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The Use of Guided Waves for Rapid Screening of Chemical Plant Pipework

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Abstract The safe operation of petrochemical plant requires screening of the pipework to ensure that there are no unacceptable levels of corrosion. Unfortunately, each plant has many thousands of metres of pipe, much of which is insulated or inaccessible. Conventional methods such as visual inspection and ultrasonic thickness gauging require access to each point of the pipe which is time consuming and very expensive to achieve. Extensional or torsional ultrasonic guided waves in the pipe wall provide an attractive solution to this problem because they can be excited at one location on the pipe and will propagate many metres along the pipe, returning echoes indicating the presence of corrosion or other pipe features. Guided Ultrasonics Ltd have now commercialised the technique and this paper describes the basis of the method, together with examples of practical test results and typical application areas.

1. Introduction

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

The use of cylindrical 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. There has been a considerable amount of work on the use of guided wave for the inspection of pipes and tubes, most of which has been on small (typically 1 inch or 25.4mm) diameter heat exchanger tubing (see, for example, Silk and Bainton (1979); Böttger et al. (1987); Rose et al. (1994); Mohr and Höller(1976)).

The authors have developed a guided wave technique designed for the screening of long lengths(>10m) of pipes for corrosion. It seeks to detect corrosion defects removing of the order of 5-10% of the cross sectional area of the pipe at a

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particular axial location. It was originally developed for use on pipes in the 2-24 inch(50.8~609.6mm) diameter range, though it can be used on both smaller and larger pipes; there have been recent applications to 36, 48 and 52 inch lines. This paper discusses the basis of the technique and presents recent practical results from different sites; it concludes with a review of typical application areas.

2. Modes and Excitation

Only two ultrasonic waves exist in a bulk solid material (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). Fig 1 shows the group velocity dispersion curves for a 6 inch(152.4mm), schedule 40 steel pipe. There are about 50 modes below 100kHz and in order to obtain signals that can reliably be interpreted, it is essential that only one of them be excited. 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.

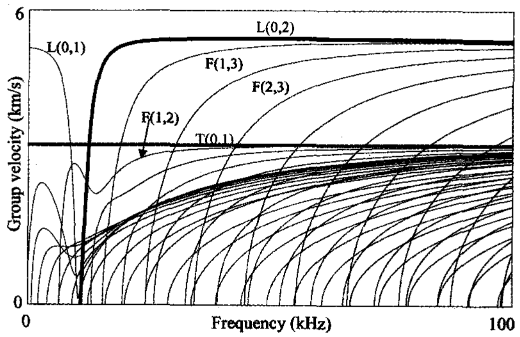

Fig. 1 Dispersion curves for 6 inch, schedule 40 steel pipe

The most attractive modes to use are those which have a mode shape which has uniform stress aver the whole cross section of the pipe. This means that there will be equal sensitivity to cross section loss at any location through the wall thickness or round the circumference. Modes with a simple mode shape are also easier to excite in a pure form which is important in controlling coherent noise. The two modes which meet these criteria are the L(0,2) and T(0,1) moses shown in Fig. 1. (The terminology used to describe cylindrical guided modes is discussed by Silk and Bainton(1979)). These are essentially extensional and torsional modes respectively. Both modes have the additional advantage of being non-dispersive over a wide frequency band, i.e. their velocities are constant with frequency which means that all frequency components of the input signal travel at the same velocity. This means that the input signal retains its shape as it propagates along the pipe, whereas a dispersive signal would spread in time as it propagates along the pipe, the maximum amplitude reducing and the signal duration increasing. Dispersion therefore reduces the signal to noise ratio and makes the spatial resolution poorer. These issues are discussed further by Alleyne and Cawley(1992); a technique for dispersion compenssation is described by Wilcox et al.(2001).

Alleyne and Cawley (1996) 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 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. When the transducers are used to excite the extensional (L(0,2)) mode, their long axis is aligned axially along the pipe, while to excite the torsional mode they are rotated through 90° so that the long axis is tangential to the pipe.

