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A Baseline and Vision of Ultrasonic Guided Wave Inspection Potential

Ultrasonic guided wave inspection is expanding rapidly to many different areas of manufacturing and in-service inspection. The purpose of this paper is to provide a vision of ultrasonic guided wave inspection potential as we move forward into the new millennium. 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. Some fundamental concepts and a number of different applications that are currently being considered will be presented in the paper along with a brief description of the sensor and software technology that will make ultrasonic guided wave inspection commonplace in the next century. [DOI: 10.1115/1.1491272]

Introduction

Basic information on the subject of guided wave propagation can be obtained in many textbooks; see, for example, [1–8]. The work in [1–8] builds upon the work presented by giants over the last two centuries in the areas of wave mechanics and elasticity. Contemporary work efforts over the last two decades illustrates some of the technology transfer efforts from guided wave mechanics to nondestructive evaluation. The works from many guided wave nondestructive evaluation pioneers are presented in [9–25]. Some of my own recently published papers that show some of the new directions in guided wave application are included in [26–40]. Additional references useful to the reader on both theoretical and experimental aspects of guided waves can be found in references [41–207]. Some basic concepts in guided wave propagation and limitations with respect to their use is followed by a section on sample problems and natural wave-guides.

Basic Principles

The major difference between bulk wave propagation and guided wave propagation is the fact that a boundary is required for guided wave propagation. As a result of a boundary along a thin plate or interface, we can imagine a variety of different waves reflecting and mode converting inside a structure and superimposing with areas of constructive and destructive interference that finally leads to the nicely behaved guided wave packets that can travel in the structure. Classic surface wave propagation example includes surface waves, Lamb waves, and Stonely waves. The Lamb wave problem is reserved, strictly speaking, for wave propagation in a traction-free homogeneous isotropic plate, although the terminology has been expanded to Lamb wave-type propagation in a variety of structures including plates, multi-layer plates, rods, tubes, etc., where the wave vector components can be both parallel and perpendicular to the particle vibration in a vertical plane through the structure, opposed to horizontal shear waves where the particle motion is only normal to the wave vector in a horizontal plane as the wave propagates along the structure.

There are many different techniques for generating guided waves, two of the most common being illustrated in Fig. 1. It is possible to use an angle beam transducer for the generation of guided waves by pulsing a piezoelectric element on the wedge placed on a test surface. As a result of refraction at the interface between the wedge and the test specimen, a variety of different waves can propagate in the structure and by way of mode conversion and reflection from the surfaces of the structure can lead to interference patterns as a resulting wave vector propagates along the structure. Snell's law can be used to calculate the resulting phase velocity, sometimes referred to as a "Cremer hypothesis." In doing calculations of finding out what interference packages might come about in the material, one can produce a so-called "dispersion curve" that shows the wave propagation possibilities of phase velocity and frequency that could possibly propagate in the structure. A second technique of producing guided waves in a structure is by using a comb transducer. The technique is presented in Fig. 1. A number of elements are placed on the structure with some spacing that pumps energy into the structure either all in phase or out of phase if we were using a phased array transducer approach, causing ultrasonic guided wave energy to propagate in both directions along the structure. The spacing and the frequency selection allow us to decide the mode types that would actually propagate in the structure.

Dispersion curves show all of the constructive interference zones that could occur as the waves reflect inside a structure, demonstrating the kinds of waves and modes that could actually propagate. Details for computing these phase and group velocity dispersion curves can be found in [8]. A tremendous amount of information can be found on the dispersion curves that can be used to design and analyze a guided wave nondestructive testing experiment. The curves are produced for an infinite plane wave excitation. Because of the transducer size itself and type of pumping action of ultrasonic energy into material, a phase velocity spectrum comes about similar to those illustrated in Fig. 2. So in addition to the well-known frequency spectrum concept, we also have a phase velocity spectrum that leads to a zone of excitation as we try to excite a particular mode and frequency. The zone of excitation is such that we often produce several modes at once. The phase velocity and frequency spectrum principles must be considered when designing a guided wave experiment. An experimental versus theoretical result for a traction-free aluminum plate is illustrated in Fig. 3 to demonstrate this source influence concept. The theoretical and experimental curves are shown plotted on top of each other, showing the approximations that come about because of the source influence in conducting an actual experiment.

