RELIABILITY OF GUIDED WAVE ULTRASONIC TESTING

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The Guided wave testing method (GW) is increasingly being used worldwide to test in-service pipe-work for corrosion. As a screening tool, GW is generally used to manage inspection tasks in a time and cost efficient manner. However, the perception of screening often encountered in the industry is that it is inferior to other methods, such as manual ultrasonic testing, when it comes to probability of detection (POD) of defects.

This paper examines the factors that affect the probability of detection for GW and manual ultrasonic testing (UT) and demonstrates that in many practical applications the POD for GW inspection is significantly higher than that for UT. Also, it is often neglected that the standard procedure for GW inspection includes prove-up of indications using a secondary inspection method, thereby optimizing the accuracy and reliability of the inspection. The effect of combining GW with manual UT as a secondary prove-up tool on the reliability and efficiency of an inspection is therefore discussed.

1 Introduction

Guided wave (GW) testing is a non-destructive testing method for finding corrosion in pipe-work. It uses ultrasonic waves that propagate along the pipe in the axial direction. As with any new method, there is initially some degree of uncertainty in the industry as to the capabilities and reliability of that method. While the GW method is now widely accepted, few independent reliability studies have been reported. A first approach often adopted is to compare the detection capabilities of the new method to those of more established methods.

In contrast to conventional ultrasonic testing (UT), where only the area underneath or in the direct vicinity of the transducer is inspected, GW testing allows the entire pipe wall to be screened from a single transducer position within the diagnostic range of the test. The range depends on a number of parameters, but in the applications considered here is generally of the order of tens of metres in both directions. This makes GW an ideal tool for screening long lengths of pipes for defects and locating them for prove-up inspection. Prove-up, for example with UT, is an integral part of the inspection procedure of traditional screening, for the purpose addressed in this paper.

One of the generally recognized figures of merit used to gauge the reliability of a non-destructive inspection system is the probability of detection (POD). GW testing capabilities are often being compared to those of manual ultrasonic testing (UT), with the perception being that GW is inferior to UT. The reasoning being that the defect size that can be ‘seen’ with UT is much smaller than that which can be ‘seen’ using GW methods. However, being capable of seeing a defect is not the same as detecting it. As will be established in the remainder of this paper, in the areas where GW testing is applicable, the POD of manual UT is governed by a geometric component, and as a result inferior to GW testing unless an impractical number of UT test locations is used.

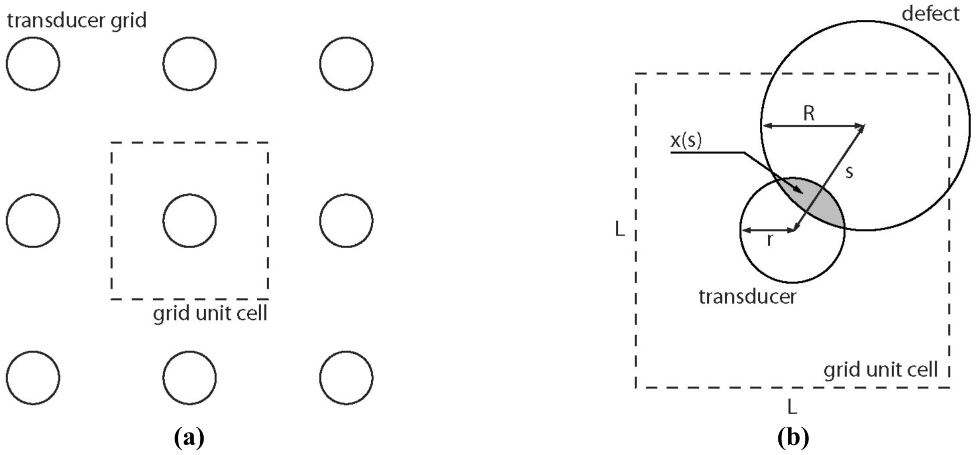

Fig. 1 (a) Schematic of an inspection grid, and **(b)** inspection grid unit cell with circular defect superimposed. The grey area is the overlap x between the defect and the transducer beam.

2 Reliability of manual UT

Generally, the POD of UT is obtained by scanning the entire surface of the test specimen. The POD achieved in this way using a specific transducer for a defect of size a shall be denoted by $\mathrm{POD}_{\mathrm{UT}}(a)$. Factors other than the size that can influence and are included in $\mathrm{POD}_{\mathrm{UT}}(a)$ are, amongst others, the depth, morphology and orientation of the defect, signal-to-noise ratio, transducer characteristics such as frequency and beam shape, as well as human factors.

