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PRACTICAL LONG RANGE GUIDED WAVE INSPECTION - APPLICATIONS TO PIPES AND RAIL

Peter Cawley

Department of Mechanical Engineering, Imperial College, London SW7 2BX, UK

SUMMARY

The inspection of large structures using conventional ultrasonic bulk wave techniques is slow because scanning is required if the whole structure is to be tested. Ultrasonic guided waves potentially provide an attractive solution to this problem because they can be excited at one location on the structure and will propagate many metres. However, guided wave testing is complicated by the presence of many possible wave modes, most of which are dispersive. These guided wave characteristics offer a wealth of opportunities for the extraction of information about the structure, but it is crucial to manage this complexity if the test is to be useable in industrial practice. This paper concentrates on long range testing using frequencies below 100 kHz. The progress from research work to a robust, commercial pipe testing system will be discussed, together with more recent research on applications to plates and railroad rails. The paper concludes with a discussion of future research opportunities.

INTRODUCTION

Guided waves of different types can propagate in any bounded medium and include the well-known Rayleigh (surface) waves on a half-space and Lamb waves in plates. Similar types of wave can propagate in rods, cylinders and elongated structures which are not axially symmetric such as railroad rails and I-beams. The use of guided waves in NDE has been discussed for over 40 years, Worlton [1] being one of the first to recognise their potential. The textbook by Rose [2] gives an introduction to the theory and application of guided waves and the same author has recently discussed the history and potential of this type of inspection [3].

Guided waves can be used in three regimes, each of which has been extensively researched: short range (<<1m), medium range (up to about 5m), and long range (up to around 100m). The short range methods include high frequency surface wave scanning (see, for example, the use of Rayleigh waves for the detection of small surface defects in artillery shells discussed by Thompson [4]), leaky Lamb wave inspection of composite materials [5] and acoustic microscopy [6] in which a leaky surface wave is generated by the lens. Medium range testing typically uses frequencies in the 250 kHz - 1 MHz range and has been applied to plate, tube and pipe testing [4, 7-11], weld inspection [12], aircraft lap joints [13], and even to ice detection on aircraft [14]. This paper concentrates on long range testing which generally requires the use of frequencies below 100 kHz. However, the boundary between medium and long range testing is somewhat blurred and many of the issues raised in this paper are relevant to both areas. In addition to the technology generated by the Imperial College group, examples of which are given below, the South West Research Institute has also had a long term interest in this field [15-17].

The main attraction of long range guided wave inspection is that it enables a large area of structure to be tested from a single transducer position, so avoiding the time-consuming scanning required by conventional ultrasonic or eddy current methods. The technique becomes even more attractive if part of the structure to be tested is inaccessible, for example a pipe passing under a road. The test is usually done in pulse-echo mode, the transducer transmitting the guided wave along the structure, and returning echoes indicating the presence of defects or other structural features.

Unfortunately the ratio of the number of practical applications of guided waves to the number of research papers in the area is rather small. This paper discusses the reasons for this and describes how the difficulties may be overcome so that the potential of the technique can be realised. This is followed by practical examples of pipe, railroad rail, plate and embedded tendon inspection, and the paper concludes with a review of future research and development directions.

THE PRACTICAL PROBLEMS - COHERENT NOISE AND DISPERSION

The main difficulty with medium and long range guided wave inspection is that it is very easy to obtain signals like that shown in Fig 1a. This shows the pulse-echo signal produced on a length of plain pipe by a group of transducers covering a quarter of the pipe circumference and connected in parallel so that they effectively act as a single transducer. Ideally the signal should contain two distinct echoes from the two ends of the pipe rather than the very complicated trace seen in the figure. The complication arises from the excitation of multiple modes which travel at different velocities in both directions, and these velocities being in general a function of frequency (i.e. the modes are dispersive). Fig 2a shows the dispersion curves for a 6 inch diameter, schedule 40 steel pipe. There are about 50 modes present at frequencies below 100 kHz and many of them are strongly dispersive. Fig 2b shows the corresponding diagram for a plate. Here the group velocity is plotted as a function of frequency-thickness product and below about 1.6 MHz-mm only three modes are present (a_0, s_0 and SH_0). Therefore in a 10 mm thick plate there are only 3 modes present below 160 kHz. Mode control is therefore easier in a plate than a pipe but other problems are more difficult, as will be discussed later.

Fig 1b shows a clearer signal obtained at an early stage in the development of the pipe screening system discussed later. Reflections from two welds approximately 15m apart in a long pipe can clearly be distinguished. However, there are many smaller signals between the two weld echoes which should not be present since this was a new pipe. Averaging did not improve the signal, indicating that the problem is coherent, rather than random, noise. The welds are approximately -14 dB reflectors and the coherent noise level is about 10 dB below the weld echoes indicating that the signal to coherent noise ratio is between 20 and 25 dB. However, the target reflection size in this application was -26 dB so the system needed further refinement to reduce the noise. The coherent noise has two main sources:

- the excitation and reception of unwanted modes;
- the transmission of waves in the opposite direction along the pipe and the reception of echoes from that direction.

The key to controlling coherent noise is therefore to excite and receive a single mode in one direction. The choice of mode will be influenced by the ease of exciting it while minimising the excitation of other modes, and by its sensitivity to the defect type(s) of interest. In addition to controlling coherent noise, it is also necessary to control dispersion. If the chosen mode is dispersive, the different frequency components in the signal travel at different velocities so the signal duration increases which compromises the spatial resolution (the ability to distinguish echoes from closely spaced reflectors). Dispersion is not very evident in Fig 1b since it was controlled by applying narrow band excitation centred on a region where the mode of interest is non-dispersive. This strategy to

