Long Range Guided Wave Inspection Usage – Current Commercial Capabilities and Research Directions

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Summary

Guided wave inspection of pipelines is now in routine use worldwide. The technique offers the possibility of rapid screening of long lengths of pipework for corrosion and other defects. A test range of 50m or more (25m in each direction) is commonly obtained from a single transducer position. Long range guided wave inspection techniques are also in development for several other applications, including the detection of corrosion in large areas of plates, the detection of cracking in railway lines, the detection of cracking in rockbolts, and the detection of corrosion in heat exchanger tubing.

This report explains the methodology, scientific basis, capabilities and limitations of the current commercial pipe testing techniques. It also discusses current research and directions for the development for pipe testing and other applications.

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1. Introduction

1.1 Purpose

This report aims to provide an overview of the capabilities of commercial long range ultrasonic guided wave testing systems and their limitations, and to indicate likely future developments based on current research. The report deals with long (>5m) range inspection which typically uses frequencies below 150 kHz. Shorter range systems employing frequencies from 200-1000 kHz are also available and are referred to briefly but they are not covered comprehensively; in favourable circumstances such as simple heat exchanger tubing, the range of these higher frequency systems can extend to around 10m, but this is not achieved in most applications. The main focus of the report is on pipe inspection since this is where the technology is most developed. However, references are also provided to work on rail, plates and rock bolts.

1.2 Background

Corrosion under insulation (CUI) was the focus of considerable concern in the oil, gas, chemical and petro-chemical industries in the early 1990s. Even external corrosion cannot readily be detected on insulated lines without the removal of the insulation, which in most cases is prohibitively expensive. 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 can cost upwards of $50k so a technique to address this problem is particularly beneficial.

The use of low frequency ultrasonic guided waves propagating along the pipe wall is potentially a very attractive solution to this problem since they can propagate a long distance under insulation and may be excited and received using transducers positioned at a location where a small section of insulation has been removed. From the 1970s onwards there was a considerable amount of work on the use of guided waves for the inspection of pipes and tubes, most of which was on small (typically 1 inch) diameter heat exchanger tubing (see, for example, Silk and Bainton (1979); Bottger et al (1987); Rose et al (1994); Mohr and Holler (1976)).

In 1991 the Imperial College NDT group started an EPSRC/DTI LINK project on the development of a guided wave technique for the screening of long lengths (>10m) of pipes for corrosion. The project was managed by TWI and also involved Exxon, ICI and Phoenix Inspection; it later continued under the CEC Thermie programme with further support from Shell, BP and Chevron. Its aim was to detect corrosion defects removing of the order of 5-10% of the cross sectional area of the pipe at a particular axial location; the main focus was on pipes in the 2-24 inch diameter range, though in principle, it could be used on both smaller and larger pipes.

Only two ultrasonic bulk waves exist (compression and shear); in contrast there are many guided wave modes in plates and pipes and they are in general dispersive (their velocity is a function of frequency). This can make guided wave inspection more complex than bulk wave and the transduction, instrumentation and signal processing has to be designed carefully in order to obtain signals that can be interpreted reliably. The main aim of the development work was to produce a guided wave test that would yield a pulse-echo A-scan looking like that obtained with bulk waves except that the distance (time) scale would be in metres (msec) rather than mm (μsec). This has been achieved by using either the extensional or torsional wave in a pipe at low frequency (usually less than 100 kHz). These waves are analogous to bulk compression and shear waves respectively.

The test procedure is to clamp a set of transducers around the pipe at one axial location; the computer controlled instrumentation then sends guided waves in each direction along the pipe and processes the returning echoes to produce an A-scan display showing the locations and amplitudes of any features in the pipe that change its cross section such as welds, branches, flanges etc as well as corrosion patches or cracks. It is possible to distinguish symmetric reflectors such as welds from non-symmetric features such as a typical corrosion patch; this is discussed later.

Three guided wave inspection systems are available commercially from Plant Integrity Ltd (www.plantintegrity.co.uk) which is a wholly owned subsidiary of TWI, Guided Ultrasonics Ltd[1] (www.guided-ultrasonics.com) and M.K.C. Korea (www.mkckorea.com/english.htm).

The Imperial College group led by the authors pioneered long range, low frequency guided wave inspection and their patented technology (Cawley et al, 1994) is licensed by Plant Integrity Ltd and Guided Ultrasonics Ltd. The other main academic group is at Penn State University under Rose, who has written a specialist textbook on guided waves (Rose, 1999); the focus of most of the Penn State work has been at higher frequencies but they have recently started working on long range testing in collaboration with Plant Integrity Ltd (Rose et al, 2005). SWRI in Texas is the other main research player; their speciality is magnetostrictive transduction and they developed the pipe inspection system marketed from Korea (Kwun and Holt, 1995).

1.3 Initial Development

Fig 1.1 shows the group velocity dispersion curves for a 6 inch, schedule 40 steel pipe. There are about 50 modes below 100 kHz and, as discussed above, successful commercial systems ensure that only one of them is excited in order to obtain signals that can reliably be interpreted. This makes the test similar to conventional pulse-echo bulk wave ultrasound as discussed above. In most guided wave testing, the sensitivity of the test is a function of the signal to coherent noise ratio, the coherent noise being caused by the excitation of unwanted modes. This coherent noise cannot be removed by averaging, whereas if low signal levels cause a poor signal to random noise ratio, significant improvements can be obtained by averaging. The original implementation of the technique used the extensional mode (this is L(0,2) on Fig 1.1; the terminology used to describe cylindrical guided modes is discussed by Silk and Bainton, 1979) at frequencies around 70 kHz. This mode is very attractive to use for long range testing (Alleyne et al, 1997; Alleyne and Cawley, 1997) since it is practically non-dispersive in this frequency range. Its mode shape is similar to that of the s_0 mode in plates at low frequency-thickness products, the particle motion being predominantly axial and the strain being roughly uniform through the pipe wall. It is therefore well suited to the detection of corrosion which may initiate at either surface of the pipe.

Alleyne and Cawley (1996a) reported the development of a dry coupled piezoelectric transducer system for the excitation of the axially symmetric L(0,m) modes in pipes. It comprises a ring of piezoelectric elements which are clamped individually to the pipe surface; no coupling fluid is required at the low ultrasonic frequencies used here. The transducers are constructed using shear-polarised piezo-electric elements, so that they impart a tangential force at the surface of the pipe; the transducers are orientated to force

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[1] The authors are both directors of Guided Ultrasonics Ltd and hence declare an interest in the company

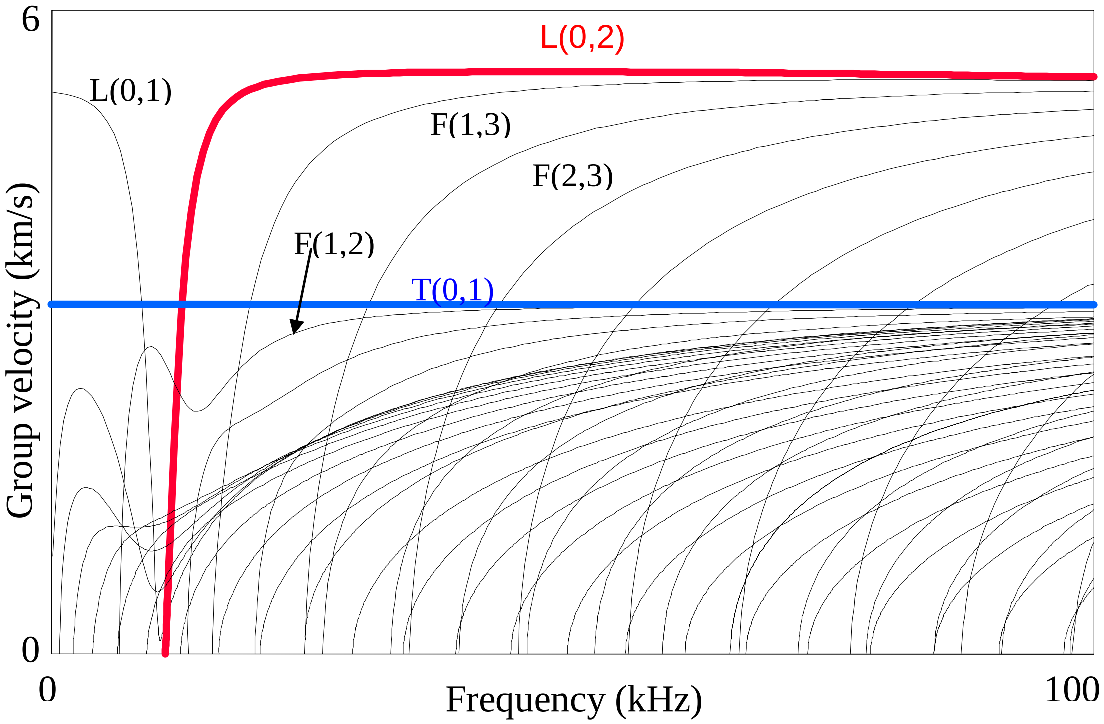


Figure 1.1 Group velocity dispersion curves for 6 inch, schedule 40 steel pipe.

in the axial direction when using these L(0,m) modes. The number of elements in the ring should be greater than n where F(n,1) is the highest order flexural mode whose cut off frequency is within the bandwidth of the excitation signal. In the initial configuration, rings of 16 elements were used on 3 inch pipes, while 32 element rings were employed on 6 and 8 inch pipes. This gave the possibility of operating at frequencies up to around 100 kHz; at lower frequencies it is possible to reduce the number of transducers in a ring. The transducer and test technique have also been patented (Cawley et al, 1994).

Initial site trials of the technique carried out in the research phase in the mid 1990s achieved propagation distances approaching 50 m and by using multiple rings of transducers it was shown to be possible to obtain uni-directional propagation (Alleyne et al, 1997; Alleyne and Cawley, 1997). Signal to coherent noise ratios of better than 40 dB were obtained on site (ie the generated signal leaving the transducer ring was more 40dB higher than the coherent noise of unwanted modes caused by imperfections of the transducers), approaching 50 dB being obtained on clean pipe in the laboratory.

1.4 Sensitivity to defects and identification of non-axisymmetric features

Guided waves such as L(0,2) that have relatively uniform stress distribution over the cross-section of the pipe are sensitive to changes in cross section of the pipe. The reflectivity of guided waves is governed by very different rules than those for bulk waves; with guided waves, it is possible to find defects whose depth is much smaller than a wavelength. A series of laboratory tests (Alleyne et al, 1998) was carried out to determine the reflection from simulated defects and these were confirmed in field trials. The depth and circumferential extent of the defect are the main determinants of the reflection obtained, so most calibration tests were done with notches of different depth and circumferential extent. At a given defect depth, the reflection coefficient is directly proportional to the circumferential extent and the reflection coefficient of a half wall thickness notch with a circumferential extent of half a pipe diameter (16% of the pipe circumference) is approximately 5% (-26 dB). This was the original target for defect detection set by the industrial partners and so a 40 dB signal to coherent noise ratio was very satisfactory.

The axial length of a defect such as a corrosion patch does influence the reflectivity; in some exceptional cases, a resonance phenomenon occurs in which the reflections from the start and end of the defect cancel each other, so a greatly reduced reflection is seen back at the transducers. This occurs at discrete frequencies for defects with a sharp beginning and end so this danger can be overcome by testing at at least two frequencies. The effect is much more severe with machined calibration defects than with real corrosion patches that tend to be much less regular so the problem does not generally arise in practical testing. This issue has been addressed by Demma et al (2003a, 2003b, 2004).

The initial site trials reported by Alleyne et al (1997); Alleyne and Cawley (1997) showed that corrosion defects of the target size 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. This makes it difficult to identify defects at welds and also introduces the possibility of a weld being incorrectly identified as a defect. 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 (with weld cap), 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 L(0,2) mode is incident, the most important mode conversion is to the F(1,3) and F(2,3) modes which have similar velocities to the L(0,2) mode in the operating frequency range (see Fig 1.1). The amount of mode conversion obtained depends on the degree of asymmetry, and hence on the circumferential extent of the defect. Fig 1.2 shows the direct reflection and the mode converted reflections from a full wall thickness notch as a function of circumferential extent for an L(0,2) mode input. At low circumferential extent (which is the region of interest for the detection of critical corrosion in practical situations) the mode converted F(1,3) reflection is almost as large as the direct reflection so if these two reflections are of similar size, it can be concluded that the feature is localised to a small region of the circumference. This allows the severity of the corrosion to be estimated. The results of Fig 1.2 are for a 3 inch pipe, but similar results are obtained with other sizes. Further details can be found in Lowe et al (1998).

1.5 Mode Choice

The field trials reported by Alleyne et al (1997) and Alleyne and Cawley (1997) employed two rings of transducers in order to excite the L(0,2) mode in a single direction. However, there is a second axially symmetric mode with particle displacements primarily in the axial and radial directions, L(0,1). This has a much lower velocity than L(0,2) in the operating frequency range above 35 kHz, as shown in Fig 1.1, but it is excited by the two ring system. The presence of reflections of this mode can make interpretation of the results less reliable so it is desirable to remove it. It is possible to suppress the L(0,1) mode by adding further rings of transducers (Cawley et al, 1994).

