Phased Array for Small Diameter, Thin-Walled Piping Inspections

Michael Moles\(^1\) and Ed Ginzel\(^2\)

\(^1\) Olympus NDT, 48 Woerd Avenue, Waltham, MA, USA 02543
Tel: +1 416 831 4428, E-mail: Michael.moles@olympusndt.com

\(^2\) Materials Research Institute, 432 Country Squire Road, Waterloo, Ontario N2J 4G8, Canada. Tel: +1 519 886 5071. E-mail: eginzel@mri.on.ca

Abstract
The paper will describe current status and on-going developments. Though used for years, conventional ultrasonics has limitations due to efficiencies, lack of permanent results, and repeatability. In many cases, the preferred method of inspection has been radiography. Phased array techniques have now overcome many of these limitations.

This paper will show how phased array can be applied to thin, small diameter pipes using appropriate Scan Plans. Ray tracing techniques can show complete coverage to Code, and also appropriate angles. The techniques can use S-scans or E-scans, and in some cases, multiple scans are required. While small diameter pipes inspections using Automated Ultrasonic Testing (AUT) are now generally viable, there are still limitations. Specifically, codes have not fully adapted to AUT yet; ASME still requires a considerable number of calibration pipes; small diameter pipes will inherently defocus the beam; sizing defects’ vertical height is difficult with thin pipes, so the results tend to be “go-no go”; developing suitable scanners is still a priority.

Keywords: Small diameter pipe, phased arrays, Scan Plans, Automated Ultrasonic Testing (AUT), COBRA scanner

1. Introduction

In the past, most small diameter pipe welds were radiographed for defects, or not inspected at all. However, radiography has significant limitations: safety and licensing issues, disruption to work schedules, chemical wastes, film storage, and poor detection of planar defects. Manual ultrasonics was permitted by some codes, but suffers from lack of recorded data and is highly dependent on the operator’s skills.

In recent years, automated ultrasonic testing (AUT) has become commercially viable with the arrival of portable ultrasonic systems [1], and now potentially offers both auditable and reliable results for small pipes [2]. However, the AUT solutions were generally lacking a reliable and low profile delivery mechanism, and also had significant beam spread in small pipe diameters. Both these solutions have been addressed with COBRA, a new small diameter pipe inspection system from Olympus NDT.

While little AUT is currently performed on small diameter pipes, there are potentially many applications: boilers, process piping and product piping in refineries, ship-building, power plants, pharmaceuticals, nuclear etc.
2. Codes

The arrival of ASME Code Cases 179 [3] and 181 [4] has permitted AUT of small diameter pipe girth welds. ASME B31.1 CC 179 is a workmanship-based Code Case. ASME B31.3 does permit manual ultrasonic inspection of pipe welds, but has the limitations listed above (slow, operator-dependent, no auditable results). As it is Fracture Mechanics-based, B31.3 Code Case 181 needs accurate defect sizing and dimensioning. This is difficult requirement for thin pipes. For small diameter pipes, the ultrasound beam naturally spreads (defocuses) on entry in the horizontal direction. This will lead to defect oversizing, and hence higher repair rates.

In summary, there are codes in place, both workmanship or Fracture Mechanics based, that permit AUT on small pipes. Hardware that can perform an adequate job has been deficient, and is the subject of this paper.

3. Mechanical Scanner

Many small pipes are closely packed together, so a low profile scanner is essential. In conjunction with an outside supplier, Olympus has developed a portable, one axis scanner that fulfills the essential requirements (see Figure 1).

![Figure 1: Photograph of COBRA scanner.](image)

The scanner is semi-automated, i.e. it is hand-propelled round the weld, and encoded for full data collection. Hand-propelling saves costs, is technically easier and is convenient for small diameter welds. The scanner itself can be adapted to a range of sizes, which can be matched to the pipe diameter. As it is spring-loaded, the scanner can inspect both carbon steel and non-magnetic materials (e.g. stainless steels) with no changes. Experience has shown that the scanner provides good coupling for 360° round the pipe, which is essential.

This scanner can inspect pipe diameters from 21 mm (0.84”) OD to 115 mm (4.5”) OD. Clearance – including the low profile array - is a mere 12 mm, which permits it to inspect most small diameter welds in most configurations. It is waterproof, rust-free and CE
compliant. As can be seen, it is portable and light (see Figure 2). Also, it is easy to change the arrays and wedges. The encoder has a resolution of 32 steps per mm, which is plenty for AUT of welds. For welds with one-sided access only (e.g. flanges or pipes-to-component), the scanner can be re-configured for single access (see Figure 3).

Figure 2: Two-sided scan being performed on small diameter vertical pipe.

Figure 3: COBRA scanner inspecting pipe-to-component weld in single-sided access.

Not surprisingly, the scanner is designed to operate in conjunction with encoded portable phased array equipment, primarily OmniScan MX. In addition, there are various accessories to complete the package, such as links to establish a full range of ring sizes, water pump and carrying case. In effect, COBRA is a complete solution for small diameter pipes and tubes.

4. Focused Arrays

Early field results showed that lateral (or horizontal) oversizing could become a major problem as repairs may become significant. This was particularly important for smaller diameter pipes, as beam spread was more critical.
Initially, an R&D project was defined to evaluate the possible solutions to beam spread with phased array units, specifically matrix (2D) arrays, mechanically curved arrays, or any combinations. Both matrix and curved arrays offer practical solutions for focusing in both axial and circumferential directions. Modeling was performed using PASS to determine the relative merits [5]. Modeling showed that only two curvatures were required to cover essentially all small pipe diameters, independent of wall thickness. The larger radius curved array was manufactured and tested on known reflectors, and compared with a standard flat (unfocused) array on pipes of 70 and 38 mm diameter. Summary results are shown below, and compared with flat arrays.

