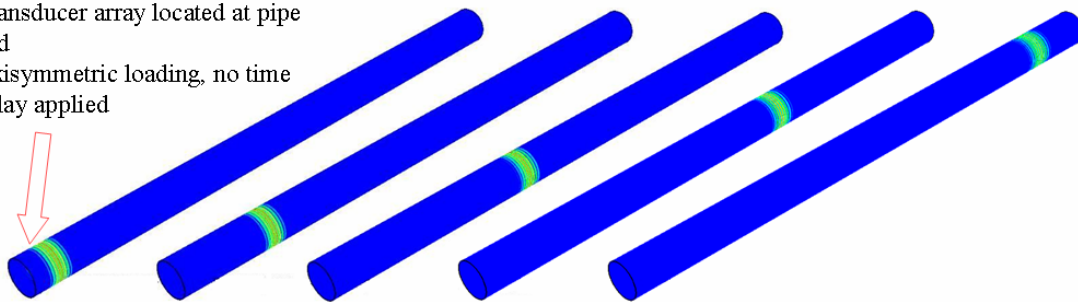


Figure 7
Axisymmetric guided wave propagation along the pipe

Table 6

Guided wave pipe focusing techniques

- **Frequency tuning**

 - axisymmetric excitation and receiving

- **Natural focusing**

 - partial loading excitation and receiving

- **Phased array focusing**

 - multi-element array excitation and receiving with time delay and amplitude tuning

Transducer array located at pipe end
Array can be segmented into 4 or 8 channels.
Time delays are applied.

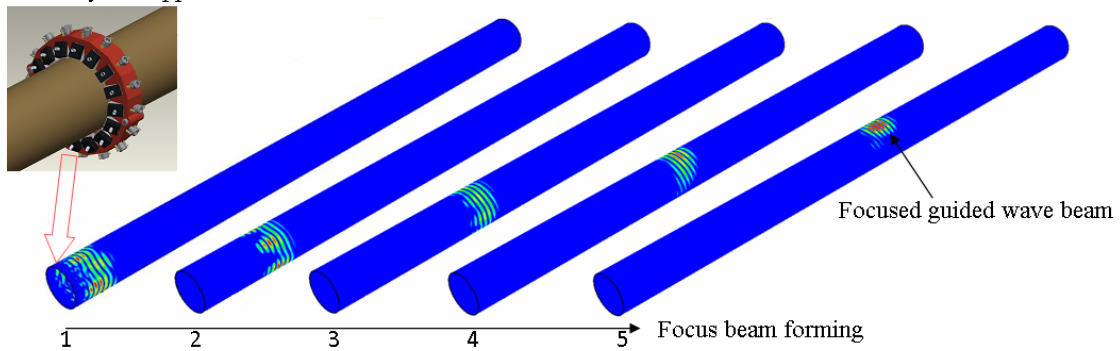
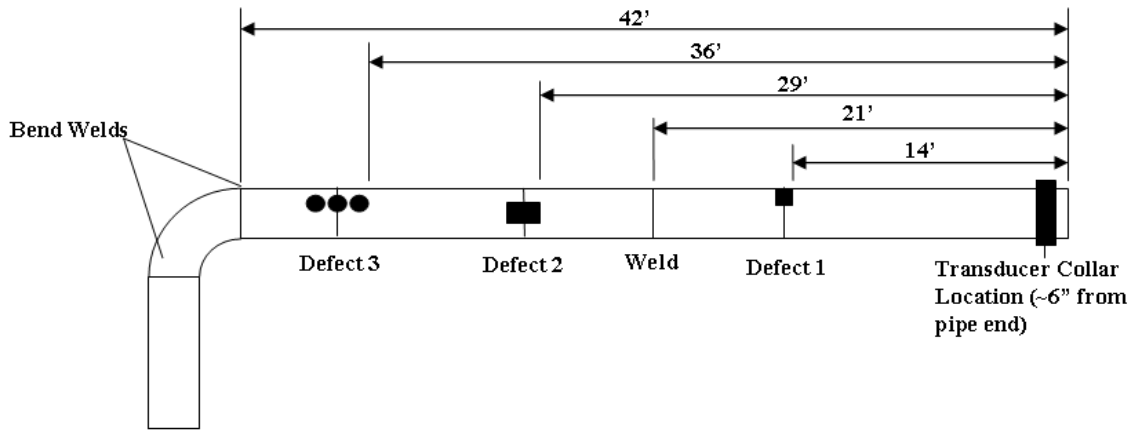


Figure 8

Guided wave active focusing in pipe FE simulation results

Table 7
Focused Guided Wave Inspection

- Improved defect probability of detection (approximately 3% CSA, compared to 9% for axisymmetric)
- Decreased defect false alarm rate
- Increased inspection confidence
- Improved penetration power for coated pipe
- Excellent defect circumferential location analysis
- Improved signal to noise ratio compared to axisymmetric
- 6 to infinite dB improvement compared to axisymmetric



Defect 1 - 0°
 ~3"x3" Blend Out
 50% Max Wall Loss

Defect 2 - 270°
 ~4"x4" Blend Out
 50% Max Wall Loss

Defect 3 - 315°
 Three Flat Bottom Holes
 1" Diameter, Depth=60%
 Spacing between holes = 1 ft.