Initial site trials of the technique carried out in the research phase in the mid 1990s used the

L(0,2) mode at frequencies around 70 kHz and have been reported previously (Alleyne and Cawley (1997), Alleyne et al. (1997)). Propagation distances approaching 50 m were obtained and by using multiple rings of transducers it was shown to be possible to obtain uni-directional propagation. The field trials reported by Alleyne and Cawley (1997) and Alleyne et al. (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 mode, which has a much lower velocity than L(0,2) in the operating frequency range above 35 kHz as shown is Fig 1, is also 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. The original commercial implementation of the system marketed by plant Integrity Ltd (Mudge (2001)) uses three rings, but the Guided Ultrasonics Ltd. Wavemaker Pipe Screening System uses four rings which gives improved suppression of this unwanted mode.

The use of three or four rings adds the cost of the system and also to the mass, which becomes significant when larger pipe sizes are being tested. T(0,1) is the only axially symmetric torsional mode in the frequency range of interest, so axially symmetric torsional excitation will only excite the T(0,1) mode. This means that only two rings of transducers are required in order to obtain single mode, unidirectional excitation. The torsional mode also has the advantage of being non-dispersive across the whole frequency range (see Fig 1). As discussed above, torsional forcing can be achieved by simply rotating the same transducers used for the L(0,2) mode through 90° so that they apply force in the circumferential, rather than axial direction; this is implemented in the Guided Ultrasonics Ltd. Wavemaker Pipe Screening System.

The torsional mode also has the advantage that, in contrast to the L(0,2) mode, it does not involve radial displacement of the pipe wall. Therefore its propagation characteristics are not affected by the presence of liquid in the pipe so in-service inspection of lines carrying a liquid is straightforward. 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. In practice, the more convenient torsional mode is most commonly used, but in occasional special applications the longitudinal mode is employed. Conversion of the system between the two modes is straightforward.

3. Sensitivity to Defects

Guided waves such as L(0,2) and T(0,1) that have relatively uniform stress distribution over the cross-section of the pipe are sensitive to changes anywhere in the 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 dimensions are much smaller than a wavelength. The reflectivity of the L(0,2) mode from notches in pipes has been reported extensively (see, for example, Alleyne et al. (1998)). It has recently been shown (Demma et al. 2002) that the torsional mode reflectivity is very similar. For example, Fig. 2 shows finite element predictions of the reflection of the T(0,1) mode from an axially symmetric crack (i.e. a crack extending round the full circumference of the pipe) in a 3 inch(76.2mm) pipe with 5.5 mm wall thickness at different frequencies. It can be seen that the sensitivity increases with frequency.

Corresponding results are also shown for a 24 inch(609.6mm) diameter pipe with 20 mm wall thickness. It is interesting that the 24 inch, 10 kHz curve (frequency-well thickness product 200 kHz-mm) is just below that for the 3 inch pipe at 40 kHz (frequency-well thickness product 220 kHz-mm). This suggests that the sensitivity to cracks is a function of frequency-wall thickness product, as might be expected.

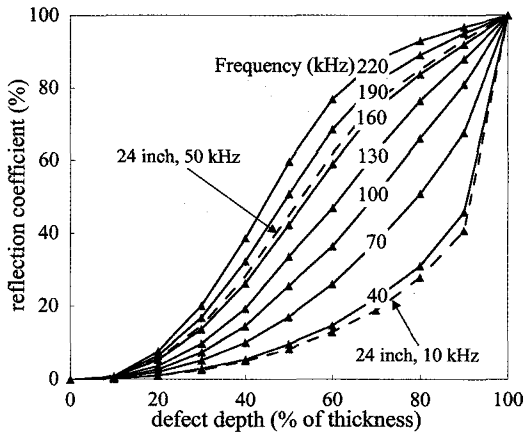

Fig. 2 Finite element predictions of T(0,1) mode reflection coefficient as a function of crack depth for axially symmetric crack in 3 inch, schedule 40 steel pipe at different frequencies. Corresponding data for 24 inch pipe shown at 10kHz and 50kHz

