ADVANCES IN 3-D ULTRASONIC IMAGING FOR QUANTITATIVE FLAW EVALUATION
M. Dalichow¹, M. Dennis², M. Kroening³, F. Mohr⁴, K. M. Reddy⁵, O. Yastrebova⁶
¹ Quality Network Inc., Sparta, NJ, USA
² Electric Power Research Institute, Charlotte, NC, USA
³ Tomsk Open Laboratory for Material Inspections, Tomsk, Russia
⁴ AREVA - intelligeNDT GmbH, Erlangen, Germany
⁵ LUCID Software Ltd., Chennai, India
⁶ University of Saarland, Saarbrücken, Germany

ABSTRACT
The value in inspecting structural components is provided by its contribution to the assessment of the structural integrity expressed by the risk of failure. Key inputs for the assumptions of absence of cracking are probability of crack detection and the flaw geometry. Ultrasonic testing is sensitive to planar material imperfections, but today’s inspection techniques do not acquire flaw data in 3-D. Advanced reflector imaging using Phased Array techniques is limited to 2-D imaging, and sector scan flaw imaging is time consuming. We propose a new imaging approach based on acoustic wave field migration for high speed scanning. The applied principles of acoustic migration are based on position controlled summation of RF A-Scan data recorded by the individual array elements; this enables inexpensive multi-channel ultrasonic equipment design. The real time imaging of reflectors with improved contrast and resolution sensitivity in 2-D has been demonstrated and applied.

In this paper we present 3-D ultrasonic imaging at high-resolution and high-contrast sensitivity with improved S/N ratios. We discuss sparse matrix arrays with element sizes close to the Rayleigh limit to achieve high-resolution reflector details and array apertures large enough for synthetic focusing of the entire component volume. The application of sparse array transducers limits the number of required instrument channels and the amount of measured data to be processed in real-time. This requires the implementation of special data filtering and beam forming techniques. We present first experimental data on 3-D reflector imaging and discuss effects of data filtering on high-resolution and high-contrast sensitivity, features that determine both, the probability of crack detection and the evaluation by the acoustic imaging technique.

Motivation
Probabilistic risk of failure assessment of pressurized loaded components has become a valuable tool of structural safety engineering. The key input data, the load and the material properties, are specified according to the intended component use. Quality control procedures assure the defect free state of component. Upper limit estimates on expected loads, material properties, and flaws assure continuing safe operation with reasonable safety margins. This deterministic design approach of mechanical engineering has been proved by many years of operational experience. Nevertheless, when components or systems fail with severe consequences, the risk of failure assessment depends also on the knowledge of how the changes of input data affect the safe operation. Material data and load conditions are stochastic and distributed following statistics, assessable by material and system tests. In addition, material may degrade under load, or unexpected load events may damage the system to a certain degree, effects that may be considered as systematic changes of the applied statistics. When already small parameter changes reduce the safety margin, we call this parameter sensitive. The parameter sensitivity can be determined by probabilistic fracture mechanics.

Basic calculations of Probabilistic Fracture Mechanics (PFM) analysis comprise two steps (Yastrebova, 2012, Dissertation to be submitted). In step 1, a value for each input variable is selected randomly based on its probability distribution. The full data set is used for the calculation of the time to failure in step 2. Basic calculations are repeated applying the “Monte Carlo” technique until the failure probability is of good statistics. PFM analysis yields a failure probability, rather than a specific calculation.
of crack size or lifetime.

The defect state, for example, is assumed by upper limit estimates of crack dimensions. When we know the probability of crack detection and the statistical distribution of remaining cracks after inspection, we can assess the probability of failure by defect states more precisely. The advantage of this procedure would be a structural design, less conservative but more precise.

A failure assessment diagram (FAD) is used for the presentation of failure probabilities. The FAD accounts for the possibility of fracture and plastic collapse of ductile construction materials (Kuna, 2010). For the plastic collapse the J-Integral is applied by most of the practiced codes (Electric), (BS7910, 1997). The two possibilities are plotted on the axes of the FAD, as $K_r$ and $S_r$. $S_r$ is a load ratio defined as a reference stress over the lower yield strength of 0.2% proof stress. The reference stress characterizes the possibility of plastic collapse. $K_r$ is the fracture ratio and is defined as the applied stress intensity factor over the material toughness. A flaw is stable if the assessment point lies inside the FAD curve. Figure 1 shows a typical failure assessment diagram, inside the FAD line the acceptable area, outside the area with critical flaw growth to failure.