However, in most practical situations, the test surface is so large that scanning the entire surface is not practicable. The overall POD for finding a defect of size a is lower than $\mathrm{POD}_{\mathrm{UT}}(a)$ because the probability that there is overlap between the transducer beam and the defect is lower. The overall probability of detection POD is therefore governed by the combination of a geometrical component, namely the probability p that there is some overlap of size x, and the probability of detection for the area of the overlap $\mathrm{POD}_{\mathrm{UT}}(x)$. Note that for $\mathrm{POD}_{\mathrm{UT}}$ the overlap area x has to be used instead of a as this is the effective defect size that would be seen by the transducer.

For pipe wall-thickness surveys, an inspection grid is used to map out the surface of the pipe, and a 0° pulse-echo measurement taken at each location. A simplified example calculation is shown in reference [1] where, a square inspection grid of length L is adopted, and the area interrogated by the transducer beam a circle with radius r. Furthermore, the defect is also assumed to be circular with radius R (see Figure 1). Without prior knowledge of the $\mathrm{POD}_{\mathrm{UT}}$, one can obtain the maximum achievable probability of detection for UT if it is assumed that the defect is detected as long as there is any overlap at all.

Therefore the total POD of a defect for UT is composed of two parts. First, a geometric component, $P(x>0)$, which defines how likely it is for the transducer to be placed overlapping the defect. Second, a component $\mathrm{POD}_{\mathrm{UT}}(a)$, which defines how likely its is for the defect to be detected if the transducer is placed overlapping it.

The probability of overlap $P(x>0)$ is shown in Fig. 2 for a grid length of 100mm and a transducer diameter of 10mm. As an example, the probability for a 50mm diameter defect to be detected is about 0.28, regardless of the wall loss, shape or any other factor. In reality, the $\mathrm{POD}_{\mathrm{UT}}(a)$ is always less than 1, further reducing the total POD for any given size of defect. This demonstrates that the total POD for UT is dominated and limited by the geometric factor, $P(x>0)$, and not the probability of detecting the specific defect in question, $\mathrm{POD}_{\mathrm{UT}}(a)$.

Most importantly, the argument above effectively renders any spot check UT, which does not even rely on coverage using a defined inspection grid, unreliable for detecting defects. Surprisingly however, this forms the basis for many risk based inspection programs and this practice is stipulated in inspection codes without any guidance regarding the spacing of thickness measurement locations (see, for example, [2]).

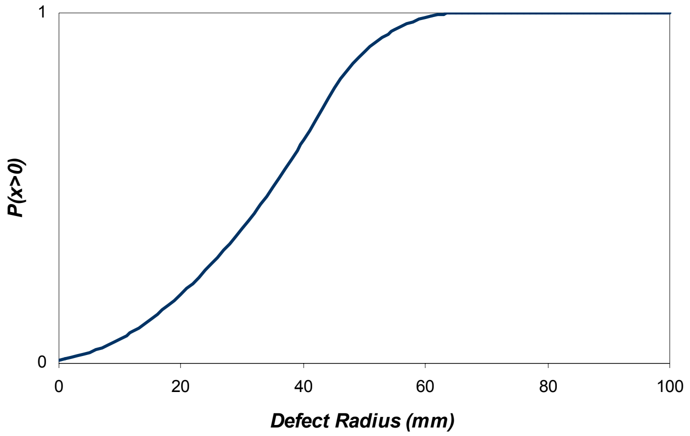

Fig. 2. Example calculation of *P(x>0)* as a function of defect radius *R* for a square grid of 100mm length and a transducer diameter of 10mm. It is equivalent to the maximum achievable total POD.

As an example, if thickness measurements are carried out in all four quadrants of the circumference of a 6 inch pipe at 130mm spacing along the length of the pipe, the probability of finding a 50mm diameter defect with a 10mm diameter transducer is less than 0.16 (16%).

3 Reliability of GW testing

Studies have shown that the correlation between the cross sectional loss of a defect and the resulting guided wave reflection amplitude is very consistent, regardless of the circumferential shape of the defect [3]. The GW method therefore primarily measures cross-sectional loss rather than wall loss. The controlling defect dimension which must be used in POD studies for GW inspection is therefore the cross-sectional area of the defect rather than the plan area which is used for manual UT studies. The remaining geometrical parameters of the defect, i.e. circumferential shape, circumferential position and through-wall position do not affect the resulting T(0,1) reflection amplitude. The axial length of defect also has an effect on the signal amplitude through constructive and destructive interference, and depends on the ratio of the wavelength of the guided wave and the length of the defect. However, this can be controlled by the use of frequency-sweeping, i.e. changing the frequency and thereby the wavelength in a way that the received signal amplitude is maximized.

