DEVELOPING THE MATRIX

JAN VAN DER ENT AND NIELS PORTZGEN, APPLUS RTD, THE NETHERLANDS AND GARRETT ATKINS AND JOSHUA SLEIGH, EXXONMOBIL DEVELOPMENT CO., USA, DISCUSS THE DEVELOPMENT OF MATRIX PHASED ARRAY SYSTEMS FOR PIPELINE GIRTH WELD INSPECTION.

Pipeline projects to transport natural gas and hazardous liquids to consumers have and continue to push into new and challenging arctic and deepwater frontiers. Pipe materials with greater strength and toughness are being developed to enable oil and gas development in these challenging environments with requisite assurance of long-term integrity, reliability and economy. In addition, continuous improvements to quality and efficiency of construction and fabrication methods, such as welding, continue to reduce the time on pipeline installation critical path processes. Close control of the welding processes is required to minimise flaws in pipeline welds subjected to demanding service and environmental conditions. Equally important is high quality weld inspection to accurately and consistently identify detrimental flaws in welds while minimising false calls that result in additional weld repairs.

It is critical that the pipeline girth weld inspection process continues to improve, in terms of probability of detection and sizing accuracy, to help enable future pipeline designs. As a step towards the future, a prototype weld inspection system based on ultrasonic matrix phased array technology has been developed in a joint effort between ExxonMobil Development Company in the US and Applus RTD in the Netherlands.

Current flaw detection approach for pipeline girth welds

Pipeline automated ultrasonic (AUT) weld quality testing practices today use a zonal concept, with each zone being roughly in

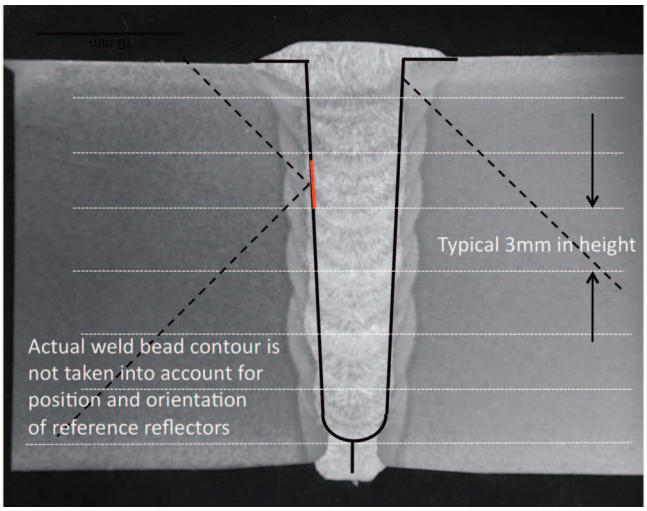


Figure 1. Conventional zonal approach, beam angles assume planar orientation on weld bevel.

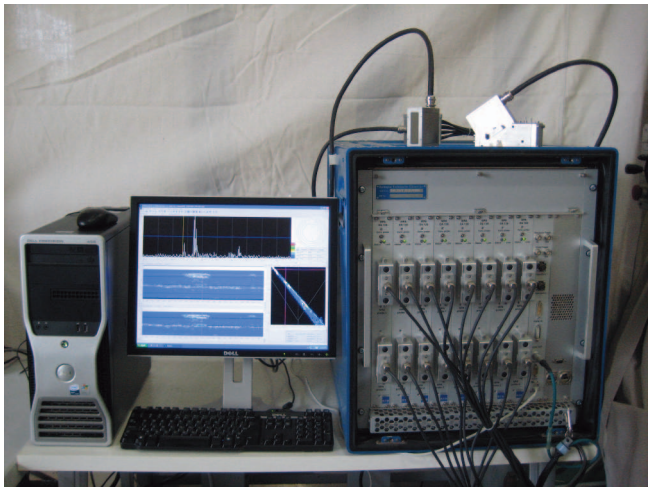


Figure 2a. The electronics of the Prototype Matrix Phased Array system.