The recent development of probabilistic fracture mechanic codes may motivate design engineers to quantify the value of NDT for its contribution to structural reliability of technical systems (D. Cioclov, 1999), (D. Cioclov, 2005). By known probability of detection (PoD) we can assess the effect of NDT on the remaining risk of failure (D. Cioclov, 2000), (A. Bulavinov, 2007).

The failure assessment diagrams in Figure 2 show the effects on failure probability for a known defect state after inspection. The blue point operations are based on data gained by experiments for lightweight materials (Cioclov, 2005).

![Fracture mechanical assessment by fail/safe decision](image)

**Figure 1: Failure Assessment Diagram FAD**

$$S_r = \frac{\sigma_{\text{eff}}}{\sigma_f}$$

*Measure of ductile response of material to loading*

$$K_r = \frac{K_{\text{I}}}{K_{IC}}$$

*Measure of brittle response of material to loading*
Each blue dot in the failure assessment diagram FAD represents the result of a Monte Carlo simulation by computing one set of the randomly distributed material, load and defect size data. On the right, the limited possible maximum defect (crack) size by NDT reduces the risk of failure (blue dots outside of the FAD curve) significantly.

For illustration, the global failure risk $R$ is a result of probability of failure $PoF$ and consequences of failure $CoF$ concurring according to:

$$R = PoF \cdot CoF$$

The risk reduction factor $RF$ achieved by NDT can be defined by:

$$RF = \left(1 - \frac{PoF_{with\, NDT}}{PoF_{without\, NDT}}\right) \times 100$$

Here, the crack initiation rate and crack growth rate are not taken into account (L. Gandossi, 2007).

In most cases the risk is reduced by one order of magnitude and more as the following numbers in Table 1 taken for a pipe system prove (Selby, 2011):

<table>
<thead>
<tr>
<th>No inspection</th>
<th>2 inspections (10yr, 30yr)</th>
<th>4 inspections (10yr, 20yr, 30yr, 40yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.22E-02</td>
<td>2.43E-02</td>
<td>2.35E-03</td>
</tr>
</tbody>
</table>

Table 1: Effects of In-service Inspections on Probability of Through-Wall Crack (TWC) and Rupture (circumferential flaws only)

This rational and valuable failure assessment procedure is challenging nondestructive testing for high and validated probability of flaw detection by the applied method and for quantitative characterization of flaw geometries.

**Probability of Detection and Contrast Sensitivity**

Two-dimensional flaws, such as cracks or lack of fusions, are critical flaw types increasing the effective stress state. Ultrasonic testing (UT) is a sensitive method for the detection of planar flaws but the flaw face must be oriented perpendicular to the acoustic wave propagation. Therefore, ultrasonic testing procedures require different angles and directions of incidence for the detection of arbitrarily aligned planar flaws. The grade of coverage may be expressed by the specific contrast sensitivity of an ultrasonic inspection procedure. The ultimate contrast sensitivity of 1 (or 100%) is reached by full space coverage of sound transmission directions.
Therefore, manual testing requires transducer swiveling for reliable detection of planar flaws. Manual testing procedures are affected by human performance that cannot be controlled until now. Automated testing procedures take credit from the beam divergence that improves the contrast sensitivity and helps for reduced number of transducers applied. However, we encounter resolution losses that are needed for flaw evaluation (I. Bolotina, 2012).

**Flaw Evaluation and Resolution Sensitivity**

Most of the applied codes and procedures of ultrasonic testing rely on measured A-Scan amplitudes for registration of material flaws and as acceptance criteria. However, it is evident that echo amplitudes do not truly correlate to flaw size and flaw geometry. Several, rather specific procedures have been proposed for quantitative flaw evaluation including crack tip detection and 2-D reflector imaging by B-Scans and C-Scans (Davis, 1998), (Standard, 1997). We propose a procedure for quantitative flaw evaluation based on precise reflector imaging by real time reconstruction codes. Reflector imaging for flaw evaluation is used and validated already by some phased array procedures. Relevant reflectors are imaged by sector scans or at least by images of several optimized incidence angles (Moles, 2007). Reflector imaging and automated scanning facilitates further the expert based determination of geometric or flaw indications.