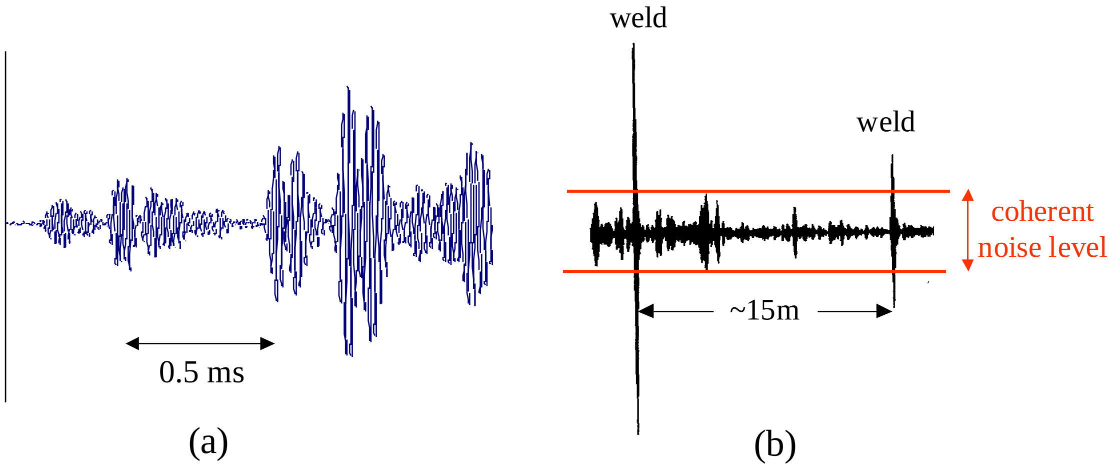


FIGURE 1. (a) Signal received on length of plain pipe using transducers over quarter of circumference; (b) signal received on welded pipe in early site test.

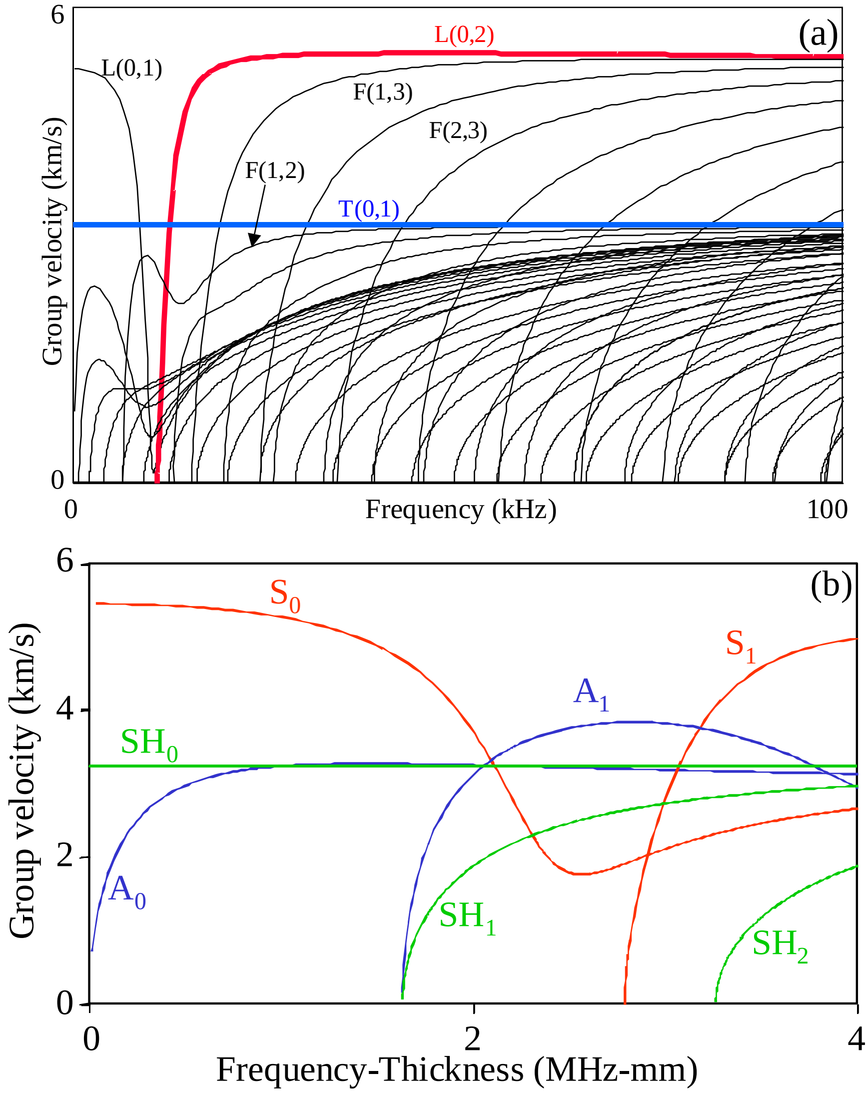


FIGURE 2. Dispersion curves for (a) 6 inch, schedule 40 steel pipe; (b) steel plate.

overcome dispersion problems is often sufficient, though dispersion compensation [18] can also be valuable.

CONTROLLING COHERENT NOISE

In medium range testing, mode control is usually achieved by choosing an appropriate transducer and excitation signal. Fig 3a shows a schematic diagram of an EMAT (electro-magnetic acoustic transducer) which generates a wave in the structure via the Lorentz force and/or magnetostriction [19, 20]. A narrow band signal (typically a few cycle toneburst) is applied to the meander coil and the current flows in opposite directions along successive limbs of the coil, so producing force in opposite directions. Therefore the spacing between the limbs of the coil controls the dominant wavelength of the excited wave. Hence a chosen mode can be excited by tuning the frequency, f, to the point on its dispersion diagram where the phase velocity is given by

$$c_p = f\lambda \tag{1}$$

where λ is the wavelength imposed by the EMAT. Direction control can be achieved by employing a second coil overlapping the first but displaced from it along the structure by a quarter wavelength. If the two coils are excited with the same signal, it may readily be shown that the waves generated in one direction interfere constructively, while in the other direction the interference is destructive. It is also possible to use a segmented coil [20].

Mode control can also be achieved with piezoelectric excitation as shown schematically in Fig 3b. Here the transducer is oriented at an angle θ_ι to the structure and directs compression waves towards the structure via a coupling medium (often a plexiglas wedge). By the coincidence principle [21] the wavelength of the wave generated in the structure, λ_p, is related to the wavelength of compression waves in the coupling medium, λ_c, by

$$\lambda_p = \frac{\lambda_c}{\sin\theta_i} \tag{2}$$

where θ_i is the angle of incidence. Hence, the phase velocity in the structure is given by

$$c_p = \frac{v}{\sin\theta_i} \tag{3}$$

where v is the velocity of compression waves in the coupling medium. Therefore a chosen mode at a particular excitation frequency can be excited by orienting the transducer to the appropriate angle. The direction of propagation along the structure can be reversed by orienting the transducer at $-\theta_i$.