Another tremendously important consideration in the selection of guided wave modes for a particular experiment is associated with wave structure. The in-plane displacement, out-of-plane displacement, or actual stress distribution itself varies across the thickness of the structure, often quite significantly; see [8]. The vibration pattern across the thickness along the entire mode is not

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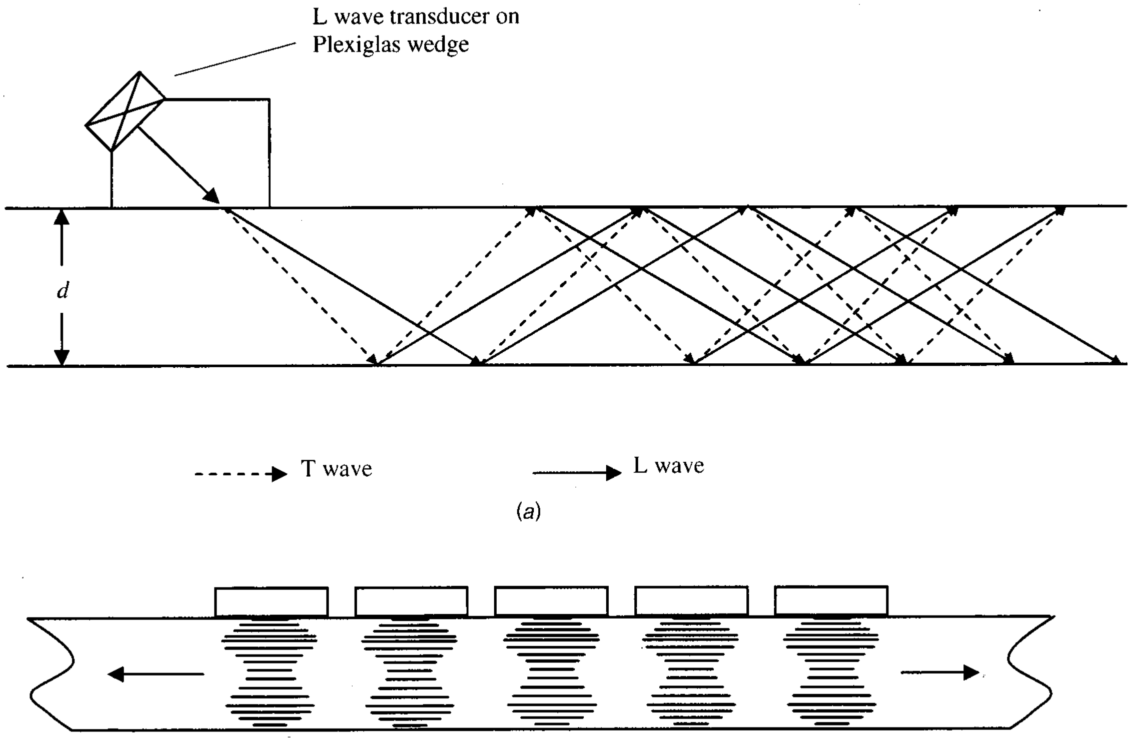


(*a*)

(*b*)

Fig. 1 Techniques for the generation of guided waves—(*a*) oblique incidence, (*b*) comb transducer

exactly the same. It changes from one point to another in phase velocity frequency space. Thus, wave structure must be considered if one were to try to establish maximum penetration power for structures, perhaps under coatings or insulation for example, as well as to establish maximum sensitivity to a defect either on the surface of the structure or at the centerline or elsewhere. A sample wave structure result is presented in Fig. 4, for a three-layer structure. Imagine a substrate bonded to a substrate. What mode and frequency could be selected in order to obtain the maximum sensitivity? We can see in this one example that if the sensitivity variable were to be longitudinal power for interface evaluation, as an example, you would select the mode and frequency illustrated in Fig. 4(*a*). If only the substrate were of importance for any defect analysis, the mode and frequency illustrated in Fig. 4(*b*) could be selected.

The ability to utilize the various wave structures that affect penetration power and sensitivity in a guided wave inspection is related to an ability to get onto a dispersion curve at a particular phase velocity and frequency test zone. Two mode excitation zone possibilities are shown in Fig. 5. In this case, a sample problem of pipe inspection is considered as discussed in references [26,27]. A variable angle beam probe is shown on the pipe, whereby energy refracted into the structure can have its phase velocity calculated by way of Snell's law. For each particular angle there is a horizontal activation line on the dispersion curve. By sweeping frequency then, it becomes possible to activate the modes illustrated in Fig. 5 along the horizontal line. On the other hand, if comb transducer excitation were selected, like that also shown in Fig. 5, spacing would determine the slope of the activation line on the dispersion curve. The slope is shown for a particular spacing, whereby sweeping frequency now moves along the sloped line from the origin as illustrated in the diagram. In this case the modes are excited in a different order. It becomes possible to change the slope by changing the spacing or by using some time delay profiling for the comb elements. Quite often an experimental search process calling for a tuning procedure of phase velocity and frequency would be required to detect the flaws of interest. This is because of the wave resonances that can be established between transducer and flaw, which depends strongly on the particular defect characteristics and size. The response function from a defect varies with frequency.