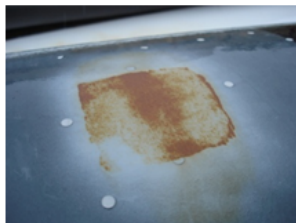


Figure 9
Details of a pipe section that was studied

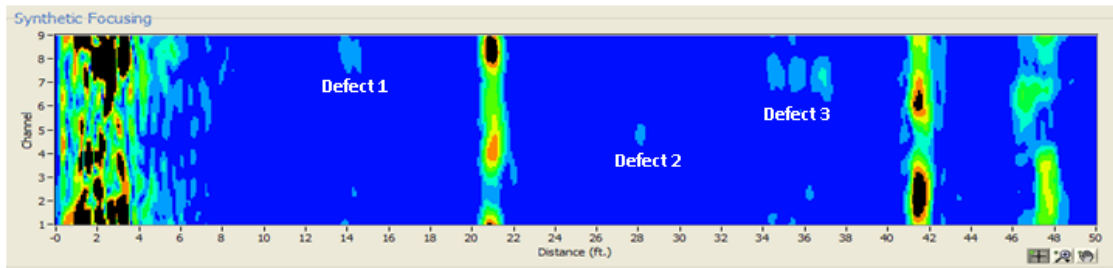
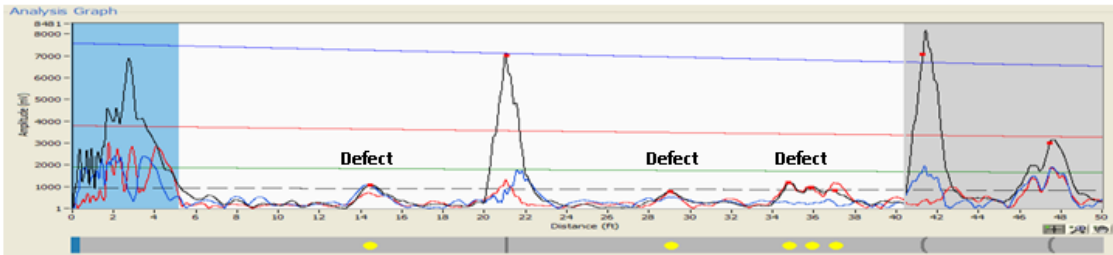
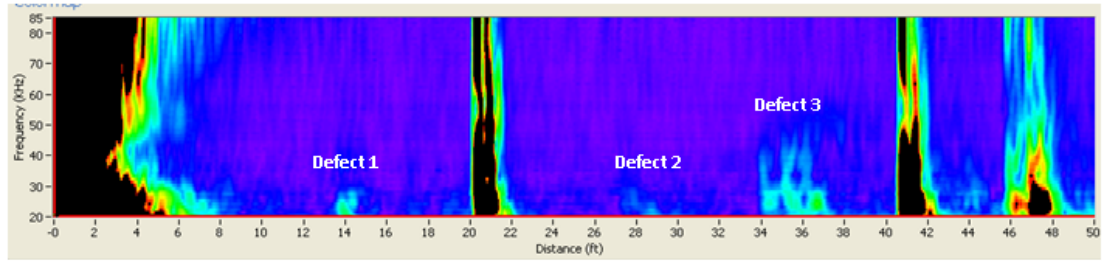


Figure 10
Fast frequency analysis [FFA], envelope, and synthetic focusing result after examining the pipe section in Figure 9