It is important to use a transducer which forces the structure in the most appropriate direction. For example, at low frequency the s_0 mode in a plate involves predominantly in-plane motion, while the a_0 mode is predominantly out-of-plane. It is therefore very difficult to obtain a satisfactory ratio of s_0 to a_0 signal by using a transducer such as a piezoelectric transducer on an angle wedge because it applies an out-of-plane force to the structure surface; if the s_0 mode is to be used in this regime, an EMAT designed to apply an in-plane force is preferable. The issue of mode excitability is discussed further in [22].

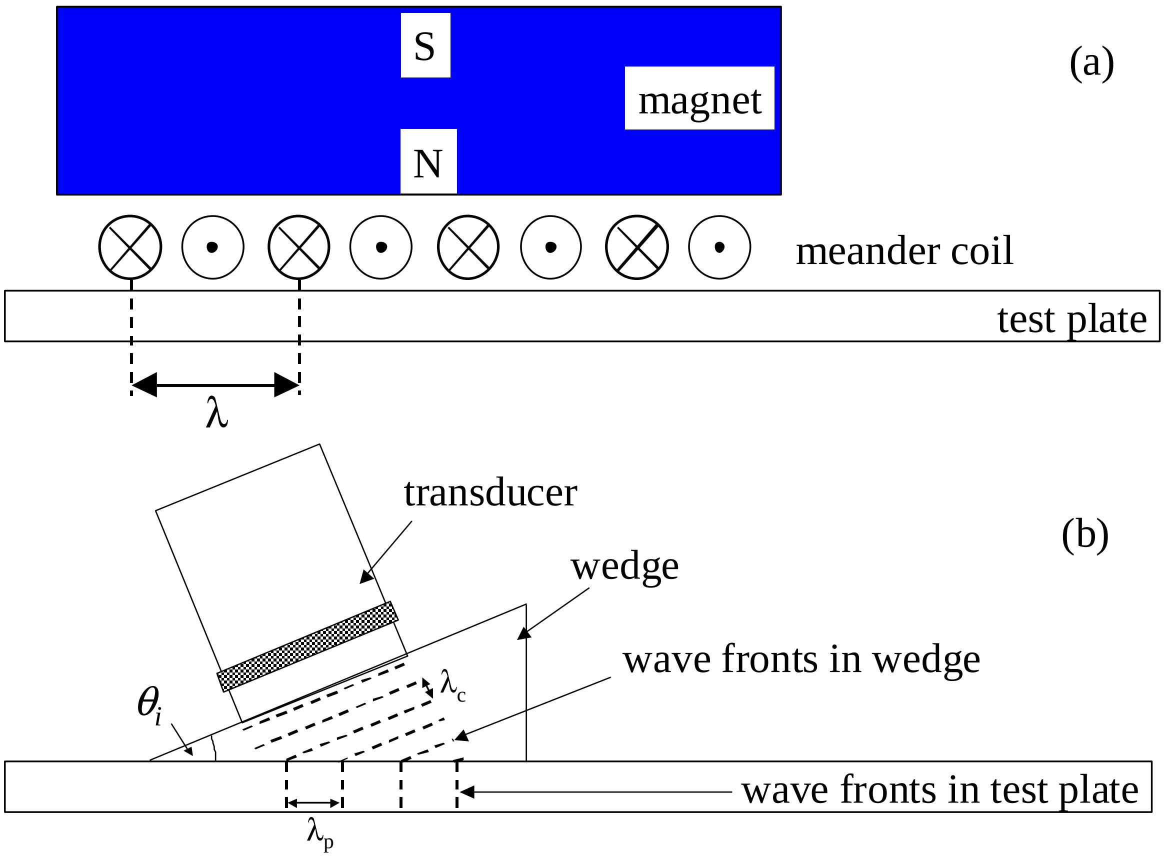


FIGURE 3. Schematic diagram of excitation of guided waves by (a) EMAT; (b) piezoelectric transducer on wedge.

FIGURE 4. Solid transducer assembly for 8 inch pipe showing array of dry coupled piezoelectric transducers.

The degree of modal selectivity obtained is governed by the size of the transducer and the excitation signal. The transducer size controls the effective wavelength bandwidth (with the EMAT) or the effective phase velocity bandwidth (with piezoelectric excitation), while the excitation signal governs the frequency bandwidth. This is discussed further in [21, 23-25]. In order to obtain satisfactory mode control, the transducer generally has to be a round 3-5 wavelengths long. For a mode with a phase velocity of 3 mm/µs, the wavelength is 6 mm at a frequency of 500 kHz so the required transducer size is modest. However, if the frequency is reduced to 50 kHz, the wavelength increases to 60 mm and the required transducer size becomes impractical. Therefore in long range testing an alternative to single, monolithic transducers must be sought and it has been found that an array of point sources is very attractive in several applications, as discussed below.

If an array is used, satisfactory mode control requires that the direction of the force applied by the individual elements is appropriate for the desired mode, and that the individual array elements have good gain and phase consistency. Signal processing makes an important contribution to extracting the desired input mode - received mode combination from the array and rejecting other combinations, so improving the signal to coherent noise ratio; this is discussed further in the examples below. It is also potentially possible to subtract a baseline signal obtained at an earlier stage in the life of a structure from the current signal in order to track changes. This is particularly applicable in 'smart structure' applications where the transducers are permanently attached, but the operation is not straightforward since, for example, temperature changes or small, unimportant changes in material properties with age will affect the dispersion relationships, and hence the received signals.

EXAMPLES

Pipe testing

The safe operation of petrochemical plant requires screening of the pipework to ensure that there are no unacceptable levels of corrosion. Since a significant proportion of industrial pipelines are insulated, this means that even external corrosion cannot readily be detected without the removal of the insulation, which can be prohibitively expensive. A quick, reliable method for the detection of corrosion under insulation (CUI) which does not involve removal of all the insulation is therefore required. The problem is even more severe in cases such as road crossings where the pipe is underground (often in a sleeve) for a limited distance; excavation of the pipe for visual or conventional ultrasonic inspection is extremely expensive so a technique to address this problem is particularly beneficial.