Let us now briefly consider some of the benefits of guided waves. The major benefits are clearly outlined in Table 1. Another concept worth considering at this point is related to the benefits of a comb transducer. Some of these benefits are summarized in Table 2. They again are self-explanatory.

Sample Problems

It is convenient to consider guided wave inspection over natural wave-guides that have portions of the structures hidden or in difficult to access situations. A few natural wave-guide examples are presented in Table 3. Let us consider a few possibilities currently receiving some attention. A rail is a natural wave-guide. Some work is reported in [37] that makes use of train-generated ultrasound traveling down the track over long distances, whereby reflections from broken rail can be determined by way of sensors placed on the rail or on the train itself. The rail has natural filtering characteristics and its own dispersion curve with respect to the kinds of waves that can travel in the rail.

Another interesting example is for boiler tube inspection over long distances, where access from only one side is possible. Transducers must be placed over the surface with less than 180 deg circumferential loading. Some techniques have been developed recently on nonaxisymmetric wave propagation making use of flexural modes that show how it becomes possible to place a transducer on one side of a tubular structure and yet be able to inspect the far side. This technique is being exploited to develop practical guided wave inspection techniques for many problems, in this case for a boiler tubing panel. A theoretical result showing how flexural modes can propagate along a pipe configuration is illustrated in Fig. 6. Imagine loading over only 180 deg where ultrasonic energy travels over a pipeline, let us say from 0 to 8 m. We are considering the out-of-plane displacement profile on the surface of the pipe in this example, in order to determine the sensitivity of finding corrosion or defects close to the surface of the pipe as you travel along the pipeline. In the diagram, you can see that for this one particular value of frequency and phase velocity, the initial distribution at 0 m is energy concentration primarily only in the contact zone; but as you travel along the structure, you can see that at 8 m, because of the interference process, the energy is totally contained on the far side of the structure. This shows how a transducer on one side of a pipe can be used to inspect the far side of the pipe. Obviously, by changing frequencies, modes, and degrees of partial loading it becomes possible then to carry out a complete inspection of the pipe along its length, even with much of the pipe hidden.

Many problems in the aircraft industry have also been considered that make use of guided wave inspection. A test protocol and sample result for a lap splice inspection on an aircraft is illustrated in Fig. 7. Some of the aircraft examples come from references [34] and [36]. The guided wave inspection approach here appears fairly straightforward, the idea being to consider ultrasonic energy traveling across the test joint from position one to position two. The difficulty that comes about, though, is that the right mode and frequency must be selected that allows energy to leak from substrate one to substrate two. If the wrong mode and frequency is selected, a false alarm is obtained, energy reflects back to position one and never reaches the receiver at position two. A tuning process of phase velocity and frequency can make this test successful. Another example on a tear strap inspection can be considered. Again, the proper mode and frequency must be selected that allows leakage of ultrasonic energy into the tear strap. Speaking of natural wave-guides, consider now the skin of an F-18 Naval aircraft. Several problems have been studied with guided waves; one in particular is related to the tail rudder assembly. A C-scan test is often conducted. In order to run a C-scan test, the entire rudder must be disassembled, removed from the aircraft, placed in a bubbler or squirter scanning tank, calling for several days of down time of the aircraft just to carry out the inspection. On the other hand, a guided wave technique could be used to look at points on a random fashion, that could easily tell skin delamination from good areas of the rudder. The test is fast. No down-time is required of the aircraft. The adhesive bond inspection process between skin and core has details that are expanded in references [34–36]. The techniques are straightforward, again though, pointing to a reasonable tuning process so that the proper modes and frequencies are selected to allow energy to leak to the core if a good bond exists.

Another aircraft inspection problem currently studied is for sections of the transmission beam of an H-60 helicopter. Crack propagation in the transmission beam is being studied with guided waves. Small leave-in-place comb-type transducers are placed on the structure at critical positions, whereby, after so many flights, a lunchbox-type PC computer with a simple Berg connector can be taken to the rotor craft, and hence inspection and data recording carried out immediately.

Continuing on with some of the benefits and potential applications of guided wave analysis, consider a pipe elbow. In order to send ultrasonic energy along a pipe, through an elbow, and to be able to inspect in the elbow region or beyond the elbow region, is quite difficult. If an axisymmetric wave is placed into the structure, blind spots could occur because of the interference patterns that occur as the wave travels around the elbow region. As reported in [38], however, if a series of probes were placed around the circumference at one end of the pipe using phased array technology, it would now become possible to control the flexural mode input, that now actually adjusts the focusing mechanisms inside that elbow and beyond to be able to focus on any point that you wish inside the entire structure, hence making defect detection and location analysis possible. This is particularly useful if sections of the elbow and pipe are totally hidden, or inaccessible by any transducer assembly.