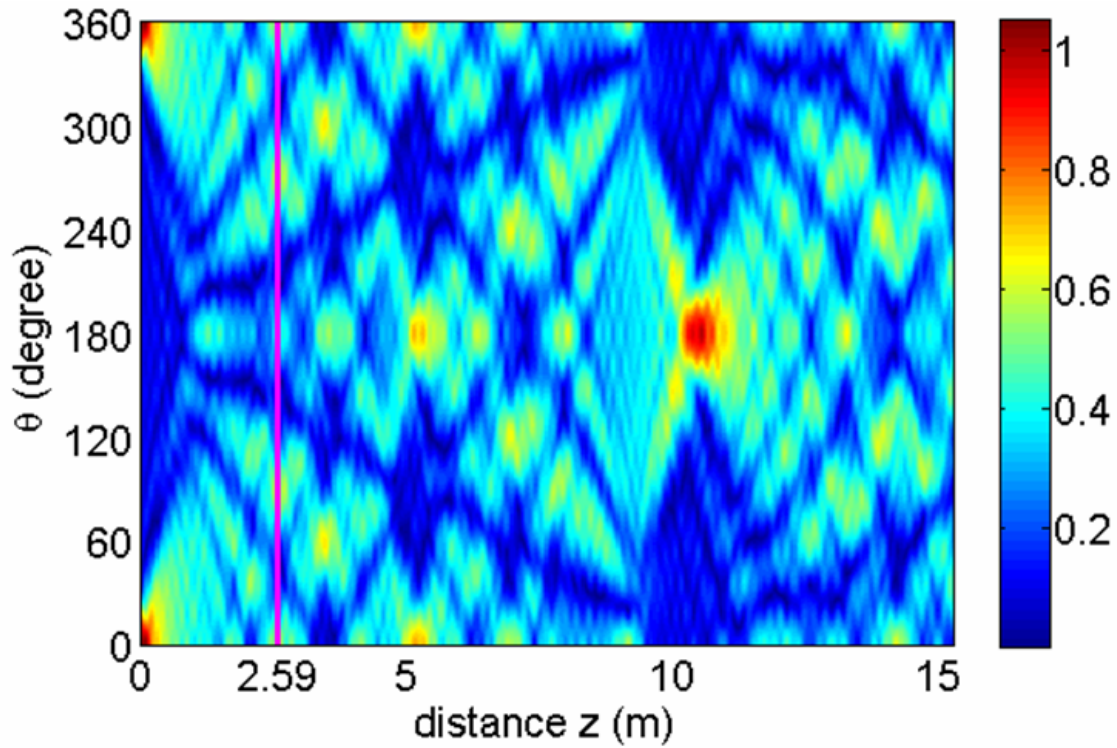


Figure 11
Guided wave displacement interference pattern in an 8 in. schedule 40 steel pipe (unwrapped). The waves were generated by a 45° source loading vibrating in the circumferential direction at 80 kHz.

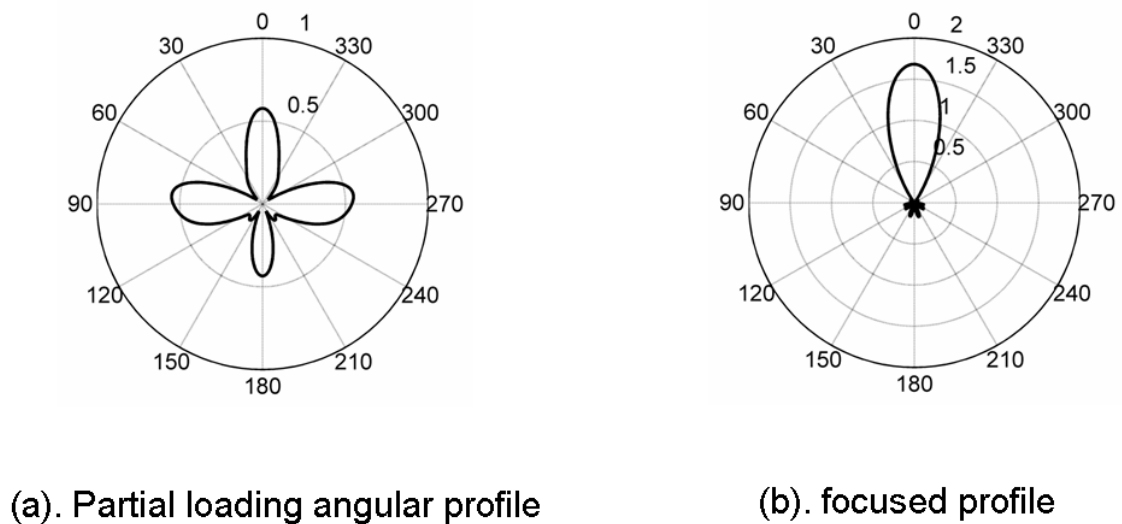
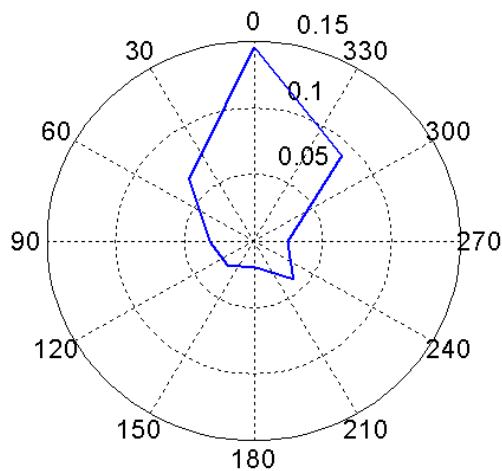
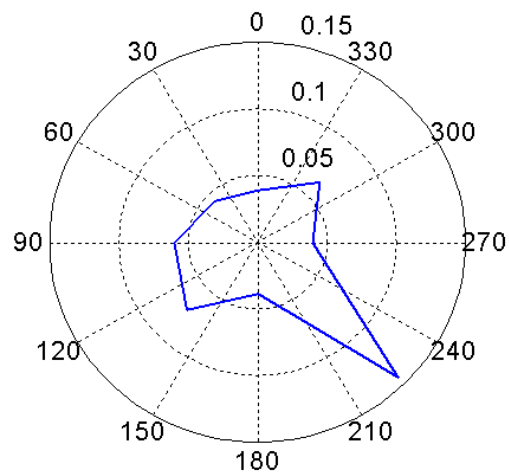


