An Introduction to Ultrasonic Guided Waves

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Introduction

Compared to ultrasonic bulk waves that travel in infinite media with no boundary influence, guided waves require a structural boundary for propagation. As an example, some guided wave possibilities are illustrated in Figure 1 for a Rayleigh surface wave, a Lamb wave, and a Stonely wave at an interface between two materials.

a). Rayleigh (surface) wave schematic

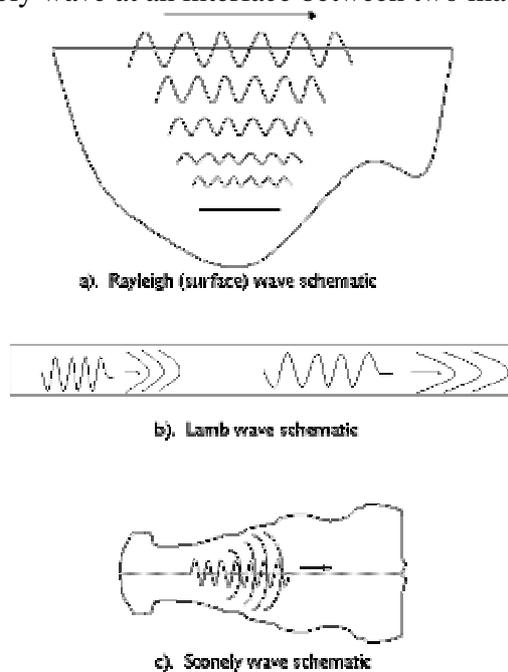b). Lamb wave schematic

c). Sconely wave schematic

Figure 1. Guided wave possibilities

There are many other guided wave possibilities, of course, as long as a boundary on either one or two sides of the wave is considered. Let's look further into a variety of different natural waveguides as outlined in Table 1.

Table 1. 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 |

When you think about it, most structures are really natural waveguides provided the wavelengths are large enough with respect to some of the key dimensions in the waveguide. If the wavelengths are very small, then bulk wave propagation can be considered, those waves used traditionally for many years in ultrasonic non-destructive pulse echo and through transmission testing. One very interesting difference, of many, associated with guided waves, is that many different wave velocity values can be obtained as a function of frequency, whereas for most practical bulk wave propagation purposes the wave velocity is independent of frequency. In fact, tables of wave velocities are available from most all manufacturers of ultrasonic equipment that are applicable to bulk wave propagation in materials, showing just a single wave velocity value for longitudinal waves and one additional value for shear waves.

To get some idea of how guided waves are developed in a wave guide, just imagine a bunch of bulk waves bouncing back and forth inside a wave guide with mode conversions between longitudinal and shear constantly taking place at each boundary. The resulting superimposed wave form traveling along the wave guide is just a sum of all of these waves including amplitude and phase information. You can visualize the outcome being strongly dependent on frequency and introductory wave angles of propagation inside the structure. The strongly superimposed results are actually points that end up on the phase velocity dispersion curve for the structure. Elsewhere there is strong cancellation. To solve for the points on the dispersion curve you could consider either a partial wave summation process accounting for all reflections and mode conversions or you could solve an appropriate boundary value problem in wave propagation.

Information on ultrasonic guided waves can be found in many excellent textbooks, see for example, references [1-6]. A very reasonable up to date state of the art literature review and evaluation of ultrasonic guided waves can be found in Rose [7].

The use of ultrasonic guided waves is increasing tremendously over the past decade because of a variety of different reasons, notably understanding and improved computational efficiency for complex problem solving. The principal benefits of guided waves can be summarized as follows. Inspection over long distances from a single probe position is possible giving complete volumetric coverage of the item to be inspected. There's no need for scanning; all of the data is acquired from the single probe position. Quite often, greater sensitivity than that obtained in standard normal beam ultrasonic inspection or other NDT techniques can be obtained, even with low frequency ultrasonic guided wave inspection techniques. There is also an ability to inspect hidden structures, structures under water, coatings, insulations, and concrete because of the inspection capability from a single probe position via wave structure change and controlled mode sensitivity along with an ability to propagate over long distances. There is also a tremendous cost-effectiveness associated with guided wave propagation and inspection because of the inspection simplicity and speed.
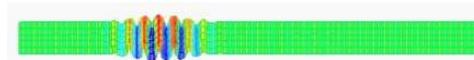
Dispersion

The subject of dispersion and the propagation of either dispersive or non-dispersive modes is a very critical one to understand when dealing with ultrasonic guided waves. In Figure 2, for example, you can see an example of dispersive and non-dispersive guided wave propagation. For non-dispersive wave propagation the pulse duration remains constant as the wave travels through the structure. On the other hand, for dispersive wave propagation, since wave velocity is a function of frequency, the pulse duration changes from point to point inside the structure. This is because each harmonic of the particular input pulse packet travels at a different wave velocity. There's a decrease in amplitude of the waveform and an increase in pulse duration, but energy is still conserved, unless of course, lossy media is considered.
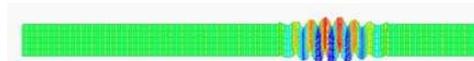
a. S0 dispersive, time = 10.0 sec
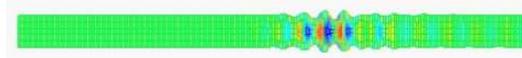
b. S0 dispersive, time = 20.0 sec

c. A0 non-dispersive, time = 10.0 sec

d. A0 non-dispersive, time = 14.0 sec

Figure 2. A0 non-dispersive and S0 dispersive waves(static shots from an ani,ation)