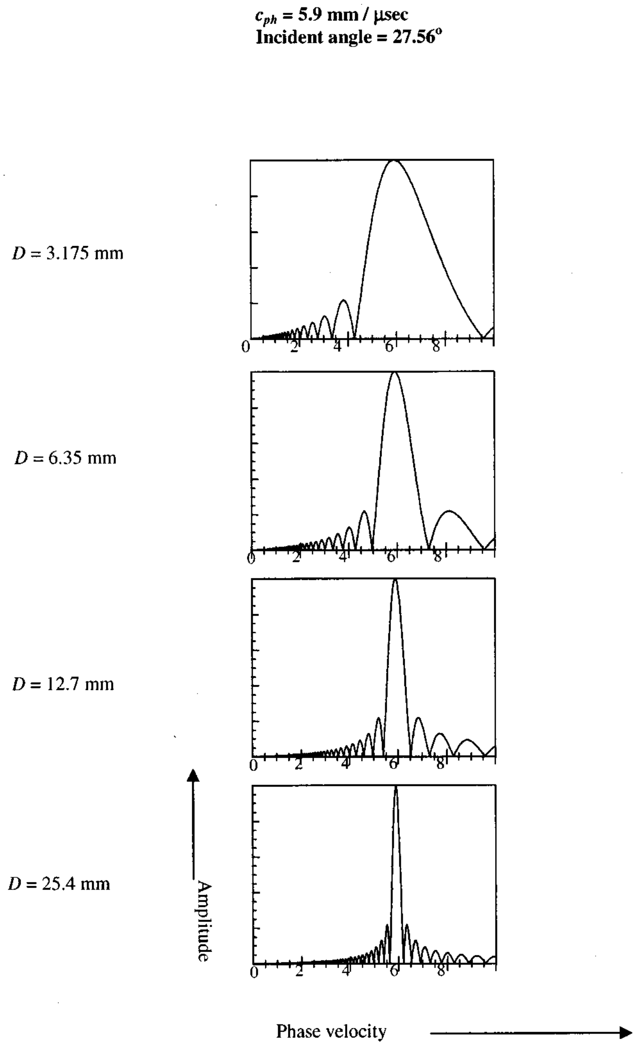


Fig. 2 Sample phase velocity spectra showing excitation amplitude versus phase velocity (frequency=4.3 MHz, bandwidth =.6 MHz)

