# Recent Progress in Phased Array UT Inspection through Complex and Wavy Surfaces

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## ABSTRACT

Phased array UT techniques are being used for inspections in nuclear and conventional power plants for more than 10 years. Applications involving simple linear arrays, using either sectorial scanning or multiple-angle raster scanning, are now commonly used and accepted. But the industry is continuously looking for inspection solutions to more challenging inspection configurations, and this requires advanced software features and phased array hardware.

This paper will present some advanced applications of phased array technology, for inspections on components with complex and wavy surfaces. It will illustrate how recently developed phased array hardware and state-of-the-art dedicated software supports these innovative phased array inspection concepts.

1D linear and 2D matrix flexible array probes can be used to improve the examination capability on components with complex surfaces. Alternatively, conformable wedges and wedges with custom contouring can be used to couple standard phased array probes onto specific regions of a wavy surface. In both cases, optimized focal law groups are required to adequately focus the acoustic energy. Various methods will be addressed to import accurate information about the component surface into the focal law calculator.

The optimized focal law groups for each probe position are calculated and stored in memory prior to the examination. During the inspection sequence, the processing power of the system allows for rapid retrieval and application of the appropriate optimized focal law group. This feature is called "position dependant focal law groups".

The presented examples will include considerations about phased array probe design, selection and generation of focal law groups, and inspection results.

## INTRODUCTION

It is well known that the examination capability of UT inspection techniques strongly depends on the surface condition of the considered components and welds. On components with a nearly flat or cylindrical surface, the nominal performance of the designed UT inspection techniques can be achieved. Unfortunately, a significant portion of the components and welds in the field do not present these ideal surface conditions. Some components have an "as-welded" surface condition, for others the weld crown has been ground to a smooth but wavy surface finish, and many nozzles have a tapered weld region.

In these cases, the examination capability of UT techniques can be strongly reduced. First of all, for contact techniques, the lack of coupling will inevitably lead to reduced coverage of the examination volume. Even when adequate coupling can be achieved by using complete or local immersion techniques, the ultrasonic beams are redirected and distorted by the surface irregularities. In addition, flaw indications that might be observed will not be correctly positioned by the imaging software, and therefore extremely difficult to interpret.

When using conventional UT techniques, the only partial solution for these issues is to reduce or adapt the footprint of the probe(s), and this often results in poor examination coverage and even poorer performance.

This paper will demonstrate the potential of phased array technology to offer adequate solutions for the UT examination of components with complex and wavy surfaces.

## PHASED ARRAY PROBE SOLUTIONS

In terms of phased array probe design, several solutions have been considered to achieve adequate coupling through a complex surface.

Flexible array probes have been successfully used in laboratory studies for more than 5 years [1]. The first generation of flexible probes were rather bulky and not sufficiently robust for field deployment, but improved 1D and 2D flexible array designs have been developed, and are ready to be evaluated in industrial conditions [1]. This paper will present some examples of the application of flexible array probes on irregular inspection surfaces.

Performing the UT examination in complete immersion is not always an option for in-service inspections in power plants. The practical alternative is to use a local immersion technique, where a standard rigid phased array probe is coupled to the surface via a “water wedge”. The water is contained in the wedge by a conformable low-loss membrane. This solution is cost-effective and its feasibility was demonstrated in recent studies [3]. Some issues may however arise with the robustness of the conformable membrane for field inspections.

For components where the surface irregularity is essentially limited to a single plane, e.g. an axisymmetric tapered nozzle, a solid wedge with a customized footprint can be an alternative for the conformable wedge. Although this design has intrinsic limitations, it can provide a feasible and practical solution for some inspection configurations [4].

## INNOVATIONS IN HARDWARE AND SOFTWARE

The phased array probe design is only a part of the overall inspection solution. Even if acoustic energy is well transmitted through the complex interface, the irregular shape may prevent adequate focusing of the sound beam in the region of interest.

A major benefit of phased array technology is that adequate focusing of the acoustic energy can be achieved by optimizing the individual element delays to compensate for the complex surface profile.