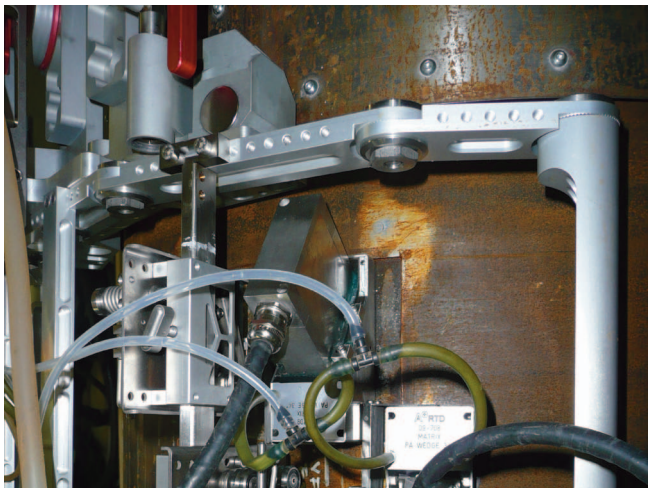


Figure 2b. The scanner mechanism of the prototype Matrix Phased Array system.

proportion to the dimension of an individual weld pass (approximately 3 - 4 mm in height) per AUT zone. Eight zones are identified in Figure 1. The examination concept assumes weld flaws are governed by the weld bevel geometry (overlaid on weld cross section in Figure 1), and that weld anomalies are oriented parallel to the weld bevel (planar anomaly assumption, indicated in red in Figure 1). The diagonal lines in Figure 1 represent the central axis for the ultrasonic beam paths and defines one of the essential AUT system variables, 'beam angle', using the planar anomaly assumption.

The planar anomaly assumption was derived in response to the change in welding practices from Shielded Metal Arc (SMA) to Gas Metal Arc (GMA) for pipeline construction in the 1980s and did not anticipate the magnitude of welding process development and the multitude of practices currently in use. Reference standards used to 'calibrate' AUT systems were designed based on the planar weld anomaly assumption.

Experience indicates these prior assumptions were applicable and represented best practice at their development, however advances are required to meet the challenges of the future. In practice, anomalies made by all welding processes can deviate from the planar assumption. These anamolies are often tilted and/or skewed in relation to the nominal weld bevel that the calibration is based on. Using this zonal concept presents challenges to the accurate characterisation of flaws with non-ideal orientation compared to the calibration standard, and can result in a reduced probability of detection and incorrect sizing of flaws.

Present performance of Linear Phased Array (LPA) systems

Current LPA AUT system performance is known to pipeline designers, constructors and AUT service providers who agree current performance levels are satisfactory for most construction projects. Requirements for anomaly characterisation performance beyond the capabilities of current LPA AUT systems, which are based on the planar flaw assumption, are expected in the future for pipeline construction in challenging environments, such as offshore fatigue loading in steel catenary risers and high strain demand applications such as differential loading in arctic environments from frost-heave and thawing cycles.

AUT system performance targets (probability of detection and sizing accuracy) required for weld inspection on future challenging pipelines are not yet defined. However, before AUT performance targets are set, advanced AUT systems will need to be thoroughly tested and their performance capabilities determined to ensure the management of reliability expectations, from design through construction. In anticipation of more stringent performance targets, a prototype next generation phased array weld inspection system has been developed to investigate performance in comparison to the current LPA systems and to evaluate a more advanced weld scanning methodology.

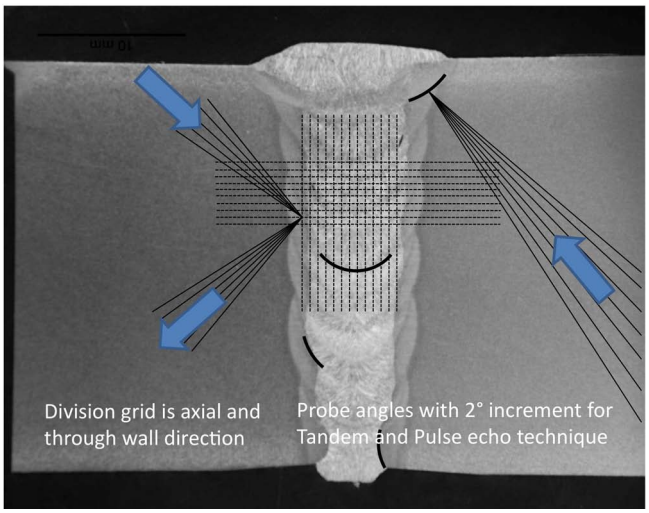


Figure 3a. Scanning pattern fine grid in radial direction.