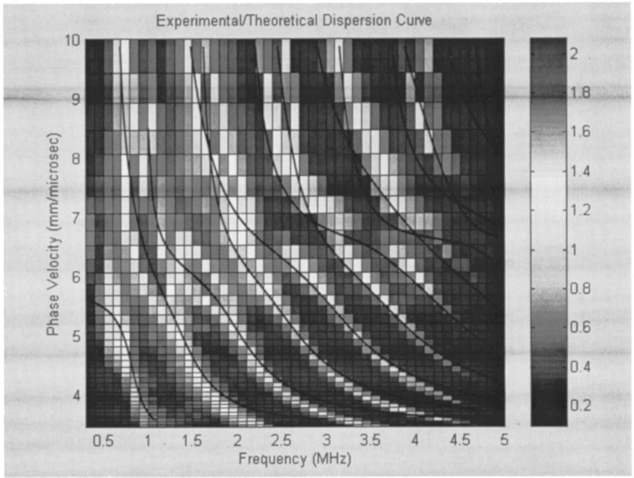
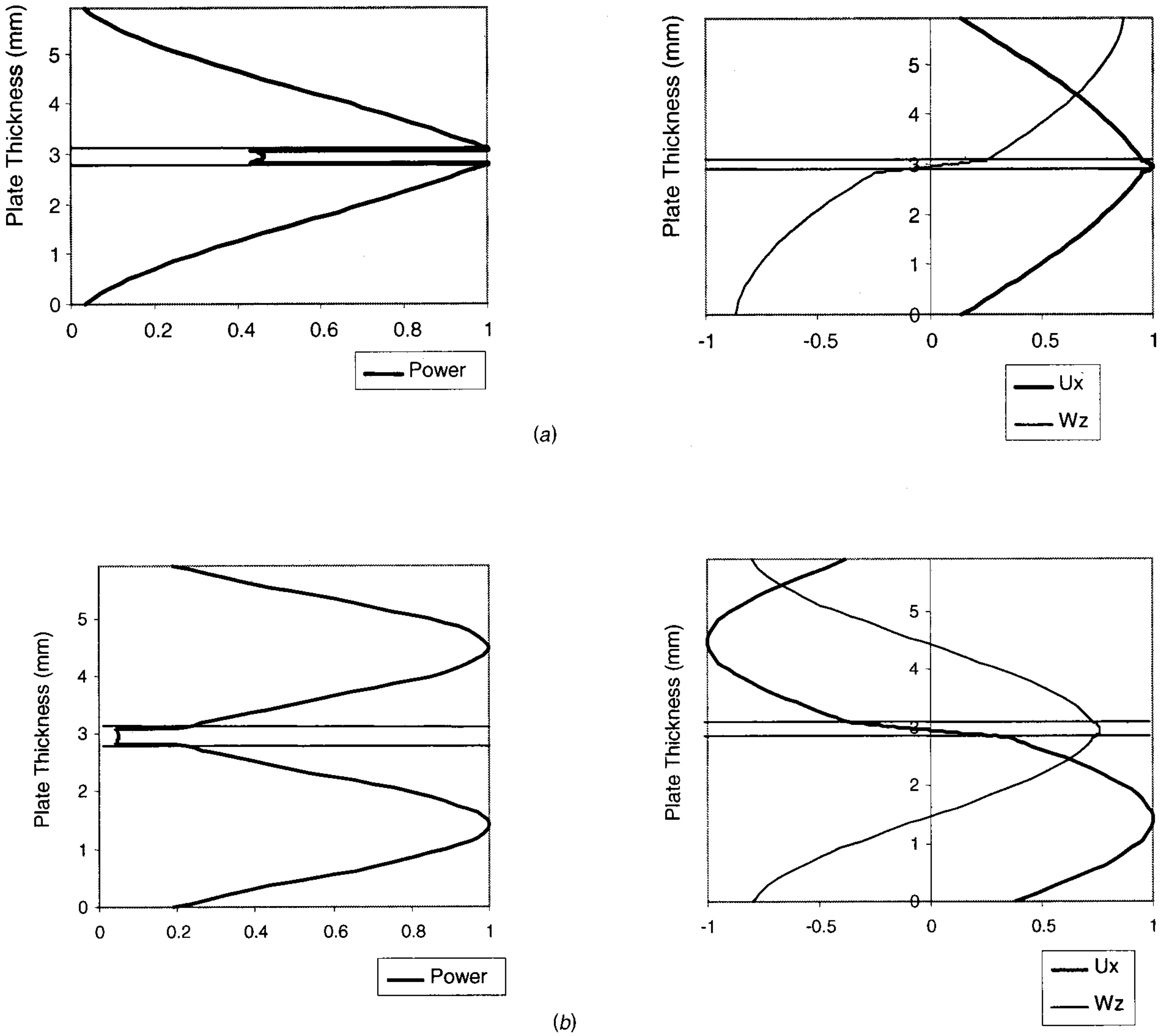


Fig. 3 Experimental versus theoretical results for a traction-free aluminum plate (showing source influence)



(*a*)

(*b*)

Fig. 4 Sample power distribution and wave structure results taken for U_x in-plane displacement, and W_z, out-of-plane displacement from specific points on a dispersion curve: (*a*) $f=0.293$ MHz, $C_p=4.48$ km/s; (*b*) $f_f=0.664$ MHz, $C_p=4.85$ km/s

Another very interesting application of guided wave analysis can be considered for a containment structure, where steel is embedded in concrete. To remove the concrete to carry out the inspection is tremendously expensive. It has been done in the past. Now with guided wave inspection, it becomes possible to send ultrasonic energy along the steel plate with minimal leakage into the concrete, allowing us to locate corrosion and cracking in the steel plate. A horizontal shear wave EMAT technique is presented in [32].

Another important problem in the power generating industry, and also for underground gas pipe inspection, is to create an opportunity to be able to inspect structures under tar coating. Guided waves make this possible. Again, it is very expensive to remove the tar coatings to carry out the inspection on a point-by-point basis. Guided waves, on the other hand, can be used to send ultrasonic energy under the coating by adjusting wave structure across the thickness of the structure. The tuning and selection of the appropriate frequency and phase velocity makes this possible. Both Lamb waves and horizontal shear wave EMATS are being considered in this work.

A great deal of work is currently being carried out on the development of pipe inspection gear that can actually travel through pipe lines at reasonably high speeds and to be able to carry out a reliable inspection. One such device being considered is associated with magnetic flux leakage in addition to a utilization of circumferential guided waves for defect sizing. Primary development of these efforts is moving forward by way of the Gas Technology Institute.