Let's now consider the development of a phase velocity computation in a wave guide. If we consider a particular wave guide, say a plate, for example, and the appropriate boundary conditions on a plate that would be traction free upper and lower surface, for example. If we now consider some form of a governing wave equation and an assumed harmonic solution for displacement, we can through elasticity derive the equations to satisfy the boundary conditions of the problem being studied. This leads to a transcendental equation, or a characteristic equation. In extracting the roots from the characteristic equation, associated with a system of homogeneous equations, the determinant of the coefficient matrix must be set equal to zero. In this case, the roots extracted determine the phase velocity versus frequency values that can be plotted, as illustrated in Figure 3. In Figure 3 are shown the phase velocity dispersion curves and group velocity dispersion curves for a particular traction free aluminum plate. The modes are labeled as antisymmetric A0, A1, etc. or symmetric S0, S1, and so on. The particular limits in the diagram as plate velocity, surface wave velocity, shear wave velocity and cutoff frequencies are all shown in the figure. Details on the development and the nomenclature considered here can be found in such references as Rose [6]. Derivable from the phase velocity dispersion curves are sets of group velocity dispersion curves. The values of the group velocity dispersion curves depend on the ordinate and slope values of the phase velocity dispersion curves. The group velocity is defined as the velocity measured in a wave guide of a packet of waves of similar frequency. This group velocity is what you actually measure in an experiment.
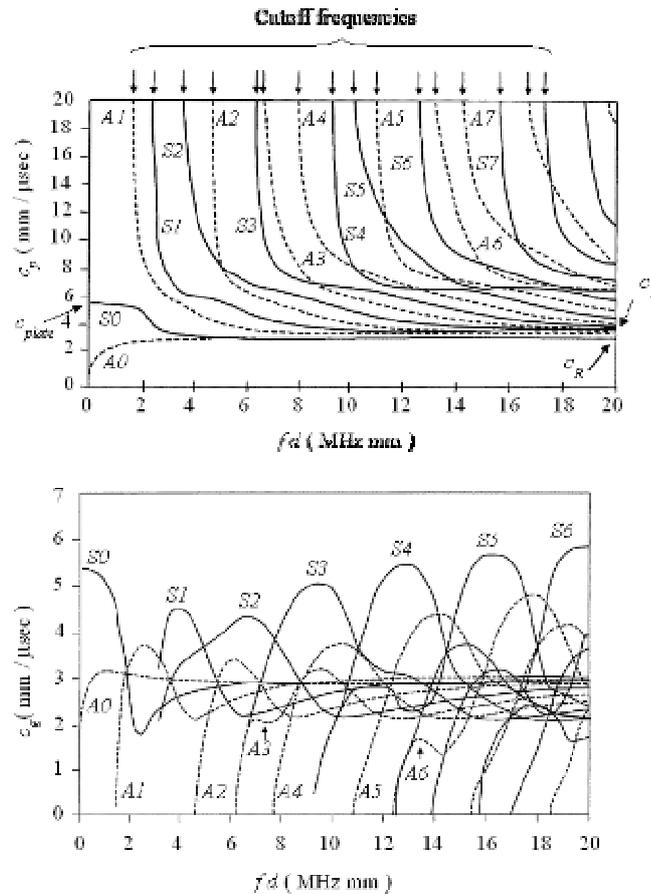
Figure 3. Dispersion curves for a traction free aluminum plate

If an aluminum plate is under water, there will be energy leakage as the wave travels along the plate, because of an out of plane displacement component that would load the liquid. The in plane displacement components would not travel into the liquid media since this would be like shear loading on the fluid. If you solve this wave propagation problem, or as another example the wave propagation associated with bitumen coating on a pipe, there would also be leakage of ultrasonic energy as the wave propagates along the plate. Following the phase and group velocity dispersion curves, the complex roots from the characteristic equation would then lead to a set of attenuation dispersion curves.

A sample set of these attenuation dispersion curves for bitumen coating on a pipe structure is illustrated in Figure 4. A pipe sample problem is used here. For the plate problem the modes are labeled as A0, A1, A2, …, S0, S1, S2, … because of symmetric and antisymmetric character. In the case of guided wave in pipes the axisymmetric longitudinal waves are labeled as L(0,1), L(0,2), L(0,3), … and the axisymmetric torsional waves as T(0,1), T(0,2), T(0,3), …. Flexural modes are also possible due to partial loading around the circumference of a pipe. See [8] for example for more details on flexural modes. Note in Figure 4 that attenuation does not always increase as frequency is increased as in a usual bulk wave problem. Some modes are attenuated more quickly than others. Note the experimental yellow dotted curve for the L(0,3) mode in this case. Note that one of the mode's attenuation improved significantly with higher

frequency, but this is the surface wave on the uncoated side of the pipe. For other modes, for higher frequency, the wave amplitudes are significantly reduced.
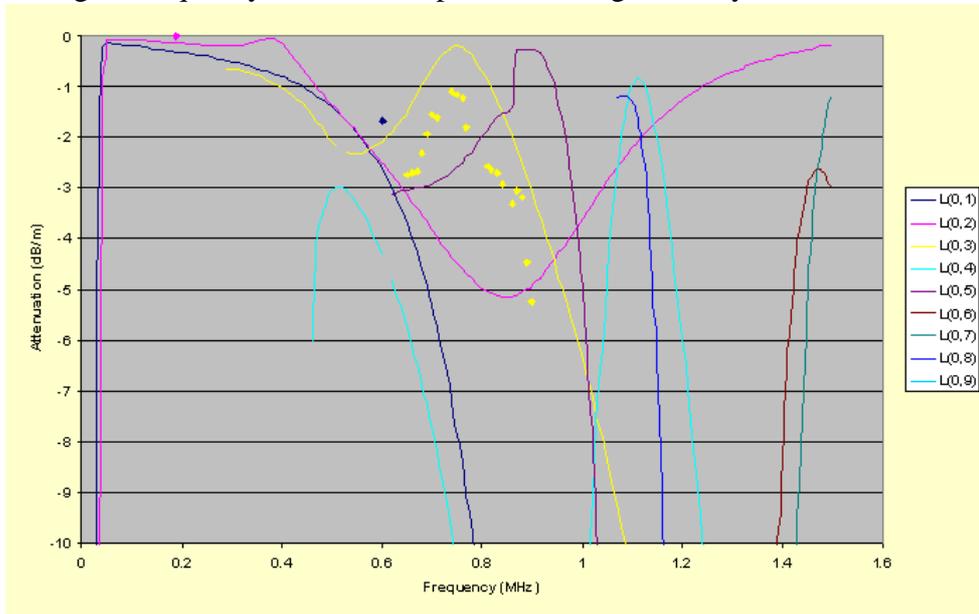