Different approaches can be used to implement the optimized element delays. Full Matrix Capture, with subsequent off-line processing of the A-scans collected from the individual probe elements has been identified as the “ultimate solution” [3],[5]. Indeed, this method allows for off-line reconstruction of sound beams with every possible wave mode, refracted angle and focusing. On the other hand, this solution is very time consuming and may not yet be appropriate for industrial inspections. Therefore, the use of predefined focal laws is worth exploring in more detail.

At the end of 2007, Zetec launched its new DYNARAY® system, and very recently the DYNARAY® Lite was added to the productline. These extremely powerful phased array UT data acquisition systems can be configured with up to 256 (64 for DYNARAY Lite) simultaneously active channels and a large number of focal laws (up to 4096), to fully benefit from the versatility of 2D matrix array probes.

The DYNARAY product line also offers improved inspection capability on complex and wavy surfaces. Owing to its raw processing power, the system supports position dependant focal law groups. This means that predefined optimized focal law groups can be sent to the phased array probe during the inspection sequence as a function of the probe position.

The new UltraVision® 3 software, with advanced data acquisition and analysis functions, is required to drive the DYNARAY systems. UltraVision 3 includes all the features of the widely used UltraVision 1 software, but in addition it offers a 3D work environment for the creation of components, 3D ray-tracing, the generation of focal laws and the visualisation of examination data. In particular, the advanced phased array calculator in UltraVision 3 can generate optimized acoustic beams through complex inspection surfaces. In addition, the software is capable of interpreting the spatial position information of the beam exit points, to correctly position the phased array data in the specimen.

A large part of the work scope for UltraVision 3 is dedicated to the development and validation of 3D tools to support advanced inspection techniques and array probes for the examination of complex surfaces. The ray-tracing, modelling and the experimental work described hereunder are part of the on-going internal validation program.


Figure 1: DYNARAY and DYNARAY Lite phased array UT systems

## TEST SPECIMENS

A number of test specimens were designed and fabricated for the internal validation program. All specimens are made of aluminum and contain simple artificial reflectors. As the objective of the test program is to investigate the influence of the surface condition, potential influences of material and flaw morphology were deliberately eliminated. At this stage, the complexity of the surface was limited to a single plane.

Several reference specimens were machined with a periodical "waviness" of the scanning surface, with various spatial periods and wave amplitudes. The wavy reference specimen in Figure 2 has a period of 50 mm and a peak-to-peak amplitude of 4 mm. Each segment of the surface is representative of a smoothed weld crown and the weld shrinkage on either side of the crown. The specimen contains two side-drilled holes with a diameter of 2 mm and a far-surface notch with a height of 10 mm. In addition, the specimen edges offer specular reflectors at 30 degrees and 60 degrees inclination.

A flat reference specimen (see Figure 2), containing identical reflectors, was used for comparison purposes.

To simulate more realistic inspections conditions, a specimen with a tapered surface was used, also containing side-drilled holes and machined notches. (see Figure 3). The profile of this specimen is representative of the dissimilar metal weld region of a PWR pressurizer nozzle.

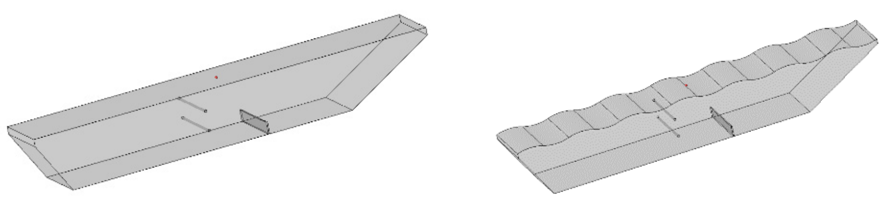


Figure 2: Flat reference specimen (left) and wavy reference specimen (right)