Many other guided wave inspection possibilities exist. Scanning acoustic microscopy is used to obtain close-to-the-surface information by using leaky guided waves along the surface of the structure. Much effort today is also being focused on a Lamb guided wave tomographic inspection. Some pioneering work efforts on the tomographic test techniques are presented in [17].

Another interesting problem is on titanium-to-titanium diffusion bonding; see [28]. Even though amplitude itself is a poor feature for solving problems, amplitude ratios are traditionally known as an excellent feature. In the sample problem illustrated here, two modes are actually produced in the titanium diffusion bonding experiment. One of the modes is sensitive to the poor bonds and one is not. Therefore, by simply examining the amplitude ratio of the two modes it becomes possible to classify the structure as good, intermediate, or a poor bond.

Much interest in guided wave analysis is now focused on defect sizing analysis. A sample very promising BEM result for SH

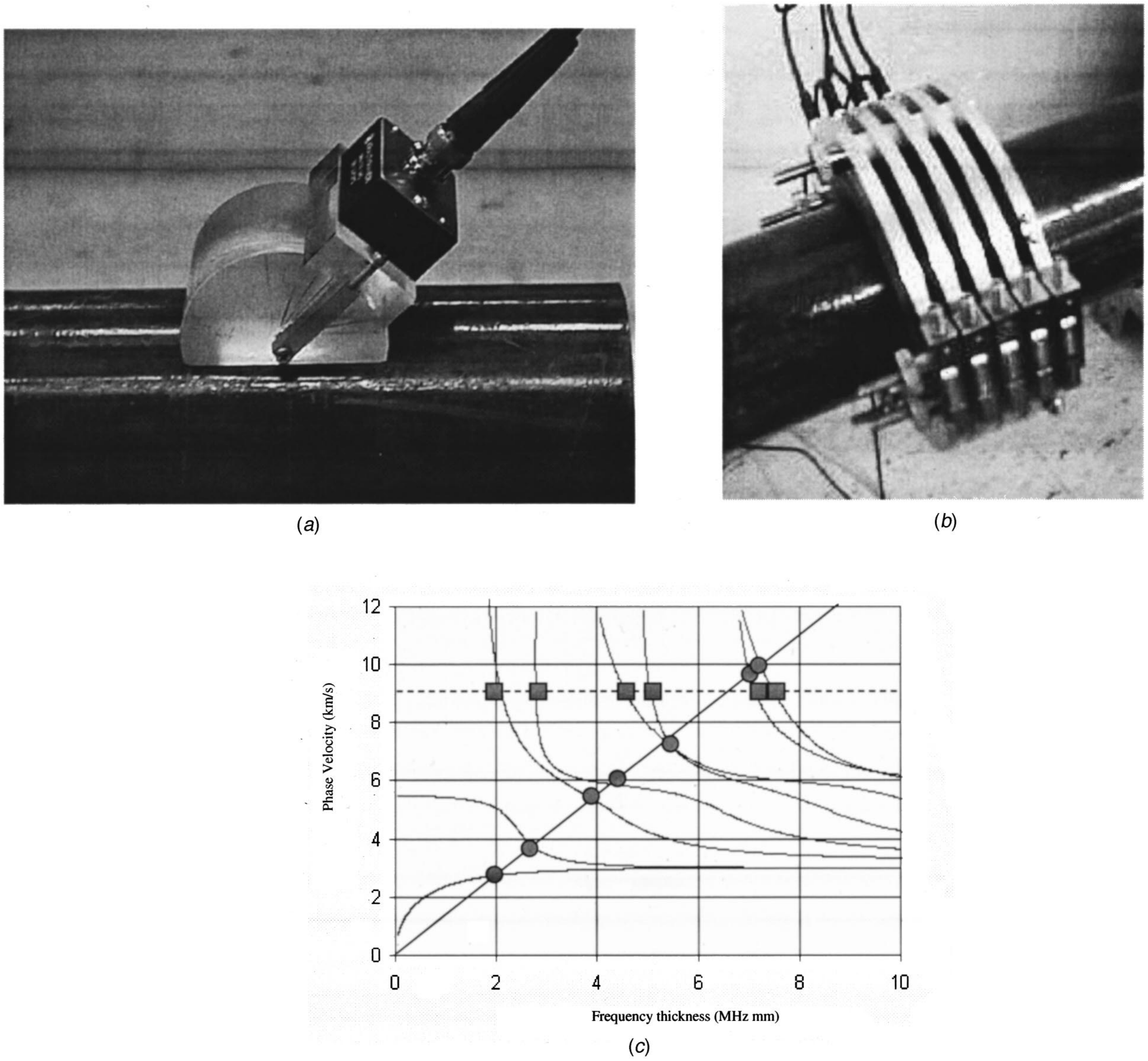


Fig. 5 Lamb wave mode activation possibilities—(*a*) angle beam probe, (*b*) comb probe, (*c*), mode excitation zones. (Angle beam shoe-constant phase velocity (horizontal line) determined from Snell's law for a given angle. Comb transducer excites modes with a constant wavelength (sloped line) determined by the spacing of the elements.)