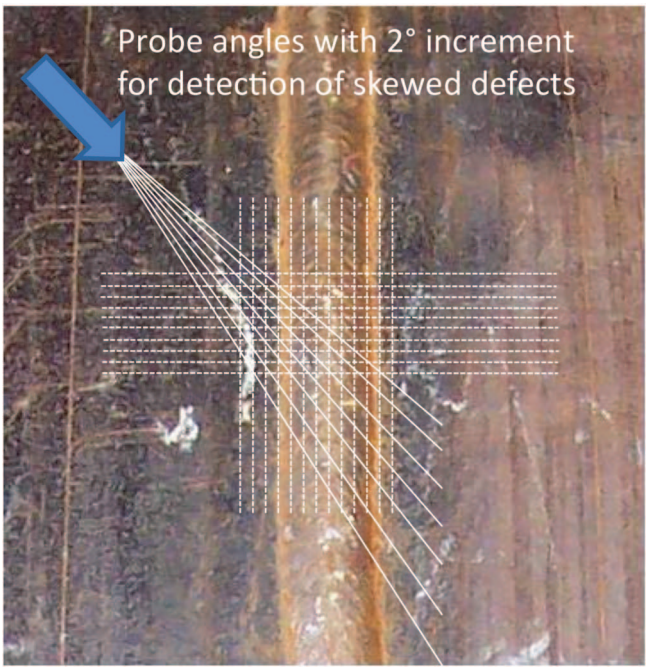


Figure 3b. Scanning pattern fine grid in circumferential direction.

Matrix Phased Array (MPA) development

The new required performance targets in terms of defect detection, sizing and defect characterisation could be achieved by using the next generation of phased array systems called 'Matrix Phased Array'; see prototype MPA system in Figure 2.

In comparison to LPA systems, this technology is capable of steering the ultrasonic beam in three different directions and can be optimised to obtain a focal spot in such a way that the ultrasonic beam spread in lateral direction is reduced significantly. This is important for those welding defects that are skewed and/or tilted in such a way that a substantial portion of reflected ultrasonic energy is not received, which can cause deviations in sizing that leads to defect misinterpretation.

Since an MPA system is able to generate ultrasonic beams with hundreds of different angles and focal points in three dimensions, the influence of weld bevel geometry on the inspection set-up configuration is minimised. The new proposed inspection concept makes use of the flexibility of the MPA to approach the weld bevel configuration by multiple angles of incidence in radial and circumferential direction in a fine three dimensional scanning grid, as shown in Figures 3a and 3b.

In this way, the MPA system is capable of addressing the negative effect of defect orientations such as tilt and skew. Furthermore, the inspection method is not necessarily limited to theoretical weld centreline, but is extended to include the overall weld volume including the heat affected zone (HAZ) of opposite weld bevel interface. This offers the ability to compare the inspection results obtained from two sides of the weld, resulting in a higher inspection confidence level and better evaluation of defect orientations.

Improved MPA inspection set-up is characterised by:

- Depth scanning instead of zone concept (small increments through wall thickness).
- Multiple angle of incidences (± 8° from perpendicular from weld bevel).
- Multiple angle of incidences circumferential (skewed angle ±20° from axial).
- Time gates extended to cover whole weld volume.
- Sectorial scanning (probe index related).

The current MPA system has a total of 1024 ultrasonic channels of which 8 x 32 channels can be used to electronically configure an ultrasonic beam. An ultrasonic matrix array probe was designed consisting of 8 x 64 elements with a centre frequency of 5 MHz. Two of these probes were manufactured with 8 connectors at each probe (one connector for each column of 64 elements), as shown in Figure 4.

The current MPA system is capable of configuring almost 400 ultrasonic beams maintaining a scanning speed of at least 10 mm/sec. Consequently, the amount of data and information can be very large.

Matrix Phased Array Performance

The performance of the design of a matrix probe has been studied using numerical simulations. These simulations showed the possibility of achieving 3-dimensional control of an ultrasonic beam in inspection volume (Figure 5).

Using the capability of the MPA probe to control the ultrasonic beam in three dimensional directions, the capability to detect welding anomalies having tilt and/or skew is possible and will be discussed.