The use of three or four rings adds to the cost of the system and also to the mass, which becomes significant when larger pipe sizes are being tested. An alternative to the longitudinal, L(0,2), mode is to use the torsional, T(0,1) mode. The torsional mode has the

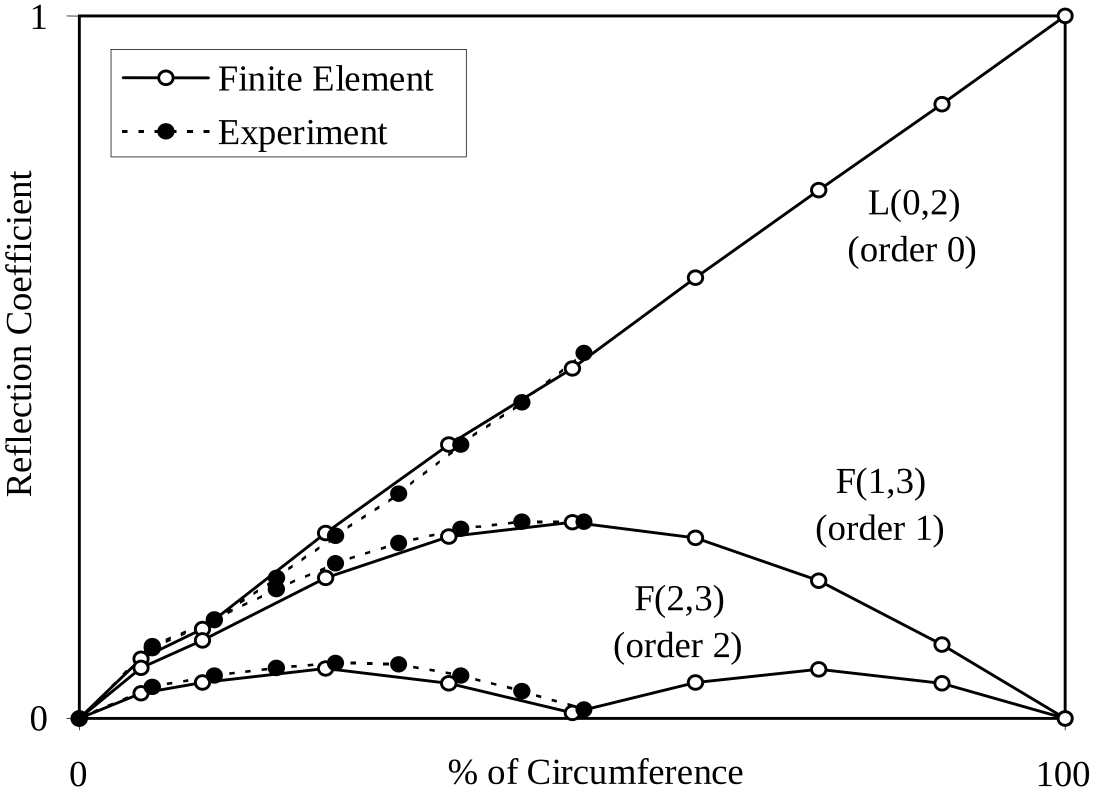


Figure 1.2 Measured and predicted reflection coefficients for a through-thickness notch in a 3 inch, schedule 40 steel pipe at 70 kHz as a function of the circumferential extent of the notch. L(0,2) mode input. After Lowe et al, 1998.

advantage of being non-dispersive across the whole frequency range (see Fig 1.1) and there is no other axially symmetric torsional mode in the frequency range, so axially symmetric torsional excitation will only excite the T(0,1) mode. This means that only two rings of transducers are required in order to obtain single mode, unidirectional excitation. Torsional forcing can be achieved by simply rotating the same transducers used for the L(0,2) mode through 90^0 so that they apply force in the circumferential, rather than axial direction. When the T(0,1) mode is reflected from a non-axially symmetric feature, mode conversion is primarily to the F(1,2) mode, rather than to F(1,3) as in the L(0,2) case shown in Fig 1.2. As in the case of an incident L(0,2) mode, at low circumferential defect extents, the amplitudes of the reflected incident and mode converted modes are similar.

The torsional mode also has the advantage that, in contrast to the L(0,2) mode, 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. A further advantage of the torsional mode is that it will detect longitudinal cracks, whereas the longitudinal modes are essentially insensitive to thin defects parallel to the pipe axis. However, a disadvantage of this sensitivity to axial features is that the torsional mode reflects relatively strongly from support brackets that are welded axially along the pipe. Large reflections from these features reduce the range of the test and also make it more difficult to detect corrosion at the brackets. This problem is most severe in small diameter pipes. In this relatively unusual case the longitudinal mode may be preferable, though if the pipe is liquid filled, leakage of longitudinal waves into the liquid removes the advantage. Some discussion of mode choices is given in Demma et al (2004).

1.6 Effect of frequency

The sensitivity of guided waves to defects in the pipe wall is a function of frequency. In general, the sensitivity of the test decreases as the frequency is reduced, but the effect is not always as severe as with bulk wave testing. For example, Fig 1.3 shows the reflection coefficient of the T(0,1) mode from axially symmetric cracks of varying depth. In a given pipe size, as the frequency decreases, the curve becomes increasingly 'concave', implying that it is more difficult to detect shallow defects. The reflection coefficient is governed by the frequency-thickness product; for example, Fig 1.3 shows that the 40 kHz curve in the 3 inch pipe (5.5 mm wall thickness) is similar to the 10 kHz curve in the 24 inch pipe (20 mm wall thickness). The corresponding frequency-thickness products are therefore 220 and 200 kHz-mm respectively. Similar results can be obtained for the L(0,2) mode.

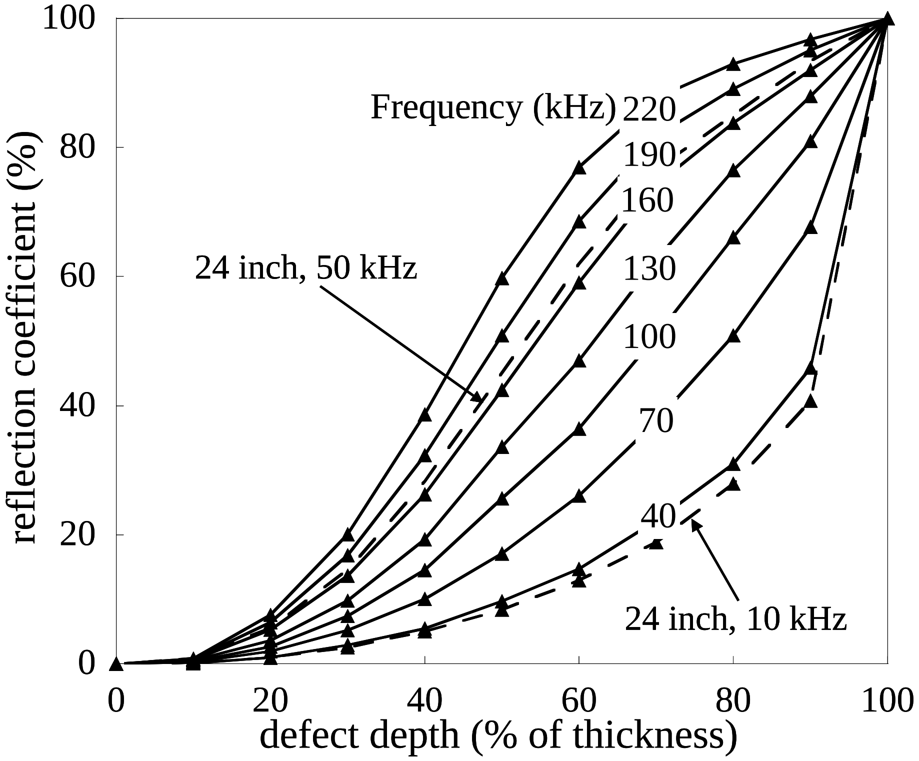


Figure 1.3 Finite element prediction of torsional mode reflection coefficient from axially symmetric crack in 6 inch schedule 40 steel pipe as a function of crack depth. Also shown are results for 24 inch pipe at 10 kHz and 50 kHz. (After Demma et al, 2003b)

The frequency used does affect the spatial resolution and the range. The speed of the torsional (T(0,1)) wave is about 3.2 km/s, while that of the extensional (L(0,2)) wave is about 5.4 km/s. Therefore at 50 kHz, the wavelengths are 64 mm and 108 mm respectively. In order to limit the frequency bandwidth of the excitation and so to ensure that only the desired modes are generated, practical systems use windowed toneburst excitation (Alleyne and Cawley, 1992a) which limits the bandwidth. A 5 cycle toneburst is often used; the bandwidth can be further reduced by increasing the number of cycles. This increases the power input and helps to increase the range. However, there is a cost in spatial resolution, though the effect can be minimised by signal processing.

This report only discusses long range guided wave testing which uses frequencies below 100 kHz. Shorter range (typically <5m) systems using frequencies up to 500 kHz or even 1 MHz are also available, the higher frequency giving better spatial resolution and detection capability at a cost of range and, unless the system is very well designed, coherent noise from the many more modes that can propagate. EMATs are the most commonly used transducers for higher frequency testing and the best-known systems are produced by IZFP in Germany (http://www.izfp.fraunhofer.de/index_e.html) and Sonic Sensors in USA (http://www.sonicsensors.com).

1.7 Crack Detection

The main focus of long range guided wave testing has been corrosion detection, as discussed above, with relatively little on cracks. Since most of the calibration work discussed above was carried out with circumferential notches, there is abundant data that is relevant to circumferential cracks; the read across from notches to cracks has been discussed by Demma et al (2003a, 2003b). The stresses in longitudinal waves are virtually entirely axial; a longitudinal crack therefore produces minimal disturbance to the wave field and so is not detectable. However, the torsional wave does produce shear stresses across the crack so a significant reflection is expected. We are not aware of any quantitative work on this though substantial reflections of the torsional wave from longitudinal notches have been reported (Liu et al, 2006). It is also possible to use flexural waves (see, for example, Shin and Rose, 1998), though these are more difficult to excite in a pure form. Axial cracks are also straightforward to detect using circumferential guided waves (see, for example, Luo et al, 2004; Valle et al, 2001) but this requires transduction to be at the axial location of the defect; this can be useful if, for example, cracking is suspected under a support.

1.8 Applications to other geometries

The main commercial application of long range guided wave testing is to pipes and tubes. However, field prototypes have also been produced for rail (Cawley et al, 2003; Wilcox et al, 2003). Laboratory prototypes of plate testers using detachable (Wilcox et al, 2005) and permanently attached (Fromme et al, 2005) have also been successfully tested. Laboratory studies and field trials have also been done on rock bolts in mines (Beard et al, 2002, 2003a,b); here it was found that high frequencies (around 2 MHz) give better range than low frequencies. This is due to the existence of high frequency modes with little motion at the outer radius of the bolt so there is only weak coupling between the bolt and the surrounding rock; this greatly reduces the attenuation due to leakage. However, use of the higher frequency increases the significance of material attenuation and it is difficult to achieve a range of more than 2-3m. The issue of attenuation due to leakage will be discussed in detail later.

2. Current Routine Usage

2.1 Commercial Systems

The piezoelectric array technology developed at Imperial College, discussed above, has been licensed to two companies: Plant Integrity Ltd (www.plantintegrity.co.uk) which is a wholly owned subsidiary of TWI, and Guided Ultrasonics Ltd (www.guided-ultrasonics.com). Both companies use rings of transducers, as described by Cawley et al (1994) and summarised above, to generate an axially symmetric mode and to control the direction of propagation, and then process the received signals to identify non-axially symmetric components which indicate non symmetric features in the pipe. Field trials of the initial commercialised instruments were reported respectively by Mudge (2001) and Alleyne et al (2001).

A magnetostrictive transduction technology has been developed independently at SWRI in Texas, USA (Kwun and Holt, 1995; Kwun et al, 2003). This is marketed by a Korean company M.K.C. Korea (www.mkckorea.com/english.htm). It has not been configured to give mode conversion information so it is not possible to use the methods described above to distinguish symmetric from non symmetric features in the pipe. The magnetostrictive technology may potentially be simpler and cheaper than the piezoelectric transducer systems used by the UK manufacturers but it has proved much more difficult to achieve satisfactory mode control; the results have generally been less satisfactory and this system is not widely used in practical industrial testing. The discussion of practical usage below therefore refers to the two UK systems.

Fig 2.1a shows the construction of a Guided Ultrasonics transducer system for a small diameter pipe. It comprises two rings of transducers configured to apply alternating forces to the pipe in the circumferential direction. Solid rings of the type shown in Fig 2.1a are manufactured for pipe diameters up to 8 inch, but above this they become bulky so a flexible, pneumatic clamping arrangement is used; an example system is shown in Fig 2.1b. No surface preparation is usually required, other than wire brushing any loose scale on the pipe. The test instrument is battery operated and is connected to the rings 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 site, but on other occasions it is better for the computer and operator to be in a van which can be up to 50m from the test site.

Fig 2.2 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 2.3 shows an example report generated by the Guided Ultrasonics 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 reflections from 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 a typical site weld is a -14 dB reflector relative to the incident wave amplitude i.e. the weld reflection coefficient is -14dB. (Note that this is determined by the typical size of the weld cap; a ground weld would not reflect the signal.). 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.

The performance of the inspection depends on the generation of a high fidelity axisymmetric signal of the chosen kind, either extensional or torsional. Imperfections could arise from non-uniform strength of excitation of the transducer elements, phase errors between the signals at the adjacent rings, ovality of the pipe, or circumferential variation of the wall thickness of the pipe. Any such imperfections could lead to the generation of some of the other, unwanted, modes of the pipe; such signals would appear as coherent noise, that is to say, they could not be removed by averaging multiple signals. A great deal of care is necessary, and is taken, in matching the transducer elements and controlling the phase in order to achieve good transduction. A laboratory study of reflections from defects in a 3 inch pipe (Alleyne et al, 1998; Lowe et al, 1998) found about 10% variation of thickness around the circumference of the pipe, yet accurate measurements were possible, and were found to agree very well with Finite Element


(a)

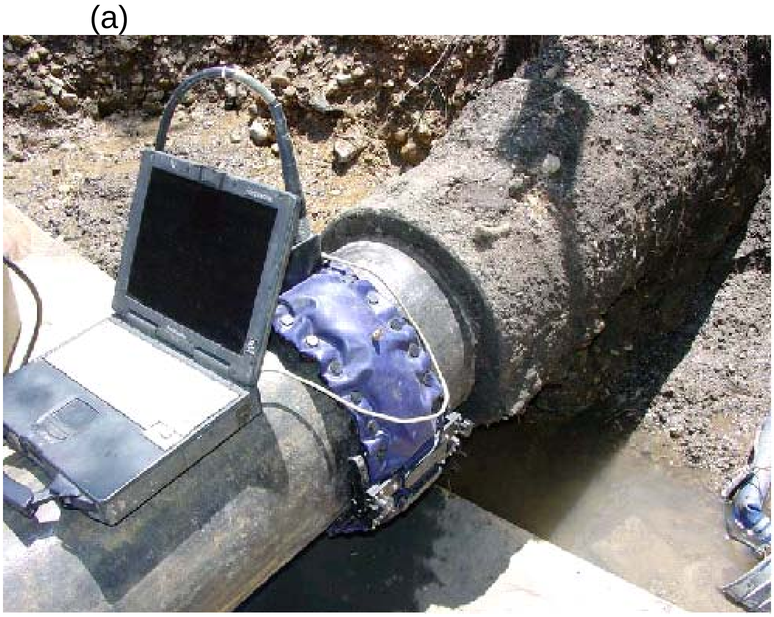

(b)

Fig 2.1. (a) Guided Ultrasonics solid transducer system; (b) flexible, pneumatically clamped system for larger diameter pipe.

predictions for a perfect pipe. In practice the natural manufacturing variations of wall thickness and ovality have not been found to be a problem.