Figure 4. Attenuation dispersion curves for a 4" schedule 40 steel pipe with a ~.005" bitumen coating

All guided wave problems have associated with them the development of appropriate dispersion curves and corresponding wave structures. Of thousands of points on a dispersion curve, only certain ones lead to a successful inspection i.e. those with greatest penetration power, maximum displacement on the outer, center, or inner surface, with only in plane vibration on the surface to avoid leakage into a fluid, or with minimum power at an interface between a pipe and a coating, etc. A sample set of wave structure curves are illustrated in Figure 5 to illustrate this point, in this case, the S0 mode propagation in an aluminum plate is considered. Notice the in plane vibration behavior across the thickness compared to the out of plane motion. The wave structure changes from point to point along every mode on a dispersion curve. The characteristics of every point on each dispersion curve are different, primarily with respect to wave structure, a critical feature for the development of an efficient test technique for a particular structure. Notice that for an fd value (frequency x thickness value) of .0.5, the in plane displacement is totally dominant across the thickness with almost no out of plane vibration. This mode, as an example, would travel very far even if the aluminum plate were under water. If we now move forward and consider the frequency x thickness product of 2.0, you can see that the in plane displacement on the outer surface of the plate is almost zero, whereas the out of plane vibration is a maximum on the upper and lower surfaces. If this S0 mode were to propagate at an fd value of 2.0, the leakage would be substantial, and wave propagation along the plate under water would not penetrate very far.
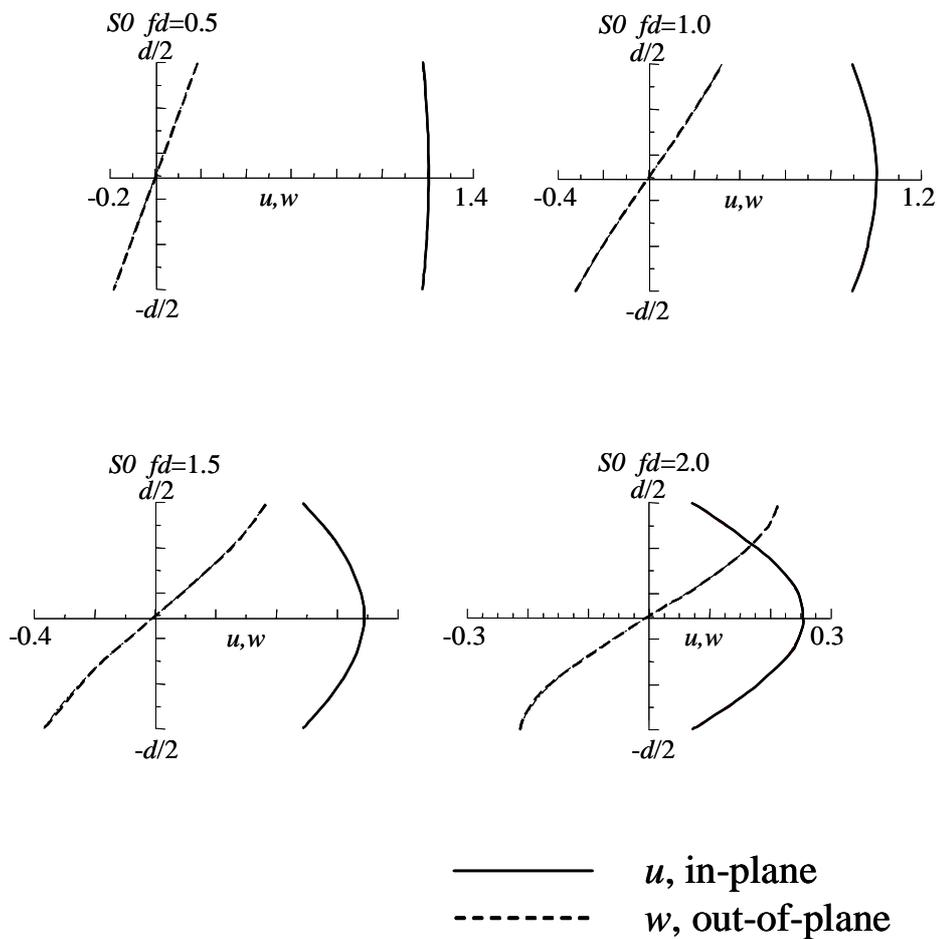
Figure 5. Wave structure for various points on the S0 mode of an aluminum plate
In addition to the Lamb type waves illustrated here so far in Figures 3, 4 and 5, there could be shear horizontal guided wave propagation in the plate as well, depending on the sensor loading situation. In this case, the shear horizontal wave produces an in plane component that's perpendicular to the wave propagation or wave vector direction but still in the plane of the plate. For the shear horizontal mode, there is no out of plane displacement. The leakage into a fluid media from an aluminum plate would be non-existent as far as wave propagation is concerned. Keep in mind, however, that mode conversion at a defect could create some leaky reflected waves.