The Imperial College NDT group, and latterly the spin-out company Guided Ultrasonics Ltd, have developed a guided wave technique designed for the screening of long lengths (>10m) of pipes for corrosion. It seeks to detect corrosion defects removing of the order of 5-10% of the cross sectional area of the pipe at any axial location. It was originally developed for use on pipes in the 2-24 inch diameter range, though it can be used on both smaller and larger pipes; there have been recent applications to 36, 48 and 52 inch lines.

The most attractive modes to use are those which have a mode shape which has uniform stress over the whole cross section of the pipe. This means that there will be equal sensitivity to cross section loss at any location through the wall thickness or round the circumference. Modes with a simple mode shape are also easier to excite in a pure form which is important in controlling coherent noise. The two modes which meet these criteria are the L(0,2) and T(0,1) modes shown in Fig 2a. These are essentially extensional and

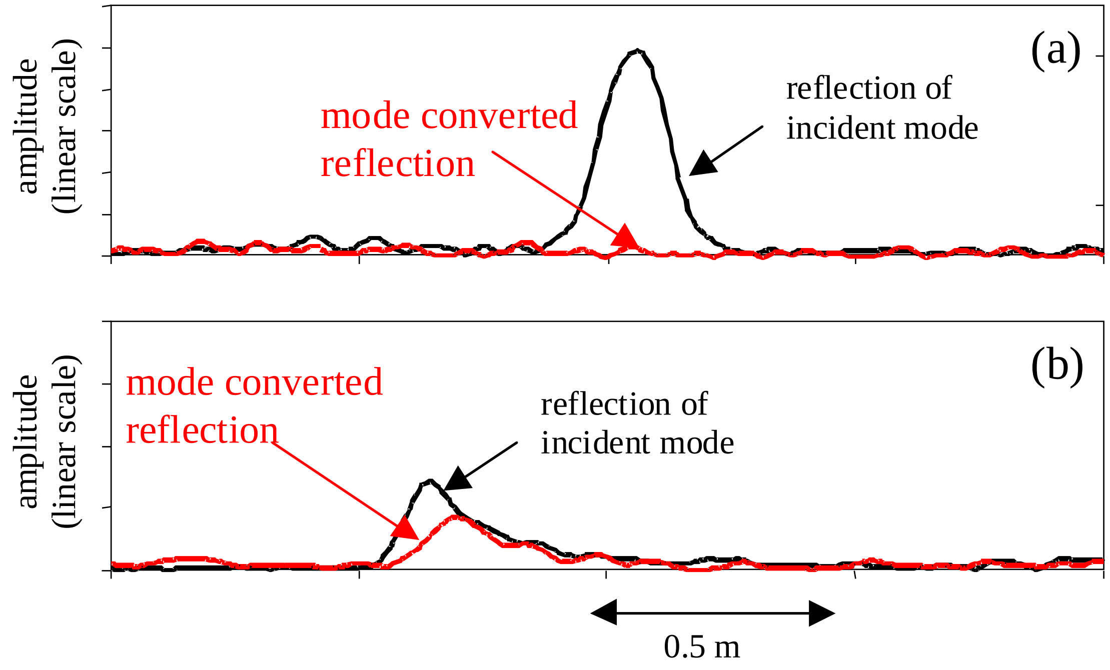
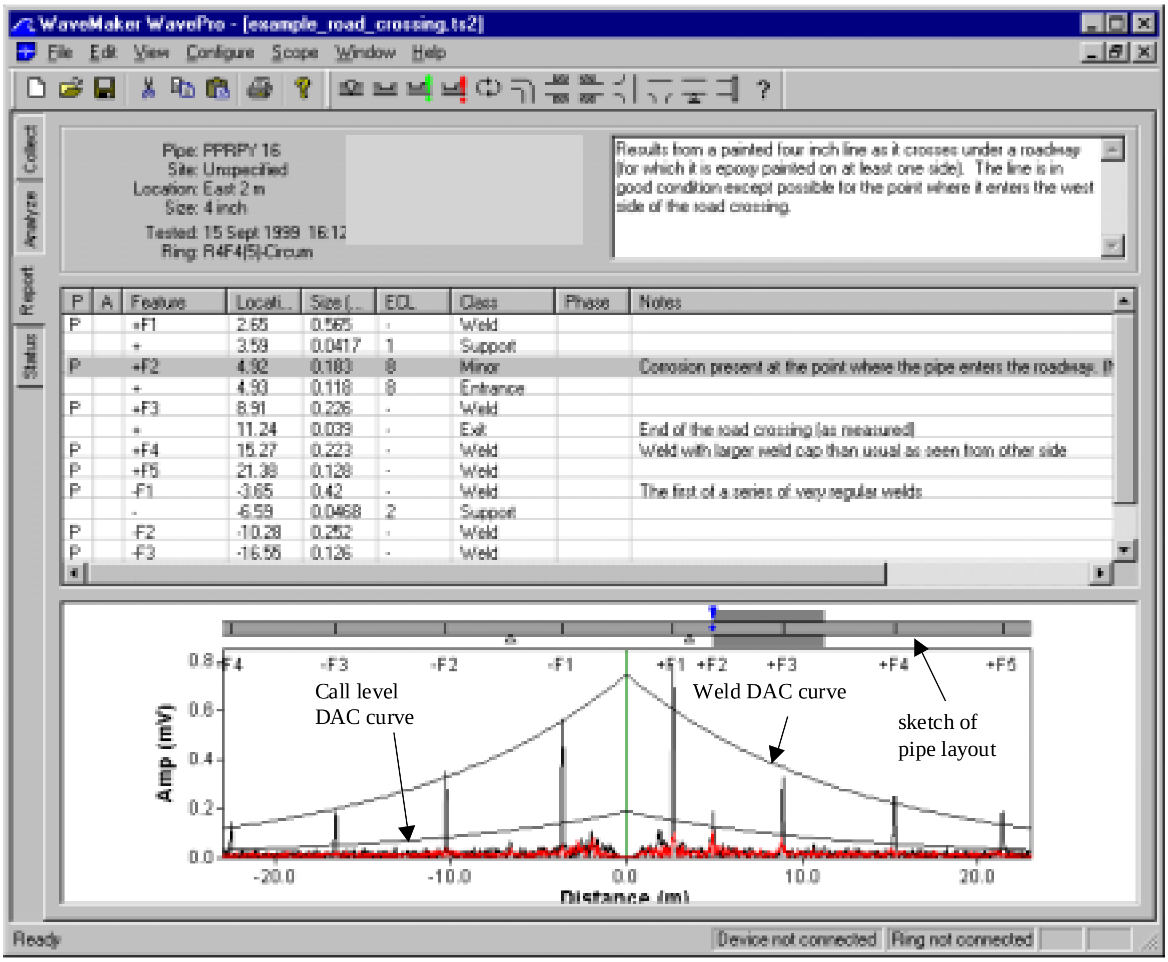