Figure 12 Pipe active focusing concept



(a). Response from actively focusing around the saw cut distance.



(b). Response from actively focusing around the cluster hole distance.

Figure 13
Active focusing results from pipe end A at 65 kHz

Rail

Guided waves are also finding increased use in a variety of different rail inspection applications. See Lee et al [43] for an example. We'll consider here the ability to cover various portions of a rail, from head, to web, to base in this brief discussion. The dispersion curves for a rail are close together, and in fact almost covers the entire phase velocity dispersion curve space except for bounds, as an example on the lower end where we only propagate a pseudo-Rayleigh surface wave mode. Despite the complexity, the curves are useful. Wave structures variations occur from one region to another in the dispersion curve space. It becomes possible with the appropriate mode and frequency choice to have energy propagate in the head only, or in the entire rail. See a few static shots in figure 14. If transverse crack detection under shelling was a goal, the energy in head only example would work well. If you were seeking a solution to find a base defect, complete rail coverage would be useful. See [43] for details.

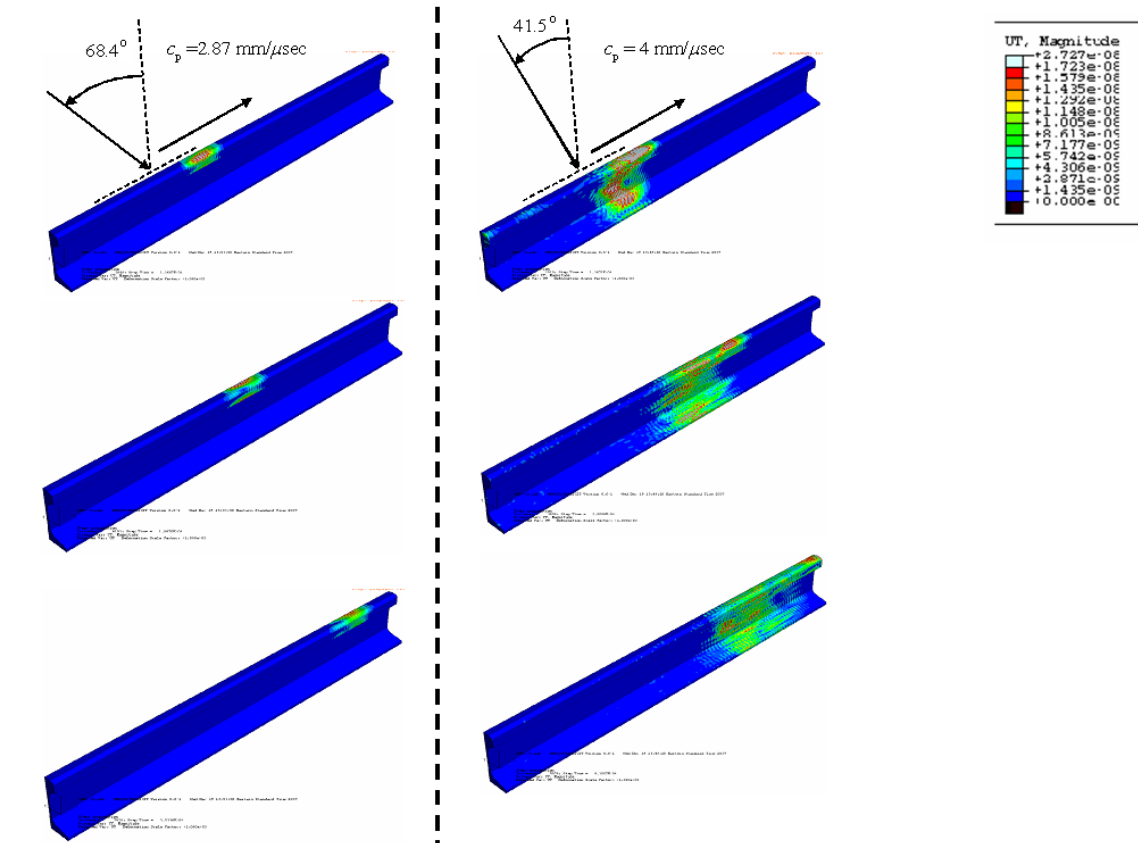


Figure 14
Rail coverage as a function of mode selection

Bonding and Composites

Mode and frequency selection are also useful when solving inspection problems with bonding situations for composite materials. Let's consider the inspection of a titanium repair patch bonded to an aluminum structure on an aircraft. If we were to find an interface weakness or a kissing bond, guided waves would be useful as we could get a dominant in-plane displacement component into the interface which from earlier work we know would be sensitive to the weak interface. To do this, consider the dispersion curve for the titanium to aluminum bonded structure as calculated in figure 15.

Superimposed on the curves is the magnitude of the in-plane displacement component. Red areas, for example, point to good portions of the curve to carry out an inspection. Of the possibilities, consider the source influence study depicted in figure 16. The mode selected is somewhat separated from the others, and can easily be generated with an actuator having a narrow phase velocity spectrum and frequency spectrum. An angle beam piezoelectric sensor or a comb type piezoelectric or EMAT activation could be designed for the inspections. See Puthillath et al.[49] for details.

u_1 at the interface of aluminum and epoxy in Titanium (1.6 mm) - Epoxy (0.66 mm) - Aluminum (3.175 mm)

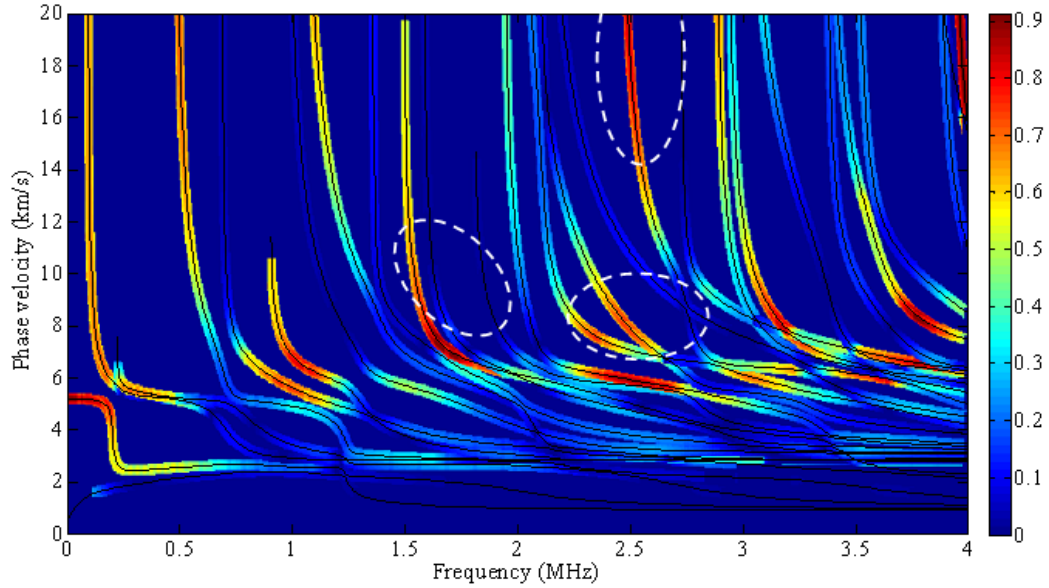


Figure 15
Interfacial Displacement (in-plane) at Al-epoxy interface in Ti-epoxy-Al specimen