Source Influence
The development of the dispersion curves discussed so far employs a harmonic plane wave excitation in the wave guide. Because of a bounded transducer problem, though, we must study a source influence problem for a particular size sensor. The finite size of a transducer and various vibration characteristics gives rise to a phase velocity spectrum. Therefore, in addition to the ordinary frequency spectrum there is a phase velocity spectrum, and because of these two spectral bandwidths of frequency and phase velocity, it makes it difficult to excite a specific point on a dispersion curve. Some interesting discussion on the source influence problem can be found in references [6], [9], and [10].

Mode separation in the dispersion curve then becomes useful for single mode excitation potential.

Guided wave energy can be induced into a wave guide by a variety of different techniques. The challenge is to excite a particular mode at a specific frequency. Normal beam probes can be used. Angle beam sensors can also be used to impart beams that lead to desired kinds of guided waves in a pipe or plate. A comb transducer can be also used, that is, considering a number of different elements at a specific spacing, that together pump ultrasonic energy into the plate, hence causing wave propagation of a certain wavelength in the wave guide. The excitation zones in the phase velocity dispersion curve can be evaluated by the source being considered in the problem. Again references [6], [9], and [10] can provide details in this exercise. A comb transducer, as an example, could be wrapped completely around a pipe or laid out as fingers or an inter-digital transducer design on a plate.

Pipeline Inspection
Guided wave inspection of pipeline materials is particularly useful because of the evaluation of a large area from a single sensor position. Some of the initial work done in this area is reported by Rose, et al [11] on steam generator tubing inspection. It was discovered in [11] that these waves could go really long distances and still be able to evaluate defects at a long distance from the sensor position. Many publications are available since then, some are reported in Rose [7]. Noteworthy are the works by Alleyne and Cawley [12] and Rose, et al in [13]. In looking at pipeline inspection over long distances and in [13] in particular, some phased array focusing techniques are reported that have some special advantages. In fact, phased array technology concepts are introduced in [14]. Beam focusing is possible, although a different computation technique to achieve focusing is necessary being different than the computations required in phased arrays for bulk wave focusing. A sample focusing result is presented in Figure 6.
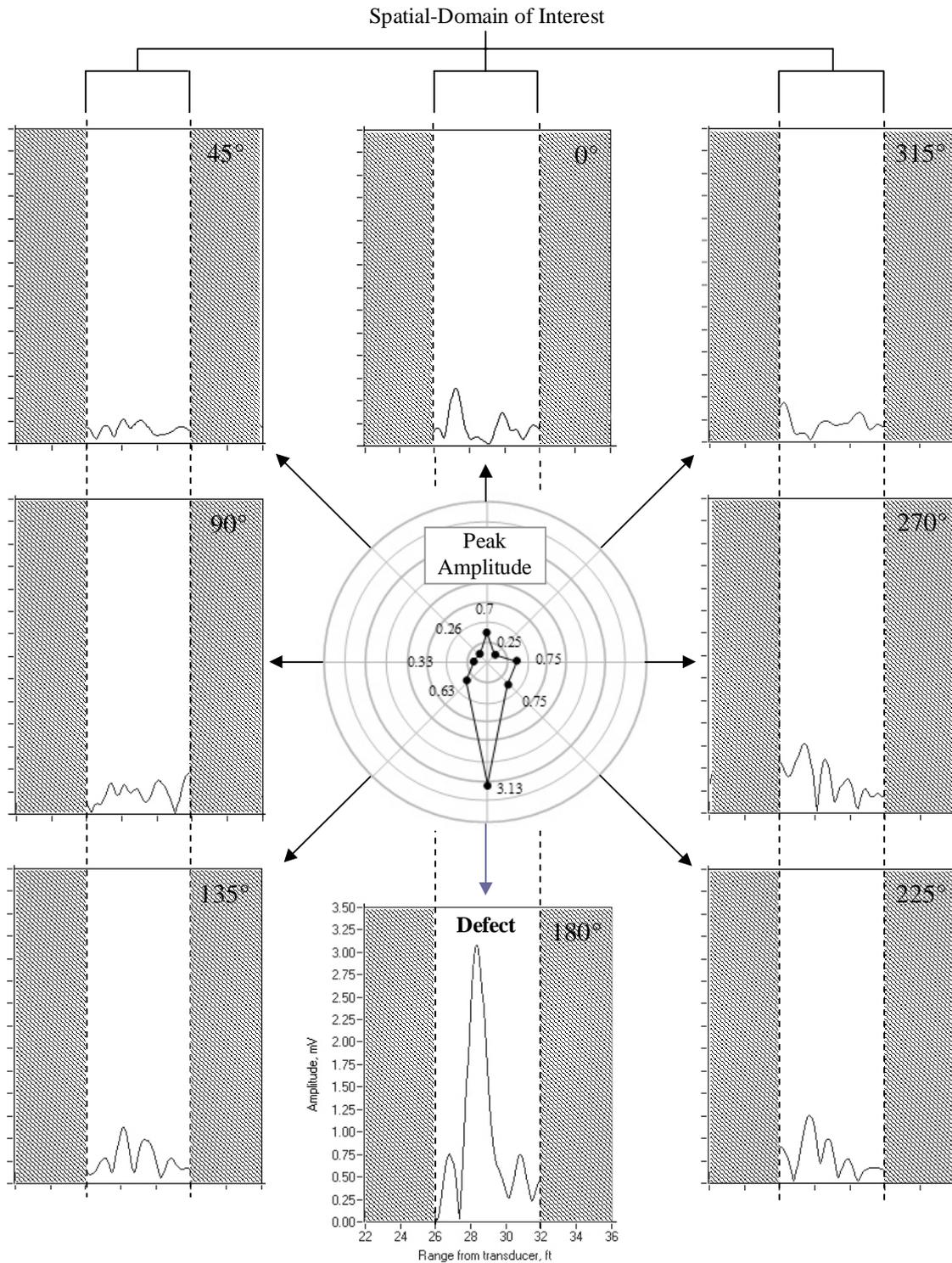
Figure 6. An example illustrating the precise circumferential defect-locating ability of the ultrasonic guided-wave phased-array focusing technique. In this example guided-wave energy is focused at 8 different angles at an axial distance of 9.14 *m* (30.0 *ft*). A sharp peak in reflected energy indicates that there is a defect located in the bottom octant (180°), at a distance 8.84 *m* (29.0 *ft*) from the location of the guided-wave inspection tool. Data taken on a .4 *m* (16.0 *in*) diameter coated pipe.