2.2 Typical Application Areas

The original research and development work on long range guided wave inspection systems was aimed at the corrosion under insulation (CUI) problem. Here the need is typically to inspect long lengths of pipe with loosely wrapped mineral wool insulation. The pipe comprises long, straight sections with only infrequent welds, branches etc; it is in generally good condition, the concern being localised corrosion caused by insulation failure, steam line leaks etc. These are ideal conditions for application of the technique and it is possible to obtain approaching 200m coverage from each transducer position (up to about 100m in each direction, or even more in some cases). However, the technology is commonly applied in more demanding cases and the range obtained decreases as the general pipe condition deteriorates, as shown in Table 2.1. General corrosion reduces the test range because energy is scattered by the rough surface, so producing attenuation of the travelling wave. Bitumen coating is a particular problem as the pipe effectively becomes a bi-layer system and any energy carried in the bitumen layer is rapidly attenuated. However, the effect is a strong function of the bitumen properties (Simonetti and Cawley, 2004), and hence its age; older coatings that have dried out and often cracked away from the pipe have relatively little effect on the propagation. Highly viscous deposits on the inside of the pipe can have a similar effect to exterior bitumen coatings. The waves do not propagate past flanges and the signal level is usually too low for reliable defect detection after about 6 welds in a given direction. (It may be possible to see subsequent welds but the signal to noise ratio has often dropped below that required for reliable defect detection.)

The test range is also a function of the defect size that is to be detected. Most industrial applications to date have been concerned with corrosion detection and the requirement has been to detect wall loss greater than about 10% of the pipe cross section; the ranges of Table 2.1 refer to this case. If it is necessary to find smaller defects the signal to noise ratio must be better so the range is reduced. The extent of the range reduction depends on the rate of attenuation of the waves as they travel along the pipe which is a function of both the features encountered and the attenuation rate in plain pipe. e.g. suppose that the basic attenuation is 0.2 dB per metre round trip and the round trip transmission loss at a weld is 3 dB (all signals from beyond a feature are interrogated by a signal that has passed through the feature and the reflection must also pass through the feature) then if the range is reduced by 15m and one weld is included in this span then the signal to noise will be improved by 6 dB. This is of the order of the improvement needed to drop from a 10% to 5% wall loss requirement (the reflection from a 5% wall loss defect is half that of a 10% defect only if the defects are full wall thickness; in other cases the improvement of signal to noise would have to be more than 6 dB (Demma et al, 2004)). In the lab or on new pipe in the field it is possible to detect defects equivalent to the loss of 1% or less of the cross section but this is not possible in the presence of general corrosion or lossy coatings.

Application	Typical Range in each direction (m)
Ideal conditions	80+
Typical 30 year old pipe with little internal or external corrosion	40
Typical 30 year old pipe with some general corrosion	20
Typical pipe wrapped in factory applied foam	15
Heavily generally corroded pipe	5
Bitumen coated pipe	5*

Table 2.1 Typical ranges obtained in different conditions with standard transducers (source: Guided Ultrasonics Ltd training manual)
* The range in bitumen coated pipe is strongly dependent on the bitumen condition

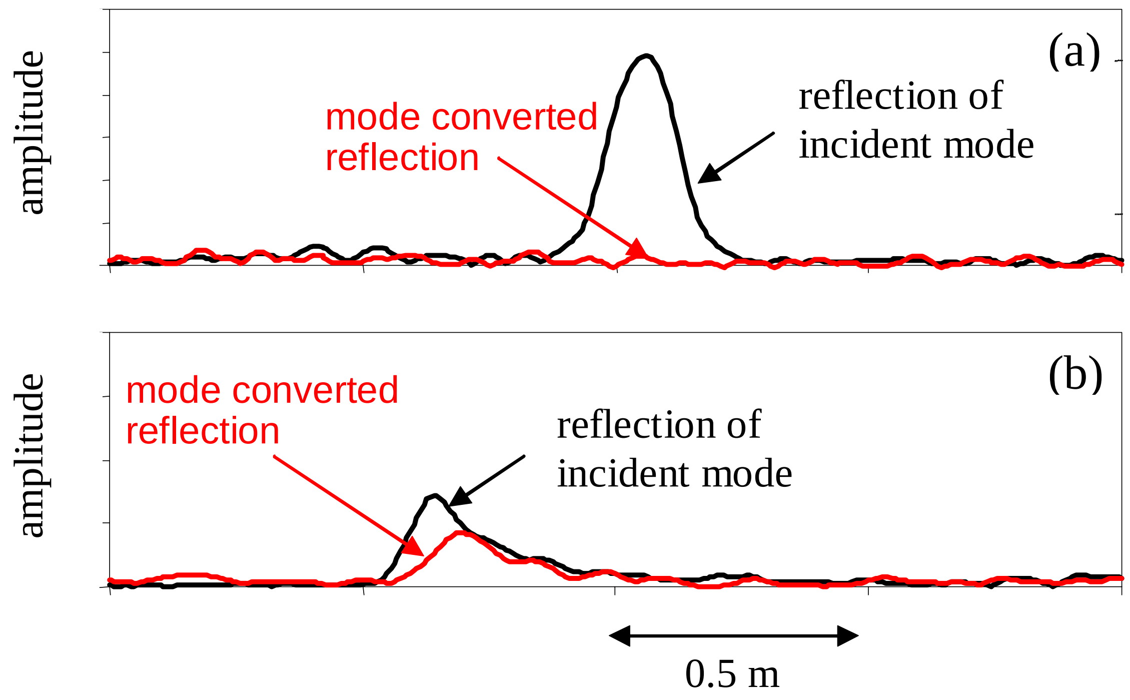
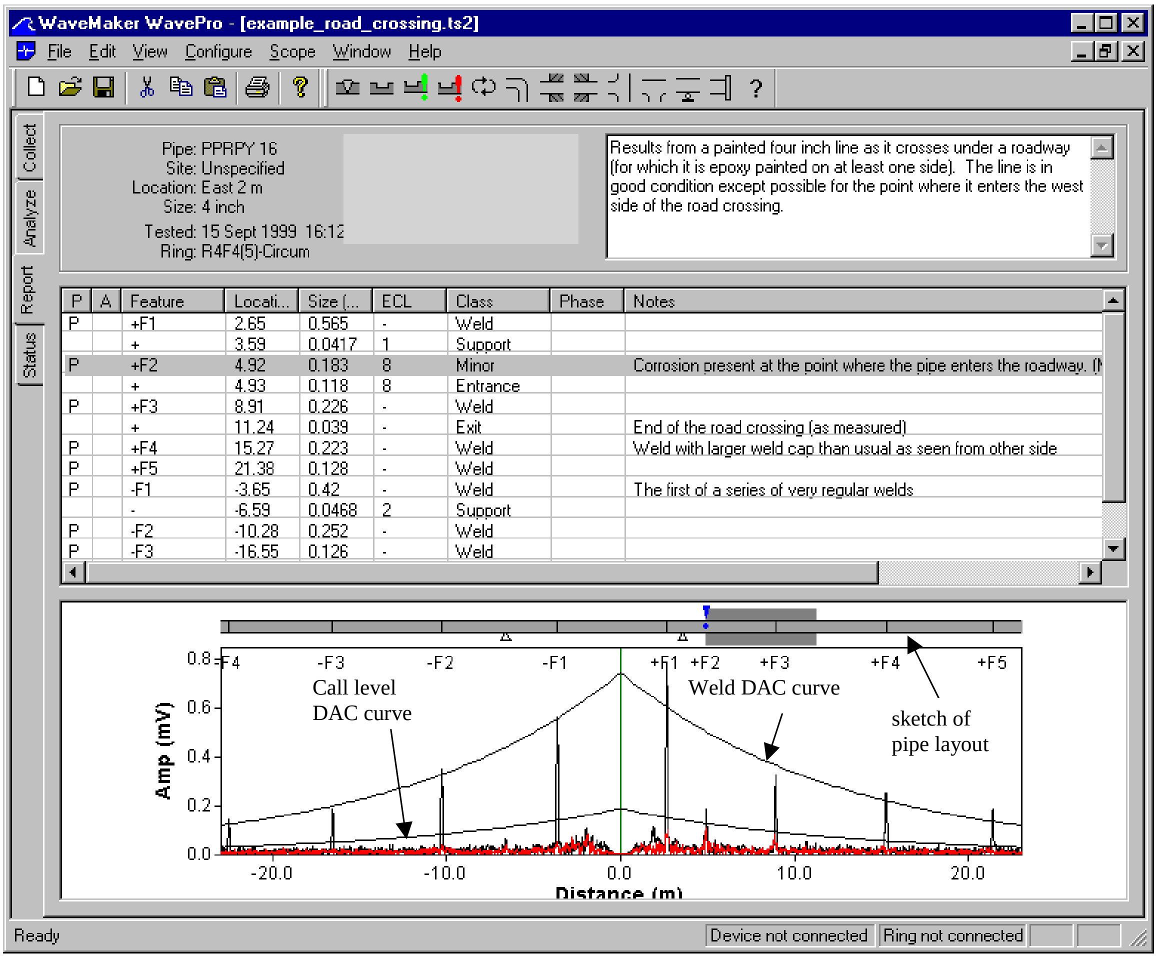


Figure 2.2 Typical signals from (a) axisymmetric feature e.g. weld; (b) corrosion.



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. (N
		+	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 2.3. Typical Guided Ultrasonics system report format.

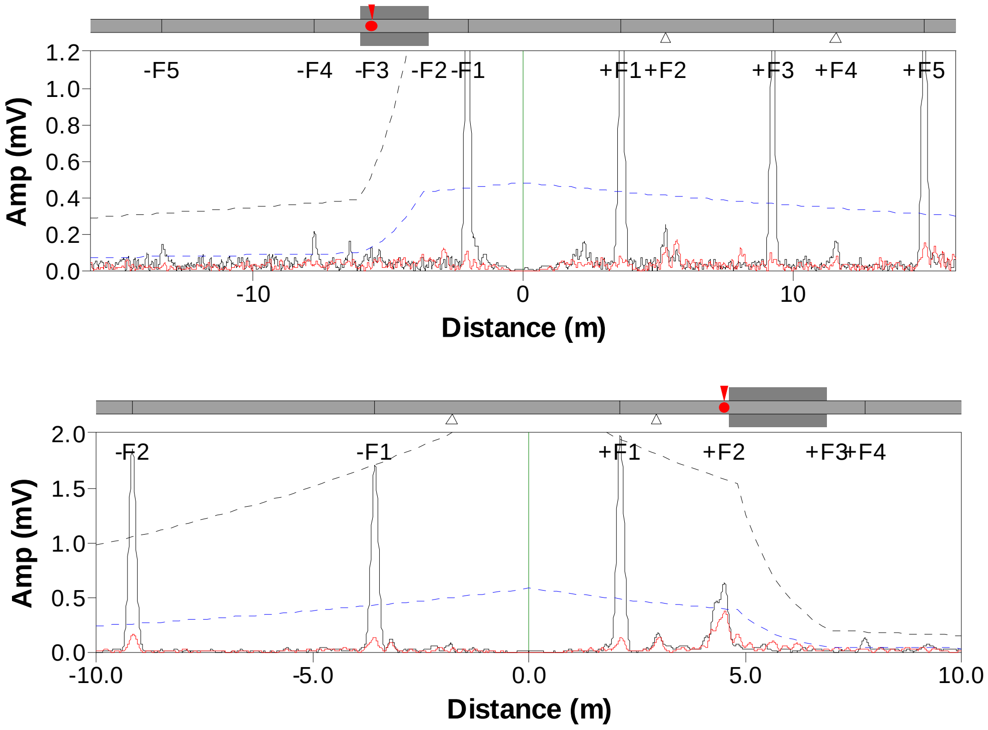
The method is essentially a screening tool since it gives only a qualitative measure of the wall loss of any defect. Its value is that it gives 100% coverage of the pipe, and so enables detailed inspection to be deployed only at areas identified as problematic. Therefore inspectors do not waste time doing detailed scanning of areas that the screening test have shown to be defect-free. The main application area of the technology is the rapid screening of long lengths of pipe. It is particularly cost effective in difficult to access locations such as:

- Sleeved road crossings
- Insulated pipes
- Wall penetrations
- Pipe racks
- Under supports
- Cases where rope access or scaffolding would be needed for conventional inspection

3. Limitations of the technology

3.1 Difficult features

The application of the technique to the detection of corrosion under insulation and similar cases where the feature density on the pipe system is low (i.e. infrequent welds, tees, bends etc) and the attenuation is low (no heavy general corrosion, no highly attenuating coating), is relatively straightforward, and the signals obtained can be interpreted by experienced NDT technicians who have done a one week specialist training course with around a further week of supervised field testing. For example, the signal of Fig 2.3 shows multiple, well separated welds in each direction, a low noise floor relative to the welds and a clear indication of a problem remote from the welds.



(a)

(b)

Figure 3.1 Inspection of 10 inch pipe passing through earth wall. (a) From side remote from defect; (b) from other side of wall.

In contrast, Fig 3.1 shows the case of a road crossing where the pipe is bitumen coated under the road. In Fig 3.1a the test has been done from the side of the road remote from the location of a defect; the gain has been increased to show the signals from the buried section (between about -3.5 and -6m on the plot) and beyond. The signals from the welds in the other (positive) direction and the first weld in the negative direction are therefore clipped on the plot. It is very difficult to set the DAC curve, and hence to gauge the size of reflections coming from the buried region. This requires much more experienced and skilled operators; similar issues arise when the pipe is embedded in concrete. In contrast, Fig 3.1b shows a test on the same pipe from the other side of the road; here the defect at the near entrance to the crossing can clearly be seen (reflection +F2).

