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Ultrasonic Guided Waves in Structural Health Monitoring

Joseph L. Rose

[1] Department of Engineering Science and Mechanics, Penn State University,
212 Earth-Engineering Science Bldg., University Park, PA 16802, USA

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Abstract. Ultrasonic Guided Wave inspection and structural health monitoring is being considered today in such natural wave guide structures as plates, multi-layer structures, rods, rails, piping and tubing, an interface, and curved or flat layers on a half space. An increased understanding of the basic physics and wave mechanics associated with guided wave inspection has led to an increase in practical nondestructive evaluation and inspection problems. Computing power today is also making dreams come true, where only a vision was possible decades ago. A principal advantage of guided waves is inspection over long distances with excellent sensitivity from a single probe position. There is also an ability to inspect hidden structures and structures under water, coatings, insulations, and concrete. Basic theoretical aspects of dispersion curve analysis, wave structure, source influence, sensor types and instrumentation possibilities and commercialization ventures will be discussed along with a variety of practical applications on ship hull, containment structures, aircraft, ice detection, pipelines, rail, overlap joints, and crystal manufacture. Phased array focusing in pipes and across elbows will be highlighted. Computational aspects of FEM and BEM analysis for defect classification and sizing analysis will be outlined. Future directions of leave in place sensors and wireless activity will also be presented.

Introduction

Ultrasonic guided waves are becoming more commonplace in industry because of the tremendous advances being made in the mathematics and mechanics of wave propagation that allows us to understand the unusual behavior characteristics that could become a major benefit in ultrasonic non-destructive testing methodologies. For the plenary talk given at the Asian Pacific Non-Destructive Testing Conference a great deal of material was covered on guided waves of which only a limited amount of information can be presented in this summary paper. Nevertheless, this summary paper serves as an instrument of knowledge for those interested and who want to get involved in ultrasonic guided wave analysis. The first three references include very basic material associated with ultrasonic guided waves in solid media along with some basic principles of dispersion curve analysis and an interesting example of the utilization of wave structure in guided wave analysis that allows us to perform guided wave testing of water loaded structures.

References 4 and 5 contain very large literature surveys of a lot of very significant work that has been carried out in guided wave mechanics over the last few decades. A vision of ultrasonic guided wave inspection potential is also outlined in those papers. To add to the basic concepts of ultrasonic guided waves visualization schemes are often quite useful. One interesting example is presented by Hayashi and Rose [6].

To think of the utilization of ultrasonic guided waves we can consider a variety of different natural wave guides as outlined in Table 1. Guided wave inspection is a natural for any of these structures so when you really think about it guided waves can be applied to many, many structures very quickly and efficiently. An understanding of the basic wave mechanics and wave propagation principles for various sensors and mode types is essential, though, if one is to carry out some reliable tests. The benefits of guided waves are illustrated in

Table **2**. The most interesting one of course is to be able to inspect over long distances from a single probe position.

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

Table 2. Benefits of Guided Waves

Inspection over long distances from a single probe position
By mode and frequency tuning, to establish wave resonances and excellent overall defect detection and sizing potential.
Often greater sensitivity than that obtained in standard normal beam ultrasonic inspection or other NDT techniques. (Beam focusing is on the horizon for even improved sensitivity.)
Ability to inspect hidden structures and structures under water, coatings, insulations, and concrete with excellent sensitivity.
Cost effectiveness because of inspection simplicity and speed.

Ultrasonic guided waves can be produced in a structure by a variety of different techniques including angle beam transducers, comb type transducers, EMATs and magnetostrictive type sensors. The utilization of a comb-type transducer outlined by Rose and Quarry [7] is an interesting one to consider. Comb transducers can produce surface and guided waves in any structure and material including very low wave velocity composite materials where generation possibilities with an angle beam technique is not even possible. Other benefits of a comb transducer are associated with overall size and low profile height and cost.

A sample phase and group velocity dispersion curve is presented in Figure 1. Every natural wave guided has associated with it a set of dispersion curves that presents to us the wave propagation possibilities in that structure. Details and analysis can be found in [1]. A sample set of wave structures are illustrated in Figure 2. At each point of a dispersion curve there is a different wave structure. The wave structure is associated with sensitivity, penetration power, and the ability to propagate in a water loaded structure, for example. In Figure 3 is an interesting concept associated with an ability to get on to a particular point in a dispersion curve. When studying the dispersion curve it is easy to understand that there is a corresponding frequency bandwidth associated with the abscissa value, but there is also a phase velocity bandwidth as illustrated in Figure 3 associated with the ordinate value on the phase velocity dispersion curve. This means that we are actually exciting a fairly large zone and multiple modes could propagate in a structure at the same time. Details on the wave mechanics of this source influence can be found in [1].

