WAVE ULTRASONIC TESTING AND HOW TO IMPROVE ITS CHARACTERISTICS BY VARYING OPERATIONAL PARAMETERS

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ABSTRACT - *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.*

1.1INTRODUCTION

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 .

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.

1.2 INITIAL DEVELOPMENT

Alleyne and Cawley 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 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.

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. Signal to coherent noise ratios of better than 40 dB were obtained on site (i.e. 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.

1.3 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. 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.

The frequency used does affect the spatial resolution and the range. The speed of the torsional wave is about 3.2 km/s, while that of the extensional 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 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 and Sonic Sensors in USA

1.4 CRACK DETECTION

The main focus of long range guided wave testing has been corrosion detection 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 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. It is also possible to use flexural waves though these are more difficult to excite in a pure form. Axial cracks are also straightforward to detect using circumferential guided waves 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.

2. COMMERCIAL SYSTEMS

The piezoelectric array technology developed at Imperial College, discussed above, has been licensed to two companies: Plant Integrity Ltd which is a wholly owned subsidiary of TWI, and Guided Ultrasonics Ltd. Both companies use rings of transducers 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.

A magnetostrictive transduction technology has been developed independently at SWRI in Texas, USA. This is marketed by a Korean company M.K.C. Korea. 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.

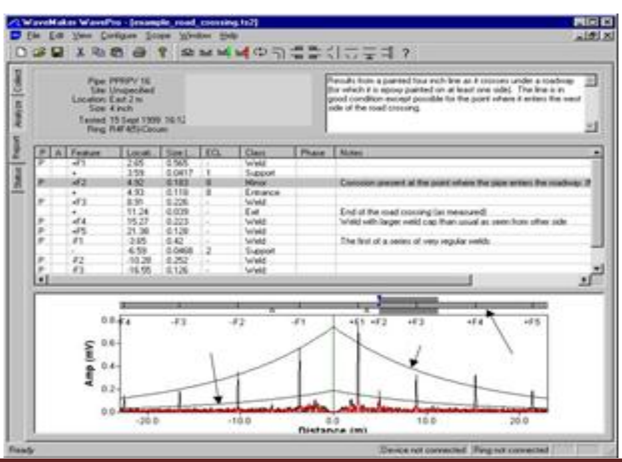
The performance of the inspection depends on the generation of a high fidelity axisymmetric signal of the chosen kind, either extensional or torsional. Imperfections could arise from non-uniform strength of excitation of the transducer elements, phase errors between the signals at the adjacent rings 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.

Fig 2.1 (a)

Fig 2.1(b)

2.1 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 the 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 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). 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 presence of general corrosion or lossy coatings.



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. 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 coursewith around a further week of supervised field testing.

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. 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 3.1 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 supporthad 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

3.1 TECHNOLOGY IMPROVEMENTS

The technology improvement 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.

3.2 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. 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.

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.

4.2 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 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. 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. The inspection of embedded bars is a well developed research topic, and is sufficiently understood for optimised exploitation.

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 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 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.

4.3 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. 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 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, 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.

4.4 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.

4.5 EFFECT OF BENDS ON THE PROPERTIES OF THE GUIDED WAVES

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 distances between welds in pulled bends also tend 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.

4.6 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.

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.

5. EXPERIMENTAL ANALYSIS

A full scale laboratory apparatus was designed to allow systematic and well-controlled experimental conditions in order to characterise the effect of the different physical parameters on the attenuation of ultrasound in a pipe.

5.1 EXPERIMENTAL APPARATUS

The buried pipe experimental apparatus consisted of a 5.67 m long, 8 in. Carbon steel pipe (9 mm wall thickness) embedded for 3-m of its length in a rectangular container of 0.76m x 0.76 m inner cross-section (Fig. 3a, b). The container walls were made from 40mm-thick plywood plate sand reinforced with a combination of rectangular section steel beams on each wall in order to support the load from the soil. The container was fitted with an inner tank-liner to allow water saturation of the soil.

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5.2EXPERIMENTAL SET UP

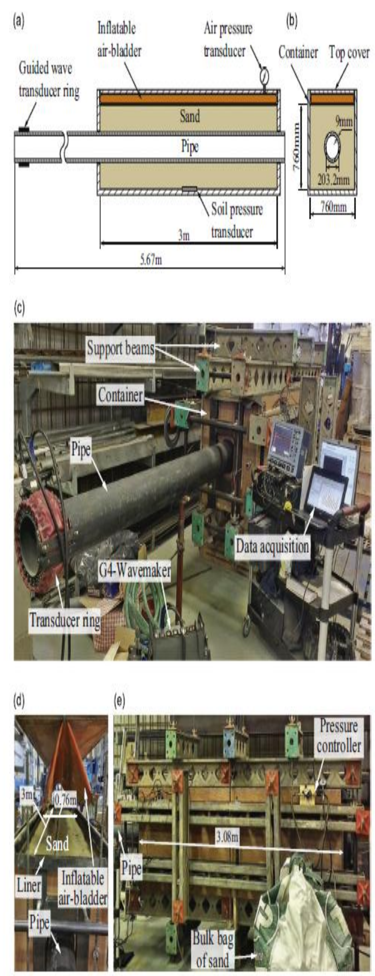
Five different sets of experiments were conducted in order to characterise the influence of the sand physical conditions on the attenuation of the guided ultrasonic waves in the pipe. The sand conditions covered in this study are: dry loose, dry compacted, dry mechanically compacted, water saturated and drained. The bulk densities were determined from measurement of the net weight of sand or sand and water used to fill the container and the volume it occupied in the container.

5.3 PROCEDURE

The system is composed of three primary components: the transducer ring, the Wavemaker® G4™ system, and a controlling computer. Transducer rings use mechanical or pneumatic pressure to dry-couple piezoelectric transducer elements to the Pipe being inspected. The transducers send waves in each direction along the pipe wall. Changes in the returning echoes indicate flaws and other features in the pipe. Long lengths of difficult-to-access pipe can be examined from a single location with minimal preparation and disruption while the pipeline is on-line.

5.4 RESULT

- Attenuation due to loss coatings and rough surfaces can be reduced by testing at lower frequencies.
- If lower frequency transducers are used, the ranges can often be extended but at some cost in defect sensitivity.
- 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.
- The comparison of the measured attenuation with model predictions confirms that the attenuation in both the longitudinal and torsional modes is essentially governed by the shear velocity in the sand.
- 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. Better Transducer Calibration, So Reducing the Excitation and Reception of Unwanted Modes, and Hence Improving the Signal to Coherent Noise Ratio.
- GPS receiver to provide approximate position and rough check on operator record.



6. CONCLUSIONS

Guided wave inspection of pipes is now in routine use worldwide. The technique offers the possibility of rapid screening of long lengths of pipe work 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. 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 minimize the number of transducers. The latter is of particular interest for Structural Health Monitoring (SHM) using permanently attached transducers.

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