Figure 3 shows an example of a GW test result. The result can be displayed in an A-Scan type representation, which shows the received amplitudes of T(0,1) and one flexural mode, called F(1,2), as a function of distance from the transducer ring in both directions, and additionally in a C-Scan type representation, which shows the received amplitudes as a function of distance and the angular position around the circumference. Cross-sectional changes appear as reflected signals as demonstrated in the A-Scan and C-Scan traces.

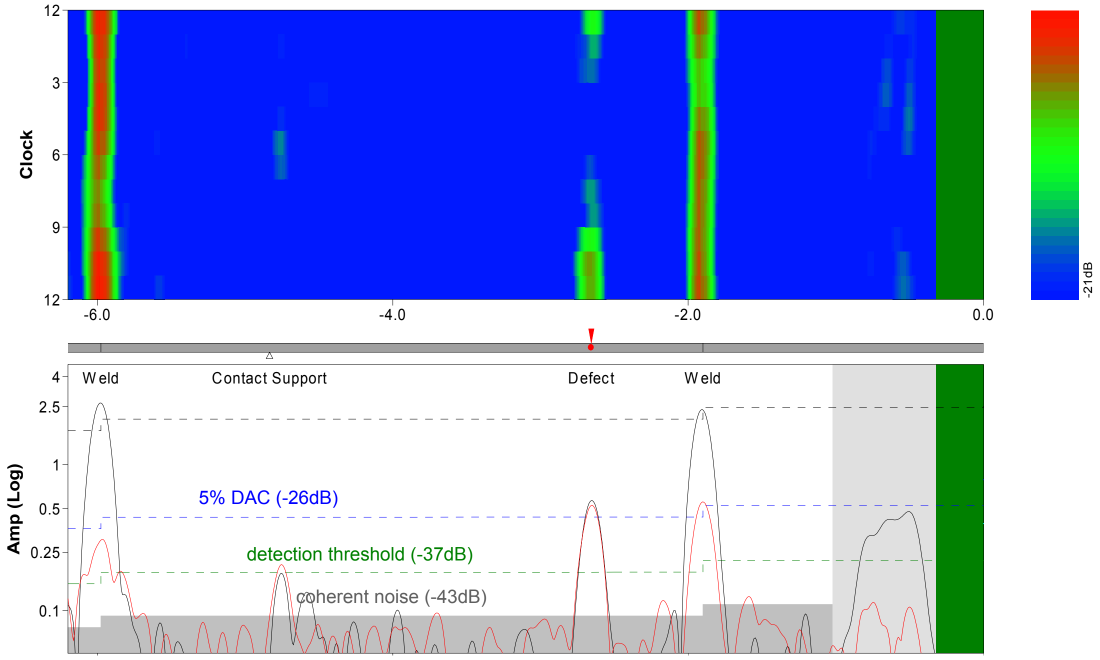

Fig. 3. Typical GW test result from a 6inch pipe with a 50mm diameter defect with a depth of half the wall thickness. The defect is clearly visible at 17dB above the coherent noise.

Note that in the dead-zone (green area) and the near-field (grey area) around the transducer ring position at 0m, interpretation of the data is not possible.

In order to demonstrate the reliability for simple GW inspections in this paper, we concentrate on the definition of POD based on signal-to-noise [1, 5]. For the sake of the comparison with UT we consider here only simple GW applications, i.e. long lengths of straight pipes with no physical attachments such as branches or welded supports. In such GW applications, the probability of detection is mainly governed by the signal-to-noise ratio. The human factor is also explicitly excluded, as it can strongly affect both the POD of UT and GW. The level of noise signals can be measured from the A-scan trace for each individual test result. The noise signal can be caused by two possible mechanisms. First, random external influences such as electrical noise or environmental vibration, which is commonly referred to as background noise or incoherent noise. The incoherent noise signal amplitude does not decrease with distance from the ring location. Second, reflections from randomly distributed discontinuities of the pipe cross-section within the inspected pipe segment. These discontinuities can be caused by natural variation of the wall thickness during manufacture of the pipe or by in-service damage such as pitting corrosion. It is referred to as coherent noise. The amplitude of the coherent noise signal decreases with distance from the transducer ring location due to the attenuation of the wave mode traveling along the pipe. To ensure a low probability of false indications, the detection threshold is set to 6dB above both the background and coherent noise level. Additionally, with the use of a reporting threshold, one can define the diagnostic range, D, as the distance from the transducer ring, where the reporting threshold falls below the detection threshold. This ensures a low probability of false indications within the entire diagnostic range.

