Developments in Ultrasonic Phased Array Inspection I

Practical Use of Phased Array UT in Power Plant Application
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ABSTRACT

Phased array ultrasonic examination of power plant components has become the preferred volumetric examination methodology even though conventional UT approaches are associated with the same physics and can achieve similar end results. The difference is in the implementation. Phased array UT offers the means of collecting and imaging significantly more information per unit volume with the benefits of fewer transducers, less scanning distances, and greater flexibility in adapting to actual plant configurations. As such, in power plants where personnel radiation exposure dictates lesser examination times and more remote and simplified applications, and where plant aging concerns are driving more frequent inspections, inspections combined with aging mitigation processes, and inspections of components not previously anticipated to be inspected, the practical uses of phased array UT are expanding.

But phased array UT is not a simple and inexpensive panacea. Such applications require more complex, specialized, and expensive transducers. Special instrumentation with unique hardware and software is required for creation of multiple beam arrays and beams skews. Implementation personnel need specialized training. This paper will focus on two recent applications where the use of phased array UT techniques excels over conventional UT techniques. One is the examination of reactor pressure vessel nozzle dissimilar metal welds from the OD surface where accessible surface areas are limited and physical access is difficult. This application matches up effectively with MSIP™, a stress improvement process to mitigate IGSCC in Alloy 600 welds. The other is the examination of axial entry blade attachments on turbine rotors where complex examination surfaces, a variety of steeple geometries, and crack orientation combine to form a three-dimensional inspection challenge. This application can be applied on nuclear and fossil steam turbine rotors, and combustion turbine rotors.

EXAMINATION OF PWR REACTOR VESSEL NOZZLE TO SAFE END WELDS FROM THE OUTER DIAMETER SURFACE

Inspection Background

Many existing PWR Reactor Vessel nozzle to safe end welds are fabricated of Alloy 82/182 weld metal that has a known history of stress corrosion cracking caused by a combination of the PWR water environment and residual stress levels. This cracking initiates at the wetted inside diameter surface. MRP-139 [1] requires that such welds be inspected using ASME Code Section XI, Appendix VIII [2] qualified ultrasonic test (UT) equipment, procedure and personnel in a specified timeframe. MRP-139 also allows for the mitigation of such cracking using various stress improvement processes; one of which is the Mechanical Stress Improvement Process (MSIP®)\(^\text{1}\). This mitigation process is implemented on the component outer diameter surface typically using equipment installed through access ports in the reactor refueling cavity floor. This mitigation process effectively squeezes the OD of the pipe to create compressive residual stresses on the ID surface which remove one of the causal factors of stress corrosion cracking. Application of this process requires that a pre- and post-mitigation ASME Code Section XI, Appendix VIII qualified UT inspection be conducted.

Such UT inspections can be applied from the inside or outside surfaces of the component. The inside surface inspection of all such welds (inlet and outlet nozzles) requires that the reactor be defueled and the complete vessel internals package be removed from the reactor vessel. Removal of the internals package requires a flooded reactor refueling cavity for radiation shielding. This process

\(^{1}\) MSIP is a registered trademark and patented process of NuVision Engineering
may take days prior to and after the MSIP® and is a rather complex activity that is typically only implemented on a 10-year cycle. Essentially there are no surface condition limitations that would prevent an ID surface-applied inspection.

The outside surface inspection requires the same access to the component as the MSIP® process and can be implemented without an extra vessel internals removal/installation cycle. However there are surface condition constraints that dictate adequate examination volume coverage and sufficient ultrasonic coupling. Figure 1 shows a picture of an example of OD surface conditions and a sketch of the weld configuration. The required ASME Section XI examination volume is the inner 1/3 thickness box shown on the sketch.

For the first application, access to the OD surface was from the reactor refuelling cavity floor through an access port as small as 24-inches (0.6m) wide by 60-inches (1.5m) long. The top of the nozzles were approximately 5-1/2 feet (1.7m) down from the cavity floor. Dose rate estimates next to the component ranged from 50 – 100 mR/hour (0.5 – 1 mSv/hr). Previous outage information on the nozzle surface conditions indicated that although some surface conditioning was required sufficient surface extent was available for scanning. As such the decision was made to perform the inspection from the OD surface.