Table 1 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 potential**
- **Sensitivity often greater than that obtained in standard normal beam ultrasonic inspection or other NDT techniques.**
- **Ability to inspect structures under water, coatings, insulation, multi-layer structures or concrete with excellent sensitivity.**
- **Potential with multi-mode and frequency Lamb type, Surface or Horizontal Shear waves to detect, locate, classify and size defects.**
- **Cost effectiveness because of inspection simplicity and speed. (Often less than 1/20 the cost of standard normal beam ultrasonic and other inspection techniques.)**

Table 2 Benefits of a comb transducer

- Can produce surface and guided waves in any structure and material including low wave velocity composite materials.
- Mode and frequency tuning and the establishment of “wave resonances” for optimal defect detection sensitivity is possible.
- Reduced energy loss compared to angle beam techniques.
- Higher frequency excitation for improved sensitivity and resolution is possible compared to angle beam techniques.
- Simple manufacture techniques are available utilizing broad band piezocomposites or PVDF film.
- Smaller size and flat low profile transducers, compared to angle beam techniques, are possible that are useful in hard to access places.
- Can be robust and compact

Table 3 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

waves is shown in Fig. 8, taken from [39]. A monotonic increase in reflection factor amplitude is shown over the entire frequency range considered. This is possible because of less mode conversion compared to that in Lamb wave studies.

Countless other examples as you extend your imagination into the world around you can be tackled with guided wave inspection technology. The sensors, the instrumentation, the software, and the basic physics and wave mechanics are available now to allow

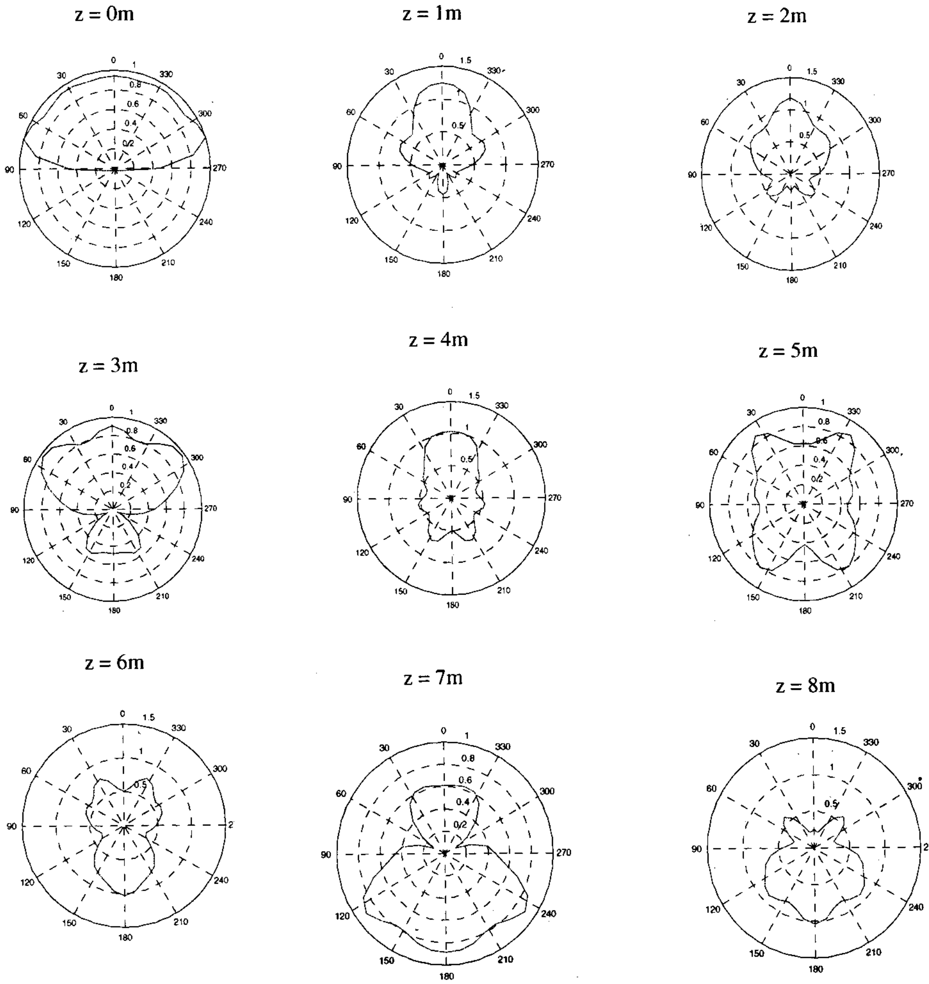
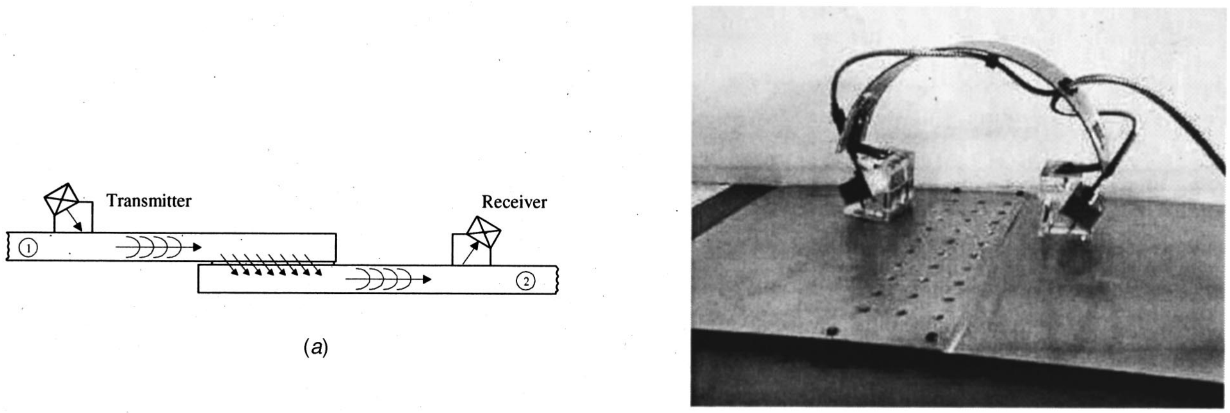


