PRACTICAL ENHANCEMENTS ACHIEVABLE IN LONG RANGE ULTRASONIC TESTING BY EXPLOITING THE PROPERTIES OF GUIDED WAVES

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Abstract: Initial implementations of guided wave techniques for long range ultrasonic testing of pipes are all essentially detection tools only, capable of identifying and locating metal loss defects along pipes, but little more. The success of the industrial application of guided wave systems has led to a desire for higher levels of performance in terms of defect detection, discrimination between defects and legitimate features, information about defect size and mitigation of effects of pipe geometry, for example bends, on the tests. This demand has prompted a considerable amount of development of the techniques. The multiplicity of wave modes present in the guided wave system and their various properties allow considerably more information to be gathered about defects present than possible hitherto. Examples are given of the possibilities for enhancing guided wave tests, by optimising the test parameters and by the use, for example, of focused waves and phased array transducers and of the performance enhancements possible for defect evaluation.

Introduction: Investigation of the use of low frequency (i.e. just above the audible range) guided ultrasonic waves for the inspection of long lengths of pipe was initiated by TWI in the UK in the early 1990s. This led, in 1998, to commercial application of guided wave systems in the oil, gas, petrochemical, power and process industries, chiefly for the rapid screening of pipes and pipelines for corrosion. The aim of guided wave examination is the rapid screening of long lengths of pipe from each test location in order, first, to achieve large area coverage of the pipes in an economic way and, second, to target suspect areas for closer examination by local NDT techniques. In this, the reduction of access costs is a significant factor in favour of applying guided waves. This method also has the ability to examine pipe lengths which are inaccessible for more conventional NDT methods by testing from the nearest accessible location, thereby increasing the proportion of any pipe system which can be inspected.

Since the commercial introduction of such systems, their use has become widespread for examination of both pressure containing pipes and structural tubulars. A summary of the principles of guided wave testing and some examples of its application were presented to NACE in 2001(1). As acceptance of the technique has increased, there has been increasing pressure for further development of it in several areas:

- Generation of more precise data on detection performance attainable and factors affecting it,
- Improvement in the sensitivity to metal loss defects,
- Production of more quantitative output about the defects detected (current systems are essentially detection tools only),
- Enhancements to the interpretation process,
- Improvements to both tools and procedures in the light of experience.

This paper describes the enhancements which can be achieved by the use of novel improvements to the standard guided wave inspection techniques. These allow increased detection sensitivity and the generation of quantitative information about flaws detected.

Detection Performance: There is now a considerable body of evidence for the practical detection performance of long range ultrasonic systems. The trend shown by Mudge(1) for 6" diameter pipes generally holds and probability of detection (PoD) curves can be plotted based on data from a variety of pipe sizes in terms of defect area. The general trend is shown in Fig.1. This plot follows the normal characteristics common to all NDT methods and shows that the likelihood of detecting a defect increases with some related parameter (in this case defect area on a circular cross section of the pipe(1)), reaching a plateau at a certain value. Figure 1 shows that there is a high probability of detection of defects greater than 250mm^2 in area. Below this figure there is a steady drop in the probability of detection with decreasing size. A limit of detection appears to be reached at an are area of approximately 25mm^2. This, is has to be stressed, is an experimental PoD which is simply an accumulation of reported metal loss defects correlated with actual defect size. Generation of a true, statistically valid PoD curve is extremely expensive, as there needs to be at least 29 individual results for each size band on the plot to maintain validity. Nevertheless, experimental plots as shown in Fig.1 provide very useful information about the performance expected from the technique in practice.

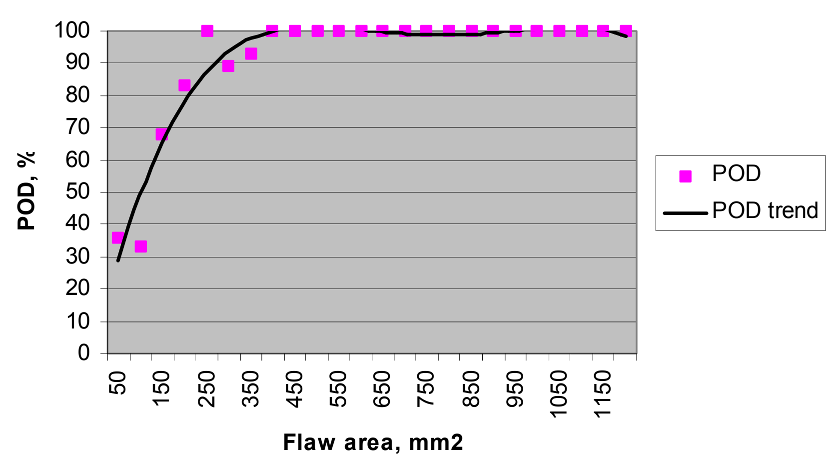

Fig. 1. Experimental probability (PoD) curve for long range ultrasonic detection of metal loss defects