However, the interaction of wave fields with flaws is rather complex. Most often, the flaw geometry generates several backscattering centers depending on the transducer position. The scattered waves may interfere, including mode conversion. The full reflected signal received may change with slight position variations. The practitioner searching for tip indications of cracks with changing depth knows the difference when he compares diffracted tip signals of notches of constant depths with crack tip signals. Only in some optimized positions he may detect the spurious crack tip signal due to the differences of time-of-flight of tip signals within the applied beam spread and pulse length. Figure 3 shows the crack root indication in front of the welding root indication imaged by a longitudinal wave Sector Scan of a 3.5MHz linear standard phased array. The tip indication is already hidden in the acoustic noise.

![Figure 3: Crack Indication in front of the Weld Root](image_url)

For better imaging of flaws by ultrasonic reflection, we have to scan the flaw geometry by well-
focused short pulses. The idea of focusing for flaw imaging has been already proved by phased array applications (Moles, 2007). However, the real world is three-dimensional and until now, only linear arrays are available focusing in 2-D cross sections (B-Scan) of the specimen.

In conclusion we state that for imaging flaw geometries we have to focus the ultrasonic beam in 3-D geometry that can be achieved by matrix arrays, for example. We call this demand resolution sensitivity for flaw evaluation. However, when applying transducers with high-resolution sensitivity, we lose contrast sensitivity or we would have to multiply the number of applied transducers, and scans respectively.

In this paper we propose and demonstrate a new ultrasonic approach with both resolution and contrast sensitivity close to the limits determined by the physics. We apply the principles of reflector reconstruction, called migration. The principles of migration are well established in geophysics, medical imaging, and other fields where techniques based on wave physics are applied (Biondi, 2006).

**Ultrasonic Migration**

Migration is an acoustic reconstruction method of reflectors when the acoustic wave field is known at the surface (Gajewski, 2010). When we measure the wave-field \( w(x,y,z=0;t) \) at the surface of the specimen, we may reconstruct the field \( w(x,y,z) \), called depth migration. Depth migration solves the inverse problem of imaging reflector geometries in the volume below the measured wave-field at the surface, called aperture or when measured by scanning, synthetic aperture. In NDT, depth migration usually can be performed under almost ideal conditions, as we know the velocity of ultrasound in isotropic materials and the surface topography. However, we may learn from migration application in geophysics how to inspect structured, anisotropic or dispersive materials.

Migration enables some advanced features of ultrasonic testing that have been developed and demonstrated in the last years (Bulavinov, 2005), (L. von Bernus, 2006), (A. Bulavinov, 2007), (I. Bolotina, June 15, 2010), (I. Bolotina, 2012). The measurement of A-Scans by the array elements is position controlled, whereas Phased Array measurements are phase controlled. For each measured A-Scan we add the accurate position data of the receiving array element. The material discontinuity is activated by the scatter of the transmitter pulse. The scattered pulse is received by all or selected array elements forming a synthetic aperture. The A-Scan and position data are stored for further processing. One important feature results from this type of measurement illustrated in Figure 4: There is no need for phase control electronics. The instrument consists of a set of parallel ultrasonic boards with fast data links to the signal processor unit and adequate storage capacity (Yastrebova, 2012, Dissertation to be submitted).

**Figure 4: Principle of Sampling Arrays (L. von Bernus, 2006)**
In case that all array elements are used as transmitter, but consecutively and all elements are receiving A-Scans A(t), we have measured the full possible information content of the array as described by the information matrix $A_{ij}$ with $i$ the number of the transmitting element and $j$ the number of the receiving element. This type of measurement with consecutive transmitter pulses and parallel receiving by all elements is called Sampling Array, as the information provided by the ultrasonic array is sampled into the columns $A_i, (j=1-n)$. The information content of an acoustic array of transmitting and receiving elements was described in detail by (R. Y. Chiao, 1994), and NDT relevant engineering aspects by (I. Bolotina, 2012).