10 degree wedge loading

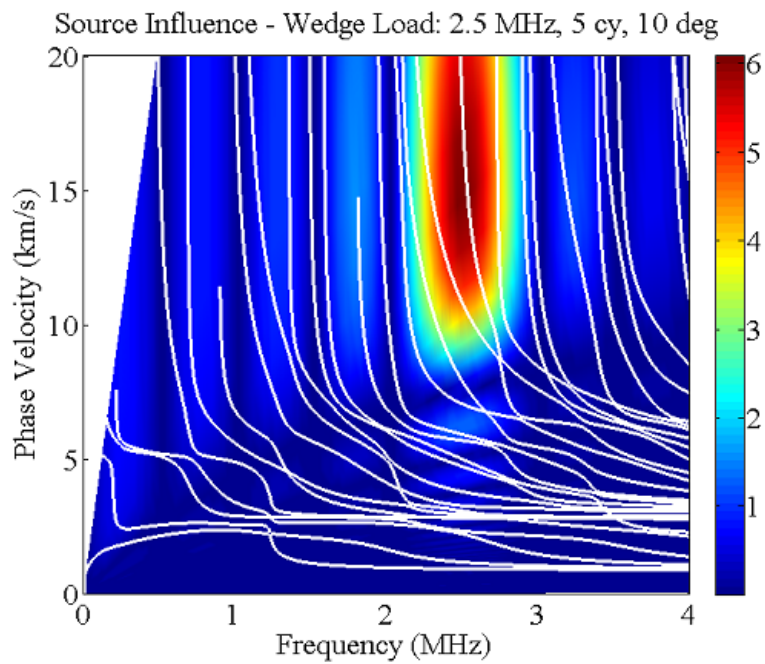


Figure 16
Source-Influence Study of guided wave loading sources

Imaging and Tomography

Ultrasonic guided wave tomography with a variety of different sensor distributions on a structure can become a valuable tool in SHM. Success depends, however, on using the right actuators. For example, in the plate with a corrosion defect shown in figure 16, a guided wave tomography experiment was conducted with a set of cylindrically shaped transducers commercially available off the shelf; very poor results were obtained when water was splashed onto the plate. On the other hand, when using a carefully designed set of annular array transducers, excellent results were obtained whether the plate was dry or wet. See figure 17. This is possible by selecting a point on the phase velocity dispersion curve space with dominant in-plane displacement so that the ultrasonic wave would not leak into the water. The annular array sensor is similar to a comb type transducer and its activation line in the phase velocity dispersion curve space can intersect the optimal text point.