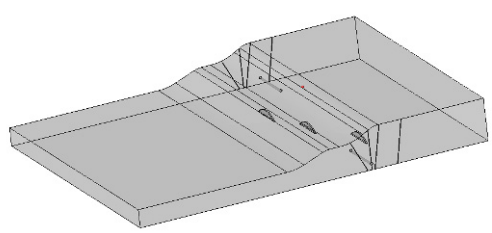


Figure 3: Realistic tapered specimen

## 3D RAY-TRACING

The 3D ray tracing tool in UltraVision 3 allows the user to draw 3D rays into a CAD model of the component and visualize the interaction with various reflectors. The software includes various templates of components and weld configurations, for which the user can adjust the geometrical parameters and postulate expected indications or reflectors. In addition, UltraVision 3 supports custom specimens, that can be imported as *.SAT files. This method was used during the test program on wavy specimens.

Figure 4 shows 3D ray tracing in a wavy reference specimen and in a realistic tapered specimen. For each position on the specimen, the ideal impingement angle (measured between the ray and the normal to the flat backwall) and the corresponding refracted angle (measured between the ray and the normal to the inspection surface at the exit point) can be determined.

Moreover, the 3D ray-tracing tool can be used to design inspection plans, to assess coverage, to determine beam direction in complex specimen such as penetrations in a boiler head, and to model the reflectors interactions for either conventional UT or phased array probes, all this in a user-friendly interface that does not require any CAD software knowledge.

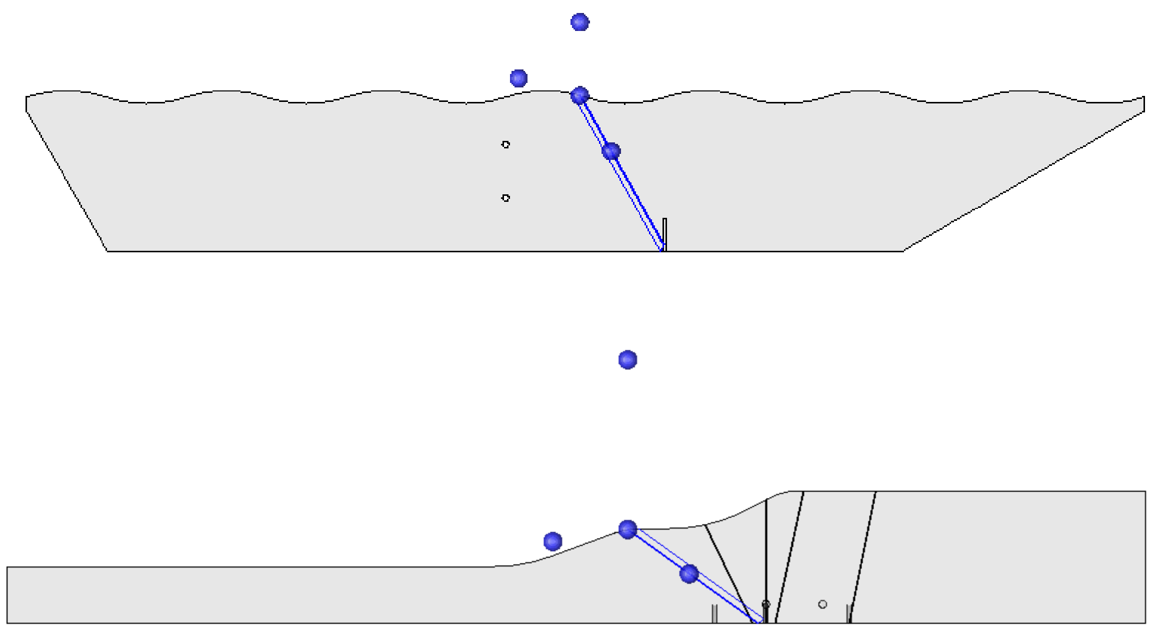


Figure 4: 3D ray tracing in complex specimens

## MODELLING AND EXPERIMENTAL VALIDATION OF FOCAL LAWS

The advanced phased array calculator in UltraVision 3 provides a 3D graphical interface, which makes it relatively straightforward to generate the required focal law groups for a phased array probe on a given component. Figure 5 shows typical images displayed in UltraVision 3 to visualize the focal law groups generated for a 1D linear flexible array, and a 1D linear rigid array fixed onto a rexolite wedge.