Testing past typical pulled bends does not present any significant difficulty, but sharp bends created by welding elbow pieces between two pipe sections do cause problems. Here the radius of curvature to pipe diameter ratio is typically 3 or less and, in addition to the reflections from the two welds, there is mode conversion produced by the bend (Demma et al, 2005). This is shown in Fig 3.2 where the features marked +F2 and -F2 are 1D bends (i.e. bends whose radius equals the pipe diameter) and the feature +F3 is a further bend. The bends are characterised by reflections from the welds placed immediately before and after the bend. For bends +F2 and –F2 the reflection from the second weld has a significant asymmetric (red) component. This is due to mode conversion produced by the bend itself, rather than at the weld. The signal transmitted past a bend contains both the original mode and mode converted components; the reflections from both welds at bend +F3 therefore have significant asymmetric components since the signal incident at the bend was not symmetric due to mode conversion at bend +F2. Therefore it is no longer possible to use the presence of an asymmetric reflected signal as evidence that the reflector is asymmetric. Unfortunately there are frequently bends immediately before and after buried road crossings since the pipe runs at ground level on either side of the road. This adds to the difficulty presented by the lossy coatings that are often applied. In some cases a skilled operator can interpret signals past two sharp bends but this is not a task that should be entrusted to an inexperienced technician. It is common practice to organise transducer placement so that it is only necessary to test through one bend and, where possible, to place the bend towards the end of the test range so that it is not required to 'see' past it.

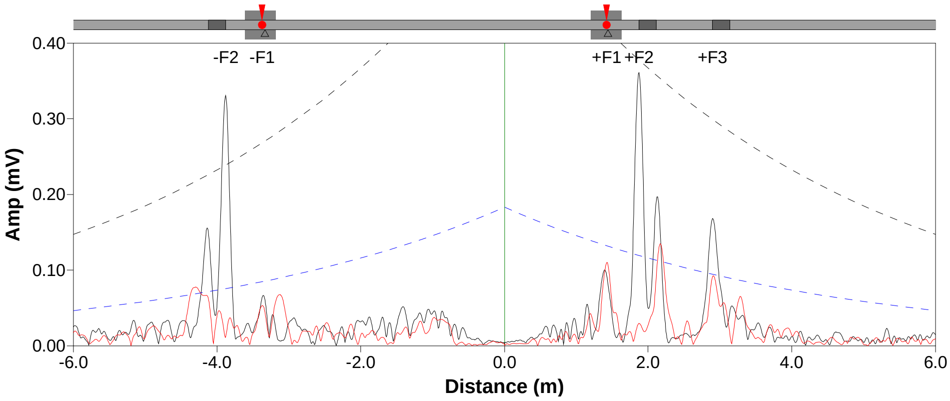


Figure 3.2 Test result on 3 inch pipe with bends at –F2, +F2 and +F3, also showing corrosion at supports (-F1, +F1). The reflection from the second bend weld at both –F2 and +F2 has a significant asymmetric (red) component, while the reflection from the first weld is predominantly symmetric (black). The bend +F3 occurs after the bend +F2 and this shows significant asymmetric reflections from both welds. This is due to mode conversion of the forward going wave at bend +F2.

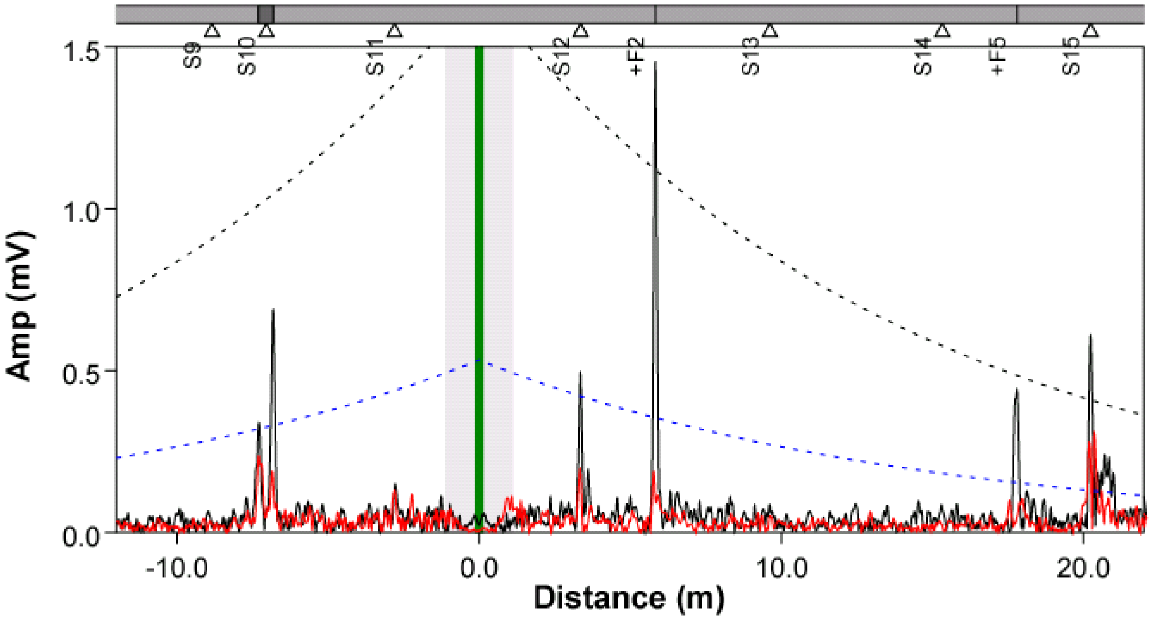


Fig 3.3 Example of corrosion at simple supports. Clear indications at S12 and S15; no significant corrosion at S11, S13, S14. The double signal at S10 relates to a bend. F2 and F5 are welds.

A common application of the technology is the detection of corrosion at simple supports; this is relatively straightforward since a simple support does not give a significant reflection in the absence of corrosion. For example, Fig 3.3 shows a case of a test on a section of pipe with multiple simple supports (indicated by triangles in the schematic above the time trace). Some give minimal reflections while there are significant reflections with a large red (asymmetric) component at two of the supports.

Simple supports give no significant reflection and hence do not affect test range, and it is straightforward to detect defects at the supports. In contrast, welded supports give larger reflections and so limit the test range; they are also asymmetric and so produce mode conversion of both the reflected and transmitted signal. Therefore it is difficult to determine whether there is a defect at the support and it more difficult to use the amplitude of asymmetric signals after the support to determine whether a later feature is symmetric. For example, Fig 3.4 shows a test result from a 24 inch crude oil line with welded saddle supports. The reflections from the supports are complex and asymmetric; those from S93, S95, S96 are much larger than that from S94 which is shown in the photograph. This is because the weld at this support had failed. Effectively therefore the defect has been detected by comparison with the other supports and this is often the way that defects at asymmetric features are identified. The echoes from the undamaged supports are within a few dB of the weld echo W3.

There are also features which cause very large reflections and mode conversions and which in practice set the limits for the inspection range. A flange joint can be considered to be the end of the inspectable range. Practically all of the energy is reflected here so it is impossible to propagate any signal beyond it. Similarly a valve reflects nearly all the energy, and additionally the non-symmetric shape causes mode conversion to multiple reflected modes. Testing past nozzles, welded fittings and other localised features may be possible if they are small, but large features generally cause too much reflection and mode conversion to enable sensible interpretation of signals from beyond them. Intuitively it might be expected that testing past a 'T' would be difficult since effectively the T introduces a large hole in the pipe. However, in practice good transmission past Ts is generally obtained.

Finally, the presence of multiple features gives rise to multiple reflections, and this can limit the inspection range. Distance measurements of the features on site can enable the sources of the multiple reflections to be identified, but such complexity can be tolerated only to a limited extent. The problems are that the additional reverberant signals can mask reflections from defects, and also that the amplitudes of indications are hard to judge after the energy has been partitioned to multiple components.

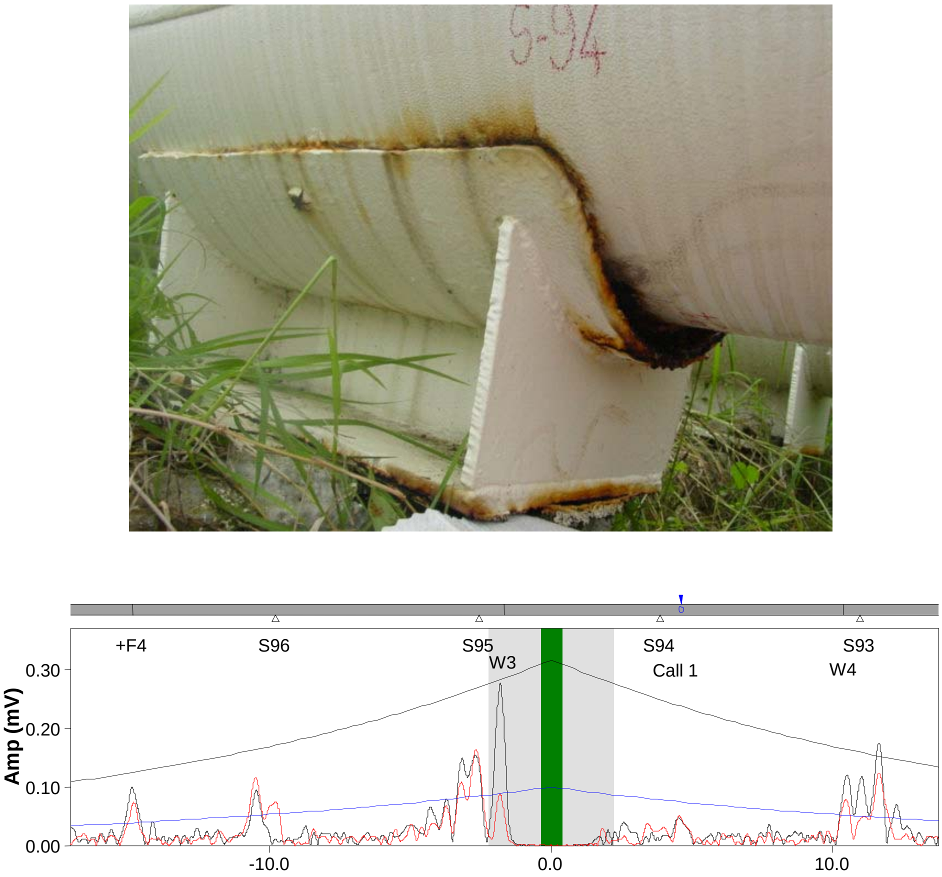


Fig 3.4 Failed welded saddle support on 24 inch crude oil line and corresponding test result.

3.2 Technology Improvements

The less straightforward cases discussed in Section 3.1 can often be tested successfully by experienced, skilled operators. Guided Ultrasonics Ltd has introduced a Level 2 operator training course and associated qualification in order to make clear to end users which operators are able to carry out the more difficult inspections. However, even relatively simple guided wave testing needs a level of skill, computer literacy and attention to detail that is not always characteristic of NDT technicians. There is therefore a danger that poor operators, although they are capable of passing the basic, Level 1, qualification, do not operate to this level on site, particularly if unforeseen difficulties arise. Guided Ultrasonics Ltd has therefore developed a new testing instrument, Wavemaker G3, in order to increase the number of automatic checks on data quality and to lock the instrument if there is a malfunction such as incorrectly coupled transducers. The major changes relative to the original Wavemaker SE16 system are:

- instrument requires operator identification key, so providing a record of who did a particular test and enabling clients to check whether the operator was appropriately qualified for the particular inspection;
- inclusion of hardware to check the capacitance of each transducer channel, so ensuring that any faulty transducers are identified;
- automatic transducer identification so that optimised setup parameters can be applied without operator intervention;
- automatic self-test procedure to check for instrumentation faults;
- better filters making the system operable even in the presence of noise from e.g. pumps operating on the line;
- higher transmission power, so improving signal levels in very lossy systems;
- increase in sampling resolution from 12 to 24 bits, so improving the ability to extract small signals in the presence of noise, and to detect small signals at long range when there is a large reflector close to the transducers in the other direction;
- better transducer calibration, so reducing the excitation and reception of unwanted modes, and hence improving the signal to coherent noise ratio;
- support for up to 32 data channels, so allowing more complex configurations to be employed by qualified operators;
- possibility of doing both pulse echo and through transmission testing to improve confidence in coverage of lossy systems.
- GPS receiver to provide approximate position and rough check on operator record.

Clearly many of these changes also benefit the best operators, but the major concern is to improve the minimum level of performance.

3.3 Mechanisms of Attenuation

Most of the difficulties discussed above result from greatly increased signal attenuation compared with plain pipe. This arises from several sources either singly or in combination:

- material attenuation, e.g. high loss coatings such as bitumen;
- scattering, e.g. rough surface produced by general corrosion;
- reflections from features, e.g. welds reduce the forward travelling signal;
- mode conversion, e.g. bends and branches reduce the forward travelling signal in the mode of interest both by reflection and by mode conversion of the forward travelling symmetric wave into non-symmetric modes;
- leakage, e.g. radiation of bulk waves into surrounding material such as soil (often not very severe) or concrete (very severe if concrete rigidly attached to the pipe)

Attenuation due to lossy coatings and rough surfaces can be reduced by testing at lower frequencies. The ranges of Table 2.1 are obtained with standard transducers working in the 25-70 kHz range; if lower frequency transducers are used, the ranges can often be extended but at some cost in spatial resolution and defect sensitivity. In systems with lossy coatings it is also sometimes possible to optimise the test frequency so that the propagating mode has minimal energy in the coating (Simonetti and Cawley, 2004). Also, with pipes buried in concrete it may sometimes be possible to operate at a higher frequency where the bulk of the energy is carried at the inner surface of the pipe, so minimising leakage losses into the concrete; this is discussed further in section 4.3 below.

4. Inspection of embedded structures

4.1 Introduction

Guided wave inspection of structures which are embedded is an important topic because there are many such structures. Examples include buried pipelines, pipelines which pass through road crossings or through containment walls, reinforcing steelwork in concrete, and anchor bolts in concrete or in rock. Furthermore, the fact that they are embedded, and therefore not accessible to visual inspection, often increases the interest in using guided waves.

A sensible way to approach the discussion of embedded structures is to separate the cases into two categories, of weakly loaded and strongly loaded waveguides.

The weakly loaded waveguides are those in which the surrounding material causes attenuation of the guided waves but otherwise has little effect on the properties of the guided waves. This is easily understood, for example, for a steel pipe which is surrounded by water: most of the guided wave modes leak energy into the water, but because the acoustic impedance of the water is much lower than that of the steel, the velocity dispersion curves and mode shapes for the pipe are almost unaffected. In practice the inspection of buried pipelines and road crossings is dealt with in this category, as discussed in Section 3. The inspection uses the usual testing approach, with choices of parameters to respond to the attenuation problem (high power and usually low frequency), but no consideration of changes to other properties of the guided waves.

