FLAW SIZING IN PIPES USING LONG-RANGE GUIDED WAVE TESTING

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ABSTRACT. The absence of adequate inspection data from difficult-to-access areas on pipelines, such as cased-road crossings, makes determination of fitness for continued service and compliance with increasingly stringent regulatory requirements problematic. Screening for corrosion using long-range guided wave testing is a relatively new inspection technique. The complexity of the possible modes of vibration means the technique can be difficult to implement effectively but this also means that it has great potential for both detecting and characterizing flaws. The ability to determine flaw size would enable the direct application of standard procedures for determining fitness-for-service, such as ASME B31G, RSTRENG, or equivalent for tens of metres of pipeline from a single inspection location. This paper presents a new technique for flaw sizing using guided wave inspection data. The technique has been developed using finite element models and experimentally validated on 6” Schedule 40 steel pipe. Some basic fitness-for-service assessments have been carried out using the measured values and the maximum allowable operating pressure was accurately determined.

Keywords: Long-Range, Pipe, Flaw Sizing, Guided Waves, Inspection
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INTRODUCTION

There are already successful commercial systems available which are used for screening of pipes for corrosion [1,2]. With these systems, tens of metres of pipeline can be inspected from a single test location and a rough idea of the cross sectional area loss due to corrosion can be determined. The challenge is to enhance the technology to the point where more quantitative information about a flaw can be gathered, such as the circumferential, axial and through wall extent. If such data were available then it could be used to carry out a fitness-for-service assessment and it may be the case that the corroded section of pipe could be allowed to remain in place without any significant risk of failure for an extended period of time. This would have the advantage that the pipe could remain in service and the repair or replacement could be carried out at a convenient time.

The aim of the work presented here was to develop a procedure for deriving quantitative information from long-range guided wave inspection data, particularly to measure the through wall extent of any corrosion damage. The approach taken was to use

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three-dimensional finite element analysis to understand the reflection characteristics of flaws of different shapes and sizes. Experimental validation of the new technique was then carried out.

THEORY

Guided Wave Behavior in Pipes

In the range of frequencies commonly used for long range inspection (20-80kHz), a pipe has a number of modes that have particle displacements in either the radial, torsional or longitudinal directions. These modes can be grouped together into ‘families’ of wave modes. Each of the families has an axisymmetric wave mode (that it is named after) and a set of wave modes with variation in particle displacement around the circumference (called flexural wave modes). Using the Silk and Bainton [3] naming convention, the three axisymmetric wave modes in commonly used frequency ranges are: L(0,1), T(0,1) and L(0,2). The naming convention adopts a letter L, F or T standing for longitudinal, flexural or torsional which relates to the displacement behavior of the wave mode. The first number in the brackets is the order of cyclic variation around the circumference of the pipe and the second number in the brackets is an index which increases with frequency. For example, L(0,1) is the first longitudinal wave mode that exists with zero variation around the circumference. F(2,3) is the third flexural wave mode to exist with two cycles of particle displacement variation around the circumference.

Each wave mode will also have a different relationship of velocity with frequency. This is called the dispersion curve and describes the level of dispersion and the velocity of the wave mode (from which the axial location of any flaw detected can be calculated). This relationship can be solved analytically for pipes and plates. Figure 1 shows the dispersion curves for a mild steel 6” Schedule 40 pipe (168.3mm outer diameter, 7.11mm wall thickness) up to 80kHz calculated using the commercially available software, Disperse [4].

Modelling Approach

Three dimensional models of a length of pipe were created using the commercial finite element software ABAQUS/Explicit version 6.7. The signals received from 29 different shapes and sizes of flaws were analyzed. Table 1 gives the details of the flaw geometry for each model analyzed. A schematic of the model is shown in Figure 2.

The models had four elements through the thickness and 144 around the circumference. The axial length of the elements was 2.5mm. The elements were three-dimensional bricks with 8 nodes and reduced integration (ABAQUS element type C3D8R). This level of mesh refinement has been validated in previous work [5,6].

All 29 flaws were modeled with the T(0,1) mode transmitted, and the mode contents of the received signals were recorded and analyzed.