A variety of different applications and other aspects of guided wave inspection are presented in this paper in the following paragraph.

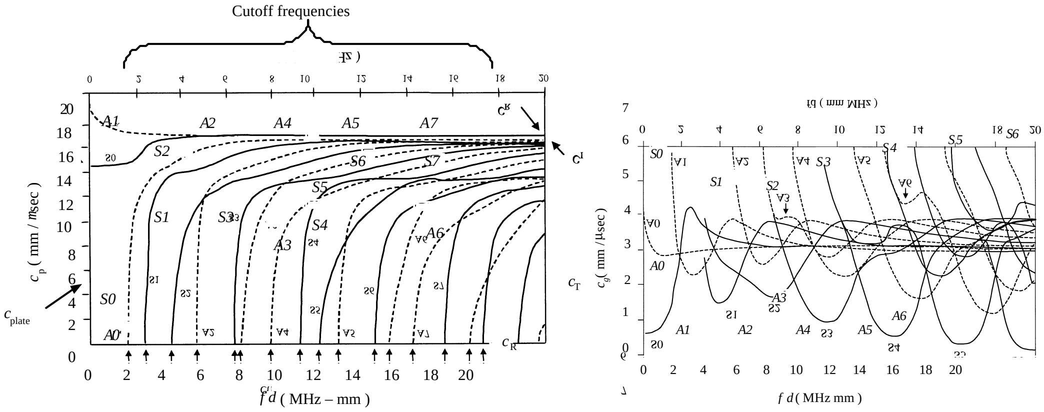


Figure 1. Phase and group velocity dispersion curves for a traction free aluminum plate

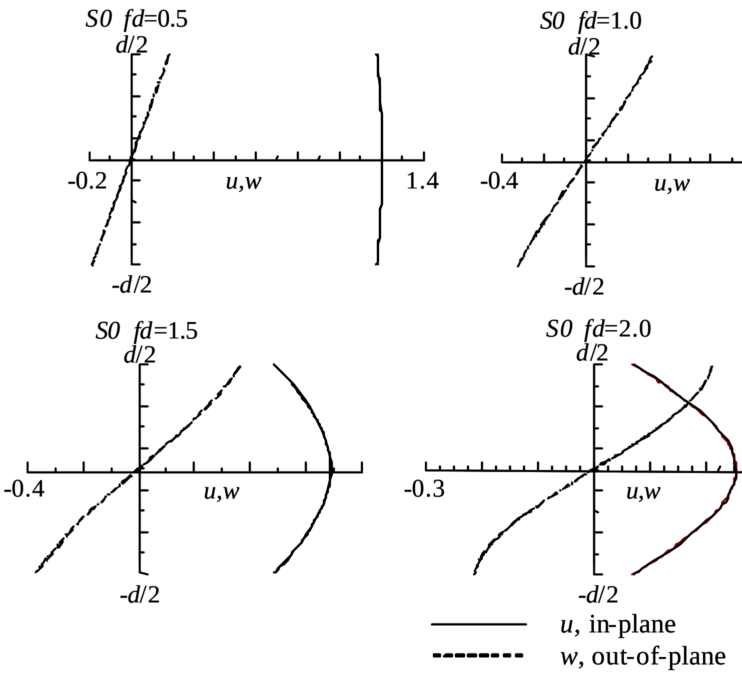


Figure 2. Sample wave structure for various points on the S0 mode of an aluminum plate