The strongly loaded waveguides are those in which the surrounding material significantly modifies the properties of the guided waves. This happens when the acoustic impedance of the surrounding material is of similar order of magnitude to that of the material of the waveguide. This is the case for pipes or bars, or probably any engineering structure, embedded in concrete or rock. In these cases the velocities and mode shapes of the waves are different from those of the free structure, and indeed modes may be lost or new modes may appear. Additional to the attenuation of the waves and the changes of the dispersion curves, another consideration is that changes to the surrounding material may cause scattering of the waves, an important example being at the entry of the waveguide to the embedded region.

In this section we will discuss the cases of strongly loaded waveguides; the weakly loaded cases are covered by the discussion of Section 3.

4.2 Effect of embedding on the properties of the guided waves

In cases of strongly loaded waveguides, the presence of the embedding material can change the dispersion curves, cause strong attenuation of the waves, and cause a reflection to occur at any position along the waveguide where there is a change to the properties of the embedding material.

Figure 4.1 shows dispersion curves for a 17 inch diameter, 0.5 inch wall thickness steel pipe, for frequencies up to 1 MHz. Only the order 0 (axially symmetric) modes are shown. Part (a) shows the phase velocity dispersion curves for the free pipe, without embedding material. Part (b) shows the phase velocity curves for the pipe when embedded in concrete. Part (c) shows the attenuation curves for the embedded pipe. The attenuation is caused by the leakage of energy from the pipe into the surrounding concrete. The curves were calculated using the modelling software DISPERSE (Pavlakovic et al, 1997). These plots illustrate clearly the way in which the curves are modified by the presence of the embedding material, including the appearance of discontinuities. The attenuation curves show the very high rates of leakage of the sound away from the waveguide.

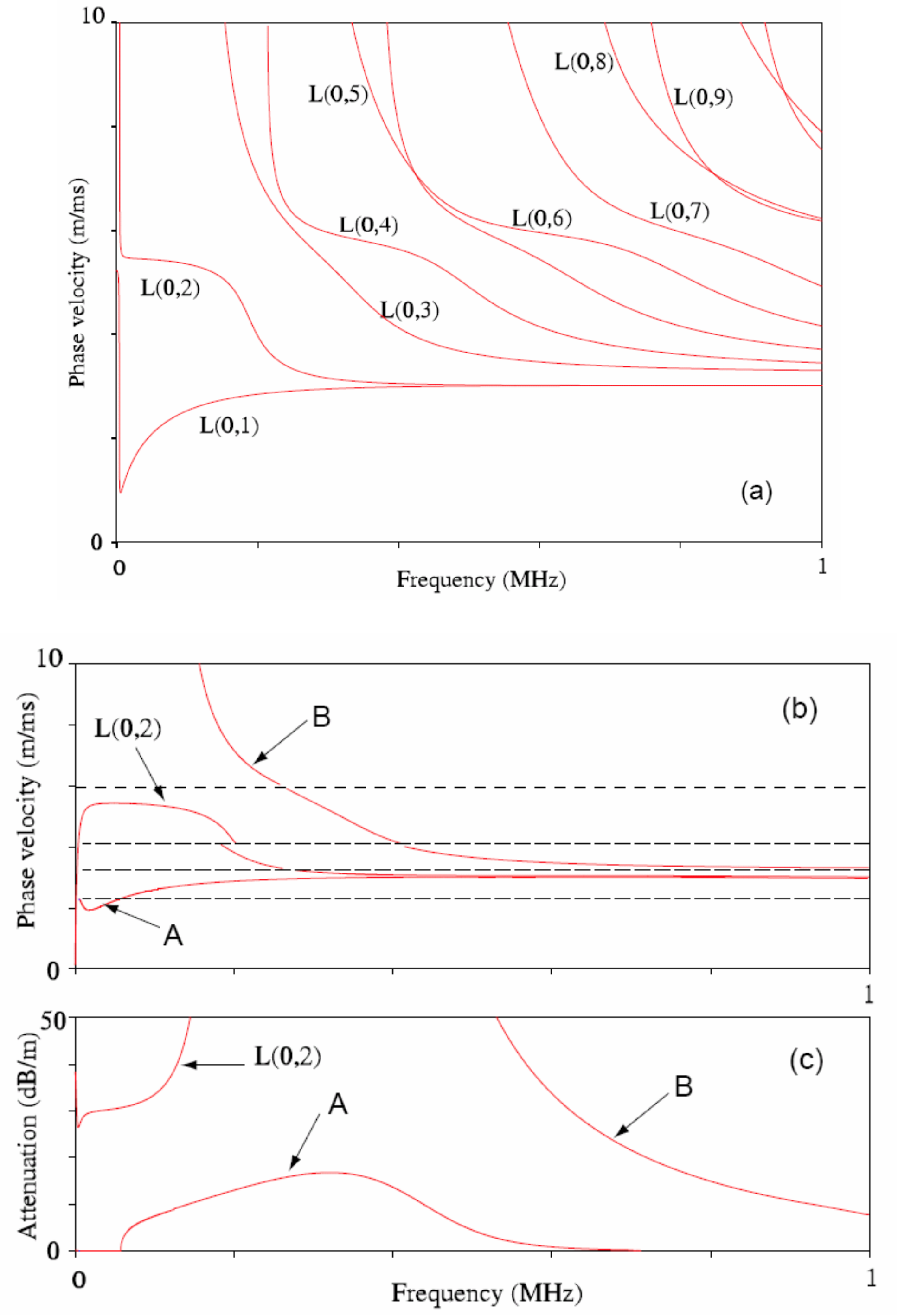


Fig 4.1 Dispersion curves for a 6 inch schedule 40 steel pipe, showing only the order 0 and order 1 modes. (a) Phase velocity for free pipe; (b) Phase velocity for pipe embedded in concrete; (c) attenuation for pipe embedded in concrete.

Figure 4.2 shows dispersion curves for a cylindrical steel bar embedded in concrete. This case was studied extensively by Pavlakovic et al (2001) and Beard et al (2002). Part (a) shows the energy velocity of the waves. This is the velocity at which a wave packet travels, and would be equal to the group velocity in an attenuation-free waveguide. The horizontal axis is plotted as frequency-radius, indicating how the results can be scaled according to the radius of the bar. Part (b) shows the attenuation of the waves, again using radius scaling. This case also shows the modification of the waves by the embedding material and the high levels of attenuation to expect. The letters A, B and C show corresponding positions on some interesting locations on the curves in parts (a) and (b) of the figure. Positions A and B identify minima in attenuation, when the waves travel with least loss of energy, whereas position C shows a relatively high attenuation after only a small change of frequency from position B. The labels on the modes correspond to the convention for waves in cylindrical waveguides, and are explained in Pavlakovic et al (2001).

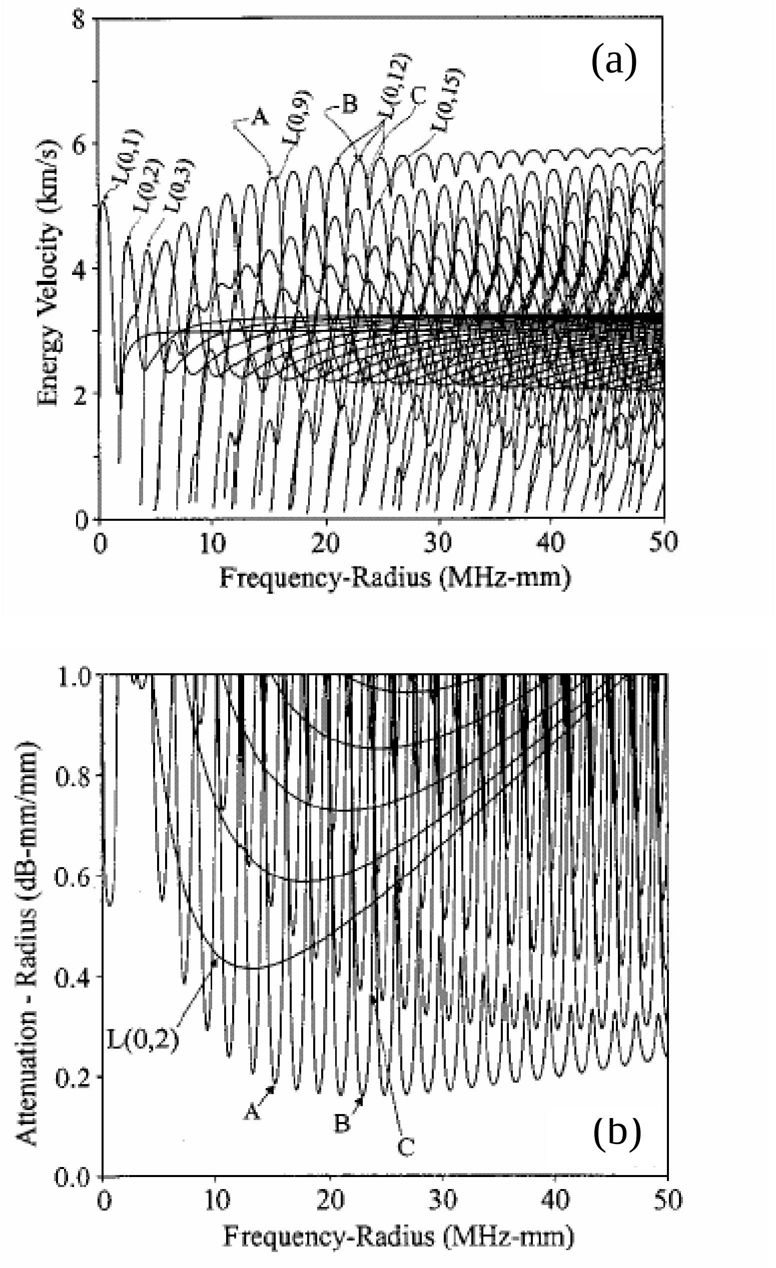


Fig 4.2 Dispersion curves for a steel bar embedded in concrete, showing only the order 0 modes. (a) Energy velocity; (b) Attenuation. After Pavlakovic et al (2001).

The reflection of waves at locations where there are changes to the embedding material is of most interest when the change is the entry of the waveguide into the material. This occurs where a pipe passes into a concrete wall (Demma et al 2003c), or an anchor bolt enters concrete or rock. Figure 4.3 shows predictions of the reflection coefficient of the extensional mode, L(0,1), for a steel bar entering a polymer adhesive (Vogt et al, 2003), this being a convenient case to study the physics of the phenomena. The reflection coefficient is the ratio of the amplitude of the reflected signal to the signal which is incident at the entry location from the free side. The horizontal axis is scaled with the radius and the results for 3 different radii are plotted. The graph shows that the reflection coefficient drops as the radius or frequency is increased. Thus we see that high frequency signals pass the entry more readily and cleanly than low frequency signals.

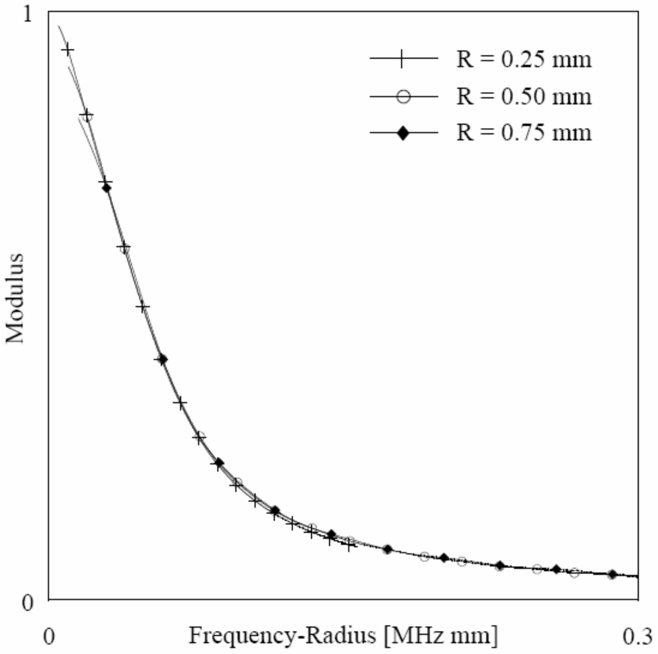


Fig 4.3 Spectrum of reflection coefficient for L(0,1) mode in cylindrical steel bar at location where bar enters polymer adhesive. After Vogt et al (2003).

4.3 Inspection approach

The key concern for practically all embedded cases is the attenuation due to leakage of energy from the waveguide into the surrounding material. As a rule of thumb, the attenuation goes up when the acoustic impedance of the embedding material is closely matched to that of the waveguide. Thus the strongly loaded waveguide cases suffer the highest attenuation. The severity of the attenuation prevents long range inspection in all strongly loaded embedded cases which have been studied so far, but successful approaches have been developed for several short range cases.

The inspection of pipelines embedded in concrete is possible when the embedded length is modest, such as when passing through a wall. The permissible wall thickness depends on many factors, including the pipe dimensions, the properties of the wall, the chosen mode and the chosen frequency. The attenuation curves for the embedded pipe in Figure 4.1c give an example of the loss to expect. The inspection of pipes passing through walls whose thickness is of the order of the pipe diameter is thus possible using the regular extensional and torsional modes and this is done routinely by the commercial operators. An important consideration when doing this is the choice of frequency: higher frequencies are preferable to minimise the entry reflection while lower frequencies may be better for the range penetration through the wall.

An alternative for the inspection of embedded pipes is to employ different modes from the regular extensional or torsional choices, exploiting modes and frequencies where the attenuation is predicted to be lowest. One example is the dispersion curve labelled "A" in Figure 4.1. At low frequency this guided wave does not leak energy into the concrete at all, although it would attenuate to a modest extent because of damping and scattering properties of the concrete (not included in the predictions of the figure). At higher frequencies it leaks, but not as severely as other modes do. Another example is the mode at higher frequency, marked "B" in Figure 4.1; this mode has low attenuation at high frequency because the energy is concentrated near the inner wall of the pipe, and so has little coupling to the concrete on the exterior. These ideas have not been developed for regular routine inspection, but they are likely to be feasible for some special circumstances, and useable over modest distances of inspection, for example a few pipe diameters.