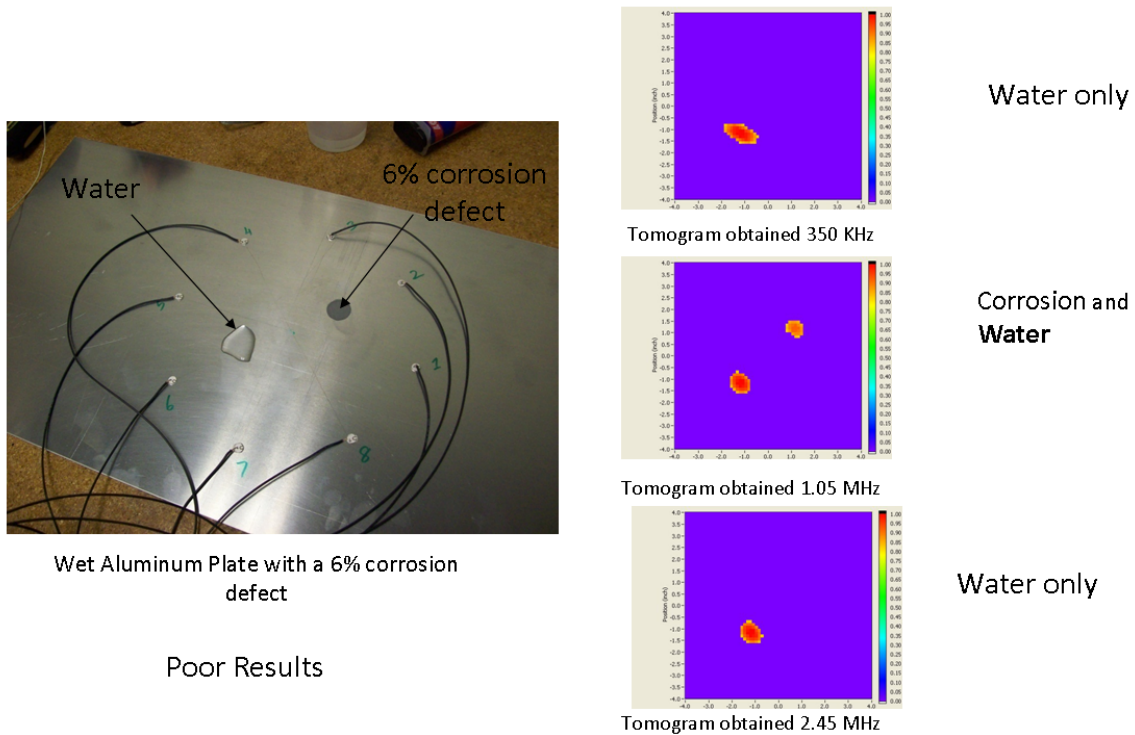


Figure 16
Water loaded plate influence

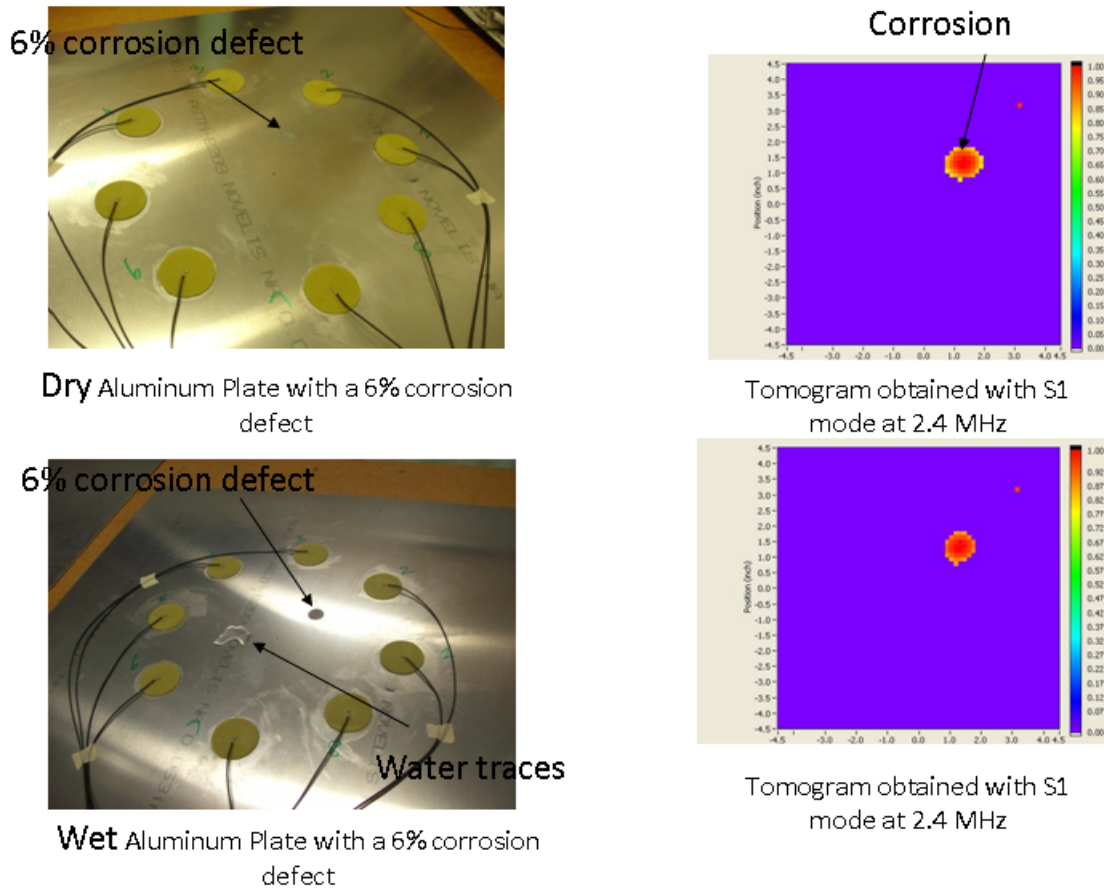