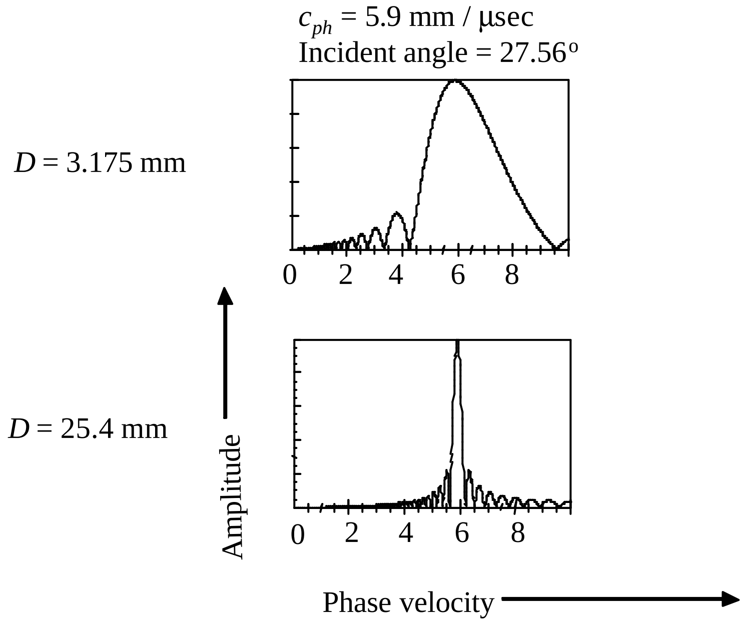


Figure 3. Sample phase velocity spectra showing excitation amplitude versus phase velocity (frequency = 4.3 MHz, bandwidth = .6 MHz)

Applications

Aircraft applications are presented in references [8-12]. A variety of different structures are considered including lap-splice joints, tear straps, landing gears, transmission beams in a helicopter and so on. A lap-splice inspection sample problem is illustrated in Figure 4. The concept is a very simple one, but please note that even though the test is based on an ability to send ultrasonic energy from material one into material two, it is joined together adhesively and perhaps even by riveted areas. The ability to send this ultrasonic energy depends on the selection of a particular mode and frequency. That particular point must have the appropriate wave structure that would allow the energy to go from position one to two. This can be achieved by frequency tuning, as an example, unless you know of course the precise point on the dispersion curve that you would like to be working with beforehand. The test is therefore very simple. If the ultrasonic energy can get through you have an excellent adhesive joint. If it cannot get through, you have a problem or delamination.

One technique is presented that shows how wing ice detection can be considered from an ultrasonic guided wave point of view. Another is on titanium diffusion bonding with guided waves. Another deals with a leave in place sensor for damage detection in a helicopter transmission beam.

A sample problem using shear horizontal EMAT transducers for damage detection in a ship hull is presented in [13]. An ultrasonic assessment of Poisson's ratio in thin wires is included in [14]. Steel cable inspection with magnetostrictive sensors for guided wave generation is presented in [15]. The utilization of various wave guides, associated with ultrasonic guided wave problems, is quite useful. In [16] for example, a technique is presented that shows how a composite wave guide can be used to get ultrasonic energy into a CaF_2 melt to monitor interface position in CaF_2 crystal manufacture. Another wave guide application is outlined in [17] where a harmonic scalpel is used to do surgery where the activation is associated with energy sent to the tip of the rod for surgical use.

Some adhesive bonding and joining applications are presented in [18-20]. Ultrasonic guided waves are particularly useful in adhesive bond inspection because they can produce both longitudinal and shear wave energy at the interface between materials, hence making it useful for both detection of adhesive and cohesive problems associated with the bonded structure. In the paper on the plate overlap [20], it is shown how frequency tuning and overall mode choice can allow ultrasonic energy to get across an unusual plate overlap or to achieve a significant reflection depending on the goal of the particular inspection.

Application for containment structures and concrete with guided waves is presented in references [21, 22]. Some new and interesting tomographic results with guided wave tomography of defects in a composite plate are presented in [23]. Fouling detection in the food industry is outlined in [24]. Viscosity measurements and in particular a magnetostrictive sensor to produce torsional waves in molten materials is outlined in [25]. A novel couplant-free mediator ultrasonic wave technique is used to detect surface cracks in green parts in [26]. The comparison of two different states of a composite material as an example for porosity variation is illustrated in [27].

Guided waves are being used in rail inspection in the railroad industry as illustrated in [28-30]. A sample guided wave dispersion result is illustrated in Figure 5 where an experimental profile is obtained from a two dimensional Fourier transform and then compared with a theoretical result highlighting dominant modes of the structure. Defect detection in rail from a variety of different means is being considered. As an example a specially prepared sensor wrapped around the rail to acquire data is reported in [28]. The ability of developing a longer range rail inspection from a test car or perhaps by detection from a train moving down the track before it actually reaches the break or defect in the rail is outlined in [29].

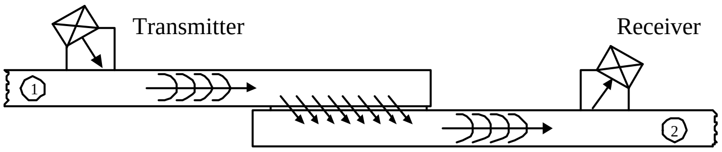
A variety of pipe applications and background material is included in references [31-38]. Many parameters associated with pipe inspection can affect the wave propagation characteristics and inspection potential. See Table 3. A sample photograph of a commercially available Teletest pipeline inspection rig is illustrated in Figure 6. Notice how the entire transducer wraps around the pipe assembly where guided waves can then be sent off into either direction into this underground pipeline. The titles of the references are somewhat self explanatory with respect to the technology explored in pipe inspection.