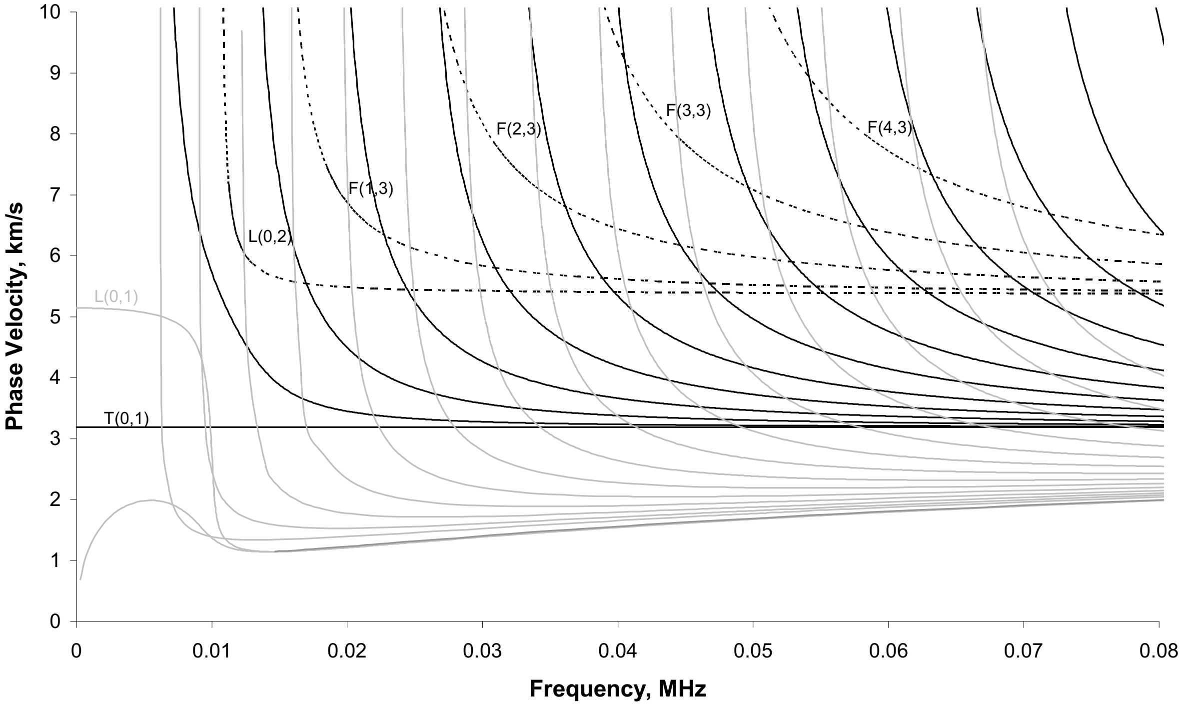

FIGURE 1. Phase velocity dispersion curves in a 6" Schedule 40 (168.3mm outer diameter, 7.11mm wall thickness) steel pipe. The three families of wave modes are shown (L(0,1) has grey lines, T(0,1) has black lines and L(0,2) has dashed lines).

Each flaw had an axial length of 10mm which was approximately equal to a quarter of the wavelength. The axial length was chosen to enhance constructive interference from reflections from the front and back wall of the flaw, so that the effect of circumferential and through wall extent could be studied in isolation from axial extent.

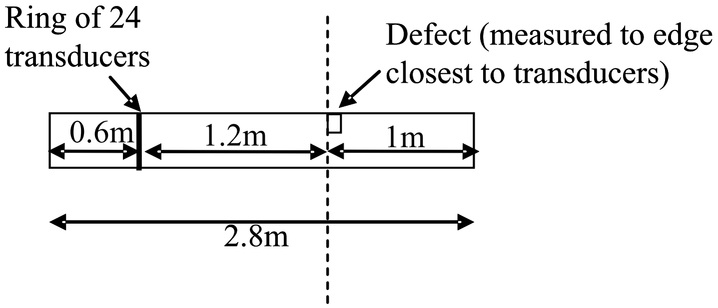

FIGURE 2. Schematic of model used for assessment of range of notch-like flaws in 6" Schedule 40 steel pipe.

TABLE 1. Details of each finite element model analyzed.

Model index number	Flaw though wall extent, mm	Flaw through wall extent, % wall thickness	Flaw circumferential extent, degrees
1	3.555	50	5
2	1.7775	25	30
3	3.555	50	30
4	5.3325	75	30
5	3.555	50	45
6	1.7775	25	45
7	5.3325	75	45
8	3.4785	49	55
9	3.555	50	60
10	3.555	50	90
11	1.7775	25	90
12	5.3325	75	90
13	3.555	50	135
14	1.7775	25	135
15	3.555	50	160
16	3.555	50	170
17	3.555	50	180
18	3.555	50	190
19	3.555	50	200
20	3.555	50	250
21	3.555	50	300
22	3.555	50	325
23	3.555	50	355
24	3.555	50	340
25	4.74	67	325
26	7.11	100	30
27	7.11	100	45
28	7.11	100	90
29	7.11	100	135

Experimental Approach

The transducers in guided wave inspection equipment vary in efficiency around the pipe circumference due to variation in individual transducer performance and ultrasonic coupling with the surface of the pipe. This variation generates flexural modes, which propagate at nearly the same velocity as the axisymmetric modes. In order to achieve accurate results, it is important for each transducer to transmit the same ultrasonic signal into the specimen as the electronic signal sent to it from the pulser-receiver, and likewise it is important that the displacements occurring beneath the transducer are recorded with the correct amplitude. Otherwise, undesired wave modes will be transmitted and the amplitudes of received signals will be erroneous.