Sizing and characterisation of a defect is done using a comparison of the amplitude received by the reflection of a defect to the amplitude received from a known reflector, such as a flat bottomed hole (calibration reflector). In practice, this

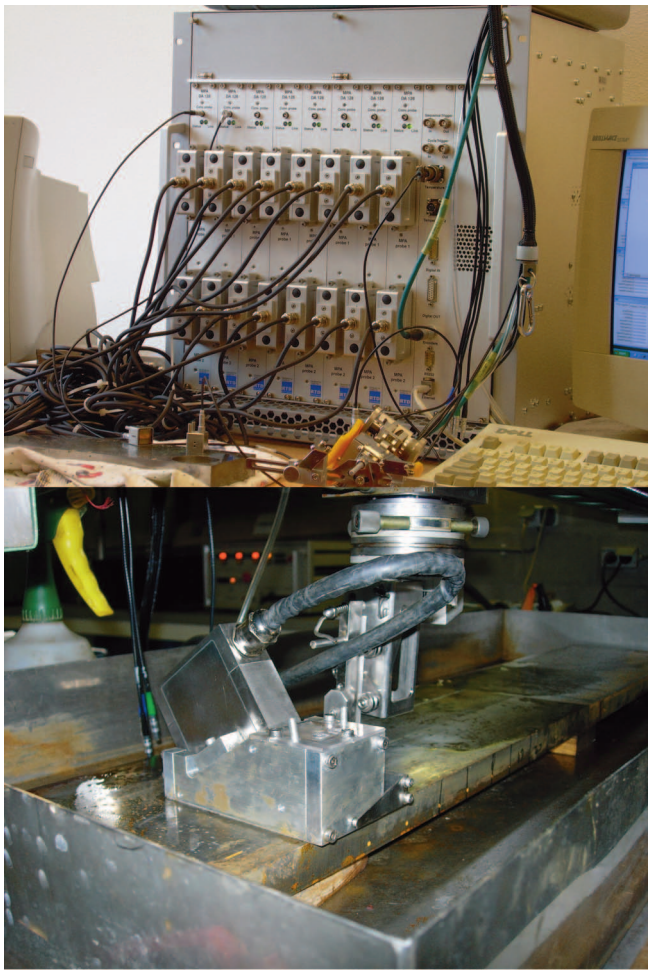


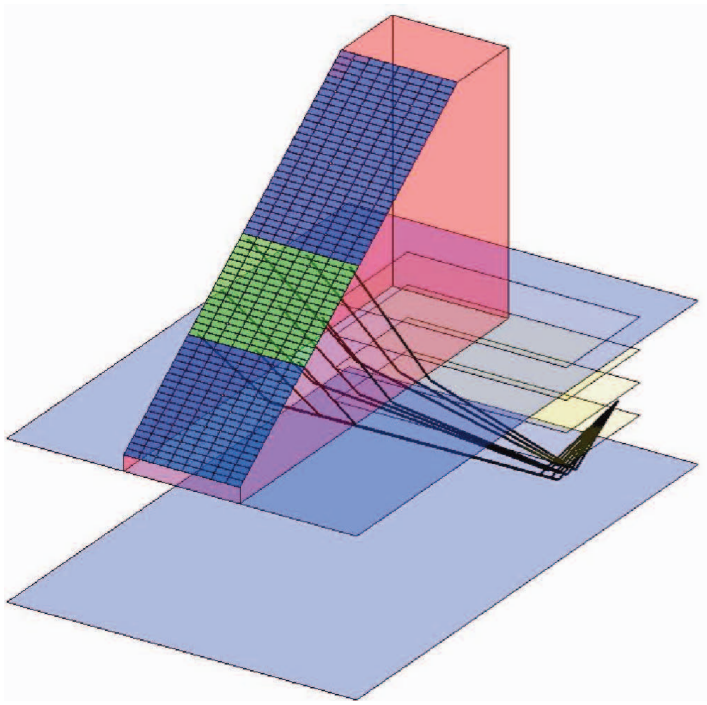
Figure 4a and 4b. Two probe of 8 x 64 elements. Each probe has 8 connectors, one for each column of 64 elements.