An interesting concept that is put forward at the current time is associated with the ability to carry out focusing in a pipeline structure. Some of the references point out how this can be done. Shown in Figure 7 though is a sample result. Notice in the neighborhood of 4300 µsec along a 16" schedule 40 pipe a raw sum without time delay, that is the so-called axisymmetric loading onto the structure where the defect is seen with a peak to peak level of 41. By using the appropriate time delay profile around the pipe of four particular segments, that is utilizing 90° loading profiles, the peak to peak value increases to about 95, roughly a 7 dB improvement. Notice the back wall echo from one of the modes used in the structure remains constant but some of the other signals are enhanced.

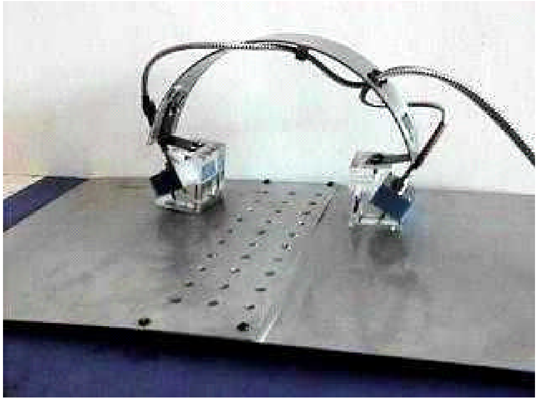
An interesting area of study now is associated with utilization of longitudinal versus torsional guided waves in a structure. Mode type and frequency is always of interest. An initial comparison is presented in Table 4. Some general comments on pipe and elbow inspection associated with the focusing potential is illustrated in Table **5**.

Table 3. Parameters affecting guided wave propagation in pipe

Pipe diameter and thickness
Longitudinal or torsional excitation
Degree of partial loading around circumference
Frequency
Frequency bandwidth
Phase velocity
Pipe anomalies like branches, elbows
Mode selected and subsequent wave structure
Loading method piezoelectric, EMAT, impact, etc.
Beam phased array wave formation
Instrumentation parameters of pulser voltage, filters, amplifiers, etc.
Defect characteristics such as shape, circumferential extent, and depth

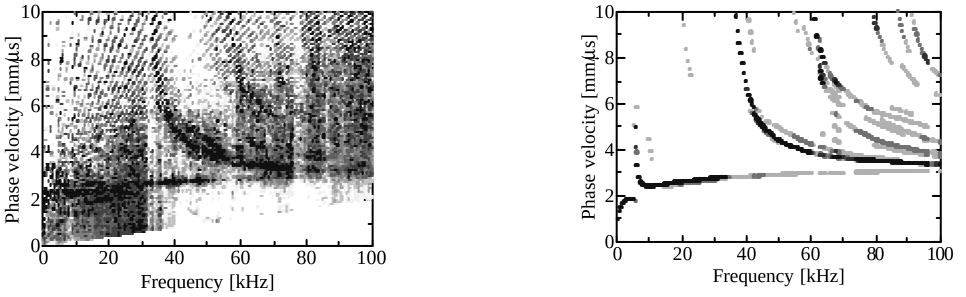


a). Ultrasonic through-transmission approach for Lap Splice joint inspection



b). Double spring "hopping probe" used for the inspection of a Lap Splice joint

Figure 4. A lap splice inspection sample problem.

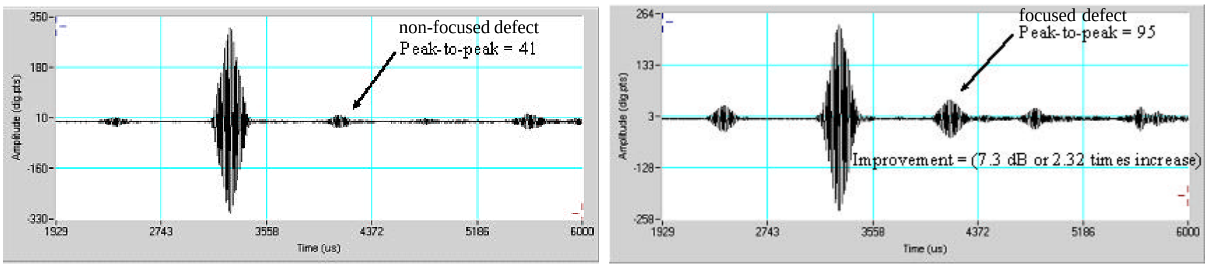


(a) Experimental, upper surface of a rail head

(b) Theoretical, upper surface of a rail head, dominant modes are highlighted

Figure 5. Guided wave dispersion curves for a bar with an arbitrary cross-section – a rail example