Figure 1 - Example RPV Nozzle to Safe End Weld Configuration

Approach

Given the environmental constraints a fully automated approach using phased array ultrasonic inspection technology was pursued. The scanner would need to be remotely installed from the reactor cavity floor and carry the full compliment of UT probes needed for the inspection. Given preparation time constraints the rights to the previously qualified Zetec/EPRI technology procedure, Zetec_OmniScanPA_03 [3], were obtained. The 3-axis scanner design included two elevated track sections that could be installed remotely from the cavity floor using poles, chain hoists and rope. The upper track section included the motors and encoders. A single encoded axis was used for probe
movement along the weld. Two independent encoded axes were used for probe movement across the weld with each axis connected to a probe fixture. Three probes were installed on the scanner on two fixtures. For four directional scanning, each of the probe fixtures was attached to a pneumatic rotational axis for remote 180-degree rotation.

The essential parameters of the phased array UT procedure were integrated into a component specific inspection procedure. The major essential parameter change was in the selection of lower axial scan beam angles in order to obtain the required >90% examination coverage for circumferential flaws. Influential parameter changes were made in order to adapt the process to the environmental and operational conditions of the inspection. Such changes included: increase of the cable length by 4.5m, addition of an intermediate active channel check using the probe/wedge configuration and adjustment in the calibration verification process. All parameter changes were supported by a technical justification.

Qualification

Whereas the inlet and outlet nozzle to safe weld diameter and thickness values fell within the PDI-qualified diameter and thickness range, the changes to the beam angles and the cable length required a component specific demonstration in accordance with PDI site specific demonstration protocol [4]. The qualification objective was to demonstrate that such changes did not impact the original procedure qualification results.

The demonstration was conducted on EPRI/PDI practice mock-up, 603/1 since it best represented the anticipated surface conditions and it contained the appropriate crack defects consistent with the PDI protocol requirements. The demonstration was conducted under the auspices of EPRI, the site Level III and the site ANII. The mock-up was masked to represent the most limiting scan length anticipated for the site application.

All the crack defects in the mock-up were detected and sized within the required tolerances. The most difficult circumferentially oriented crack, having a through-wall depth of 0.32-inch (8.2mm) and a length of 9-inches (233mm), was located in the buttering material between the ferritic steel/stainless steel cladding intersection and the buttering/weld material interface. These metallurgical reflectors complicated the data analysis process.

Detection of this crack with high confidence could not be accomplished with any longitudinal wave test angle less than 30-degrees although lower test angles from 20-degrees to 29-degrees were applied. Additionally, this detection could not be accomplished unless a minimum scan length was available on the safe end side of the weld. As such the component specific procedure was considered qualified, however only longitudinal test angles equal to and greater than 30-degrees functioning over a minimum surface distance from the ferritic nozzle to buttering OD surface interface could be used to obtain examination coverage credit of the most susceptible weld materials. Such restrictions limit the use of the OD surface inspection approach for other plants.

As such the demonstrated and justified component specific procedure uses a dualelement, linear array, PA UT probe for circumferential flaws operating with longitudinal waves and then again with shear waves; discrete test angles are used ranging from 30- to 70-degrees. Dual-element matrix array PA UT probes are used for axial flaws. One probe is used for longitudinal wave inspection and the other is used for shear wave inspection. Discrete test angles ranging from 25- to 55-degrees are used with discrete skew angles between -25- to +25-degrees.

Field Application

The inspection system was applied in the field in October 2008. It was successfully applied to two outlet nozzle to safe end welds for the pre-MSIP® inspection. Figure 2 shows the scanner installed on an outlet nozzle.
Problems with plant obstructions and longer scanning durations prevented the use of the system for the other six nozzles in the pre-MSIP® inspections and seven nozzles in the post-MSIP® inspections. The other nozzle welds were inspected using an alternative manual phased array UT process [5] that was also demonstrated on the 603/1 mock-up.