FIGURE 5. Typical signals from (a) axisymmetric feature e.g. weld; (b) corrosion.



Pipe: PPRPY 16
Site: Unspecified
Location: East 2 m
Size: 4 inch
Tested: 15 Sept 1999 16:12
Ring: R4F4(5)-Circum

Results from a painted four inch line as it crosses under a roadway (for which it is epoxy painted on at least one side). The line is in good condition except possible for the point where it enters the west side of the road crossing.

P	A	Feature	Locati...	Size (...	ECL	Class	Phase	Notes
P		+F1	2.65	0.565	-	Weld		
		+	3.59	0.0417	1	Support		
P		+F2	4.92	0.183	8	Minor		Corrosion present at the point where the pipe enters the roadway. It
		+	4.93	0.118	8	Entrance		
P		+F3	8.91	0.226	-	Weld		
		+	11.24	0.039	-	Exit		End of the road crossing (as measured)
P		+F4	15.27	0.223	-	Weld		Weld with larger weld cap than usual as seen from other side
P		+F5	21.38	0.128	-	Weld		
P		-F1	-3.65	0.42	-	Weld		The first of a series of very regular welds
		-	-6.59	0.0468	2	Support		
P		-F2	-10.28	0.252	-	Weld		
P		-F3	-16.55	0.126	-	Weld		

FIGURE 6. Wavemaker Pipe Screening System report from test adjacent to road crossing.

torsional modes respectively. Both modes have the additional advantage of being non-dispersive over a wide frequency band.

Initial site trials of the technique carried out in the research phase in the mid 1990s used the L(0,2) mode at frequencies around 70 kHz [26, 27]. However, there is a second, unwanted, axially symmetric mode with particle displacements primarily in the axial and radial directions, L(0,1). This mode, which has a much lower velocity than L(0,2) in the operating frequency range above 35 kHz as shown in Fig 2a, makes it more difficult to obtain pure mode signals. In contrast, T(0,1) is the only axially symmetric torsional mode in the frequency range of interest, so axially symmetric torsional excitation will only excite the T(0,1) mode. The torsional mode also has the advantage that, in contrast to the L(0,2) mode, it does not involve radial displacement of the pipe wall. Therefore its propagation characteristics are not affected by the presence of liquid in the pipe so in-service inspection of lines carrying a liquid is straightforward.

The Guided Ultrasonics Ltd Wavemaker Pipe Screening System transducer array for an 8 inch pipe is shown in Fig 4. The array comprises two rings of dry-coupled, piezoelectric transducers [28] which apply a tangential force to the pipe surface, so exciting the torsional mode; the two rings of transducers positioned roughly a quarter wavelength apart along the pipe (the precise fraction of the wavelength depends on the test frequency used) enable direction control. The transducer array is connected to the battery-operated testing instrument by a flexible cable; the test is controlled by a portable PC that is connected to the instrument by an umbilical cable. In some cases it is convenient for the operator of the PC to be adjacent to the test location, but on other occasions it is better for the computer and operator to be in a van that can be up to 50m from the test location. Solid rings of the type shown in Fig 4 are manufactured for pipe diameters up to 8 inch, but above this they become bulky so a flexible, pneumatic clamping arrangement is used.

The initial site trials [26,27] showed that corrosion defects of the target size (half wall thickness deep and half pipe diameter (16% circumference) in circumferential extent) could reliably be identified. However, echoes were also seen from butt welds since the weld caps are not generally removed so the weld presents a change in cross sectional area, and hence in effective acoustic impedance. The presence of the echo from a good weld makes it difficult to identify defects at welds, and also introduces the possibility of a weld being incorrectly identified as a defect in cases where the pipe is insulated or buried so the weld cannot be seen. This problem can be overcome by measuring the extent of mode conversion produced by a reflector.

If an axially symmetric mode is incident on an axially symmetric feature in the pipe such as a flange, square end or uniform weld, then only axially symmetric modes are reflected. However, if the feature is non axially symmetric such as a corrosion patch, some non axially symmetric waves will be generated. These propagate back to the transducer rings and can be detected. If the T(0,1) mode is incident, the most important mode conversion is to the F(1,2) and F(2,2) modes. The amount of mode conversion obtained depends on the degree of asymmetry, and hence on the circumferential extent of the defect. The use of an array of transducers facilitates detection of the mode converted signals; if a monolithic transducer (equivalent to wiring all the elements of one ring of the array together) were to be used, the mode converted signals would not be detected since their displacements vary harmonically around the pipe so that the mean displacement is zero. In order to measure the mode conversion it is therefore necessary to access the signals received by individual transducers (or groups of adjacent transducers around the pipe) separately and to add them together in software with the appropriate phase shifts; the principles of this procedure are given in [29].

Fig 5 shows typical reflections from symmetric and asymmetric features; the increase in the mode converted signal can clearly be seen in the asymmetric case and this is a key element of the defect identification scheme. Fig 6 shows an example report generated by the Wavemaker WavePro software for an epoxy painted, 4 inch pipe at a test position adjacent to a road crossing. The test range extends over more than 20m on either side of the rings which are located in the middle of the plot. The software identifies welds and computes a distance-amplitude correction (DAC) curve for the welds. It then calculates the defect call level by comparison with the weld echo level and the calculated output amplitude, knowing that an average site weld is a -14 dB reflector. The received axisymmetric signals are shown as a black curve while the non-axisymmetric, mode converted signals are shown as a red curve. The echo identified as +F2 is the only one where the red (mode converted) signal is significant compared to the black (reflection of incident mode) signal and this indicates possible corrosion at the entry point to a road crossing.