However, the main use of the guided wave pipe screening system is the detection of corrosion patches which have significant axial extent, rather than narrow cracks. It has recently been shown that the sensitivity in both the torsional and extensional modes increases rapidly as the axial length of the defect increases, reaching a maximum when the axial extent is 25% of the wavelength (Demma et al. (2002), Cawley et al. (2002); the extensional mode case shown in Fig. 3. (The L(0,1) mode is similar to that of the L(0,2) mode at higher frequencies). This behaviour is simply explained by interference between the reflections from the start and end of the notch. It is particularly interesting to note that the maximum reflection

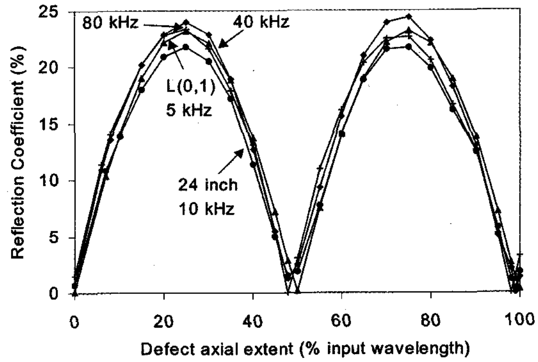

Fig. 3 Reflection coefficient as function of defect axial extent for 20% depth, axially symmetric notches. (L(0,2) mode in 3 inch pipe except where stated)

coefficient is very similar at different frequencies and pipe sizes, though since it is reached at an axial extent of 25% of the wavelength, the absolute length of the defect has to be higher at lower frequencies. This suggests that while low frequency testing is less sensitive to circumferential cracks, it may be more sensitive to defects with significant axial extent. This is potentially of great practical importance since propagation range can be greatly extended at lower frequencies as the attenuation reduces (see section 6).

The predictions done to date are for square-sided defects which are very rarely seen in practice. They suggest that it is wise to test at as high a frequency as possible, consistent with obtaining the required propagation range and maintaining a high signal-coherent noise ratio by avoiding the generation and reception of non-desired modes, since the sensitivity to defects with low axial extent is then maximised. It is also desirable to test at more than one frequency in order to guard against the possibility that a single test frequency coincides with a minimum in the reflection, due to interference effects. However, field experience has suggested that the reflection from real corrosion patches is often stronger at low frequencies. This may be a result of the scattered waves from successive 'steps' in a rough corrosion patch being more nearly in phase at low frequencies, and so summing to give a larger reflection than is seen at higher frequencies, where there is more phase cancellation. These effects are currently being studied. Current practice is generally to test at several frequencies; this reduces the risk of missing defects and also assists with feature classification.

4. Defect Identification

The initial site trials reported by Alleyne and Cawley (1997) and Alleyne et al. (1997) showed that corrosion defects of the target size (half wall thickness deep and half pipe diameter (16% circumference) in circumferential extent) could reliably be identified. However, echoes were also seen from butt welds since the weld caps are not generally removed so the weld presents a change in cross sectional area, and hence in effective acoustic impedance. For example, Fig. 4 shows a test on a 3 inch diameter pipe with a series of butt welds along its length. In this particular case, the pipe was not insulated so the welds could be identified visually. The presence of the echo from a good weld makes it difficult to identify defects at welds, and also introduces the possibility of a weld being incorrectly identified as a defect in cases where the pipe is insulated or buried so the weld cannot be seen This problem can be overcome by measuring the extent of mode conversion produced by a reflector.