After normalizing the tool, each flaw was tested by transmission of T(0,1) using 24 individually controlled transducers. Nine representative flaws were put into the pipe using a milling machine. A schematic of the experiment is shown in Figure 3. The through wall extent of the flaws varied from 1.8mm (0.07”) to through wall (7.11mm or 0.28”) and the circumferential extent was varied from 30 degrees to 325 degrees.

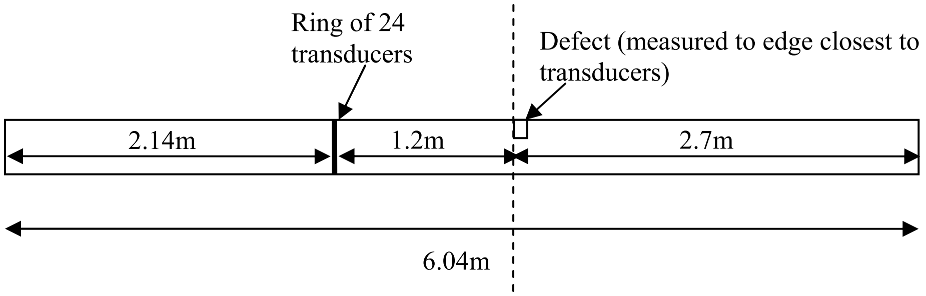

FIGURE 3. Schematic of experimental set up used for assessment of the range of milled notch-like flaws in 6" Schedule 40 steel pipe.

RESULTS

As expected from previous research [7], the finite element modelling and experimental data confirmed that there is a linear correlation between the cross sectional area (CSA) of a flaw and the response of the T(0,1) mode as shown in Figure 4.

The equation for partial through wall extent flaws, derived from the modelling results was:

$$C = 1.2729 \cdot T \tag{1}$$

Where C is the cross sectional area loss of the flaw normalized by the cross sectional area of the pipe and T is the ratio of the peak-to-peak T(0,1) signal from the flaw to the peak-to-peak T(0,1) signal from the pipe end.

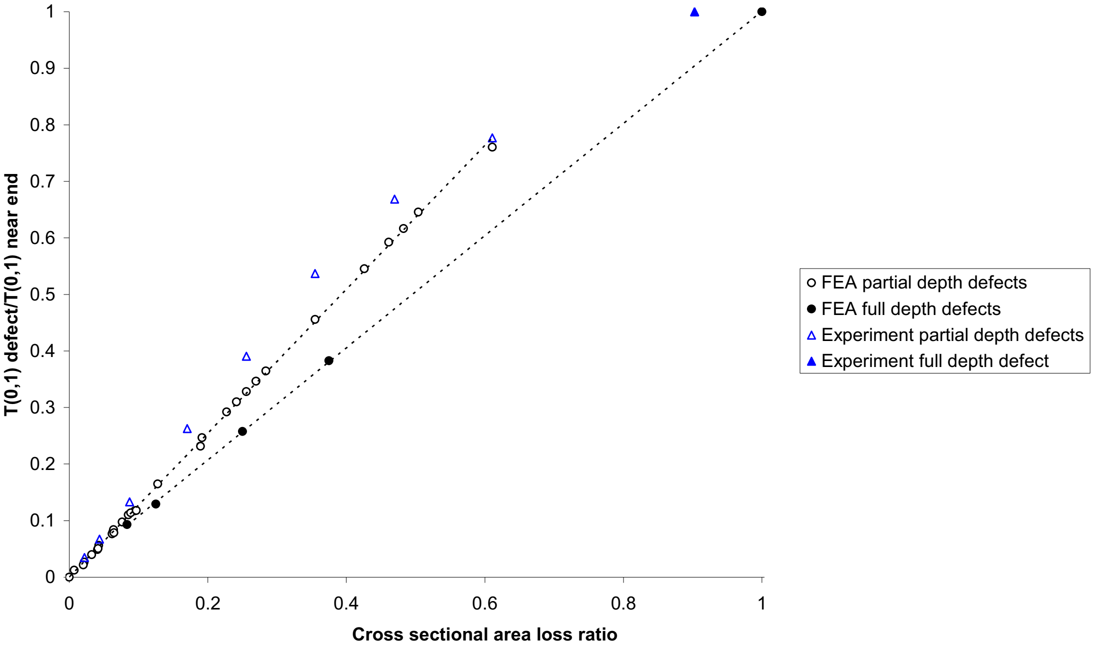

FIGURE 4. Reflection coefficient of incident torsional wave mode T(0,1) against cross sectional area loss ratio of flaws. The dotted lines represent straight line fits to the finite element modeling data. The experimental results are also shown for comparison.