In experimental work it is also difficult to obtain defects which represent the whole range of different shapes and characteristics which may be encountered in the field. This leads to a requirement to model the interaction of the ultrasonic waves with defects in order to understand the effect of defect size and shape on the interaction, and hence to identify improvements which can be made to the test technique. A considerable amount of work has been done in this area because this relatively new inspection technique requires such information to underpin its credibility for use on operational plant. Modelling offers the potential to vary defect parameters systematically and to examine the effects of such changes on the performance of the long range techniques.

Cawley et al(2) reported the effect of shape and size of two simple shape defects on the responses from longitudinal waves using a finite element modelling method. The two shapes were:

- fully circumferential, extending part way through the pipe wall, and
- full thickness, extending part way around the circumference.

This work showed substantial changes in response with defect size and also with frequency, but the defect geometry was rather artificial, in that the generalised defect shapes studied are unlikely to be met in practice. Moreover, the differences in behaviour between the two types suggested that there were likely to be different responses from the more typical part circumference/part wall defects. To investigate such effects a more detailed finite element approach was used to examine the influence of defect size and aspect ratio on the responses form both longitudinal and torsional waves(3). This approach enabled more realistic defect shapes to be modelled and also examined the influence of the use of different ultrasonic wave modes. The finite element model used is illustrated in Fig. 2.

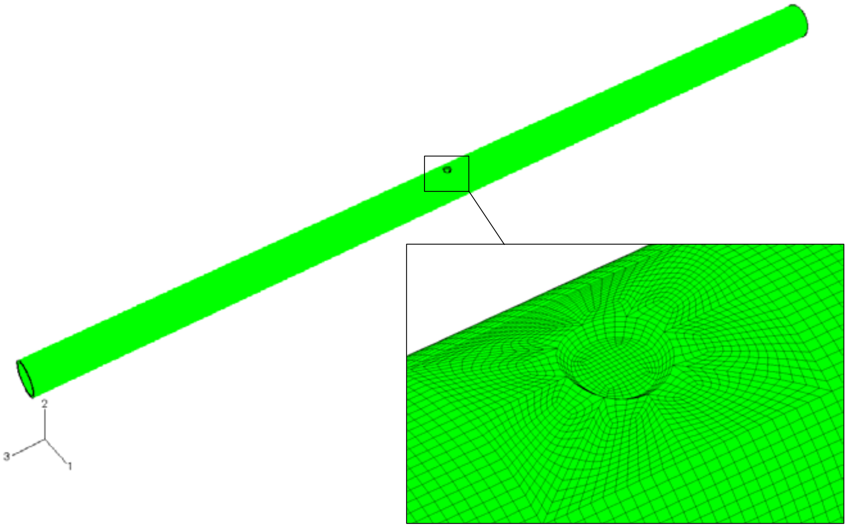

Fig. 2. Finite element mesh for a 8:1 diameter-to-width simulated meal loss defect(3)

Three defect aspect ratios were studied. A part-wall hole with an aspect ratio (diameter to depth) of 2.5:1, a 'cup' defect with an aspect ratio of 8:1 (see Fig.2.) and a 'saucer' defect with an aspect ratio of 29:1. The results showed that the overall area of the defect had a more significant effect than the aspect ratio on the overall response. In addition ,the greater levels of mode conversions into the so-called flexural ultrasonic wave modes – F(m,n), see below – with longitudinal waves had the potential to provide more information about the defect itself. A summary of the results is shown in Fig.3.

From Fig.3 it may be seen that the reflection coefficient (i.e. signal amplitude) of the directly reflected signal (plotted in black) is of the same order for each defect for both the longitudinal L(0,2) and torsional T(0,1) wave inputs. In fact there is a slightly higher dependence of signal amplitude on flaw area with the torsional wave input, shown in Fig.3b, which suggests that there is more potential for the torsional wave mode to be used to infer the size of the defect. Similar results have been obtained by Rose(4).