Figure 4 shows the modeled results, with beam profiles displayed in both beam axis and cross-section. Comparing the images in the third (last) row with either the first or second row, it was immediately clear that the flat, unfocused beam had significantly worse beam spread than either the matrix array or the curved array. Wall thickness had been demonstrated as relatively unimportant since multiple skips were required for thinner walls, so beam paths tended to be quite constant. (Note that PASS cannot simulate the field with a beam skip, so the OD field is calculated by ignoring the pipe ID reflection and by just considering total metal path.)

There was no obvious advantage in using the matrix probe over a linear array probe with an optimized radius of curvature. Matrix arrays would be more expensive and complex to implement. Curved arrays can be implemented with no extra hardware or software, unlike matrix arrays. Subsequent modeling with a 10 MHz linear array confirmed these results for 25, 30, 50, 75mm diameters.
16x8 matrix. Focal depth 5mm. Field displayed in beam incidence plane.

16-element linear probe with radius of curvature of passive axis 22mm. Focal depth 5mm. Field displayed in beam incidence plane.


16x8 matrix. Focal depth 5mm. Field displayed in beam plane.

16-element linear probe with radius of curvature of passive axis 22mm. Focal depth 10mm. Field displayed in beam plane.


Figure 4: Modeled beam profiles of matrix array (top), curved array (middle) and flat array (bottom) under various parameters (from reference 5).

In summary, the modeling showed that one probe with 40mm radius of curvature is suitable for pipe OD greater than 25mm diameter, and one probe with 30mm of radius of curvature for pipe OD smaller than 25mm. Two curved arrays effectively covered all pipe diameters.
5. Experimental Confirmation of Modeling Results

Two pipes were selected for testing: 2.75” (70 mm) pipe and a 1.5” (38mm) pipe. Two wedges were contoured to match the pipe diameters, as per standard practice. Appropriate notches and holes were used as reflectors. The notches and holes were scanned with an OmniScan MX using typical phased array inspection procedures based on S-scans. The same setup was used for the two probes except the gain was necessarily reduced for the curved probe. The 6dB drop criterion was used for sizing.

Figures 5 and 6 show sample scans results from the 70 mm and 38 mm pipes, comparing flat and focused arrays.

(a) Flat probe. The measured notch length is 9.6mm.

(b) Curved probe. The measured notch length is 7.1mm.
Figure 5: 70 mm pipe. Detection of the 6.9mm long notch using the flat and curved probes (single skip).

(a) Flat probe. The measured size is 10mm.

(b) Focused probe. The measured size is 3.6mm.

Figure 6: 38 mm pipe. Detection of the OD end of the 1mm thru-hole with the flat and curved probes (double skip).

All the calibration reflectors in the two tubes showed consistent results: smaller diameter tubes gave more severe defocusing (beam spread) than larger diameters, and focused arrays gave much better lateral sizing results than flat arrays.
Rather than have multiple curved arrays, a manufacturing compromise was made. The modeling was performed on 5 MHz and 10 MHz arrays; in practice, we chose a 16 element 7.5 MHz. The two curvatures selected as optimum were 30 mm for diameters less than 25 mm, and 40 mm for diameters above that. A compromise radius of 35 mm was chosen. Along with a 60° natural angle wedge for high angles, this became the COBRA standard [6].

6. COBRA Scan Results

Figure 7 shows a typical COBRA scan of a weld from both sides; the pipe was 115 mm in diameter, and approximately 12.7 mm thick. The ultrasonic parameters are slightly varied to illustrate possibilities.
Figure 7, a, b, c and d: 115 mm diameter, 12.7 mm thick weld scanned using variations in set-up parameters.

Note in Figure 7 a-d that different set-ups generate different scan images. This is expected, and will depend on the operator’s ability to calibrate and set-up. However, once a standard set-up has been prepared, it can be e-mailed to all inspectors.

As with all OmniScan inspections, considerable detail can be viewed in the tables above in Figure 7, e.g. defect depth, amplitude, position. In addition, cursors can be used to box in a defect for measurements [1]. The angle of maximum amplitude can be determined using the cursor, and displayed as an A-scan for those who prefer such views. Overall, there is the usual choice of OmniScan views available: A-scan, B-scan, S-scan, C-scan. These more than fulfill the code requirements.

In contrast, Figures 8 a and b below show very small. thin pipes: 25 mm (1”) diameter and 3 mm wall. One is carbon steel, the other stainless steel.
Note that the carbon steel notches show better than the stainless steel, but this is primarily due to the problems with ultrasonic inspection of austenitics.

### 7. Comparison with Radiography

Figure 9 shows a radiograph of a weld with known and labeled defects.
A similar scan with COBRA shows the same defects (see Figure 10). However, with COBRA, the various defects can be more accurately sized and positioned.

The correlation between radiography and COBRA was good in all cases evaluated.

8. Conclusions

1. Olympus NDT has produced a novel semi-automated small diameter pipe scanner with two major features:
   a. Low profile for clearance, and
   b. Focused arrays to minimize lateral beam spread (and hence overcalls).
2. The scanner has a number of useful features:
   a. Adaptable from 21 mm to 115 mm diameters
   b. One-side access scanning
   c. Works on both carbon and stainless steel
3. The experimental results confirm that using the scanner and focused arrays produce significantly better defect length estimates.
4. The correlation between radiography and AUT was good in all cases investigated.

References

1. Olympus NDT, “Introduction to Phased Array Ultrasonic Technology Applications”, Published by Olympus NDT, August 2004.
3. ASME B31.3 CC 179, “Use of ultrasonic examination in lieu of radiography for B31.3 applications for materials ½” and less in wall thickness”, 28 June 2006.

Acknowledgements

Blue Star India provided some of the scans and the radiographs.