Further practical examples of the use of the Guided Ultrasonics Ltd Wavemaker Pipe Screening System can be found in [30-32]; another commercial system based on the earlier work [27] is described in [33]. The technique offers the possibility of rapid screening of long lengths of pipework for corrosion and other defects. A test range of 50m (25m in each direction) is commonly obtained from a single transducer position. No surface preparation is usually required and the transducers can be attached in less than 1 minute so long lengths of pipe can be screened in a day. Typical applications are the rapid, full coverage screening of long lengths of pipe. The method is also commonly used for the inspection of difficult-to-access locations such as sleeved road crossings, insulated pipe, wall penetrations and areas where rope access is required.

Rail Testing

Ultrasonic inspection systems that operate in the MHz range have been used for many years for the in-service testing of rail. Two specific areas that can present significant challenges for ultrasonic testing as currently deployed are the detection of smooth transverse/vertical defects and the volumetric examination of alumino-thermic welds. These two areas are of great importance as 39.5 % of rail breaks on the UK rail network operated by Railtrack plc. have been attributed to transverse/vertical defects and a further 22.4 % to faults at alumino-thermic welds [34].

Traditional ultrasonic techniques make use of transducers operating in pulse-echo mode that are applied at 0º (normal incidence) and 70º to the running surface of the rail on the centre line. The normal incidence transducer enables the depth of the rail to be determined and will also detect inclusions, horizontal cracks etc. The 70º transducer is designed to detect cracks running in the transverse direction and it is ideally suited to detecting cracks in a plane at 20º to the vertical and many cracks do run at approximately this angle. There will also be some reflection from truly vertical cracks running normal to the axis of the rail, particularly if they have rough surfaces. A tandem arrangement of a pair of transducers operating in pitch-catch mode may be better suited for the detection of transverse cracks, but it is more complicated to deploy. A serious problem with either method for detecting transverse/vertical defects is that the wave path is often blocked by cracks running close to and almost parallel to the running surface of the rail. In the case of alumino-thermic welds, the large material grain size strongly scatters ultrasonic waves at the frequencies that are used giving rise to high attenuation and reflected signals that are very difficult to interpret.

Guided wave inspection is very attractive in this application as it is particularly sensitive to transverse vertical defects since the waves travel along the length of a rail. Small defects close to the surface will also not mask more severe, deeper, transverse cracks. A further advantage is that at the frequencies used, material attenuation due to grain

FIGURE 7. Prototype rail testing instrument.

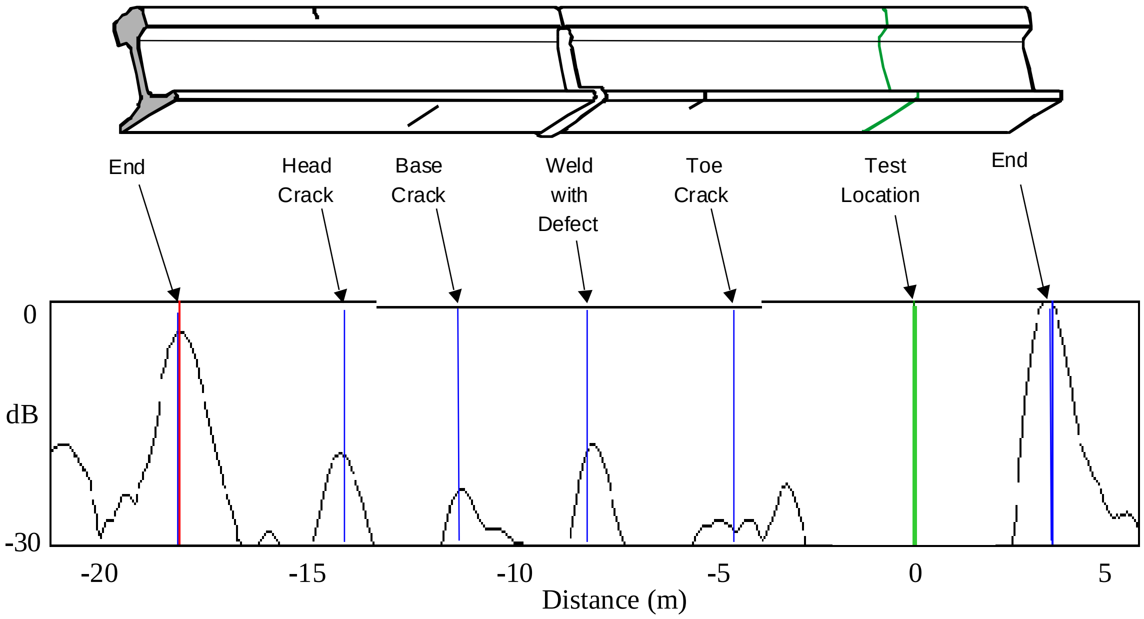


FIGURE 8. A-scan display of results on 20m long section of rail with a variety of artificial defects.

boundary scattering is very low and hence alumino-thermic weld material can be readily penetrated and tested.

Analytical models exist for the exact calculation of the dispersion curves of structures with simple cross sectional geometry such as plates and pipes [35]. However, no such exact model exists for complex profiles such as a rail. Instead, a two-dimensional (2D) finite element (FE) method has been employed to predict the modes-shapes and guided wave characteristics for structures with complex cross sections such as rail [22]. Rail dispersion curves and example mode shapes calculated using this technique are presented in [36]. It is particularly interesting that different modes have energy concentrated in the head, web or foot of the rail, so introducing the possibility of improving the sensitivity to particular locations of defect by appropriate mode choice, and also of determining the likely location of a defect in the cross section.

The Guided Ultrasonics (Rail) Ltd prototype rail testing system is shown in Fig 7. In order to obtain mode and propagation direction control it is necessary to deploy an array of transducers all around the perimeter of the rail (excluding the underside). The individual transducers are similar to those employed in the pipe tester described above and are dry-coupled to the rail using a combined mechanical and pneumatic actuation system. In this case the instrumentation is integral with the transducer assembly so the tester is a single, battery operated unit.

