AUTOCOVERAGE – AN AUTOMATED ASSESSMENT OF THE COVERAGE ACHIEVED IN INSPECTION OF A NOZZLE INNER RADIUS BY UT BEAMS

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A key requirement of the RSE-M code is that un-inspected areas must be described in the inspection report. In many applications this is a relatively simple process, but in the inspection of components of complex geometry it can be difficult to assess, and report the location and extent of un-inspected areas.

In order to assess coverage of the inspection volume situated in the inner radius of branch nozzles in PWR primary circuits, a Mathcad routine, “Autocoverage”, has been developed to calculate the actual coverage achieved by the wide variety of ultrasonic beams used to provide detection in these complex geometries.

Given the inspection geometry, the best detection mechanism for surface-breaking defects of radial/axial orientation is normally the corner effect. For a defect to be detected by corner effect, an ultrasonic ray within the beam must intersect the corner in a direction normal to the surface breaking edge. Of course the ray must also be launched from a position on the component surface at which ultrasonic coupling is suitable.

This paper describes the Mathcad routine, how it is used to simulate coverage that could be achieved on the basis of the component geometry, the techniques applied and the scan plan that is followed. The paper further explains how the actual coverage is determined based on these parameters but also by taking account of the actual coupling conditions obtained during automated inspection.

Objective

The RSE-M code, which governs PSI/ISI of nuclear power plant in France, requires for any inspection that, in addition to demonstrating that defects can be detected and localised or characterised, the actual coverage of the examination volume be assessed and reported.

For inspections of components with constant cross section, such as pipe-to-pipe butt welds, coverage can be established without difficulty but where the component has more complex geometry coverage assessment requires calculation. This is an onerous task where phased-array techniques involving multiple beams are applied. Branch nozzle geometries typically require many beams and present significant challenges to inspection design and also to the assessment of inspection coverage. This is especially true for inspections of the nozzle inner radius.

Experience shows that the geometry of branch nozzles in primary-circuit piping may deviate from the theoretical configuration given in plant drawings. While these deviations are normally small in relation to the overall dimensions of the nozzle, they can have a significant effect on the coverage achievable in practice, given that this is almost always limited by the constraints of the component geometry (for example, the axial extent of the nozzle reinforcement). Experience also shows that the surface form of a branch nozzle may not allow for good coupling of the ultrasonic probe, particularly around the boundary of the nozzle-to-shell weld where manual grinding is applied. A proper assessment of the coverage achievable in inspection of a branch-nozzle inner radius must therefore take account of the as-built geometry of the nozzle. A proper assessment of the actual coverage of such an inspection must also take account of the quality of coupling achieved.

To facilitate assessments of this kind, a routine called “Autocoverage” has been developed using Mathcad software to simulate the geometric characteristics of an inspection and to quantify the coverage which it achieves both in theory and in practice, taking account of the ultrasonic techniques applied, the scan plan which is optimised to maximise coverage of the particular nozzle under investigation and the quality of coupling achieved.

The “Autocoverage” routine is designed to assess the coverage of phased-array inspections for inside-surface breaking defects in typical branch-nozzle geometries. Current versions provide for inspections carried out from the outside surface of the nozzle reinforcement (including its conical part) or
from the outside surface of the main pipe. They provide for assessment of coverage of the inside surface comprising the nozzle bore, the inner radius and the inside surface of the main pipe.

The examples presented in the present paper are for detection of surface-breaking, radial/axial planar cracks in the inner radius of a branch nozzle where the ultrasonic beams are deployed on the cylindrical surface of the nozzle reinforcement. This inspection makes use of the "corner-effect", in which the ultrasonic beam is reflected from the corner formed by the plane of the defect and the local surface of the component. For effective detection of defects by this technique, the beam should be incident on the defect in a direction close to normal to the line of the corner. Where a defect has a significant extension the line of the corner may vary along the defect length; at any position along the defect, the corner is characterised by the orientation of the tangent line to the curve of intersection of the defect and the surface.

In the examples presented, a phased-array probe is used to generate a number of beams at a variety of refraction angles and skews so as to obtain suitable incidence conditions over the range of geometries encountered around the nozzle. The use of a phased-array probe also allows a straight (0°) beam to be included so that the effectiveness of coupling can be continuously monitored by observing the signal reflected from the internal surface of the nozzle. This feature allows the production of detailed maps of the coverage actually achieved in application of the inspection.

A schematic representation of the inspection configuration for a single ultrasonic beam is shown in Figure 1.

![Figure 1 Schematic showing ultrasonic beam in radial/axial plane in the bore configuration (on the left) and in the inner radius (on the right)](image)

**The Autocoverage routine**

The purpose of the Autocoverage routine is to provide a computerised means of assessing and quantifying ultrasonic coverage actually obtained for each nozzle inspected. This assessment is based on the geometry of the component, the techniques and scan pattern applied and the amplitude of the backwall echo at each point on the scan plan.