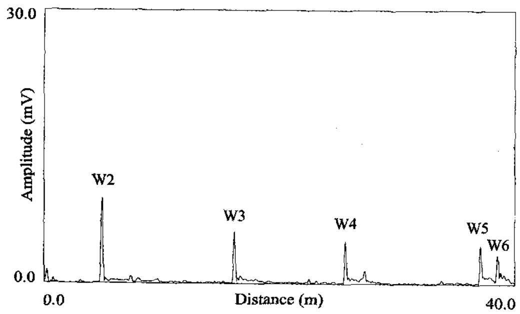

Fig. 4 Initial site trial using L(0,2) mode on 3 inch pipe with series of butt welds(marked W)

If an axially symmetric mode is incident on an axially symmetric feature in the pipe such as a flange, square end or uniform weld, then only axially symmetric modes are reflected. However, if the feature is non axially symmetric such as a corrosion patch, some non axially symmetric waves will be generated. These propagate back to the transducer rings and can be detected. If the 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 and mode shapes to the L(0,2) mode in the operating frequency range (see Fig. 1), while if the T(0,1) mode is incident, the most important mode conversion is to the F(1,2) and F(2,2) modes. The amount of mode conversion obtained depends on the degree of asymmetry, and hence on the circumferential extent of the defect. Fig. 5 shows the direct reflection and the mode converted reflections from a full wall thickness notch as a function of circumferential extent for a T(0,1) 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(1,2) 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. Combining this information with the amplitude of the reflection allows the severity of the corrosion to be estimated. The results of Fig. 5 are for a 3 inch pipe, but similar results are obtained with other sizes. Further details of the torsional mode case can be found in Demma et al. (2002); the extensional mode case is covered by Lowe et al. (1998).

5. Commercial Instrument

The Guided Ultrasonics Ltd. Wavemaker Pipe Screening System instrument and transducer assembly for an 8 inch pipe are shown on site in Fig. 6. The 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

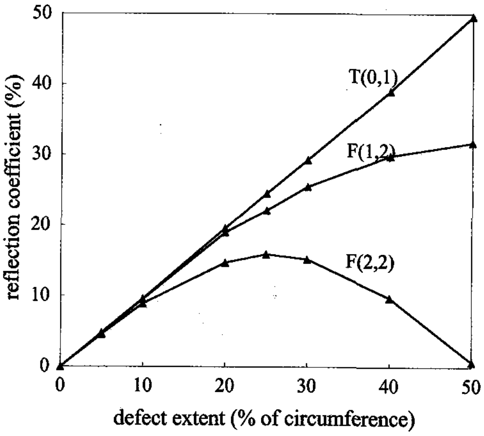

Fig. 5 Torsional mode reflection coefficient as function of circumferential extent for through thickness notch in 3 inch pipe at 50kHz. Mode conversion to F(1,2) and F(2,2) modes also shown.

to the instrument by an umbilical cable. In some cases it is convenient for the operator of the PC to be adjacent to the test location, but on other occasions it is better for the computer and operator to be in a van that can be up to 50 m from the test location. Solid rings of the type shown in Fig. 6 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 deployed offshore in Fig. 7. The assemblies shown in Figs. 6 and 7 are for the torsional mode so each contains two rings of transducers so that unidirectional excitation and reception can be obtained, as discussed above. No surface preparation is usually required.

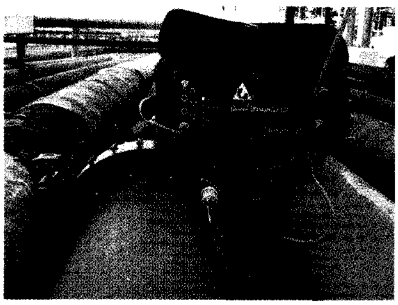

Fig. 6 Solid transducer ring for 8 inch pipe and battery powered test instrument on site.

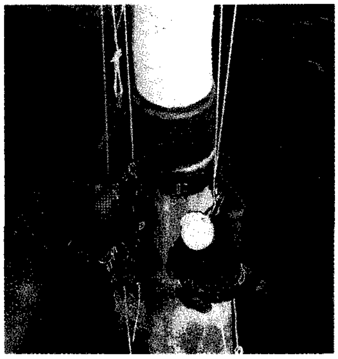

Fig. 7 Flexible transducer ring deployed offshore.