The inspection of embedded bars is a well developed research topic, and is sufficiently understood for optimised exploitation (Pavlakovic et al, 2001; Beard et al, 2002, 2003a,b). The most successful application is in the mining industry, using guided waves to measure the lengths of security bolts in rock, thus demonstrating their integrity. The technique uses a transducer on the exposed end of the bolt and a pulse-echo measurement from the remote, embedded end. A pulse-echo range of up to 3m is achieved in typical 20-25mm diameter bolts, and as a rule of thumb this range can be scaled approximately linearly with the bolt diameter. The range is achieved by using the mode with the lowest attenuation, indicated by the label "A" in Figure 4.2. Interestingly, this results in the selection of a high frequency for the inspection, typically around 2 MHz, which is quite contrary to conventional expectation.

A much-needed goal would be the development of a guided wave inspection method for reinforcing bars in concrete, a particularly high profile application being the inspection of tendons in post-tensioned concrete bridges. A number of research groups have investigated this idea, but it has been shown (Pavlakovic et al, 2001; Beard et al, 2003a) that the attenuation of all of the possible guided waves is too high to allow the inspection of whole spans of bridges. Nevertheless, using the low-attenuation bar mode, it would be possible to inspect the critical first few metres from the anchor location.

4.4 Guidelines for inspection

The use of guided waves for inspecting embedded waveguides requires a much higher level of skill and training than for those which are exposed. As discussed in section 3.2, Guided Ultrasonics Ltd have introduced a Level 2 operator training course and qualification, and only these inspectors are considered to be qualified to inspect the more challenging cases. However, the common and relatively simple case of pipes which pass through walls can be tackled by a Level 1 operator under the supervision of a Level 2 operator; thus there is recognition that the task is more difficult than for exposed pipe, but is manageable routinely. The additional training for the more challenging tasks is required to develop the judgement for the choice of mode and frequency, and for the interpretation for the signals, to deal with the complex problems of attenuation and entry reflections. Even so, these inspections are limited to the use of the usual extensional and torsional modes; the exploitation of the special modes such as the non-leaky mode in Figure 4.1 has not been taken beyond research studies.

A very important practical consideration which has not been discussed so far is the quality of the bonding of the embedding material to the pipe. The model studies of pipes and bars embedded in concrete have assumed perfect bonding of the concrete to the waveguide, and indeed experience indicates that this is achieved in very many cases. However, it is quite common in practical testing of pipes in concrete for the bond to be found to be imperfect (Demma et al, 2003c), in which case the guided wave may travel along the embedded section without influence from the concrete. A possible reason for this is stressing of the interface in service, either through thermal cycling or vibration from pumps, but it is also possible that concrete shrinkage or movement damages the interface during manufacture. Thus in practice it is useful to attempt to assess the condition of the interface prior to inspection, since a weak interface may make the inspection task much easier.

When making the measurements, the amplitude of a reflection from a known feature on the far side of a wall, for example a weld or flange, can often be used to estimate the attenuation by the contact with the wall, and thus to set DAC curves.

5. Testing past features

The current practical capabilities for inspecting past features are discussed in section 3.1. Field experience has been vital for developing practical strategies, particularly in ill-defined cases such as clamped supports where the tightness of the clamps can greatly influence the interrogating signal. However scientific studies also inform and underpin the practical judgments. Here we discuss the nature of the effect of features on waves and cite some research work aimed at improving the capability of inspecting the pipe region beyond features.

5.1 The influence of features on guided waves

Guided waves are scattered by any changes to the geometry, material properties, supports or attachments of the guiding structure. Thus loss of material due to corrosion or separation of parts of material by cracking present geometrical changes which cause the reflections that are used for the inspection of pipelines. However, reflections are also caused by joints, valves, supports, bends, and indeed any changes to the regular run of a pipeline. Furthermore, the multi-mode nature of guided waves means that energy can be reflected in mode conversion to modes other than that of the incident signal.

Reflections from such changes, or features, are sometimes useful. For example, the well-characterised reflection from butt welds with weld caps in pipes is used in practice to calibrate the amplitude of the signal and thus to set Distance Amplitude Correction (DAC) curves. The axially symmetric nature of this reflection is also used conveniently to distinguish it from the non-axially-symmetric reflections from any defects at the same location, as discussed earlier. But most reflections from features are not useful, presenting challenges for inspection. Indeed the presence of features is normally the limiting characteristic in determining the range of inspection which can be achieved from any transducer location.

The proportion of the energy of the wave which is scattered by a feature is determined by the extent of the change to the waveguide properties. From an engineering perspective, this can be considered as an impedance characteristic: large changes to the impedance cause large reflections. A good example of a large change of impedance is a flange joint on a pipe. The change of the cross section from a pipe to a flange and then the change of material from the a flange to a gasket present enormous changes of impedance and practically all of the energy in the signal is reflected. On the other hand, the reflection from a butt weld is small because the weld cap and weld bead present only a small change to the geometry. Large reflections from features are troublesome because the unwanted signals complicate and can mask wanted reflections from defects, but the energy going into them also reduces the amplitude of the remaining interrogating signal travelling forward in the pipe. In practice the spatial separation of multiple signals depends on the frequency and the form of the signal; as a rough guide, a typical short signal consisting of a 5 cycle tone burst would require at least 5 wavelengths separation between reflectors in order for separate reflections to be identified.

In thinking about the scattering of energy by features, it is also necessary to consider the shape of the feature and the mode shape (shape of displacement) of the wave. Signals are reflected strongly when the shape of the feature is such that it perturbs the shape of the wave. This is a practical interpretation of advanced arguments based on the theorem of reciprocity; more detail of the concepts can be pursued for example in Auld's well-known text (Auld, 1990), and an explanation of the interpretation of these ideas in the context of guided waves is given in Lowe et al (2002a). For our purpose here it should be sufficient to illustrate this by two examples. In the case of the detection of an axially aligned crack in a pipe, it is found that the torsional wave (T(0,1)) reflects very much more than the extensional wave (L(0,2)). The reason for this is that the shear stress of the torsional wave causes shearing along the crack (a jump of the axial displacement from one face of the crack to the other), thus perturbing the shape of the wave. On the other hand, the extensional wave passes by the crack without causing significant difference in displacement from one side of the crack to the other. Similarly, when considering an axially aligned feature, such as an axially welded support plate, the torsional wave is reflected much more strongly than the extensional wave, in this case because the torsional wave imparts circumferential motion to the support plate.

5.2 Effect of bends on the properties of the guided waves

As discussed in section 3.1, bends affect the waves in 2 ways: the signal is scattered from the welds and it is mode converted in the curved region. Pulled bends are generally less severe than fabricated ones because the larger radius causes weaker mode conversion. The distance between welds in pulled bends also tends to be larger, so that the separate reflections can be identified more reliably. The outcome is that it is possible to inspect pipes beyond one or two pulled bends (provided they have bend radius to pipe diameter ratio above about 3), but the signals need to be interpreted with care, and the inspection cannot be extended beyond any further features downstream. The interpretation depends on understanding of the nature of the modes which propagate beyond the bends.

Demma et al (2005) studied the reflection and transmission of waves in bends, using simulation models and experiments. They considered the case of a pipe consisting of a straight section followed by a uniformly curved bend followed by another straight section. The study included ranges of radius of curvature and of angle of curvature of the curved section. The extensional (L(0,2)) or torsional (T(0,1)) mode was incident in the straight section and both the reflected and the transmitted signals were studied.

A key to revealing the nature of the behaviour in bends was the calculation of the dispersion curves. As a first approximation, one might assume that low frequency waves in a curved pipe should travel similarly to those in a straight pipe. However, Demma et al (2005) showed that the curvature introduces the possibility of slightly different modes and that interference phenomena between these determine what happens to the transmitting signal. Figure 5.1(a) shows the dispersion curves for the extensional (L(0,2)) and flexural (F(1,3)) modes in a straight steel pipe of 2 inches outer diameter and 5.5mm wall thickness. Part (b) of the figure then shows what happens if the pipe is bent to a curvature radius of 0.45m.

The significant difference can be seen here that the curved pipe has two possible flexural modes with slightly different speeds: one acts in the plane of the bend while the other acts at right angles to this. The difference between these two modes increases as the radius of curvature is decreased. The incident L(0,2) wave arriving at the bend mode-converts some of its energy to the in-plane F(1,3) mode. At the exit to the bend mode conversion takes place again, converting energy back to the extensional mode in the straight pipe. However, the re-conversion is not in phase, because of the different speeds of the L(0,2) and F(1,3) modes in the bend, and so there can be a constructive or destructive combination. Thus the amplitude of the transmitted wave depends on both the curvature and the length of the curved section, as well as the frequency. The value of the outcome from this is not obvious but must be considered on a case by case basis. This point is illustrated by the example of transmission coefficients shown in Figure 5.2

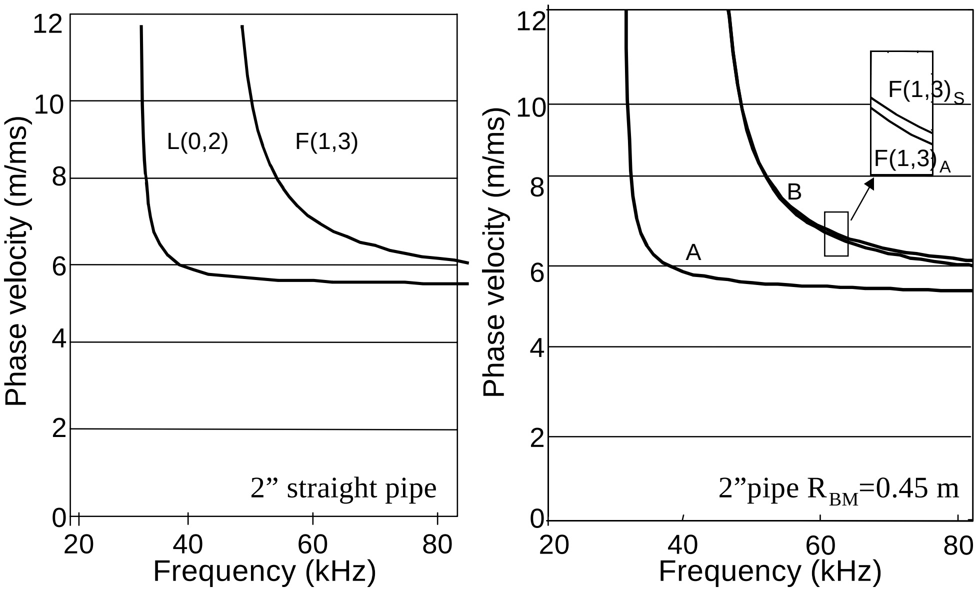


Fig 5.1 Comparison between dispersion curves for a straight pipe and those for a curved pipe. (a) Fundamental extensional and flexural modes for a 2 inch diameter (5.5mm wall thickness) steel pipe; (b) The equivalent modes in the same pipe when bent to a curvature radius of 0.45m. After Demma et al (2005).

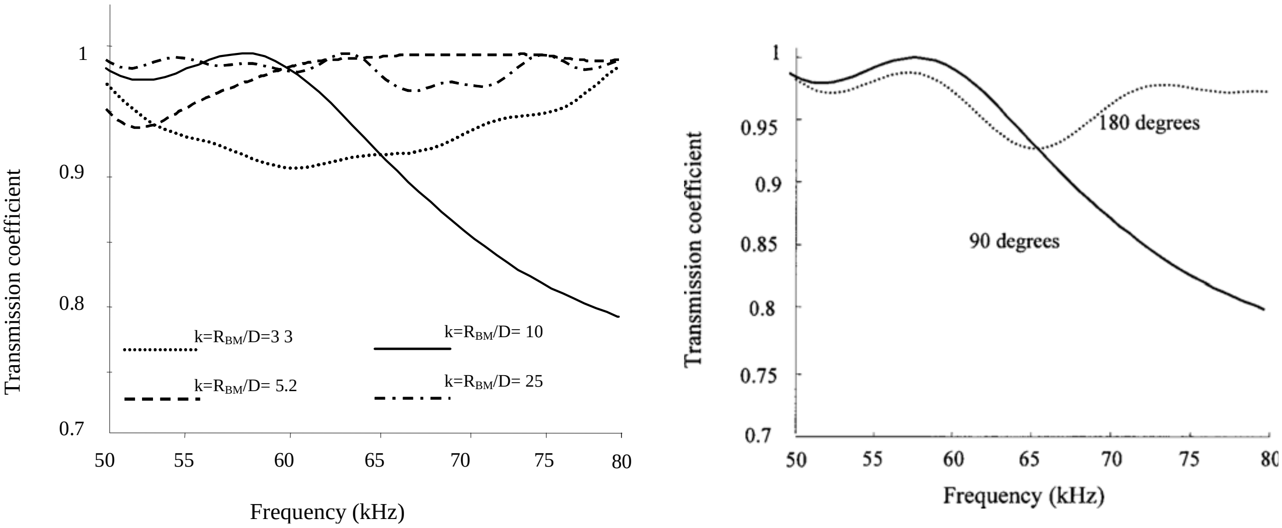


Fig 5.2 Predicted transmission coefficients for extensional mode (L(0,2)) passing through bend of 3 inch pipe (wall thickness 5.5mm). (a) Coefficients versus frequency for different bend radii; (b) Coefficients versus frequency for different bend lengths. From Demma et al (2005).

Another approach for detecting defects beyond bends has been investigated by Rose and co-workers, see for example Rose et al (2003, 2005), Li et al (2002). They have developed a strategy of focusing the guided waves at particular axial and circumferential positions in pipelines in order to improve the sensitivity of detection at those chosen locations. In the context of pipe bends the attraction of such an approach would be to make sensitive inspections of the pipe wall in the bend region and in the near distance on the far side of it. One way to focus the energy on target locations would be to use a phased array of guided wave transducers. However, avoiding this hardware necessity, they identify and demonstrate an alternative possibility for pipe bends through "natural focussing" (Rose et al, 2005). This exploits the way in which the bend affects the waves passing through it, different ray paths being affected to different degrees. They vary the frequency of the signal, and also the amplitudes of the elements in the transducer ring, and thereby create the focusing. However, the focusing approach assumes that the geometry of the bend is known, whereas in practice there are often pipe schedule changes and misalignment which introduce considerable errors. More work on these issues is needed before the method can be considered to be a robust inspection tool.

5.3 Effect of step changes in thickness on guided waves

Step changes in thickness can occur where pipes of different wall thickness are butt-welded. The step introduces a reflection and causes a change to the transmission, though the axially symmetric nature of such a joint means that axially symmetric modes which are incident at the step do not mode convert to any non-axially-symmetric modes.