$\mathrm{POD}_{\mathrm{GW}}(a)$ for a defect of size a is defined as for UT by the probability that the defect signal amplitude is greater than a pre-defined detection threshold. For example, assuming a Rice probability distribution for the guided wave signal amplitudes [5], a signal with an amplitude at the detection threshold would have a POD of approximately 58%, and a signal with an amplitude of twice the detection threshold a POD of more than 99%.

The overall POD for GW can now be treated in the same way, with a geometric component and the inherent $\mathrm{POD}_{\mathrm{GW}}$ component:

$$POD_{GW}^{total} = \int_0^L POD_{GW}(x(s))p(s)ds\,,$$

where L is now the distance between two test positions along the length of the pipe, and s is the distance between the transducer ring and the defect (see Figure 4). If the probability for a defect, *p(s)*, is the same at any point within the unit cell can be written as

$$p(s) = 1/L\,.$$

The diagnostic range D is defined as the length of pipe where the sensitivity is sufficient for the target defect size a, i.e. the distance s from the ring position, where the reflection from a reflector of size a falls below the detection threshold. Note that the near-field length, N, around the transducer position further reduces the diagnostic range as in this region only limited interpretation of the signal is possible. Similarly to UT one can then define the overlap x, with $x = 0$ when the defect is located outside the diagnostic range. Similarly to the calculations carried out for UT we assume that the defect will be detected if it is located within the diagnostic range:

$$POD_{GW}(x(s)) = POD_{GW}(a)H(x(s)) = \begin{cases} POD_{GW}(a) & \text{for} \quad x(s) > 0 \\ 0 & \phantom{\text{for}} \quad x(s) = 0 \end{cases}.$$

The total probability of detection for GW becomes

$$POD_{GW}^{total} = POD_{GW}(a)\int_0^L H(x(s))p(s)ds = POD_{GW}(a)\frac{D-N}{L}\,.$$

For the applications considered here, the distance between the test positions can be chosen such that it is the same or even smaller than the diagnostic range with a realistically achievable number of test locations. Importantly, complete coverage of the pipe can be achieved with only a limited number of tests and so the inspection effort is kept to a minimum. It is therefore apparent that, in contrast to UT, the total POD of GW is not governed by a geometric component, but by POD_{GW}.