A sample configuration of pipeline inspection with a typical wraparound guided wave sensor arrangement is illustrated in Figure 7. There are a number of ways that this can be done via normal beam sensors, angle beam sensors, EMAT possibilities, magnetostrictive sensors, etc. at frequencies ranging from 20 kHz ranging on up to 800 kHz depending on the distance range of propagation and the defects that one would like to find. Typically, state of the art of the currently available low frequency inspection systems is finding defects that have a 5% cross sectional area (CSA) or more. Higher frequencies are able to go down to 1% CSA or even less. See a few static shots from animations in the Appendix.
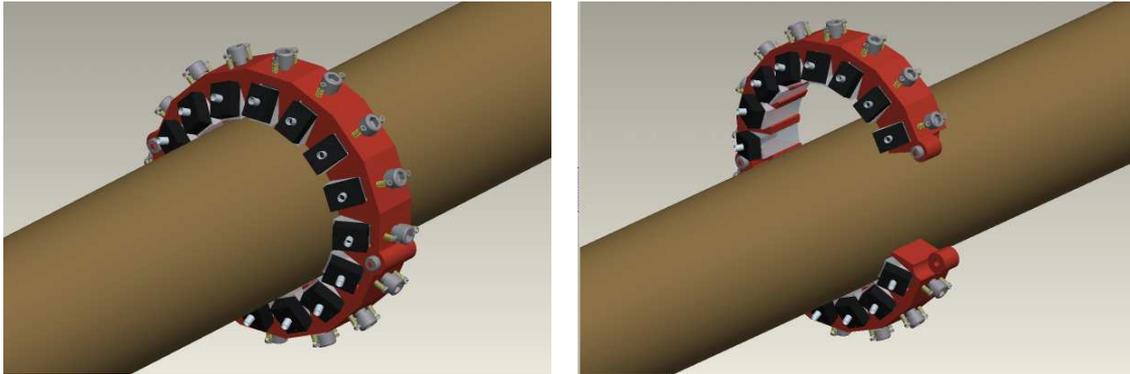
Figure 7. Typical wrap around ultrasonic guided wave sensor arrangement for long range ultrasonic guided wave inspection of piping

Aircraft Inspection

Aircraft skins are particularly suited to guided wave inspection as well; see [15] for a variety of different problems that could be tackled in the aircraft industry. Note in Figure 8 a possibility of guided wave inspection. Note in Figure 8a that if ultrasonic energy can be passed from a transmitter to a receiver across a lap splice joint, we could then indeed evaluate the integrity of that bond line in the lap splice inspection problem. Keep in mind though, the problem is not as simple as it initially looks because the wave structure has to be adjusted in such a way as to have sufficient energy at the interface to allow propagation into media 2. The wave structure variation and the kind of energy obtained can come about from calculations of wave structure for a particular mode and frequency in a phase velocity dispersion curve. Once the technique is developed, tools can be used as illustrated in Figure 8b, as an example, the double spring hopping probe illustrated here can be placed on a material quite easily and at the appropriate mode and frequency can evaluate the integrity of the lap splice joint.
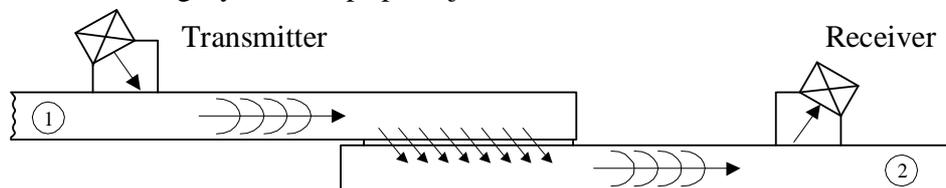
a. ultrasonic through-transmission approach for lap splice joint inspection

b. double spring "hopping probe" use for the inspection of a lap splice joint
Figure 8. a lap splice inspection sample problem

See a few static shots from animations in the Appendix along with several from plates and rail.

Concluding Remarks

Because of the tremendous advancements in the understanding of guided wave propagation and the superb computational ability that is now available via methods of analytical equations and finite element analysis, guided wave analysis and inspection is becoming a reality today. The future for solving lots of problems using guided wave analysis in non-destructive evaluation and structural health monitoring is very bright. See appendix A for some interesting static shots of wave propagation taken from a few of our guided wave animations.