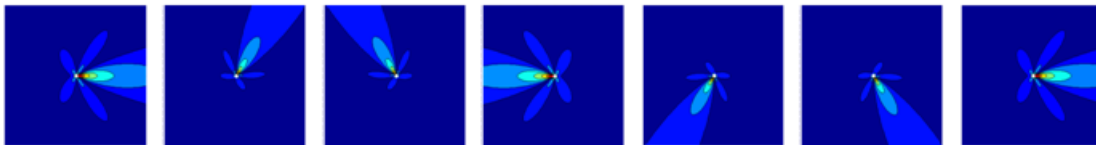
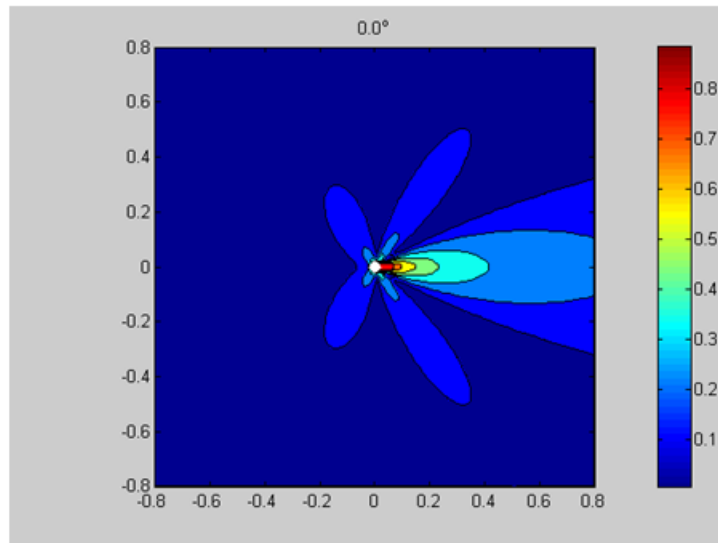