It was noted that there was a different trend for full through wall flaws. As for the partially through wall flaws it was linear, but with a lower gradient, nearer to 1. The experimental result indicated that this was possibly a real effect but additional through wall flaw inspection data would be needed to confirm this.

Detailed examination of the modelling data resulted in a parameter made up of the reflected wave modes that is independent of flaw through wall extent, but sensitive to the circumferential extent. Thus, signals can be recorded from an unknown flaw, and a CSA and circumferential extent can be measured. The results of these can then be used to solve the following relationship to give an estimation of the through-wall loss of a flaw:

$$\text{Flaw through wall extent} = r_o - \sqrt{r_o^{\,2} - \frac{360 \cdot C \cdot (r_o^{\,2} - r_i^{\,2})}{\theta}} \qquad (2)$$

where:

r_o = Outer radius
r_i = Inner radius
C = Cross sectional area of flaw normalized by the pipe CSA
θ = Circumferential extent of flaw in degrees

Therefore, a measure of the circumferential extent can be combined with a measure of the CSA to derive an estimate of a flaw's through wall extent. This formula is based on a notch-like shape for the corrosion damage. A possible enhancement could be to modify the formula to be based on typical corrosion profiles depending on the circumferential extent of the flaw.

Table 2 gives the experimental results and an estimate of the flaw's through wall extent and circumferential extent using the above formulae and the associated errors. It was found that the through wall extent was predicted with an accuracy of better than ±1mm and the circumferential extent was predicted with an accuracy of better than ±30°. The circumferential extent trend line nears vertical for smaller flaws, which means that the level of accuracy for flaws of less than around 45° circumferential extent will be reduced. For flaws greater than 45° the accuracy of the estimate for circumferential extent for the flaws studied experimentally was actually found to be better than ±21°.

TABLE 2. Experimental through wall extent measurement results.

Expt. Index	Flaw through wall extent, mm	Flaw circ. extent, degrees	Estimated flaw through wall extent, mm	Error in flaw through wall extent, mm
1	1.80	30	1.12	-0.68
2	1.80	60	1.67	-0.13
3	1.80	120	2.21	0.41
4	3.56	120	3.65	0.09
5	3.56	180	3.85	0.29
6	3.56	250	4.46	0.90
7	4.74	250	5.10	0.36
8	4.74	325	4.82	0.08
9	7.11	325	6.11	-1.00

In this study, notch-like flaws were used whereas corrosion is likely to cause a more gradual change in material loss. The approach presented here is aimed at gaining a global estimate of flaw dimensions rather than creating an accurate profile of the shape of the corrosion. This information alone is a big step forward since it makes the difference between qualitative and quantitative assessment of the pipe. Since the wavelength of guided waves is inherently large compared to the flaw dimensions it is unlikely that guided waves alone could be used to gain more accurate data. For the same reason, is unlikely that the exact shape of the flaw will significantly affect the result. Therefore, it is expected that this procedure will work on real corrosion damage. Confirmation of this will be the subject of future modeling and experimentation.

A fitness-for-service assessment was carried out using the experimentally measured flaw through wall extent values. The code used was ASME B31G [8] and in the absence of axial length data, the flaw was conservatively assumed to be long. The operating pressure for an undamaged pipe was assumed to be 696psi and then the maximum allowable operating pressure was calculated using the measured values from the guided wave inspection experiment. Figure 5 shows the results. It can be seen that the pressure is calculated relatively accurately. The average error in maximum allowable operating pressure was 40psi.