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Appendix A
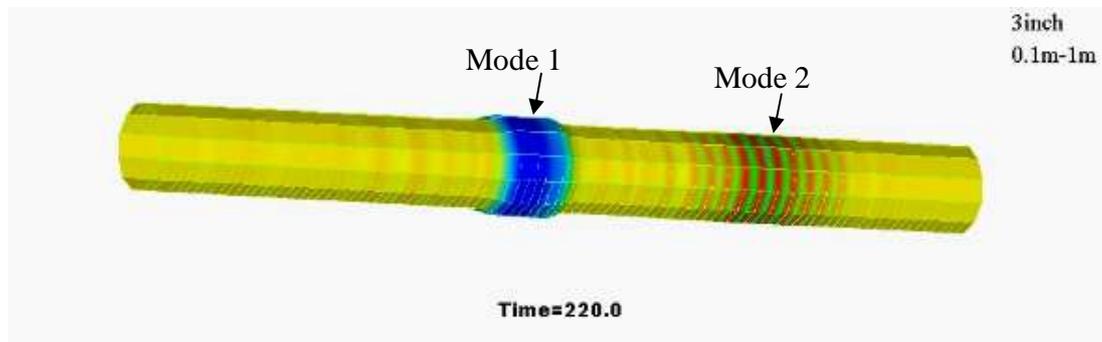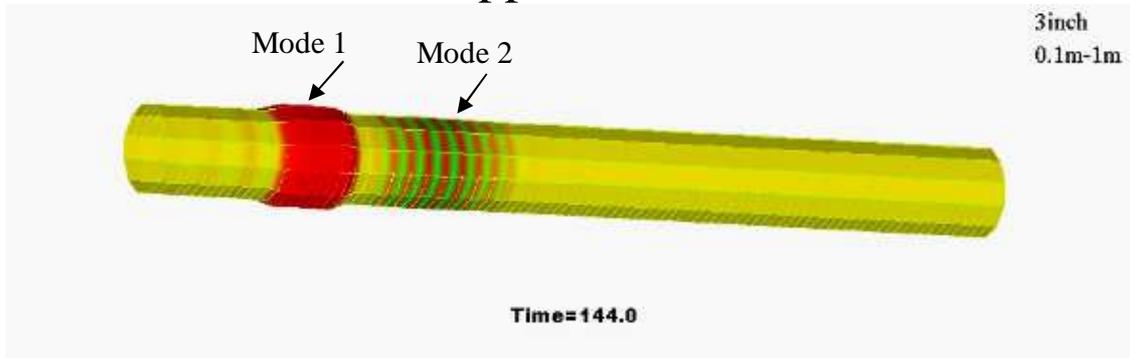
Figure A1. Axisymmetric longitudinal wave propagation in a pipe (static shots at two times)

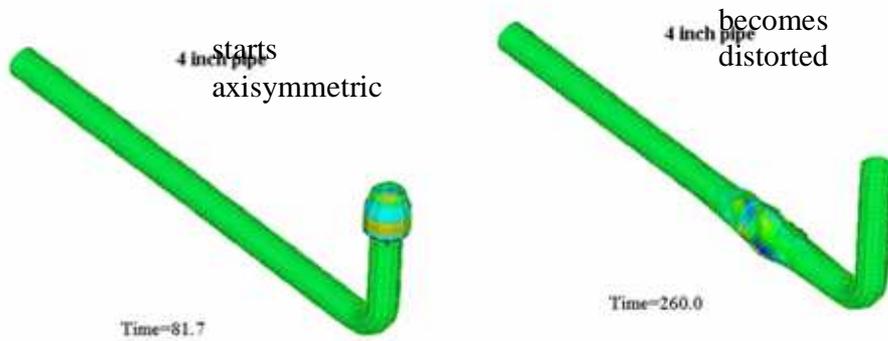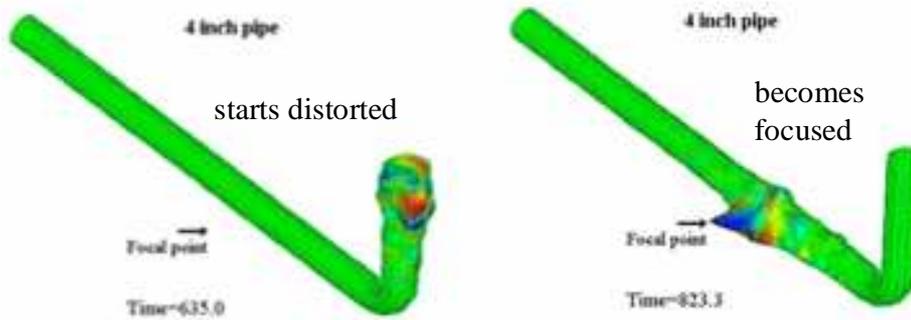Time=82.0