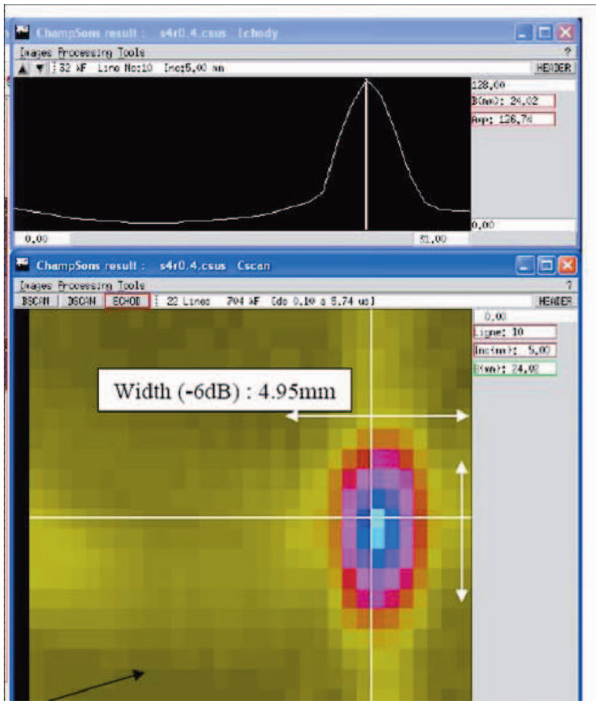
comparison proves to be difficult because the shape of a real defect is often different from the shape of the calibration target. In addition, the orientation and position of real defects are not always in agreement with the weld fusion line, as seen in Figure 6. As a result, sizing of defects can be cumbersome and inaccurate, and sometimes in severe cases, it may even result in detection misses (amplitude of reflection not exceeding threshold levels).

With the capabilities of the MPA system, it is possible to extend the zonal concept to an incremental raster concept. For each inspection depth layer, several different beam configurations can be programmed, with different skew and tilt angles. This increases the likelihood of an ultrasonic beam to interact with a defect under the optimal orientation and hence, increase detectability. Also, the orientation of a defect can be determined, even when the defect is skewed, by identifying the beam angle that produced the highest response.

Future potential

Because the system is capable of recording a very large amount of data, displaying the data poses a new challenge but also a new opportunity. At this moment, it is common practice that the AUT technicians have to manually seek out which of the multiple UT scans is showing the highest amplitude response, with many welding imperfections being displayed at and over 100% full screen height. The MPA system software facilities could be automated in order to determine which of the individual scans should be used for interpretation. Furthermore, sophisticated data analysis software routines can be implemented that are able to determine the actual orientation and size of the defects deriving





Figures 5a and 5b. Simulation of ultrasonic beam in three dimensions.

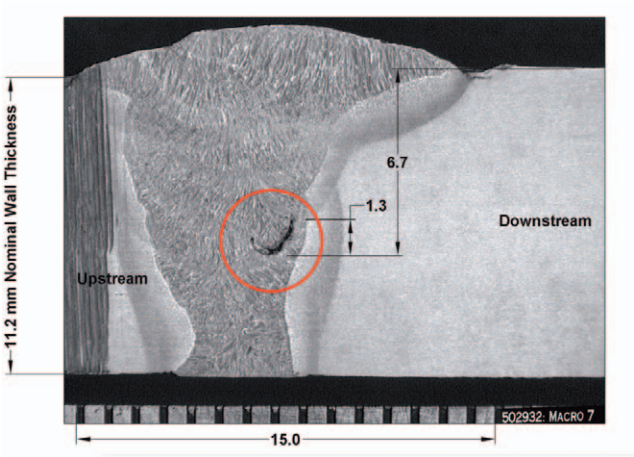


Figure 6. Examples of a defect in a pipeline girth weld. The orientation of the defect is not according to the weld fusion line, hence the reflection of the ultrasonic beam will not be optimal. Potentially, this causes misinterpretation of results.