Figure 6. Pipeline inspection of "bell holes" and unpiggable pipe sections (Teletest®)



Raw sum without time delays

Phase aligned sum with excitation time delays

Figure 7. Comparisons of focused and non-focused results

Table 4. Comparisons of longitudinal vs. torsional guided waves

Generally less mode conversion with torsional waves.
Wave structure is constant for a particular mode for all torsional mode frequencies compared to considerable variation vs. frequency for Lamb waves.
Torsional modes are less sensitive to pipe boundary conditions of roughness, coating, etc. because of lateral particle velocity.
Torsional modes are not sensitive to water loading conditions in a structure because of in plane displacement vibration characteristics; hence no need to tune Lamb waves to achieve this in plane vibration condition.
Torsional modes could be insensitive to certain kinds of defects that Lamb waves could be extremely sensitive to because of having both in plane and out of plane displacement components.
Penetration power of both modes could also vary significantly with frequency and presence of certain boundary conditions, presenting no specific advantage to one or the other.
Regardless of input mode, reflection and transmission from a truly 3-dimensional defect situation can produce both non-axisymmetric Lamb and Torsional modes.
Many additional comparisons will be developed as a result of new research efforts already underway.

Table 5. Comments on pipe and elbow inspection

Natural focusing can be accomplished by using frequency tuning and/or non-axisymmetric loading of a pipe structure via variations in the angular profiles.
Phased array focusing can be accomplished by using time delays and multiple sensors impinging non-axisymmetric energy into a pipe.
Long range ultrasonic guided wave inspection with focusing and frequency tuning will be able to achieve better sensitivity to smaller defects with significant improvement in S/N ratio for a variety of test conditions.
Both longitudinal and torsional waves should be included in the guided wave inspection tool box.

Computational

Many computational aspects of guided waves are being considered by groups all over the world. One result is shown here. See [39, 40]. Notice in Figure 8 a very powerful result. The amplitude of the reflection is proportional to the depth of the defect. This is not always true however, but for the right mode and over a particular frequency range this is often possible.

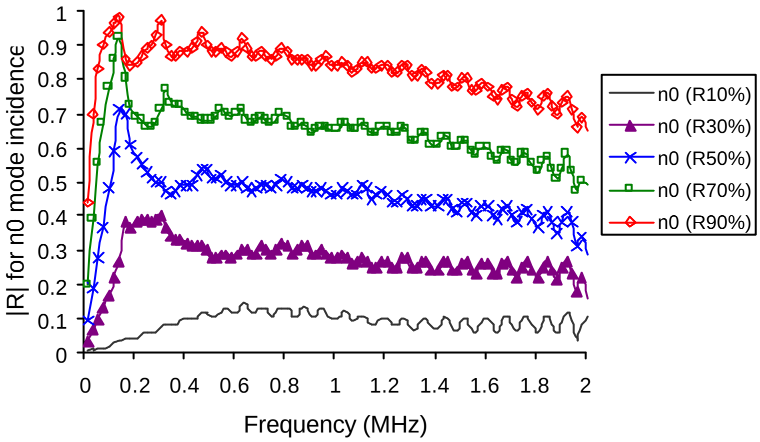


Figure 8. Sample computational result – approximate reflection coefficients for n0 mode under n0 incident for 0.012” (0.3mm) elliptical defect length and 10%, 30%, …, 90% through plate thickness depth

Concluding Remarks and Future Directions

- Greater penetration power resolution and sensitivity as a result of advances in guided wave physics and mechanics is becoming possible.
- Technology transfer of current studies to industry is taking place.
- Automated defect and location analysis followed by sophisticated computational and artificial intelligence algorithm development for defect classification and sizing analysis is on the way.
- Smart structures and materials with embedded sensors is becoming a reality.
- Miniature leave-in-place sensors on aircraft, pipelines, etc. are becoming commonplace.
- Wave resonance automatic “tuning” algorithms of frequency, phase velocity, and mode type for defect detection is on the way.
- Guided wave phased array focusing methods are being developed for improved penetration power, sensitivity, S/N.
- Wireless activation and reception with miniature batteries, pulser receivers, chips, antennas, etc. are on the way.
- More air coupled and laser based systems are being considered.

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