An example display in A-scan format from a 20m length of rail with a variety of defects is shown in Fig 8. All the defects are seen and it is also possible to classify them by measuring the signals obtained in different transmitted mode - received mode combinations. This is made possible by individual addressing of the different transducers within the array. Further details are given in [36].

Plate Testing

At first sight, extending the long range guided wave inspection concept to plates is straightforward since at a given frequency there are fewer modes in a plate compared with a one dimensional structure such as a pipe or rail of similar thickness, and also the maximum propagation distance required is likely to be much shorter. However, the waves can propagate in an infinite number of directions in a plate, whereas they can only travel in two directions in a one dimensional structure. Therefore the main source of coherent noise in plate inspection is waves travelling in unintended directions. This is illustrated schematically in Fig 9 which shows an array testing a simple plate. A large echo will be received from the edge of the plate if a wave is sent from the array in the direction normal to the edge. Unless waves coming from the direction of the edge are perfectly eliminated by the signal processing, there is a danger that 'ghost' reflections will be produced that apparently come from other directions, and may be misinterpreted as defects.

One approach to the problem is to use a transducer such as an EMAT of the type shown in Fig 3a which is several wavelengths wide. This will propagate waves in essentially one direction so the whole plate can be covered by scanning the transducer in the direction normal to the propagation direction [12]; in a strip mill, this scanning can be achieved with a stationary transducer positioned above the steel strip as it moves between the rollers [37]. However, in other cases it is more convenient to have a stationary transducer and to 'look' in different directions across the plate by scanning electronically. This can be achieved by employing an array of point sources [38, 39]. In many cases such as pressure vessels or storage tanks, it will be desirable to test plate-like structures in service when they may have liquid on one side. In this case it is desirable to use a mode such as S_0 or SH_0 which has predominantly in-plane surface displacements in order to minimise energy leakage into the liquid.

Wilcox et al [39] have developed an EMAT array using the s_0 mode at frequencies around 170 kHz for the inspection of plates between 5 and 25 mm thick. The individual EMAT elements comprise a pancake coil with the magnetic field provided by a rare earth permanent magnet. These elements act as essentially point sources (and receivers) of the s_0 mode. The need to avoid side lobes in the processed image sets a minimum spacing between the transducers and this minimum spacing is smaller than the transducer diameter required for efficient transduction. This problem has been overcome by printing the coils on a multi-layered printed circuit board, the coils on different layers overlapping. The array is placed on the plate to be inspected and the test sequence is initiated from a controlling laptop PC. The signal processing applied to the data obtained from the array provides beam steering and wavelength selectivity. The overall effect is to mimic the operation of a monolithic guided wave transducer operating in pulse-echo mode placed at the test location

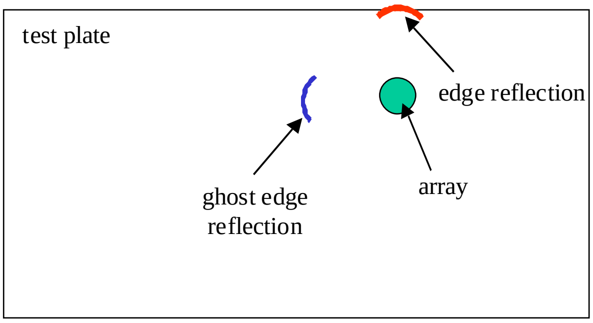


FIGURE 9. Schematic showing potential problem of ghost echoes in plate test.

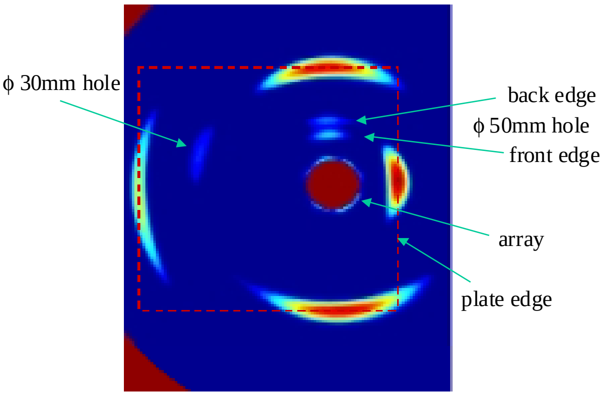


FIGURE 10. Example result on 1m square, 5mm thick aluminium plate.

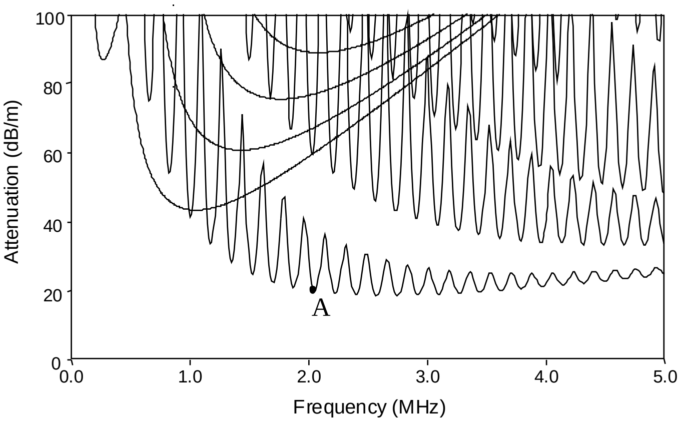


FIGURE 11. Attenuation dispersion curves for axially symmetric modes in 22m diameter steel bar in limestone.

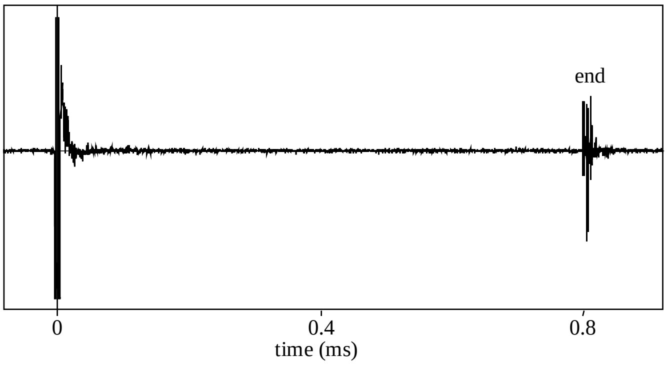


FIGURE 12. Example signal from 2.4m long rock bolt in mine.

and rotated though 360°. The result is an omni-directional B-scan (effectively a C-scan) of the surrounding area of the plate under test. The signals visible in the scan indicate the amplitude and position of reflectors in the plate and include signals from both features (such as edges) and defects.