As far as the authors are aware, this problem has not been studied in the specific case of a welded pipe. However, the behaviour of the fundamental shear-horizontal (SH0) mode at a step in a plate has been investigated by Demma et al (2003a). The SH0 mode in a plate is very closely analogous to the T(0,1) mode in a pipe, and so the results for the plate can be used with confidence for the pipe case. Furthermore, the principles of the behaviour, as discussed in the paper, can be used to understand more about the nature of scattering from all kinds of step-like shapes. Indeed the purpose of the paper was to show how the reflection from a notch or crack can be understood in contributions for a step down followed by a step up. Example results for the reflection from a step up and from a step down are shown in Figure 5.3. In both cases the thinner plate is 50% of the thickness of the thicker plate, and the step is at one side of the plate, while the surface of the other side remains continuous across the joint. The modulus of the reflection coefficient at the step is given approximately by

$$R = \left| \frac{1-\alpha}{1+\alpha} \right| \tag{1}$$

where $\alpha = t_2/t_1$; t_2 is the larger thickness and t_1 is the smaller thickness i.e. $\alpha < 1$ for both up and down steps (Demma et al, 2003a). This gives a good approximation to the reflection coefficient modulus, giving R = 0.333 for a 50% step which is the low frequency asymptote seen in Figure 5.3. The vertical scale of Figure 5.3 is very fine and although the results are frequency dependent, equation (1) is a good approximation over the frequency-thickness range of interest in long range guided wave testing. Equation (1) is also a good approximation in pipes and it does not matter whether the change is at the inner or outer diameter provided that the diameter to wall thickness ratio is in the range normally encountered in practice i.e. the pipe is not very thick-walled. Equation (1) and Figure 5.3 relate to a sharp step; if the step is tapered over a significant fraction of a wavelength, the reflection coefficient can fall substantially and it is mimimal for a taper extending over many wavelengths. However, it should be remembered that at 50 kHz the wavelength of T(0,1) is about 60 mm so modest tapering to reduce stress concentrations does not have a significant effect.

6. Reflections from corrosion and cracks

The controlling mechanical characteristic of corrosion is the loss of a volume of material from the structure. This can be understood to represent a change to the impedance of the waveguide, and thus to cause scattering of the waves. Cracks, on the other hand, do not remove material, but by virtue of the disconnection of surfaces they still change the impedance and cause scattering.

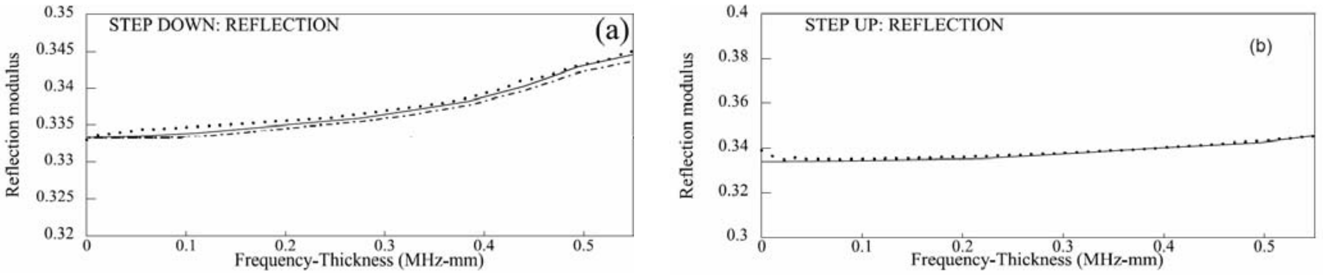


Fig 5.3 Predicted reflection coefficients for fundamental shear horizontal mode (SH0) incident at a 50% step change in the thickness of a plate. (a) Step down; (b) Step up. From Demma et al (2003a).

Real corrosion and crack defects are geometrically complex, requiring multiple parameters to describe them, and thus to characterise the reflection behaviour. Assumptions of simplified shapes reduce the number of parameters but the problem still remains challenging. In the case of a crack, the simplest assumption for any chosen orientation involves two further parameters: a length and a depth. In the case of corrosion, there are three: a length, a width and a depth.

The study of the scattering of ultrasonic waves from defects is a very large and involved topic which has evolved throughout the history of the development of NDT. Restricting attention to long range guided wave NDT, the literature is very much smaller, but nevertheless significant and indeed growing fast. We present here a summary of relevant work done on the reflection of waves from defects in plates and pipes. Although the application of guided wave inspection is easier in pipes then in plates (only one dimension rather than two), the theoretical principles for studying scattering are easier in a flat geometry then in a curved one, so it is logical to discuss the plate case before the pipe case. We then make some references to work done on the nature of the scattering; this kind of understanding can be helpful to make engineering judgements of likely detectability in cases which have not already been studied directly.

6.1 Reflections from corrosion and cracks in plates

The majority of work on the scattering of guided waves in plates has reduced the problem from three dimensions to two, by making the assumption of a plane strain section across a plate and defect. Thus the defect is assumed to be prismatic in shape, extending infinitely in the direction normal to the section, and the wave is assumed to be similarly infinite in that direction, and incident normally to the defect. These are gross simplifications, but nevertheless they do deliver very useful understanding about scattering.

A number of authors, particularly in early days, made analytical studies of the scattering of waves from defects in such a two-dimensional space, including Rokhlin (1980, 1981), King et al (1982), Fortunko et al (1982), Datta et al (1982). More recently the use of numerical methods has been favoured, principally using the Finite Element method (Koshiba et al, 1984, 1987; Alleyne and Cawley, 1992b; Lowe and Diligent, 2002a; Lowe et al, 2002b; Hayashi and Kawashima, 2002; Demma et al, 2003a) but also the boundary integral method (Cho et al, 1997; Cho and Rose, 1996; Zhao and Rose, 2003) and normal mode theory (Ditri, 1996; Castaings et al, 2002; Le Clezio et al, 2002). The majority of the modelling has been limited to simple shapes, principally straight cracks and parallel-sided notches, with the waves normally incident to the crack faces, in order to understand the principles and to limit the number of geometric parameters involved. This reflects the state of progress of the topic: although the numerical techniques are increasingly capable of addressing complex shapes of defects, the logic for exploiting the findings of the more complex cases is still being developed.

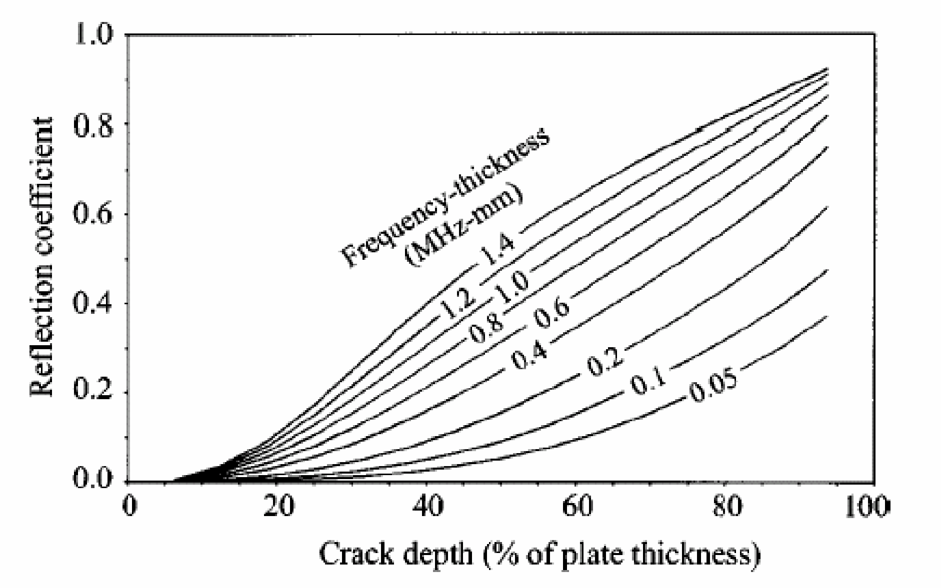


Figure 6.1 Reflection ratio of fundamental extensional Lamb mode S0, for S0 mode incident at a crack in a steel plate. Curves are for different values of the frequency-thickness product, where the thickness is of the plate. Predictions by Finite Element simulation. After Lowe and Diligent, 2002a.

Examples of results of guided wave scattering model studies are shown in Figures 6.1 and 6.2. Figure 6.1 shows the reflection coefficient of the fundamental symmetric mode S0 from a crack (Lowe and Diligent, 2002a) and Figure 6.2 shows the equivalent results for the case of the fundamental antisymmetric mode A0 incident (Lowe et al, 2002b). These results illustrate the power of modelling (Finite Element in this case) to produce a range of predictions of scattering behaviour covering the range of parameters of the problem. For completeness of the illustration, results of the remaining fundamental mode, the shear horizontal SH0 mode, were presented in Figure 1.3 and are discussed in the next section: conveniently the scattering of the fundamental torsional mode (T,(0,1)) from a circumferential crack in a pipe is the same as for the SH0 mode in a plate.

Moving on from the two-dimensional cases, a number of researchers have studied the three dimensional problems of guided waves in areas of plates, with the motivation of developing guided wave area inspection techniques; this has included much interest in recent years in Structural Health Monitoring (SHM). Some simplified analysis is possible if the fundamental modes are exploited at low frequency, because of the relative simplicity of the shapes of the displacement and stress fields through the thickness of the plate, particularly if the defect shapes are also simple. The majority of published work has considered the simplest problem of a circular hole through, or part-through, the plate. Further information on these studies may be found in Norris and Vemula (1995, 1997), McKeon and Hinders (1999a), Grahn (2003), Diligent et al (2002), Diligent and Lowe (2005). A key issue in the full three-dimensional study of scattering in plates is that in general there are two angular functions to consider in addition to the parameters of the defect itself: the orientation of the defect with respect to the incident beam, and the angle of interest for scattering. The latter is not a separate parameter in a conventional pulse-echo setup, but it does become an important consideration for the multi-transducer concepts that are often favoured for SHM applications. These parameters are conveniently avoided in the case of a circular hole but will be important for any non-circular shape. This is an ongoing area of work and there is much still to be done.

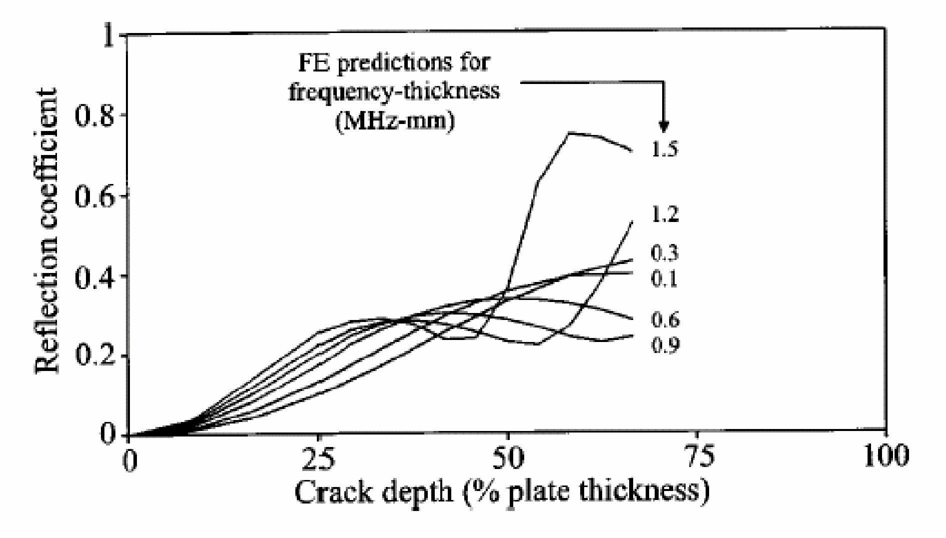


Figure 6.2 Reflection ratio of fundamental extensional Lamb mode A0, for A0 mode incident at a crack in a steel plate. Curves are for different values of the frequency-thickness product, where the thickness is of the plate. Predictions by Finite Element simulation. After Lowe et al, 2002b.

6.2 Reflections from corrosion and cracks in pipes

At a small scale local to a defect, much of the work which has been done on studying scattering in plates can be carried over to the pipe geometry. A clear example is the scattering of the fundamental torsional mode, T(0,1), for which, as discussed above, the results apply equally to the SH0 mode in a plate. There are also similarities between the fundamental extensional mode S0 in a plate and its counterparts in a pipe, the L(0,1) and L(0,2) modes (Lowe, 1998). These two examples are particularly convenient because the T(0,1) and the L(0,2) modes are the two most favoured for pipeline inspection. Thus in many cases the pipe can be considered approximately to be a plate which has been wrapped around into a cylinder. But the wrapping of the plate into a pipe introduces the possibility of waves whose direction of propagation has a component around the circumference, and thus which travel in spirals around the pipe. This, and some other effects of curvature, mean that the scattering of waves from defects must be studied properly in the context of pipes.

Most of the work which has been done on the scattering of axially-propagating waves from defects in pipes (Ditri, 1994; Alleyne and Cawley, 1996b; Zhuang et al, 1997; Alleyne et al, 1998; Lowe et al, 1998; Lowe, 1998; Bai et al, 2001; Zhu, 2002; Demma et al, 2003b) has been focused on obtaining knowledge of the sensitivity of proposed schemes for screening applications. The target of screening, rather than sizing, and the relatively long wavelengths, has conveniently enabled the technique to be developed on the basis essentially of a one-parameter representation of the defects. It was observed in early work (Alleyne and Cawley, 1996b) that the reflection of the extensional mode (L(0,2)) from a notch defect was not much affected when the notch was ground out to form a trough of the same depth. Thus the axial extent of a corrosion defect could be neglected, and the reflectivity is governed by the area of the defect as seen in the cross-sectional view along the pipe. Notches which are not aligned perfectly normal to the axis of the pipe have not been studied, but it is expected that they would not affect this observation significantly, provided that the range of axial location of the notch remains much shorter than the wavelength. More detailed discussion about the axial extent can be found in Demma et al (2004).