Figure 17
Corrosion detection with annular array sensors

Phased array for plate

Phased array application is now going beyond medical and ultrasonic bulk wave phased arrays, to guided wave phased arrays for pipe, and now to guided wave phased arrays for plates. A simulation of a radar like scan is simulated in figure 18 with static shot shown at 7 positions. Proper sensor design is required to do this from a small circular array of sensors at the center of a plate. Keep in mind here that appropriate mode and frequency control is also necessary in order to optimize defect detection sensitivity, to scan a composite plate, and to overcome skew angle and group velocity variation in the plate. Multiple scans might be necessary. Some of the challenges in moving this method forward are outlined in table 8.



Notes: Guided wave beam can be steered into different directions by applying phase delays to the elements of an array, circular array example.

Figure 18
Ultrasonic Guided Wave Beam Steering Using Phased Arrays

Table 8

Guided wave phased array technical challenges and solutions

Technical Challenges	Solutions
-Multi-modes application environment	-Guided wave transducer design and mode tuning to achieve single mode excitation and detection ([Giurgiutiu, et al], [Raghavan and Cesnik], (Rose, et al])
-Guided Wave Dispersion	-Wave number/frequency domain beam steering ([Wilcox],[Ruzzene])
-Skew effects in anisotropic plates	-Select a guided wave mode and frequency that is insensitive to the material anisotropy

Ultrasonic Vibrations

A new ultrasonic guided wave method to provide a robust signature of a structure has recently been introduced by Rose et al [64]. This technique bridges the gap from transient high frequency guided wave analysis to more traditional low frequency ultrasonic model analysis. The characteristics of the methods are presented in table 9. The high frequency ultrasonic modal patterns or modes depends on the ultrasonic loading function. Sensitivity optimization is possible here, again, by selecting the proper mode and frequency for the phase velocity dispersion curve space. This approach is particularly useful in manufacturing hundreds of a complex shaped part and follow up later in service.

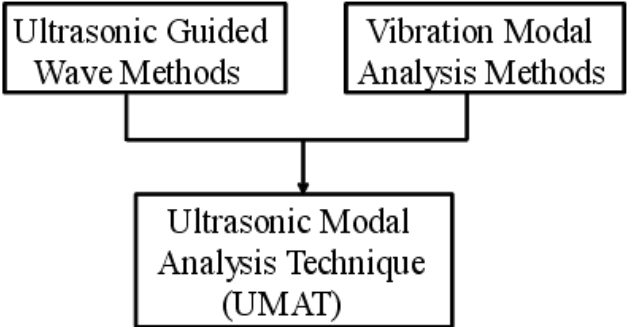
Table 9

A short comparison of ultrasonics, model analysis, and UMAT techniques

	Defect detection size	Sender positions	Speed
Ultrasonic Guided Wave	Very small ✓	Many X	Slow X
Vibration Modal Analysis	Large X	One ✓	Fast ✓
UMAT	Small to intermediate ✓	One ✓	Fast ✓

✓ good news, X bad news

Ultrasonic Modal Analysis Technique (UMAT)



Block diagram associated with Table 9

Other

Guided wave innovation goes beyond application in NDE and SHM. For example, it is shown by Zhu et al [67] that selection of a suitable wave structure, hence mode and frequency, which then can fracture/delaminate a layer or patch of ice from a substrate. Guided waves can also be used in ice detection. See [2]. The same principle can be extended to gas entrapment detection in a pipeline by measuring guided wave energy transferred from one position in a pipeline to another. Again, the right mode and frequency must be selected to ensure success so that appropriate amounts of ultrasonic energy can leak into the fluid, but will certainly not leak into the gas entrapment regions.

Concluding Remarks

Advances in guided wave understanding and computational power are making guided wave inspections a reality today. Of particular significance are applications in aircraft, pipelines, rail and bridges.

New directions point to NDE and SHM with inexpensive distributive sensor networks and sparse arrays for a line of sight analysis, tomography, phased array work, and ultrasonic vibration. Besides defect detection and location analysis for screening, new work also points to more detailed quantitative characterization analysis

Guided wave innovation can go beyond application in NDE and SHM. Examples in ice detection, de-icing, and gas entrapment detection were cited.

For successes and challenges in ultrasonic guided applications to date, see Rose [74]

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Acknowledgements

Thanks are given to my MS and PhD students over the years as well as all of the employees at FBS, Inc for their contributions to the field of ultrasonic guided waves. Cooperation has been a fun and rewarding experience. Thanks also to all of my sponsors over the years and many worldwide friends and colleagues in ultrasonics.