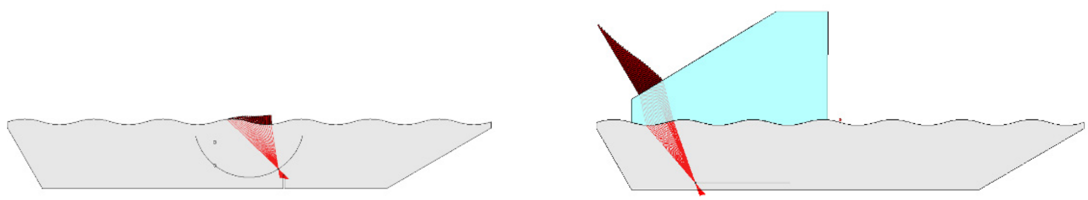


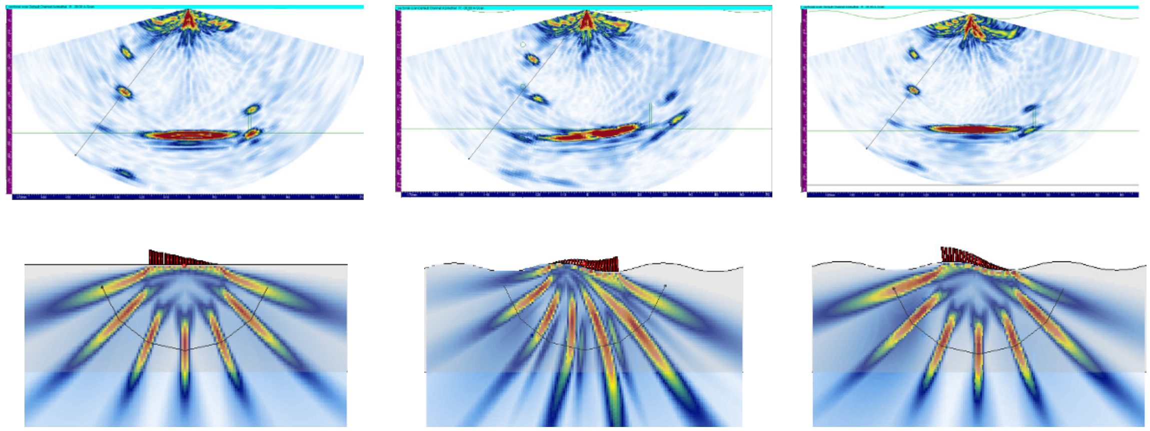
Figure 5: Generation and visualization of focal laws in complex specimen

Figure 6 shows the results obtained with a flexible 1D array (2 MHz, 24 elements, pitch 1.4 mm) for three different configurations. The leftmost images show actual UT images and acoustic beam simulations obtained on the flat reference specimen, using azimuthal scanning from -75° to 75°LW. The two side-drilled holes (left) and the machined notch (right) are well detected and accurately positioned. As expected, the sound beams in the flat specimen are coherent and correctly oriented.

The images in the middle show the results when the flexible array is applied onto the wavy reference specimen without adapting the focal laws for the surface condition. In this specific case, surprisingly, detection of the artificial reflectors is still fairly good, but the positioning is off by at least 5 mm. This behaviour is corroborated by the results of the acoustic beam modelling: the sound energy stays reasonably well-focused, but the orientation of the beams deviates from the intended directions.

The rightmost images show the results for the flexible array on the wavy reference specimen with optimized focal laws and on-line correction of the sector scan image for the actual surface geometry. The quality of the UT image, in terms of reflector detection and positioning is very close to the situation for the flat reference specimen. Also, the simulated beams are very similar to those calculated for the flat specimen.