The adequacy of coverage at any given point of the inside surface of the component is defined in terms of the angle of incidence on the target area. The routine can be broken down in 3 main functions: (a) the input data module groups all parameters required to set up the simulation; (b) the calculations module evaluates coverage by applying criteria defined in (a); and (c) the output data module synthesises the results obtained from various computations and defines the display format for cell maps and coverage statistics.
The input module verifies that the geometrical dimensions of the component are within the acceptable range of variation allowed by the Technical Justification of the inspection. It also uses the data from acquisitions to determine those probe positions where adequate coupling has been achieved. The criterion for this is that the amplitude of the back-wall signal at the position considered differs from the modal value over the whole inspection by less than a tolerance defined in the examination procedure. Positions where the insonification is not effective either because of a failure of coupling or due to local surface degradation are excluded from the subsequent calculations.

The calculation module first defines a grid of potential reflection positions over the examination area (on the inner surface of the nozzle/pipe).

Figure 3 illustrates the establishment of this grid and a map of valid probe positions.

For each of the ultrasonic beams applied, the calculation then proceeds as follows. For each combination of reflection position and valid probe position, the ray joining the points is examined. The reflection point is said to be insonified if the following criteria are met:

- the ray lies within the cone of divergence of the beam (where the divergence is defined by a given dB drop relative to the beam axis);
- the distance between the reflection point and probe position is such that the reflection point lies within the range gate applied.

If the beam reaches the reflection point according to these criteria, then the angle between the ray and the surface tangent line at the reflection point (i.e. the line of the corner formed were a surface-breaking defect of the relevant orientation to be present) is calculated. The incidence angle is defined as the difference between this angle and 90°. At each reflection point, the minimum incidence angle over all combinations of grid points is retained.
The output module presents maps of the incidence angles calculated for each beam individually and of the minimum incidence angle for the combination of all beams. An example of such a map for a small group of beams is shown in Figure 4. In this example of the map for a group of beams applied to inspection of the inner radius of a 14 inch nozzle, the cell size in the radial (R) direction is 4mm, and the lower edge of the map corresponds to the junction between the inner radius and the inside surface of the main pipe. The map shows immediately the sectors of the inside surface of the main pipe adjacent to the inner radius over which coverage is effective and the sectors where it is not effective.

**Figure 4 Example of coverage mapping of a group of 52° beams on a 14 inch nozzle. Axes are radial, r and azimuthal, θ. Colours represent the deviation of incident beam from the direction normal to the defect edge.**

Examples of coverage maps

The coverage result for a typical case of a phased-array inspection of the inside surface of the main pipe adjacent to the inner-radius of a 14-inch branch nozzle is shown in Figure 5. A study of the detection conditions conducted as part of the Technical Justification for the inspection concluded that radial/axial defects of the size of interest would be detected by the corner effect provided that coverage was achieved at the inside surface of the main pipe over a strip adjacent to the inner radius/inside surface junction of minimum width 12mm. The Autocoverage result shows coverage of 100% of this strip. It can be seen that there is a slight difference in the mapping between the intended coverage, based only on the extent of the surface scanned, and the actual coverage taking account of the coupling achieved (as deduced from the amplitude of the backwall echo with the 0° beam). The coverage result is the same because the critical area (first 3 cells or 12mm, measuring from the bottom of the map) is filled in red, indicating that the angle of at
least one of the beams intersecting the cells concerned does not deviate by more than 1° from the local direction of the defect edge passing through the cell; the 1° criterion having been established as adequate for detection in the Technical Justification for the application.

Figure 5 Example of overall coverage: coverage corresponding to the area scanned is shown on the left and actual coverage taking account of coupling on the right (vertical scale mm, horizontal scale degrees).

An example of an Autocoverage result where coverage did not reach 100% is shown in Figure 6. Here the strip adjacent to the inner radius has some “missing cells” where the colour indicates that the angle of deviation of the beam from perpendicularity exceeds 1°. While the coverage map indicates that these areas are insonified, the incidence conditions are not ideal so that defect detection is less certain than for areas where the 1° criterion is met.

Figure 6 Example of mapping showing missing cells in the critical area (row n°1, 2, 3) around 90° and 270° (i.e. cells where the criterion: deviation from perpendicularity ≤ 1° was not met)

Analysis of this result showed that the missing cells were due in part to the axial extent of the surface available for scanning on the nozzle boss being less than expected and in part due to areas where the surface conditions prevented effective coupling.

Site application

The use of Autocoverage for coverage mapping has now been integrated into the ultrasonic inspection procedures deployed by Doosan Babcock for the inspection of certain 6 inch and 14 inch branch nozzles in EDF 900MWe plants in France. Several interventions have been carried out and Autocoverage has allowed the extent of coverage on each nozzle inspected to be established and documented in detail.
Conclusion

A software tool “Autocoverage” which allows assessment of the coverage which is potentially and actually achievable in the inspection of the inside surfaces of branch nozzles in primary circuit piping has been established and demonstrated.
The tool has been deployed successfully on site.

Acknowledgement

“Autocoverage” has been developed and applied in the context of the EDF application “Inspection of Boron Injection and Surge Line Branch Nozzles on 900MWe PWRs”.
We acknowledge the helpful comments of EDF CEIDRE in developing and finalising Autocoverage and in integrating it within the site procedures for implementation of the inspection application.