Fig. 6 Nonaxisymmetric wave circumferential displacement distribution (circum. angle =180 deg, freq.=0.39 MHz, modes: $L(0,1)-F(10,1)$, wall thickness=5/16 in.)



(a)

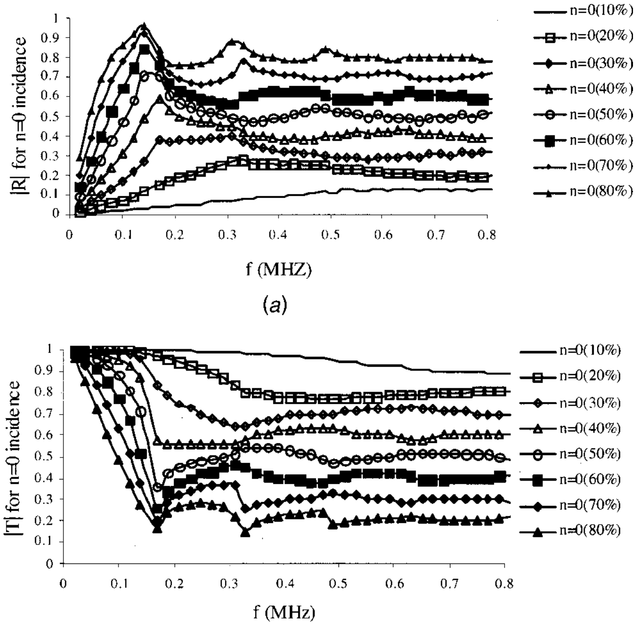
(b)

Fig. 7 A lap splice inspection sample problem—(*a*) ultrasonic through-transmission approach for lap splice joint inspection, (*b*) double spring "hopping probe" used for the inspection of a lap splice joint

us to advance the state of the art and to benefit from all of the advantages possible with guided wave inspection.

Concluding Remarks

Technology transfer efforts of many of the problems discussed in this paper will continue. Future directions will include miniature leave-in-place sensors complete with appropriate components for data recording and analysis as well as antennas for wireless activation. Phased array tuning to generate all sorts of guided waves will become available. Sophisticated software will become available to establish appropriate wave resonances via phase velocity, frequency, and mode-type tuning. Automated defect detection and location analysis will lead the way, followed by sophisticated computational and artificial intelligence algorithm development for defect classification and sizing analysis.



(a)

(b)

Fig. 8 Reflection (*a*) and transmission (*b*) coefficients for *n* = 0 mode under *n* = 0 incident mode for 0.012 in. elliptical defect width (notch) and 10, 20, . . . 80% through-plate thickness depth

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