Figure 7 shows the results obtained with the flexible array on the realistic tapered specimen. The UT image and the acoustic beam simulation on the left side are obtained when the flexible array is applied onto the specimen without adapting the focal laws. The machined notch (h = 5 mm) is simply not detected, most probably because of the redirection of the acoustic beam caused by the tapered surface. The images on the right side are obtained with optimized focal laws and sector scan correction: the tip and the corner of the notch are well-detected and accurately positioned; at the same time the sound beam is correctly oriented through the complex surface.

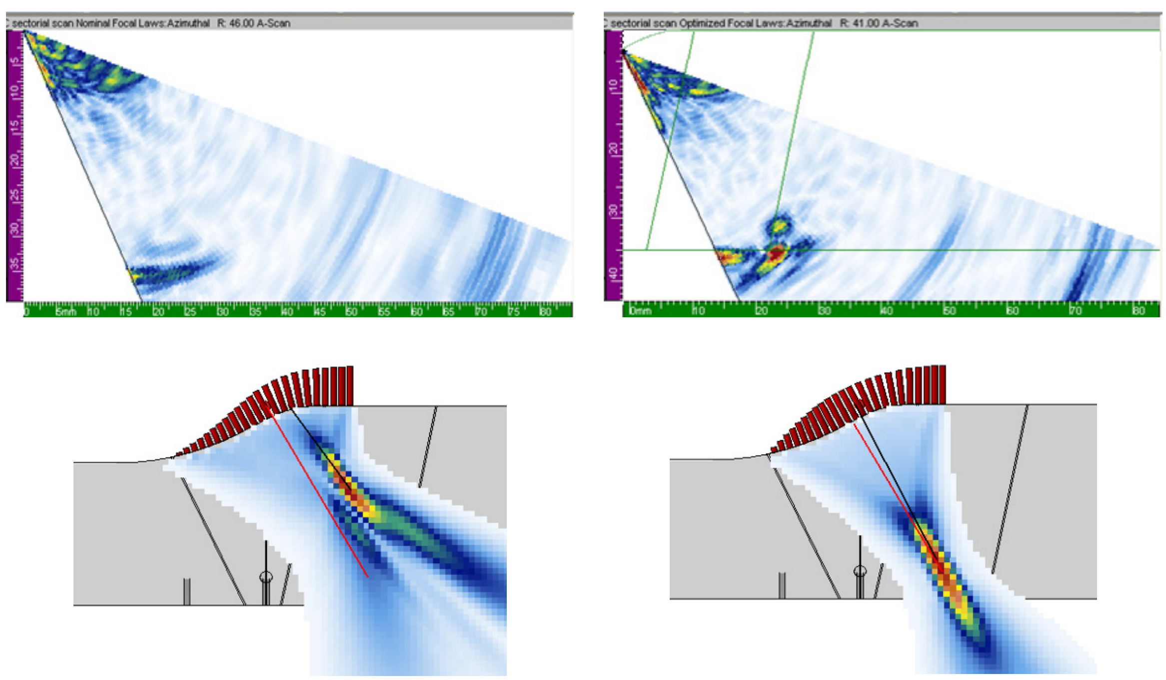


flat reference specimen

wavy reference specimen
nominal focal laws

wavy reference specimen
optimized focal laws
on-line sector scan correction

Figure 6: Actual UT data (above) and corresponding acoustic beam modelling (below) from azimuthal scanning with flexible array on reference specimens




realistic tapered specimen
nominal focal laws

realistic tapered specimen
optimized focal laws
on-line sector scan correction

Figure 7: Actual UT data on machined notch (above) and corresponding acoustic beam modelling (below) from azimuthal scanning with flexible array on realistic tapered specimen

The optimization of the focal laws to compensate for the surface profile at a specific probe position implicitly means that they are not adapted for any other position. This issue can be overcome by using position dependant focal law groups.

This advanced tool of the UltraVision 3 software allows the user to divide a complex inspection surface into “regions” with constant surface profile, as shown on Figure 8. Optimized focal law groups for each region of the complex surface can be generated and stored during the setup process.

The DYNARAY systems can dynamically select focal laws sent to the phased array probe during the inspection sequence as a function of the probe position. Up to 4,096 different focal laws can be handled for a given setup. The encoder feedback informs the equipment about the position of the probe so it can apply in real-time the correct set of focal laws for the corresponding surface profile.