Fig. 8 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. 9 shows an example report generated by the Wavemaker WavePro software for an epoxy painted, 4 inch (101.6mm) pipe at a test position adjacent to a road crossing. The test range extends over more than 20 m on either side of the rings which are located in the middle of the plot. The software identifies welds and computes a distance-amplitude correction (DAC) curve for the welds. It then calculates the defect call level by comparison with the weld echo level and the calculated output amplitude, knowing that an average site weld is a -14 dB reflector. The 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.

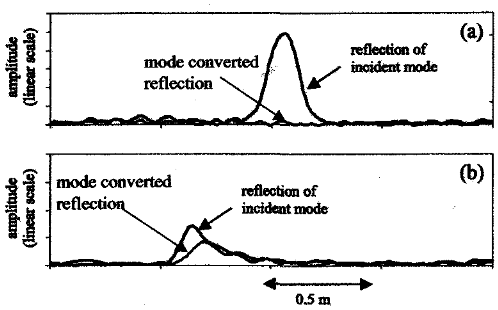

Fig. 8 Typical signals from (a) axisymmetric feature e.g. weld; (b) corrosion.

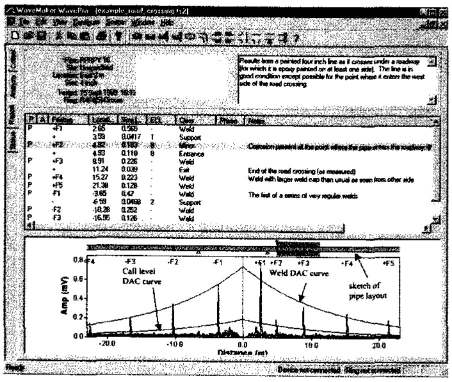

Fig. 9 Wavemaker Pipe Screening System report from test adjacent to road crossing.

6. Example Results

Fig. 10 shows an example of localised corrosion in a 3 inch pipe at the positions marked +F1 and -F1. These defects occurred at the location of pipe supports and were therefore difficult to detect visually. In each case, the defect is characterised by a strong mode converted (red) component. In the absence of corrosion, these simple supports would give minimal reflection. 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 reflec- tions from the welds placed immediately before and after the bend. In each case, the reflection from the second weld has a significant non-axisymmetric (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. These issues are discussed by Demma et al. (2001).

An example of defects at welds is shown in Fig. 11. This test was on an 8 inch pipe that had been used for carrying acid. There is a significant non-axisymmetric (red) component associated with the weld reflections, particularly those marked +F1, -F1 and -F3. This was due to internal erosion at the welds. There is also evidence of defects below the call level at the lacations marked -F2, -F4, -F6

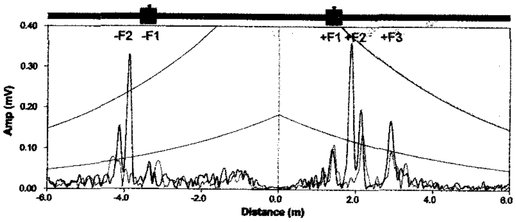

Fig. 10 Test result on 3 inch pipe with bends showing corrosion at supports.(black curve - axisymmetric, T(0,1) reflection; red curve - mode converter, asymmetric, F(1,2) reflection)

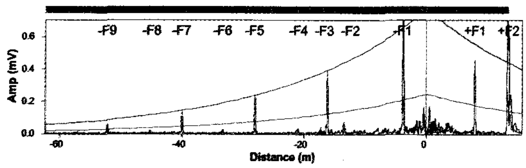

Fig. 11 Test result on 8 inch pipe showing internal erosion at welds. (black curve - axisymmetric, T(0,1) reflection; red curve - mode converted, asymmetric, F(1,2) reflection)

and -F8; the +F2 reflector is a flange. A clear signal is obtained from weld -F9 about 60 m from the transducer rings.

Fig. 12 shows a test on a 12 inch pipe at a road crossing, only the data from the direction of the crossing being shown. There is a severe defect at location +F2 indicated by a large reflection with a strong antisymmetric component. There is also evidence of corrosion at the entrance to the crossing (+F1) and another area of concern under the road at +F3. The reflection +F4 is from the far end of the crossing where the sleeve was welded to the pipe (it was not welded at the near end).