focal spot

Time=142.0
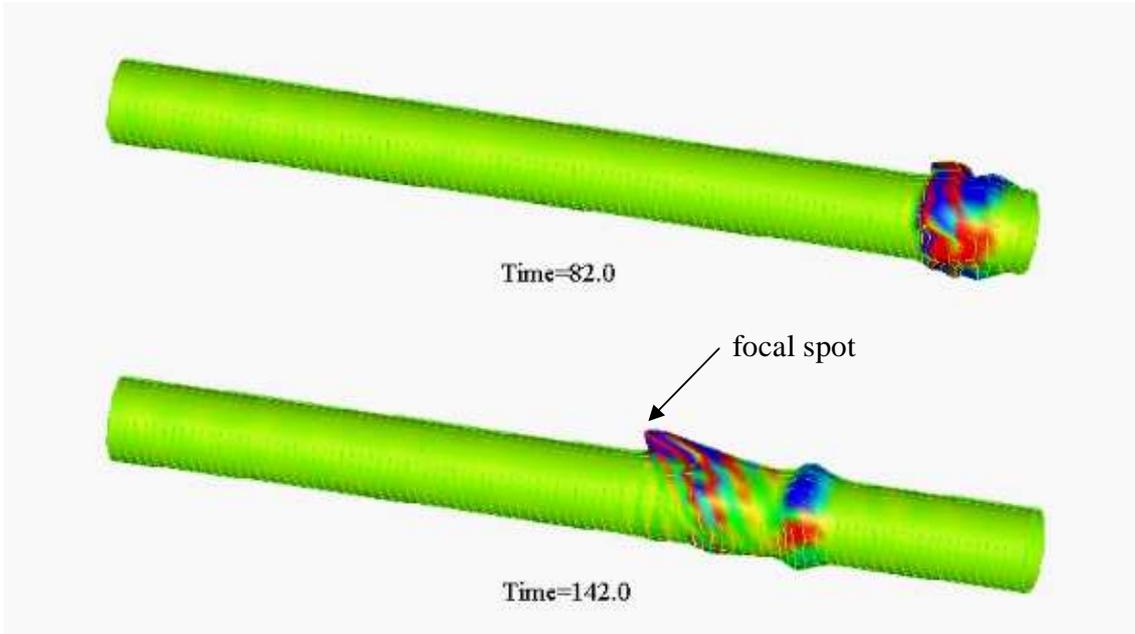
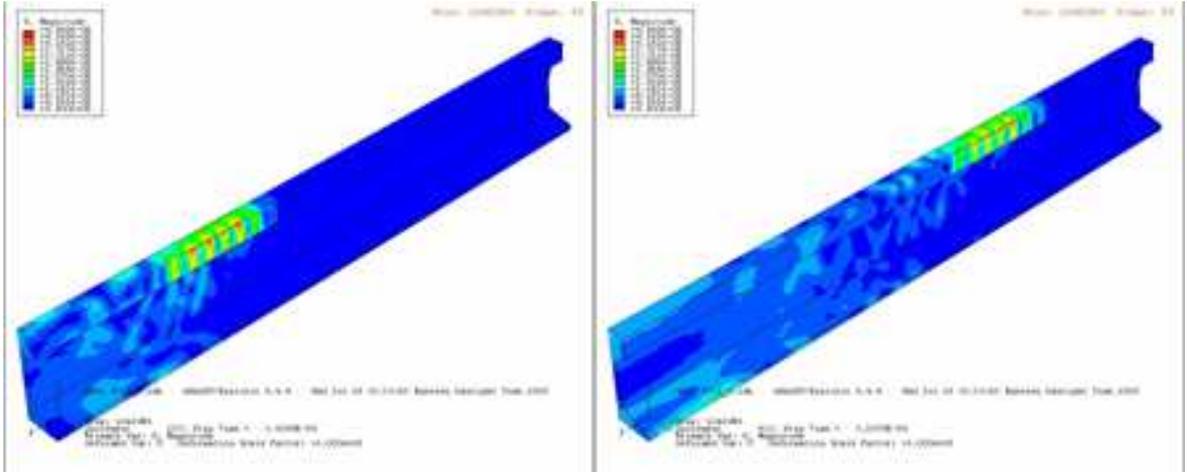Figure A2. Focusing development in a pipe (static shots at two different times)

a. Axisymmetric waveform impingement onto and elbow region showing wave distortion beyond the elbow.
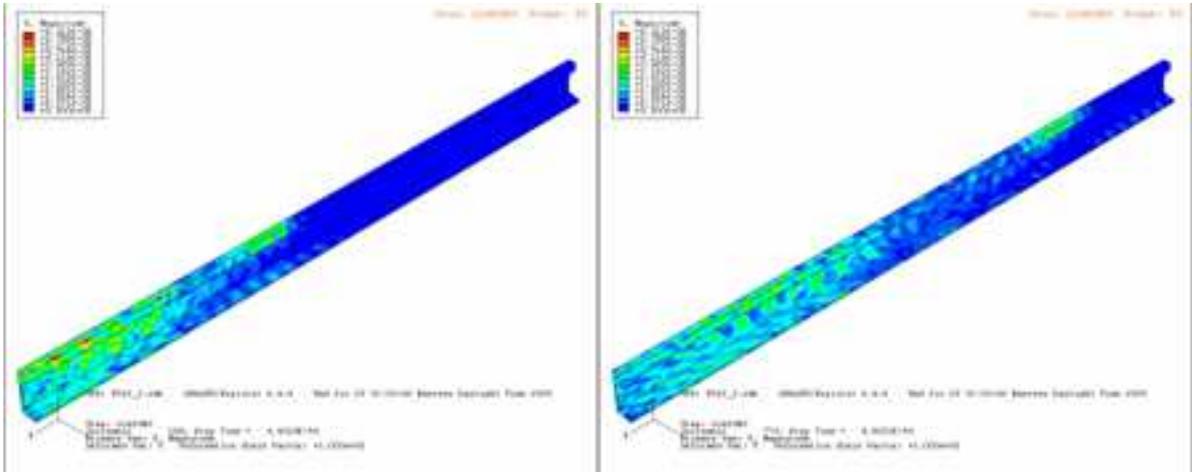

b. Phased array flexural mode packet impingement onto an elbow region showing nicely behaved focusing beyond the elbow.

Figure A3.