The data acquired for each region can then be merged offline and visualised as a single group, as shown on Figure 9.

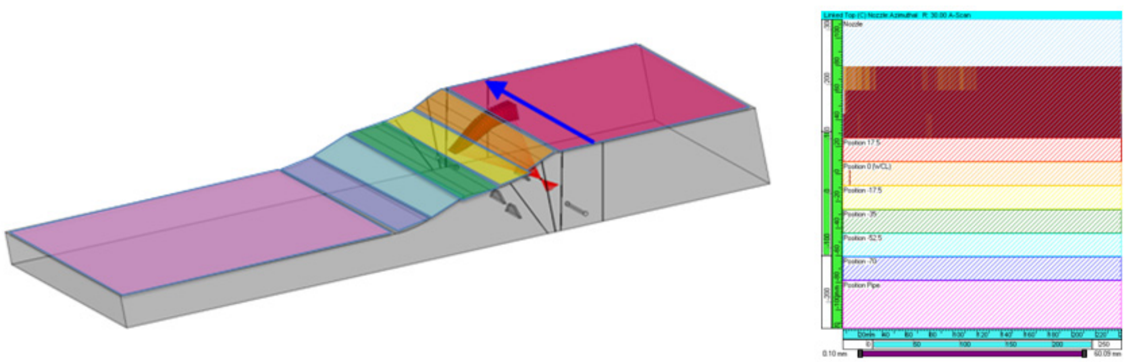


Figure 8: Definition of the “regions” on the realistic tapered specimen surface

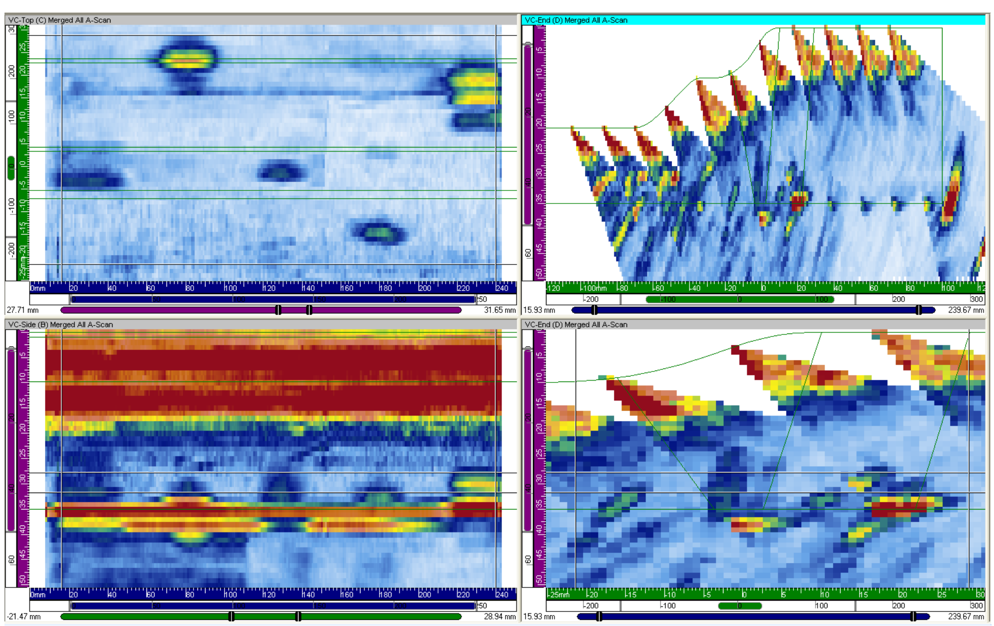


Figure 9: Actual UT data acquired with flexible array on realistic tapered specimen using the position dependant focal law groups tool

*Generic observations*

- The inspection capability of a system based on flexible arrays is basically limited by the capability to mechanically "fit" the flexible probe to the considered wavy surface.
- The generation of optimized focal laws through a complex surface is rather straightforward, if the surface doesn't present major discontinuities.
- The capability to generate vertically polarized shear waves is very limited, and therefore not adequate to obtain volume coverage with an azimuthal sweep.
- The use of the position dependant focal law groups allows acquiring optimized inspection data for different positions of a complex specimen in real-time and in a single data file.