The examples of Figs. 10 and 11 used frequencies around 40 kHz; the frequency was reduced to 27 kHz in the case of Fig. 12 in order to increase the range under the road. However, the standard transducers are not designed to work below around 20 kHz and there are cases, particularly of bitumen coated pipe, where the range is insufficient at this frequency. For example, Fig. 13a shows the result on a 20 m long, 24 inch diameter bitumen

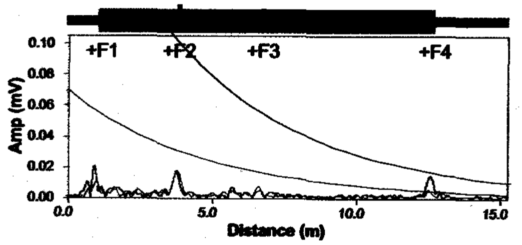

Fig. 12 Test result from 12 inch pipe at road crossing showing severe corrosion under the road. Only the signals from the direction under the road are shown. (black curve - axisymmetric, T(0,1) reflection; red curve - mode converted, asymmetric, F(1,2) reflection)

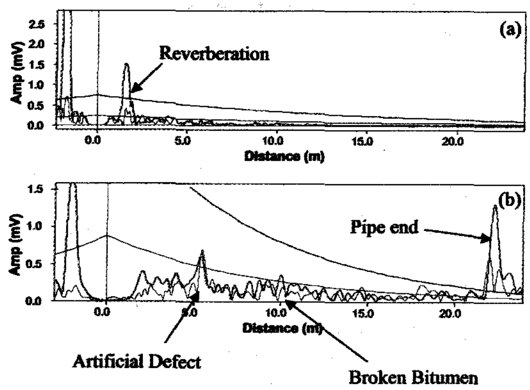

Fig. 13 Results from tests on bitumen-coated sample. (a) standard frequency transducers; (b) low frequency transducers. (black curve - axisymmetric, T(0,1) reflection; red curve - mode converted, asymmetric, F(1,2) reflection)

coated test specimen at a frequency of 27 kHz when the transducer rings were placed close to the left hand end of the pipe; the signal at the left of the trace is from the left hand end of the pipe, and reverberation from tihs end is also seen. The right hand end of the pipe cannot be seen at this frequency. The corresponding result using new, lower frequency transducers at a frequency of 12 kHz is shown in Fig. 13b where the right hand end of the pipe can clearly be identified, and the reverberation from the left hand end of the pipe has been suppressed by better cancellation of the signals from this direction. An artificial defect placed in the pipe is clearly seen and there is also an indication from a location where the bitumen was broken.

Table 1 indicates typical test ranges in each direction along a pipe obtained with the standard transducers for different pipe conditions. These ranges are doubled if the lower frequency transducers are used. The range is also limited by the number of pipe features encountered, typical maxima being 6 standard butt welds or two bends or branches. Features that are not significant reflectors such as simple, un-welded supports have little effect on the test range. Further example applications are given by alleyne et al. (2001), Sheard and McNulty (2001) and Wassink et al. (2001).

7. Conclusions

Guided wave inspection of pipes is now implemented commercially. The technique offers the possibility of rapid screening of long lengths of pipework for corrosion and other defects. A test range of 50 m (25 m (75 feet) in each direction)

Table 1 Typical ranges obtained with standard transducers. These ranges are doubled with lower frequency transducer.

Pipe condition	Range in each direction using standard transducers(m)
New, clean pipe	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 corroded pipe or pipe that is bitumen wrapped	5

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 technique is well suited for the inspection of pipes buried at road crossings and in this application, the ability to reduce the effect of attenuation by reducing the test frequency is particularly beneficial.

Typical applications are the rapid, full coverage screening of long lengths of pipe. The method is also commonly used for the inspection of difficult-to-access locations such as sleeved road crossings, insulated pipe, wall penetrations and areas where rope access is required.

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