Careful laboratory work using machined notches in 3 inch steel pipes, combined with Finite Element simulations, demonstrated this assumption to be sensibly accurate (Alleyne et al, 1998; Lowe et al, 1998). Some key results from these papers are presented in Figure 6.3. Part (a) shows the extensional mode (L(0,2)) reflection coefficient versus notch depth for a notch which extends around 11% of the circumference of the pipe. This shows that the assumption of a linear relationship between reflection coefficient and defect cross-sectional area is not precise but is a reasonable engineering approximation. Part (b) shows the reflection coefficient versus circumferential length for the case in which the notch is through the whole wall of the pipe. The strength of conversion into two of the non-axially symmetric modes is also shown; this information is used to discriminate between defects and welds, as discussed in section 1.5 above.

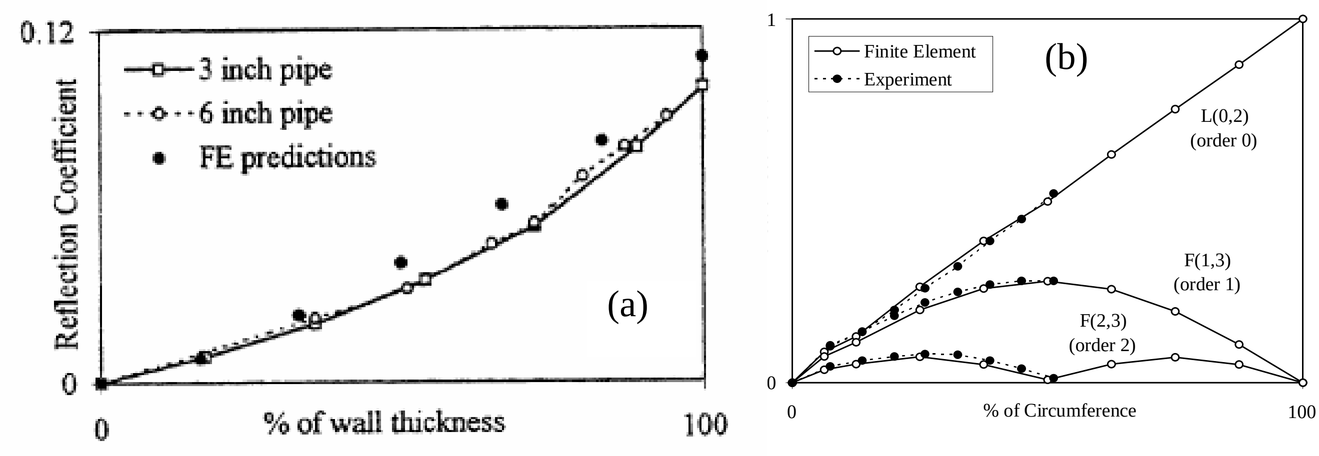


Figure 6.3 Reflection coefficient predictions and measurements for the fundamental extensional mode L(0,2) at 70 kHz incident at a circumferential notch in a pipe; (a) a part-depth notch extending around 11% of the circumference; (b) a through-thickness notch extending around part of the circumference, also showing scattering conversion to other modes. After Alleyne et al, 1998; Lowe et al, 1998.

Models combining these two effects, that is to say, for defects which are simultaneously part-depth and part-circumference, were also run, demonstrating that the reflection coefficient for any such case could be combined simply by multiplying the coefficients from parts (a) and (b) of the figure (Demma et al, 2004). Very similar results have been found for the torsional mode (T(0,1)) (Demma et al, 2003b); example results for that mode were shown earlier, in Figure 1.3.

The studies supporting the screening applications have built up sufficient knowledge for developers to be confident about understanding the scattering behaviour of axially-propagating waves for corrosion defects and for circumferentially aligned cracks, in other words when the defect has a significant footprint in the section across the pipe. The significant other case is cracks which lie along the axis of the pipe. This has received very little attention, although the principles discussed earlier in Section 5.1 can readily be applied and are observed in practice. The extensional wave (L(0,2)) does not cause significant change of displacement across the crack, and so it hardly reflects at all. On the other hand the torsional mode (T(0,1)) causes shearing of the crack faces (a jump in the axial displacement values from one face of the crack to the other), and so reflects much more strongly. Liu et al (2006) have reported on this effect with axially-aligned notches.

Also, Shin and Rose (1998) have considered the use of flexural waves, which similarly are reflected from cracks in this alignment.

Guided waves propagating around the circumferential direction of pipes have also been considered (Wilcox et al, 1996; Lu and Qu, 1998; Valle et al, 1999, 2001; Gridin, 2003; Luo et al, 2004; Zhao and Rose, 2004). Such an approach has application for a local inspection when only one side of a tubular structure is accessible, or for inspecting pressure vessels or under saddle supports of pipes. An important task in these studies was to investigate the significance of the curvature on the waves, and thus to ascertain when it is permissible to approximate the guided wave behaviour around a cylinder as that in a flat plate. The result depends on the wave mode under consideration, but as a rough guide, it seems that cylinders may be approximated as plates when the radius to thickness ratio is about 10 or more. The scattering itself is not significantly affected unless the curvature is very sharp, so for engineering purposes it is sufficient to use the scattering results which have been established for defects in plates.

Another category of waves travelling around a curved surface is creeping waves. These are observed to travel around the free surface of a hole in a plate and are somewhat similar to a Rayleigh wave on a curved surface. Nagy and co-workers (Nagy et al, 1994; Hassan and Nagy, 1997) calculated the solutions for the properties of these guided waves, and used them to develop a method of inspecting cracks starting from holes in plates in aircraft structures. Whereas this work is a little outside the scope of long range guided wave NDT, the existence of such modes is important for considering the nature of the interaction of waves with defects, since creeping waves around defects can affect the scattered signal. Creeping waves were observed, for example, in the studies of scattering of Lamb waves from circular holes in plates (Diligent et al, 2002).

6.3 The nature of guided wave scattering

It is evident from the discussion so far that the scattering of guided waves from defects is a complex problem. Good understanding has been gained in a number of cases of wave modes and kinds of defects, driven by the developments of techniques for particular applications. But there is much to do, and new candidate inspection cases emerge as the use of guided waves grows. Therefore an important aspect of the work on scattering is the development of understanding of fundamental principles which can lead to good engineering judgment. Many of the papers cited earlier in this section, particularly those involving analytical study, reveal the nature of the scattering in addition to the raw values of the scattering coefficients. This is a large topic, but we think it useful to summarise here a few of the observations.

- The strength of reflection of guided waves from defects varies enormously with the choice of mode and frequency, and the shape and orientation of the defect. A mode must be chosen to have significant stress in the appropriate direction at the location in the thickness of the waveguide where the defect is to be found. Furthermore, unlike conventional ultrasonic inspection, the strength of reflection for a chosen mode does not increase simply with the frequency. This is because the shapes of the displacement and stress fields vary with frequency, and therefore so does the nature of the interaction. The S-Parameter approach of Auld (1990), based on the principle of reciprocity, is a rigorous approach which nevertheless is amenable to an engineering conceptual application and is very useful for assessing the likely sensitivity of candidate modes. It implies that scattering will be strong if the stresses of the incident wave are such that they impose a large discontinuity in displacement at the defect. Thus, for example, a wave whose stresses are such that they cause a crack to open and close will tend to be scattered strongly. Some discussion of these ideas is given by Lowe and co-workers (Lowe, 1998; Lowe et al, 1998; Lowe and Diligent, 2002a; Lowe et al, 2002b).

- The experience of the development of guided wave screening techniques seems to show that the reflection behaviour is not particularly sensitive to the shape of the defect (Alleyne and Cawley, 1996b). Thus the strength of the reflection of the guided waves from corrosion defects is not affected strongly by the shape of the corrosion. This observation is very helpful for screening, but it is important to be careful here to limit drawing conclusions for all guided wave cases. In fact the insensitivity is limited to long wavelength cases, where the axial extent of the defect is relatively short.

- The scattering behaviour at complex defects can be determined by the superposition of scattering results for simple constituent shapes. For example, Demma et al (2003a) showed that the scattering at a notch can be constructed from the results for a step-up and a step-down in the thickness of a plate. The result is a function of the interference between these two solutions and so varies with changes of the notch width. They also examine how the zero-width-notch limit of this approach can be used to study a crack. The examples of Demma et al (2003a) showed that this simple superposition approach works well with separation between the constituent shapes down to approaching 1% of the wavelength; at smaller separations, the interaction of non-propagating modes generated at one feature interacting with the next becomes significant and the accuracy of the method is reduced.

- The scattering of guided waves has many parallels to the very large literature on the scattering of bulk waves. The established literature on the latter tends to categorise cases according to the wavenumber and the characteristic dimension of the defect, the "ka" value. At small values of ka, the scattering is often amenable to quasi-static analysis, involving fracture mechanics and crack opening displacement concepts, whereas at large values of ka, the scattering is amenable to ray-theory kinds of analysis. The most difficult range is at values of ka close to unity, when the asymptotic approaches of neither extreme are valid. Unfortunately this is the case for many (but not all) examples of the scattering of guided waves in the context of the applications which have been discussed in this document. Some discussion of these ideas, and means to exploit them, is given in Lowe (1998), Lowe et al (1998); Lowe and Diligent (2002a), Lowe et al (2002b) and Demma et al (2003b).

7. Sizing

To date, the application of guided waves to long range inspection of pipelines has been to screening. The strategy is to use the technique to check long lengths of pipe rapidly, and then to follow up with local inspection using conventional methods if the screening identifies locations of concern. The method therefore only gives an approximate indication of defect severity corresponding roughly to the cross sectional area of the defect, as discussed earlier in this report. Applications of guided waves to the inspection of plates has so far followed the same concept of screening (Wilcox et al, 2005; Fromme et al, 2005).

However, attention amongst researchers is now being applied to the possibilities of using guided waves for sizing, that is to say, to perform the follow-up task of characterizing a defect after the screening has found it. The motivation for this is to be able to inspect parts of the structure where access is difficult so that the conventional inspection cannot easily be deployed. Examples of this are pipelines buried in soil, pipelines passing through walls, or pipelines or vessels with possible corrosion under saddle supports. In such cases the emphasis is not particularly on long range, or rapidity, but on avoiding having to dig up or remove materials to obtain access.

A first approach is to work on improving the interpretation of existing signals. More detailed knowledge of the scattering behaviour could be used to improve the estimation of the severity of defects from the signals already obtained. This is done to some extent, in fact, in current testing. The extent of the mode conversion from the symmetric to the non-symmetric modes gives some indication of the circumferential extent of the defect, though the indication is very insensitive, particularly for small defects (Demma et al, 2004). The variation of the reflection with the frequency can also be used to distinguish between different kinds of reflectors. Also, detailed knowledge of how the reflections vary with defect shape, pipe dimensions and frequency can enable a more precise interpretation of the defect size. The effects of the various parameters were examined in detail by Demma et al (2004).

An alternative approach is to develop an array imaging technique in which multiple transducers are used to develop an image of the defect. Such an approach could be taken using the current arrangement of a ring of transducers around a pipe, or using a linear array on a plate, and indeed is also of interest in the growing field of Structural Health Monitoring. If the lateral extent of a defect can be determined by imaging, and the cross sectional area can be determined using the current approach, then it should be possible to obtain a much improved measurement of the key parameter, the depth. Reliable calibration of signal amplitude will be essential if the reflection coefficient from the defect is to be obtained sufficiently accurately to give a good indication of defect depth.

Research aiming at developing sizing techniques is ongoing in several organisations. With the current configuration of a ring of transducers, Rose and co-workers have identified that "natural focusing" at particular locations along the pipe length and circumference can be achieved by sweeping the frequency (Rose et al, 2003; Li et al, 2002; Hayashi et al, 2003; Sun et al, 2005). However the current trend is towards imaging procedures using multiple addressed transducer elements and processing built on imaging and tomography algorithms (Hutchins et al, 1993; McKeon and Hinders, 1999; Li and Rose, 2002; Sicard et al, 2002, 2004; Hayashi and Murase, 2005; Li, 2005; Davies et al, 2006). A basic array capability for pipe inspection is being offered by Plant Integrity Ltd (www.plantintegrity.co.uk).

8. Conclusions

Guided wave inspection of pipes is now in routine use worldwide. The technique offers the possibility of rapid screening of long lengths of pipework for corrosion and other defects. A test range of 50m or more (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. The test can also be applied in different geometries but detailed modelling and special transduction is usually required so the inspection is expensive for one-off cases.

Operator quality is a major issue for the true field capability of the technique and this is being addressed via hardware improvements to increase the number of automatic diagnostic checks on data quality, and also multi-level operator qualifications.

The pipe testing technique can be used in the presence of a range of common features, including butt welds, most kinds of supports, insulation and anti-corrosion coverings, and modest lengths of embedding in soil or concrete. It cannot be used for testing past major features such as flanges, or for long embedded lengths with highly attenuative coatings; these limitations are imposed by the physics of the wave propagation phenomena and are unlikely to be changed significantly by further research. Table 8.1 summarises the current capabilities and limitations (see also www.guided-ultrasonics.com).

Category	**Description**	**Characteristics**
Current, simple	Can be done easily using current available technology.	Long, straight, lines, with up to two bends. Butt welds with intervals greater than 5 metres. Some knowledge of pipe contents. Pipes exposed or covered in low density insulation. Pipes passing through walls (short distances). Light or modest corrosion, or cracks with significant circumferential alignment. Simple supports.
Current, advanced	Can be done using current available technology and specialist support	Pipes under road crossings. Sleeved pipes. Modest lengths of immersed or embedded pipes (under ground, in water, passing through thick walls) Pipes with a high density of features (bends, welds). Nozzles, Ts, welded attachments. Welded supports. Dense or strongly absorbing coatings. High levels of corrosion.
Feasible	May be achievable, but requiring development work	Complex attachments. Limited access with major features close to ring position.
Not feasible	Unlikely to be achievable	Long range (>15-20m) in highly attenuative systems; across flanges; detection of small, isolated defects (pin-hole type) at long range; pipe systems with inadequate access for transducer attachment.

Table 8.1 Summary of current capabilities and feasibilities for pipe screening.

Current research areas for pipeline inspection are largely related to focusing energy at specific locations in order to improve:

- confidence in making defect calls;
- sizing capability;
- inspection of features which give a reflection even in the absence of a defect;
- ability to test round bends.

The key area of research relating to applications other than pipelines is in the inspection of large areas of plate structures. Deployable and permanently attached arrays for imaging featureless areas of plates have been developed to prototype demonstration level. Work is ongoing in addressing the challenge of inspecting past stiffeners and other features, and in developing systems which minimise the number of transducers. The latter is of particular interest for Structural Health Monitoring (SHM) using permanently attached transducers.

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