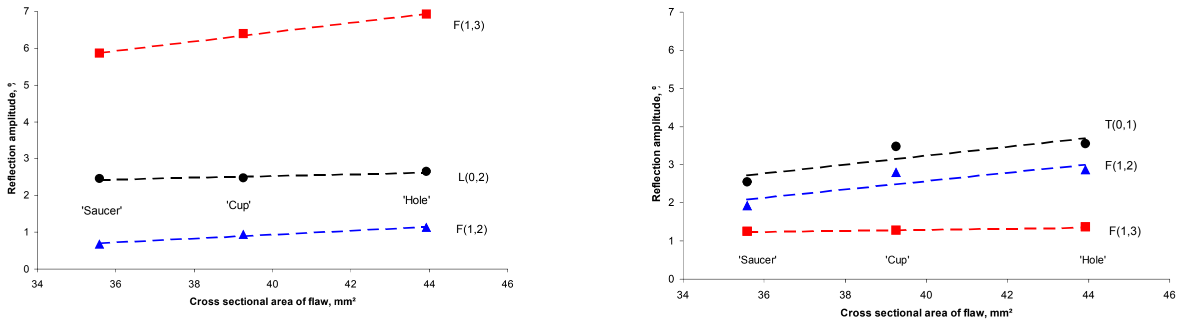

Fig. 3. Responses (reflection coefficients) from 'hole', 'cup' and 'saucer' defects
(a) longitudinal wave input and (b) torsional wave input

The most significant feature, however, is the amplitude of the scattered F(1,3) mode when the longitudinal wave interacts with the defects. This is more than twice the amplitude of the direct reflection and results from the tendency of L modes to scatter easily into other modes. In contrast, the scattering of the T(0,1) mode into its associated flexing mode – F(1,2) – is very low. This suggests that for detection purposes the use of longitudinal waves is preferred as there will be stronger interactions with defects and hence a greater chance of detecting a defect of a given size.

From Fig.3 it may also be seen that there are other wave modes present. For the longitudinal waves there is some scattering into the F(1,2)mode, which is torsional in nature, and for the torsional waves there is a similar level of scattering into the F(1,3) mode, which is longitudinal. This suggests that, were the transducer tool to be configured to collect more of this available information, better detection and diagnostic performance could be obtained. Further analysis of the received signals(3) showed that there were 6 wave modes present in the received signals from the defects when longitudinal waves were used. This again indicates that there is more information present in the responses from defects than is currently utilised by commercial systems and that this type of detailed analysis points the way to developments which will lead to improvements in test performance.

Note that the nomenclature L(0,2) and so on – the general form being L(m,n) – is used to identify the different guided wave modes present in pipes, as guided wave systems always contain more than one ultrasonic wave mode. The detail of this need not concern us here; the main point being that L modes are longitudinal, T modes are torsional and F modes are flexural waves. The L and T modes are axi-symmetric, i.e. the vibrations are uniform about the pipe axis. These types are normally transmitted by the transducer tool. The F modes are primarily generated by scattering, resulting from the interaction of the waves with defects.

Improving sensitivity: Currently available guided wave systems all rely on generation of axi-symmetric waves to examine pipes. One drawback with this approach is that the effect of the presence of a defect is effectively averaged out around the whole circumference. This limits the detection performance. If the sound energy could be focused on one part of the circumference only, then the local sensitivity could be increased. Plant Integrity Ltd has been working on this in conjunction with Penn State University in the USA for several years(4,5). This effect can be produced by treating the transducer tool as a phased array and concentrating the sound energy at a specified point on the circumference at a given distance from the tool. This is achieved in practice by using a segmented tool and multi-channel driving electronics. A schematic arrangement of the transducers is shown in Fig.4.

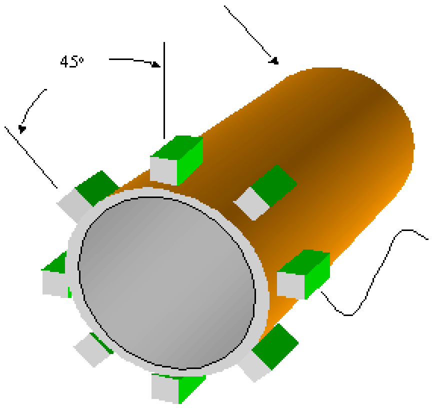

Fig.4. Schematic arrangement of ultrasonic transducers for focusing of guided waves(5).