## 3D IMAGING OF PHASED ARRAY UT DATA

In order to facilitate and expedite the analysis process for phased array inspections on complex components, the Volumetric Merge tool in UltraVision 3 has been enhanced to allow for realistic 3D visualization of phased array data in the CAD model of the component.

Figure 10 shows the 3D visualization of merged phased array data at 50°SW, recorded with a rigid 1D linear array and custom wedge, in a tapered nozzle specimen. Obviously, this type of representation allows for accurate positioning and sizing of flaw indications, even in complex components, thus drastically improving the examination performance.

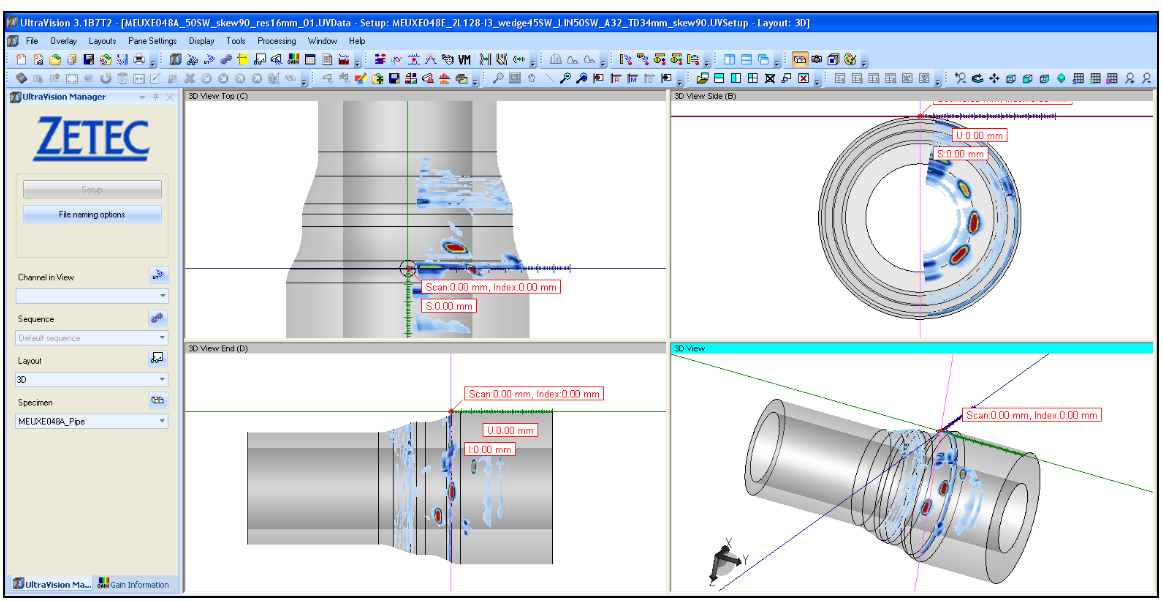



Figure 10: 3D image of merged phased array UT data obtained with rigid 1D linear array and custom wedge, in tapered nozzle specimen

## CONCLUSIONS

From the work presented in this paper, the following conclusions can be drawn:

1. Phased array technology definitely has the potential to offer adequate solutions for the UT examination of components with complex and wavy surfaces.
2. Several alternatives are feasible in terms of probe design: flexible array probes, and rigid array probes with a conformable or customized wedge
3. The use of position dependant focal laws that compensate for the irregularity of the surface in each region, is essential to obtain adequate examination capability on complex and wavy surfaces.
4. Enhanced UT imaging, taking into account the surface geometry, can drastically improve the interpretation of the examination data.
5. State-of-the-art software supporting these advanced inspection solutions is commercially available, and further development of new features is on-going.

## REFERENCES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