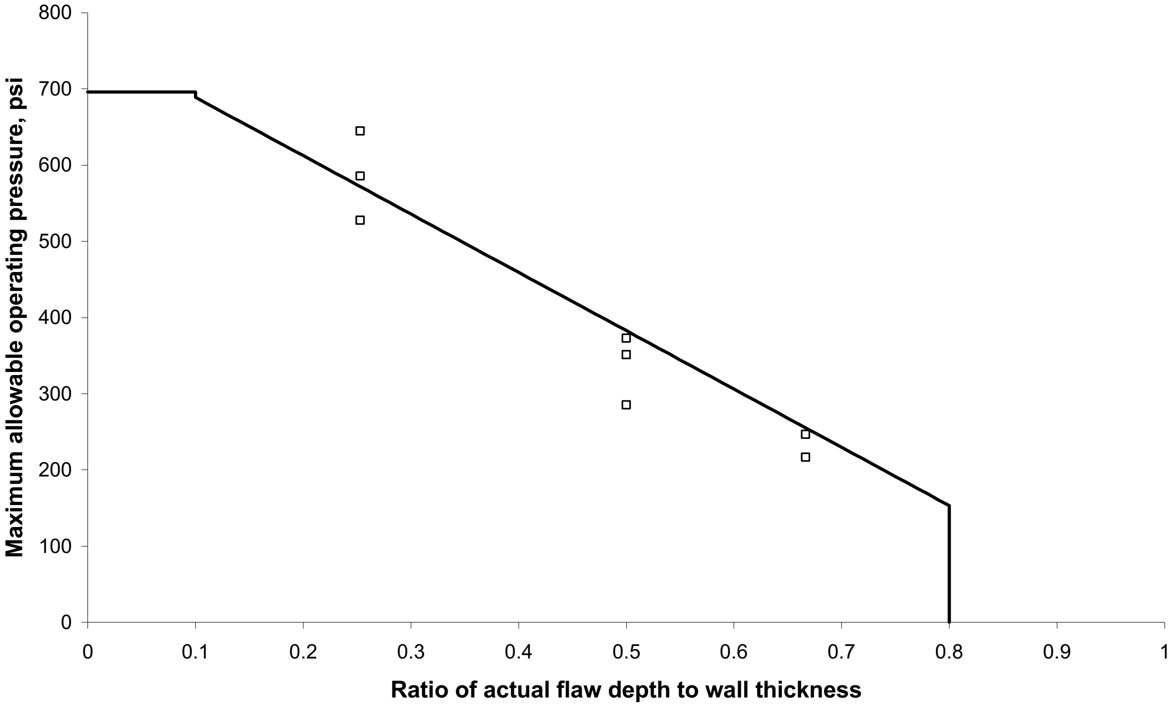

FIGURE 5. Fitness-For-Service assessment diagram from ASME B31G. The line represents the accurate maximum allowable operating pressure for a known flaw through wall extent to wall thickness ratio. The points are the maximum allowable operating pressure derived from the experimentally measured flaw through wall extent.

CONCLUSIONS

For the first time, a flaw sizing technique has been developed for long-range ultrasonic testing with the assistance of three dimensional finite element analysis. The technique has been tested experimentally and has been shown to be able to determine the circumferential extent of a flaw with an accuracy of better than ±30° and the flaw through wall extent with an accuracy of ±1mm in a 6 inch schedule 40 steel pipe.

It has also been demonstrated that the guided wave flaw sizing data has the potential to be used directly in a fitness-for-service assessment with reasonable accuracy. The average error in estimation of maximum allowable operating pressure based on the measured flaw through wall extent was 40psi.

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REFERENCES

1. P. J. Mudge, “Field application of the Teletest® long-range ultrasonic testing equipment”, Insight**,** 43(2) 74-77.
2. D. N. Alleyne, B. Pavlakovic, M. J. S. Lowe and P. Cawley, “Rapid, long range inspection of chemical plant pipework using guided waves”, AIP Conference Proceedings, April 30, 2001, vol. 557, pp. 180-187.
3. M. Silk and K. Bainton, “The propagation in metal tubing of ultrasonic wave modes equivalent to lamb waves”, Ultrasonics, 1979, pp11-19.
4. B. Pavlakovic, M. Lowe, D. Alleyne and P. Cawley, “Disperse: a general purpose program for creating dispersion curves”, 1997.
5. R. M. Sanderson, “Long range ultrasonic guided wave focusing in pipe with application to defect sizing”, ICU Conference, Vienna, April 9-13th, 2007.
6. D. N. Alleyne, “The non-destructive testing of plates using ultrasonic Lamb waves”, PhD Thesis, Mechanical Engineering Department, Imperial College London, 1991.
7. A. Demma, P Cawley, M. Lowe and A. G. Roosenbrand, “The reflection of the fundamental torsional mode from cracks and notches in pipes”, J. Acoust. Soc. Am. 114 (2), August 2003.
8. B31G - Manual for Determining the Remaining Strength of Corroded Pipelines: Supplement to ASME B31 Code for Pressure Piping, 2009.