The effect of focusing is shown in Fig.5. Figure 5a shows the experimental set up, on a 16” (405mm) diameter coal tar coated pipe. Figure 5b shows the responses from the same pipe with and without focusing the ultrasound at the notch. There is more than a factor of four (12dB) improvement in the signal amplitude from the notch as a result of the focusing, with a corresponding improvement in the signal to noise ratio. It may also be seen that the signal from the far end of the pipe specimen is reduced, because the input signal is no longer optimised at that range. The effect of this is to improve the ability of the long range technique to detect defects. In experimental work, improvements in the signal to noise ratio (which is the main factor governing the limit of detection) of four to five times have been regularly achieved. This focusing technique is now incorporated in field equipment.

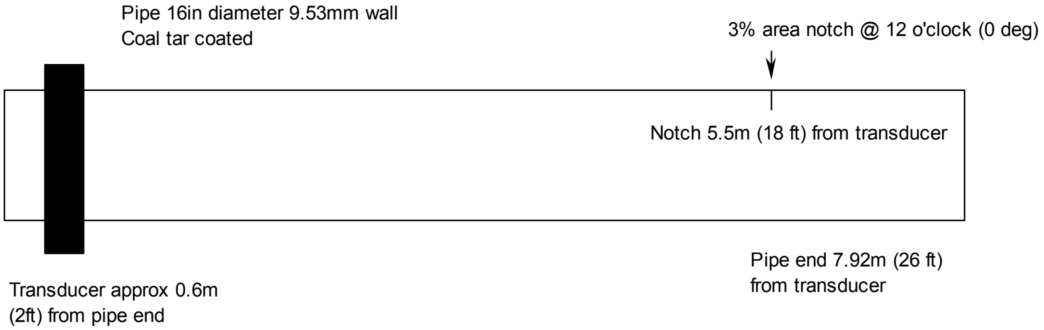

Fig.5a. Experimental arrangement for focusing test

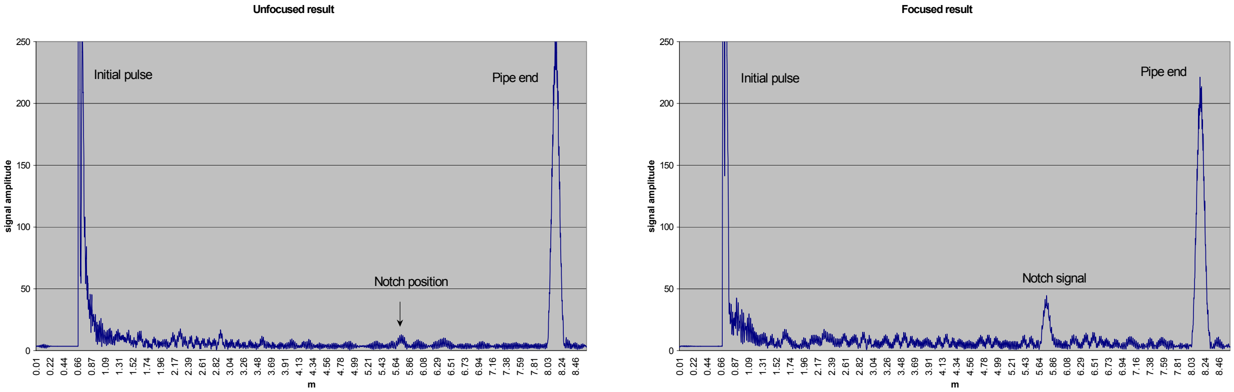

Fig.5b. Unfocused axi-symmetric (left) and focused (right) responses from the notch in Fig.5a

Obtaining quantitative information about defects: It must be remembered that the main aim of long range ultrasonic techniques is the rapid screening of large volumes of pipe wall as a precursor to more detailed examination. The principal benefits are:

- Minimisation of access costs for pipe which is coated, insulated, buried, sleeved or elevated.
- Confirmation that the pipe tested is free from detectable defects, so that no further examination is required,
- Concentration of the follow up local detailed examination on suspect areas detected, thereby optimising usage of resources.

However, currently available systems only provide a yes/no detection decision. There is no information provided about the nature or size of the defect itself. Although there is a basic relationship between the reflected signal amplitude and defect size, as with conventional ultrasonics, there is no information provided about the remaining wall thickness. Therefore, additional tests are required to confirm the severity of suspect areas detected. A major area of improvement for long range systems is therefore provision of size details, as there are many instances where the follow up tests are costly, or even impossible, where pipes are inaccessible.

There are two main ways of obtaining size information from long range tests;

- By altering the geometry of the test,
- By utilising more of the information already contained in the signals.