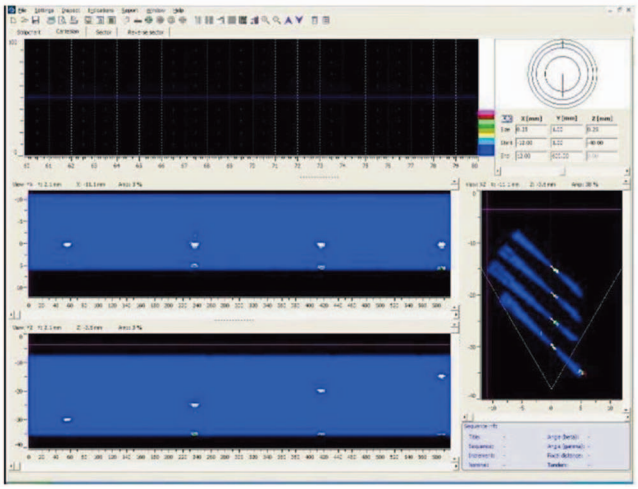


Figure 7. MPA result example based upon Cartesian view and reversed sectorial presentation.

from the assumption that the incident angle giving the highest ultrasonic response will correspond to the defect orientation.

Alternatively, all the information can be combined and displayed in an overall image. A software module in the Applus RTD MPA system calculates the coordinates in the weld volume that caused the reflection from the responses of all ultrasonic beams as shown in Figure 7.

This is calculated since the beam angle is known and the distance to a target is obtained from the transit distance time within the A-scan. Using this approach, a map can be constructed of the weld cross-section.

With this flexibility, it is possible to extend the standard zonal discrimination concept for pipeline girth weld inspection. The detectability of defects that are not orientated along the weld fusion line and the possibility of characterising flaws that are not of comparable shape with the reference reflectors is improved. The MPA data presentation example shown in Figure 8 demonstrates how a system or operator can review the amplitude height changes with different tilt and skew angles to find the beam at closest perpendicular interaction.

Current girth weld AUT standards, like API 1104, require that the AUT technician evaluates indications using a set of interaction rules. These specify if indications that are close together should be treated as one, or as multiple defects. Discussion in the code and standards community indicates that some of these may become more complex. It will become increasingly difficult for an AUT technician to do this correctly while under the time pressure of lay barge weld production. The Matrix Phased Array system could be used to develop automated rule based interpretation logic to help the technician make his decision in a reproducible and reliable way.

This MPA inspection concept and expected improvements in terms of reliability and sizing performance however need to be verified in the field on pipeline girth welds having actual welding anomalies. WP

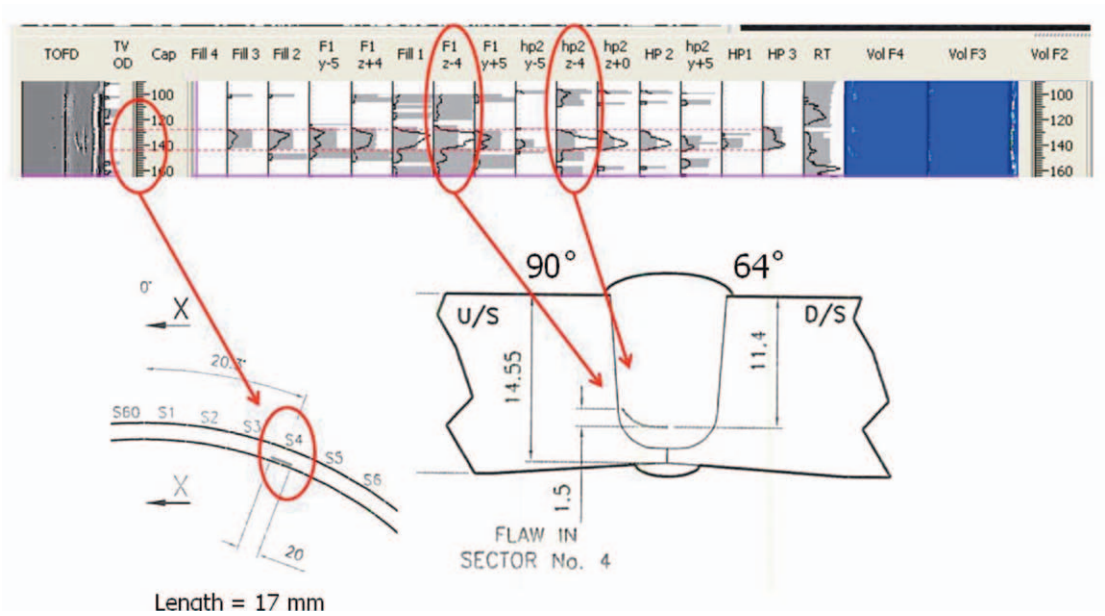


Figure 8. MPA inspection result example showing amplitude response variation caused by defect orientation.