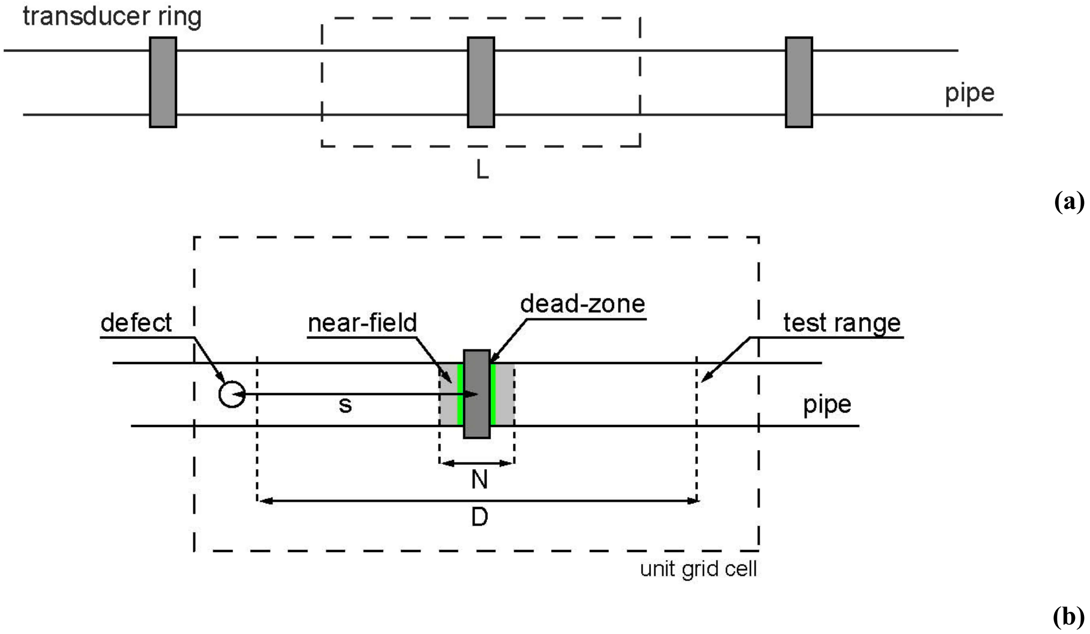

Fig. 4. (a) different test positions at distance L from each other on the pipe, and (b) schematic of a unit grid cell for GW.

4 Comparison of GW and manual UT for Bare Pipe

The following comparison assumes that the pipe under test is fully accessible externally for UT inspection.

Consider a 6m section of 6 inch steel pipe with an OD of 168.3mm and a nominal wall thickness of 7.1mm. Assume a defect consisting of a flat-bottomed hole of 50mm diameter and 50% wall loss. This can be considered as a large defect and the POD_{UT} is close to 1. The overall POD of UT is then entirely dependent on the grid size that is adopted for the survey. Figure 5 shows a plot of the overall POD as a function of the grid size L assuming a 10mm diameter transducer probe. If a POD of 90% is desired, the grid size would have to be approximately 54mm which would require more than 1000 measurement points. In order to detect a pinhole defect, whose diameter is of the order of the wall thickness, with a probability of 90%, the grid size has to be of the order of 15mm which would require more than 14,000 measurement points. Neither of these scenarios are practically possible due to the enormous time and cost required. In a practical testing situation not more than 50 test points would be selected, for example the four quadrant points around the circumference, every 0.5m along the pipe length. This would give a POD for the 50mm diameter defect of 0.04 (4%).

The analysis of UT reliability is independent of the severity of the defect, i.e. the remaining wall thickness at the defect location. For GW on the other hand, the reflectivity does depend on the severity of the defect. Assuming a wall loss of 25% for the circular corrosion type defect with a diameter of 50mm as in the UT example, the cross-section change would be approximately 2.5%. For a 50% wall loss defect, it would be approximately 5%. Referring back to Figure 3, which shows a GW result obtained from a 6 inch pipe, a defect of 50mm diameter and 50% wall loss was introduced in order to evaluate the detection capability. The coherent noise level was determined to be -43dB. The defect can be clearly seen at 11dB above the detection threshold, indicating that the defect can be found with a POD of more than 99% using only two test positions to screen the entire pipe section.

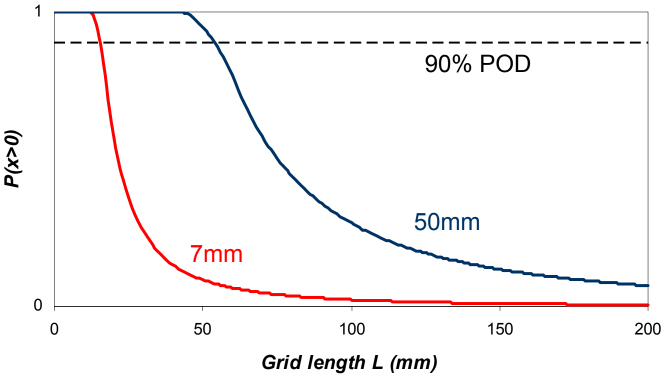

Fig. 5. Example calculation of *P(x>0)* as a function of length *L* of a square grid and a transducer diameter of 10mm. The curves show the probability of detection for a 50mm diameter defect (localised corrosion) and a 7mm diameter defect (pinhole defect). The dashed line indicates a POD of 90%.

5 Combination of GW and manual UT

The combination of the GW screening method with the UT prove-up method does not (significantly) increase the probability of detection above that of the GW method alone. However, the reliability of an inspection system is not only dependent on the ability to detect a defect, but also to characterize it. One of the current areas for improvement for GW as a screening method is the fact that, if the defect morphology is not known, one cannot “exactly” determine the remaining wall thickness at the defect location. There are also limitations regarding the circumferential resolution in the C-Scan, which means that one cannot accurately calculate the wall thickness from the cross-section change and circumferential extent.

The remaining wall thickness is however the main characteristic parameter needed for pipe integrity calculations. For internal corrosion, UT can be used as prove-up tool to provide the remaining wall thickness at the location and clock position indicated by the GW result. It therefore complements GW optimally in this respect and improves the reliability of the inspection.