The first may be implemented as part of the routines for focusing, described above. The ability to concentrate the ultrasound on a particular part of the circumference and to sweep the focal point around through 360° enables the circumferential extent of a metal loss defect to be determined. This information can then be combined with signal amplitude to give at least a semi-quantitative measure of the through wall extent of the defect. This can provide the basis for a ranking exercise on behalf of the owner/operator so that repair and rectification can be optimised. Figure 6 shows the use of the focusing technique to determine the circumferential extent of a flaw. Responses are only obtained when the defect is in the focal zone. As the focus is moved around the circumference, the extent of the flaw can be determined.

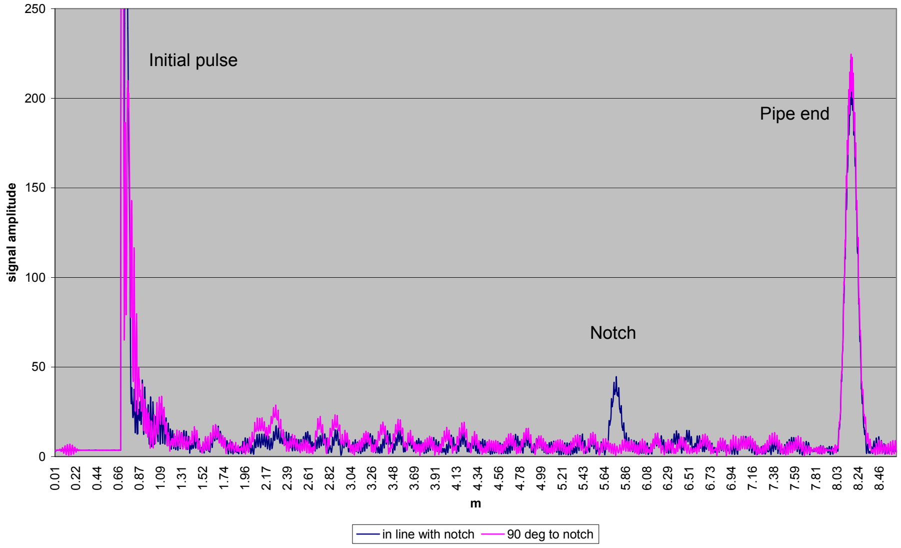

Fig.6. Responses from the notch in Fig.5a. The blue trace is when focused in line with the notch and the pink trace is when focused at 90º to it at the same range.

The second is to perform a more detailed analysis of the responses obtained. Sanderson(3) has shown that the defect shape influences the nature of the scattering when the ultrasound interacts with a defect. This is manifested in the number, type and intensity of the wave modes present in the returned signal. Figure 7 shows the relative amplitudes of modes present from the ‘hole’ defect in the study described above.

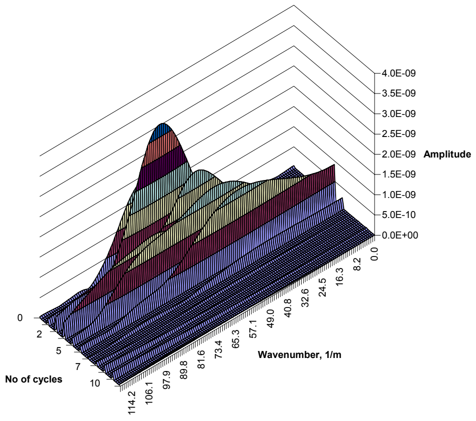

Fig.7. Mode composition in the reflection from the ‘hole’ defect in Fig.2(3).
Each peak represents a different wave mode and the amplitude shows relative intensity.

It has to be stated that this analysis was from a finite element model. Such an approach is considerably more difficult to implement in practice and is only realistic if the tools used are capable of gathering the data necessary to extract the required information.

Conclusions: The increasing acceptance of long range testing using guided waves for initial screening has also fuelled a desire to increase the capabilities of the method, by increasing sensitivity and providing more detailed information about any defects detected. To meet this need and to provide an on-going improvement to the equipment and procedures a number of studies have been carried out into the means of expanding the capabilities of long range testing. Significant improvements in test performance have been demonstrated and the outcome of such work has also been used to formulate the design of improved test equipment which is now being applied to field work. In particular, the test instrumentation has been updated to provide the multi-channel capability required to implement the focusing technique and transducers have been improved to allow multiple wave modes to be transmitted and detected, leading to implementation of the enhanced diagnostic procedures.

References:

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