This manual UT process used the Intraphase™ portable phased array UT instrument. Of significance was the detection and sizing of one suspected circumferential planar flaw indication located in the buttering. It was sized as 24% of the thickness in throughwall and 2.3% of the circumference in length. This flaw indication size was less than the applicable flaw size restrictions for application of the MSIP® process, thus the mitigation process was implemented. Automated post-MSIP® inspection of this flaw indication demonstrated a significantly reduced response thereby attesting to the effectiveness of the MSIP® process.

EXAMINATION OF AXIAL ENTRY BLADE ATTACHMENTS FOR STEAM AND COMBUSTION TURBINE ROTORS

Inspection Background

Axial entry blade attachments are subject to high levels of stress during operation due to the centrifugal mass of the blade as well as steam forces. Such attachments allow for turbine blades to be installed in the axial direction with each blade having its own steeple or tree configuration. The steeple has a number of lands that provide pairs of load transferring surfaces. The root fillet corner of these lands acts as a stress concentration center that can form into a stress corrosion cracking initiation site. Figure 3 provides an example of a curved axial blade attachment geometry.
There are a number of inspection challenges with the axial blade attachment inspection. Whereas Figure 3 shows a curved blade attachment design, other existing designs may be straight or slanted. The scanning surface is may be either flat or curved. The steeple geometry itself offers multiple sites for beam reflection and beam re-direction.

**Approach**

Phased array UT offers the means to scan a region at a time along the axial length of an attachment with single matrix array probe at a single probe location by using an array of beam angles. In addition, PA UT offers the means to scan along the cross-section of an attachment looking at all the potential crack initiation sites by using an array of skew angles. In either case a matrix phased array probe affixed to various contoured wedges provides the most flexible means of adapting to a wide range of rotor disc geometries.

Typically both the axial and circumferential beam sweeping approaches are used. The axial beam sweeping detects gross cracking, offers better length sizing measurements, and assists in providing more details of the attachment design. The circumferential beam sweeping allows for detection of smaller defects and offers better flaw depth sizing measurements.

Flaw detection is through pattern recognition. The steeple configuration provides a series of geometrical reflections that are consistent from one attachment to the next using the same probe at the same position on the disc examination surface. Deviations from this pattern are indicators of potential degradation. Beam re-directions from actual defects into the steeple features or from geometrical features to an off-angle flaw require an experienced data analyst. Figure 4 shows one example of a signal pattern from a circumferential beam sweeping inspection of a curved axial blade attachment.
Qualification

The basic approach of axial beam and circumferential beam skewing has been applied to various turbine rotors having different blade attachment curvatures and different examination surface contours. These samples contained a variety of notches of different sizes, orientations and locations on the steeples. Several of the configurations contained actual cracking that was confirmed with magnetic particle (MT) testing after blade removal.

Planar flaws (notches) having lengths under 0.125” (3.2mm) and depths under 0.01” (0.3mm) were detected in the qualification of the inspection procedure. Tip diffraction depth sizing of flaws having depths > 0.06” (1.5mm) were possible. Scans of discs from a field removed rotor detected actual cracking that was later confirmed by supplemental MT inspections [6]. Figure 5 is an example of a detected crack of unknown depth.
CONCLUSIONS

In these two power plant applications, phased array UT technology provided significant advantages over conventional UT. The ability to scan with an array of beam angles with no skew angle, with an array of skew angles with a fixed beam angle, and with an array of beam angles with an array of skew angles using an appropriately selected probe were instrumental in reducing the number of required probes, obtaining substantially more examination volume coverage, reducing inspection times, and overcoming complex geometries.

REFERENCES

3) Zetec, “Procedure for Encoded, Manually Driven, Phased Array Ultrasonic Examination of Dissimilar Metal Piping Welds, Zetec OmniScanPA_03”, Revision D.
5) Electric Power Research Institute, “Procedure for Manual Phased Array Ultrasonic Examination of Dissimilar Metal Welds, EPRI-DMW-PA-1”, Revision 0.