a. 30-1

b. 30-2

Figure A4. Guided waves in a rail with mode and frequency control; a. Pseudo-Rayleigh surface wave mode at 30 Khz,most of the energy in the head, b) wave covering total cross section of the rail, higher phase velocity than that used in a, also at 30 Khz.
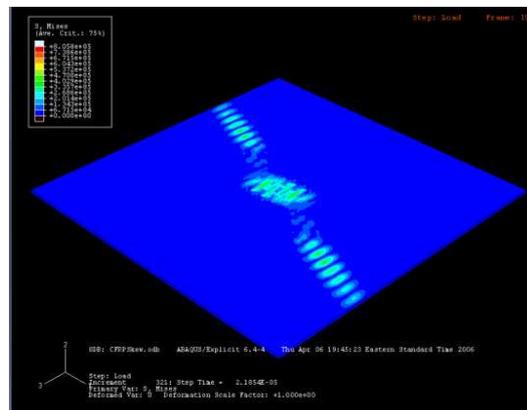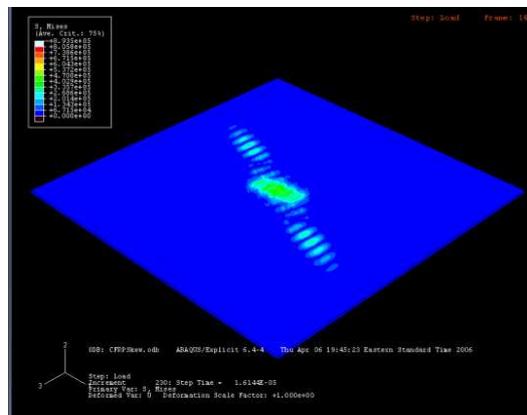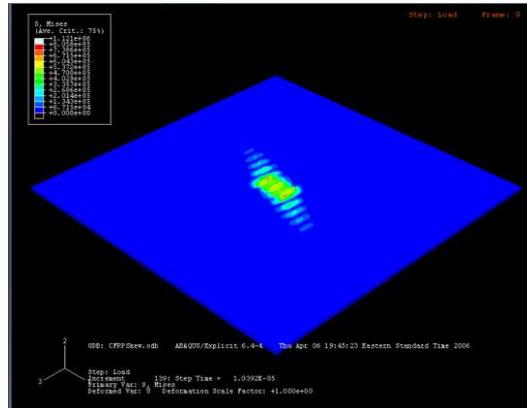
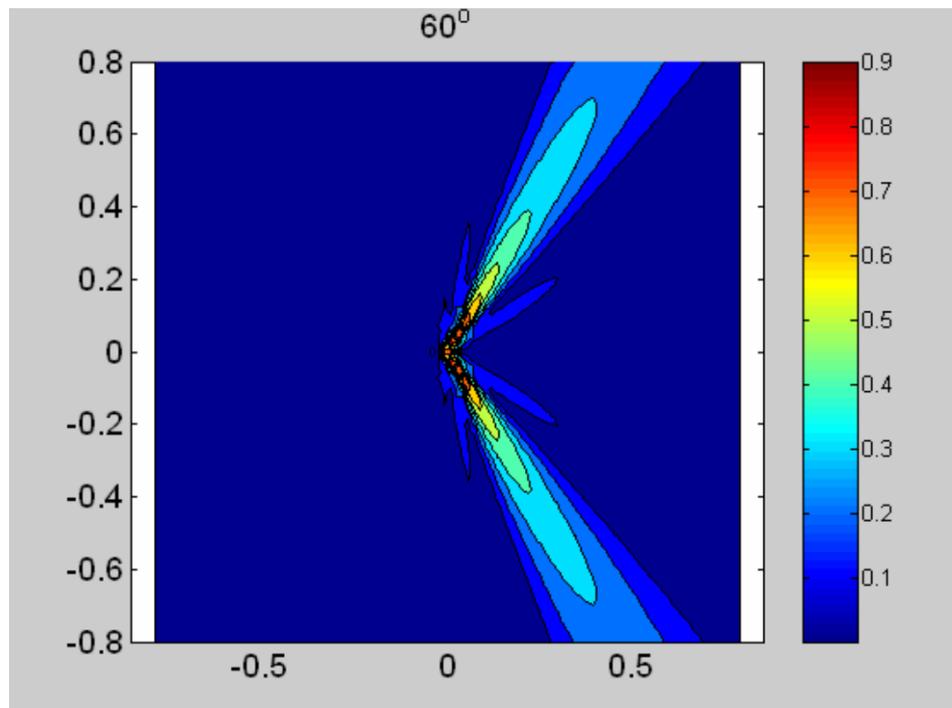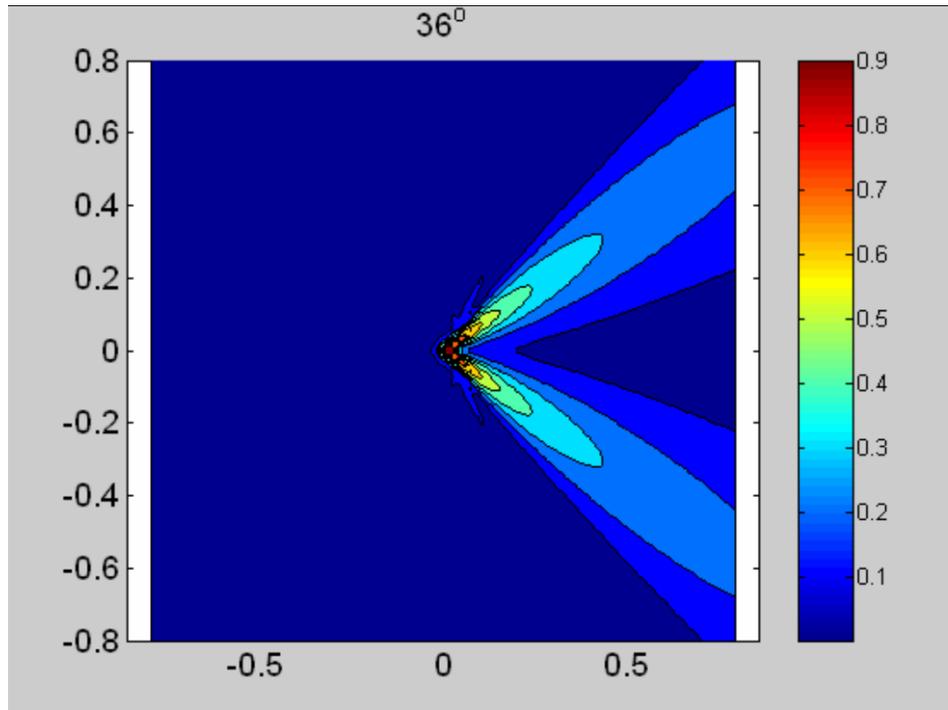Figure A5. Guided waves in a composite plate (showing beam skew formation at three times)

Figure A6. Guided wave phased array in a plate (static shots at two different positions)