For the example given in section 4 the defect of 50mm diameter can be detected using GW with a POD of 0.99 (99%) using only two test locations. The GW result gives the location of the defect to within ±0.1m along the length of the pipe and ±45° circumferential orientation, as demonstrated in Fig 3. Manual UT can then be carried out on this small section of pipe (200mm*140mm) with a grid size of 50mm which would require only 12 test locations. With this grid size the POD for the UT measurement is 1 (100%) and therefore the exact wall loss can be measured.

In the case of external corrosion, manual UT is not normally possible but direct assessment methods can be used to measure the depth and extent of the corrosion defects once their locations have been detected using GW.

6 Comparison of GW and manual UT for Insulated Pipes

External, thermal insulation is commonly used for piping in the petro-chemical industry. Removal and replacement of this insulation is time consuming and expensive, usually requiring pipes to be taken out of service. Inspection of insulated lines is very problematic due to the very limited access which is available to the external surfaces of the pipe. A common strategy which is adopted for inspection is to provide small removable sections of insulation which are just big enough to allow a single UT measurement to be made. Typically these are located at the 4 quadrant points around the circumference of the pipe and are spaced at 10m intervals along the pipe length. For comparison purposed let us assume the same 6" pipe size with 50mm diameter half wall defect as before. Using 4 inspection points at 10m intervals for the entire length of the pipeline would give a POD of 0.002 (0.2%).

In order to carry out GW inspection of insulated piping a section of insulation must be removed to allow access to the entire pipe circumference at each test location, Fig. 6a) shows an insulated line which has been prepared for GW inspection. As previously demonstrated, the POD_{GW} for the defect in question is close to 1 so the overall total POD of GW is governed by the distance L between the test locations, the range D of the inspection and the near-field length N. Typically the diagnostic range D will be of the order of 60m and the near-field length will be not more than 3m. If the distance between test locations was 60m then the total POD of GW would be 0.95 (95%), to increase this to 100% the near-field would have to be inspected either by additional GW tests or by UT methods. To achieve a POD of only 0.002 (to match the performance achieved for the UT inspection) the GW test locations would have to be more than 25km apart.

(a) (b)

Fig. 6 **(a)** Typical insulated line, and **(b)** Difficult access due to elevated pipe.

Elevated pipe-work also presents access difficulties, as demonstrated in Fig. 6b). Due to these access difficulties it is common for UT inspections to be carried out using a similar protocol as has been described for insulated pipe, i.e. the 4 quadrant points around the circumference of the pipe and spaced at 10m intervals along the pipe length, which results in the same POD of 0.002 (0.2%) for the pipe/defect scenario discussed above.

7 Comparison of GW and manual UT for Inaccessible Pipes

There are many situations where access to the external surface of the pipe is not possible. For example, pipe sections under supports, cased sections of pipe, pipe sections which have limited clearance (for example between adjacent pipes). For the pipes sections with no external access it is not possible to carry out UT inspections so this limits the POD for UT. For example, a pipe which passes through a casing has no external access along the entire length of the casing, therefore the POD of UT for this section is 0.

GW inspection can be carried out for cased pipe sections as the guided wave travels along the length of the pipe and is not affected by the casing. Again, considering the same 6” pipe with 50mm diameter defect the POD of GW is governed by the distance L between the test locations, the range D of the inspection and the near-field length N. For optimal performance test locations are chosen to be 1.5m from both ends of the casing. If the casing is 30m in length the distance between test locations will be approximately 33m. If the test range is 35m and the near field is 3m, which are both typical values for this application, the total POD of GW will be 1 (100%). The only un-inspected areas would be within the near-field of each test location. The test locations are chosen such that the near-field does not extend into the casing and so these sections can be inspected using and additional GW test, UT or an alternative NDT method.

8 Conclusions

Based on simple considerations, it has been shown that for typical GW applications, the probability of detection for GW is higher than that of manual UT. This is due to a geometric component related to the coverage of the scan, which governs the POD of UT but not that of GW.

The only way to ensure high probability of detection, keeping an economically viable inspection effort and cost in mind, is therefore by using a screening approach such as GW.

However, overall reliability is not only related to the ability to detect a defect, but also to characterize it in terms of severity. As a consequence, it is the combination of GW, giving high probability of detection, and of UT or direct assessment, giving a high probability of correct classification, that results in much improved inspection reliability.

References

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