An example image of a 1m square, 5 mm thick aluminium plate with 30 mm and 50 mm flat bottomed holes machined to half the plate thickness deep is shown in Fig 10. The largest signals are from the four edges of the plate; both holes are clearly seen, the spatial resolution being good enough for the echoes from the front and back of the larger one to be resolved. Further details of the plate tester with results on larger plates are given in [39]. The range obtainable from a single array position is likely to be of the order of 5-10m in all directions and the test time is less than one minute so very rapid coverage of large areas can be obtained.

Rock bolt testing

The system of mine roof support known as rock bolting is increasingly used to reinforce coal mine roofs in the UK and elsewhere, as it offers considerable safety and productivity improvements over the use of conventional steel framework. Rock bolts are steel studs that are fixed into the roof to prevent the movement and expansion of rock strata, hence improving the stability of the roof. There is a considerable amount of strata movement data available to predict the condition of rock bolts, but there is currently no effective non-destructive test. Standard rock bolts for this application are 21.7mm in diameter, and up to 3 meters long. The installation procedure involves pre-drilling the roof with an oversize hole, which is then filled with fast-setting epoxy resin capsules. A portable installation machine is used to spin the rock bolt into the hole, which causes the epoxy bags to puncture and the resin and hardener to be mixed. After curing, a nut and plate assembly is driven up the bolt and into contact with the roof.

When rock strata above the mine tunnel move there is a danger that the rock bolts will be deformed or broken so the main inspection requirement is to measure the length of the bolt. This is very straightforward with a free bolt in the laboratory since a compression wave transducer coupled to the end of the bolt will send a cylindrical guided mode along the bolt and the length of the bolt can be estimated from the time at which the first end reflection is received. However, when the bolt is embedded in rock, there is severe leakage of the guided wave energy into the surrounding rock so the guided wave attenuation is very high which limits the propagation distance. Fig 11 shows attenuation dispersion curves for a 22 mm steel bar in limestone. There are different families of modes whose attenuation oscillates with frequency. The minimum attenuation is seen at around 2 MHz (point A), rather than at low frequencies as might intuitively be expected. This is because as the frequency increases, the energy at the points of minimum attenuation is increasingly concentrated in the middle of the bar and the surface motion, which controls the leakage of energy into the surrounding medium, is small [40]. The attenuation at point A is around 20 dB/m which is small enough for the end reflection from rock bolts to be identified. For example, Fig 12 shows the signal obtained from a 2.4m long bolt in a mine. Further details of rock bolt testing can be found in [41].

SOME FUTURE DIRECTIONS

In one dimensional structures the chief research challenge is to increase the test range on attenuative systems. For example, when pipes are coated with bitumen for corrosion protection, the guided wave mode propagates along the steel-bitumen bi-layer system and is attenuated due to material losses in the bitumen. The degree of attenuation is very dependent on the properties and thickness of the bitumen layer, its attachment to the pipe and the frequency. A key requirement is to be able to test bitumen coated pipes at road crossings so a 10m test range is required. The test system has been improved to increase the fraction of such pipes that can successfully be inspected [30], but more work is needed to understand the influence of bitumen properties [42].

The attenuation in bitumen coated pipes is caused by the viscoelastic material, whereas in the rock bolts discussed above the attenuation is produced by leakage into the surrounding medium. It would be very valuable to be able to increase the test range on embedded systems such as grouted post-tensioned cables in bridges but this is extremely difficult and likely to be feasible only to a limited extent [43].

All the successful applications of long range testing to date have been on structures with low feature density. This means that the coherent noise produced by multiple reflections between different features is modest. It would be very valuable to be able to test more complex structures such as aircraft fuselage where the spacing between stiffeners is typically less than 300mm. Some initial work has been done on propagation in structures of this type [44, 45] which indicated that long range propagation was only likely to be possible at frequencies below around 200 kHz. This implies relatively long wavelengths which will reduce the spatial resolution obtainable, so making it very difficult to detect a defect close to another feature such as a stiffener. It may be possible to overcome this problem by using a subtraction algorithm to track changes in the received signal compared to a baseline measurement. This would be particularly relevant in smart structure applications where the transducers are permanently attached. However, simple subtraction of signals is unlikely to be satisfactory as they will be affected by temperature changes, minor changes in material properties with age etc.

Another interesting possibility is to use guided waves to probe inaccessible areas of a structure. For example there may be critical areas of a pipe network inside a containing wall and it would be desirable to inspect them from outside the wall. This is possible with the pipe testing system discussed above, but in some applications it will be necessary to find very small defects. Li and Rose [46] have used an array of transducers around the pipe to focus energy at particular positions on the pipe circumference at chosen axial locations, the focusing being a result of constructive interference of the various guided modes excited by each transducer in the array. This approach also has potential in more complex structural geometries.

CONCLUSIONS

Guided wave inspection potentially enables a large area of structure to be tested from a single transducer position, so avoiding the time-consuming scanning required by conventional ultrasonic or eddy current methods. However, until recently, this potential has only been realised in a small number of practical applications. This is largely due to the difficulty of controlling the different possible modes and propagation directions so that the signal-to-coherent noise ratio is satisfactory and simple, easily interpretable signals are obtained. It is therefore important for research in this field to concentrate both on exploring the opportunities offered by the multiple possible modes, and on managing the complexity that the presence of so many modes can produce.

It has been shown that an array of transducers acting as point sources provides a basis from which these problems can be overcome and examples of pipe, rail and plate testing have been presented. To date, most applications have been on simple structures with a low density of joints, stiffeners etc. Future research directions include the inspection of more complex structures and developing techniques to test systems where the attenuation is very high.

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