Migration measurement combines elements of synthetic focusing technique (SAFT) and Phased Array instruments with the following advantages (I. Bolotina, 2012):

- The achieved resolution depends on the element aperture and is almost constant within the near-field of the array aperture. It is limited by the Rayleigh criterion for element apertures less than half the wavelength.

- Migration sector scans measured by linear arrays enables the computation of A-Scans for arbitrary synthetic pulse propagation direction within the chosen reconstruction angle. The reconstructed A-Scans can be used for compliance tests with existing UT procedures currently applied.

- The element distribution of the transducer array must not comply with the sampling theorem. We may design large sparse apertures with reasonably limited number of elements. However, we have to apply special filtering and beam-forming techniques for element distances larger than two wavelengths with optimized (stochastic) element arrangement.

The reconstructed image pixels result from the intersection of reflector locus curves, as illustrated in Figure 5 for a pitch/catch measurement. The image quality improves with the number of independent locus curves $N_{RLC}$ as a function of the number of array elements according to:

$$N_{RLC} = \frac{n(n+1)}{2}$$

Figure 5: Elliptic Reflector Locus Curve for Array Elements: S (Transmitter) and E (Receiver)

An array with 16 elements will provide 136 reconstruction locus curves. Increasing the number $n$ we acquire higher reflector amplitudes, resolution is improving and reconstruction artifacts are disappearing as shown in Figure 6.

Figure 6: Effects of Increasing the Number of Array Elements (Zhantlessov, 2012)

Most commonly, migration codes are based on Kirchhoff algorithm (Y.F. Chang, 2001), (N.
Bleistein, 2001). We have used the SynFoc© code, the first commercial software for NDT application developed by LUCID Software Ltd.¹.

**Sparse Apertures**

For technical reasons, we have to limit the number of array elements. However, we need a reasonably large array aperture for depth focusing – a contradiction when we comply with the sampling theorem. The focusing depth depends on the squared aperture dimension. Migration allows, to a certain extent, the thinning of aperture as we have proved by experiments (see Figure 7 and Figure 8):

![Migration of Linear Array Data with Sparse Aperture](image)

In Figure 7, the linear 64-element phased array transducer has a frequency of 5MHz and a plane wedge for 0° center angle of incidence; only 16 elements have been used. In Figure 7b we activated 16 center elements, and in Figure 7c every fourth element with a skip between the active elements of two wavelengths was activated. We improved the image quality by data filtering and by optimization of element arrangement. The developed filter reduces noise and eliminates reconstruction artifacts. Non-homogeneous distribution of elements suppresses the reconstruction artifacts by some kind of averaging. Figure 8 shows the effects of both, advanced filtering and non-uniform distribution (DF: Distribution Factor; DF=2 corresponds to skip of one wavelength for half wavelength element aperture).

![Standard Migration DF=2](image) ![Filtered Migration DF=2](image)
Applying these principles, we can design matrix transducers with 64 or even 32 half by half wavelength elements with an aperture of about 20 mm by 20 mm that render 3-D images without artifacts. 32 or 64 elements can already be controlled by existing multi-channel systems.

The current challenge is the manufacturing of matrix transducers with distributed ($\lambda/2 \times \lambda/2$) elements; we call these elements P-elements. For resolution sensitivity close to the Rayleigh Criterion of half a wave-length, we require element apertures of less than half a wave-length. Therefore, we have to stack at least three piezo-layers for effective transmitter pulse generation and sensitive receiver performance. The technical task was assigned to experts for micro-assembling and packaging. For that reason, we can only present experimental results for 3-D imaging by applying a full matrix array with 8 by 8 active P-elements.

**Experiments**

In spite of the experimental limits set by the available transducers until now, we can demonstrate the real-time imaging capacity of migration type measurements, achieved high resolutions at longer distances (in 2-D experiments with linear arrays), and 3-D imaging by matrix arrays. We called the 3-D images “cone scans” as distinguished from sector scans measured by linear arrays. The sector scan and the cone scan can be composed into compound scans with the effect of the virtual enlargement of the array aperture and averaging of redundant measurement information, respectively higher resolution at longer distances and further noise reduction.

**Real-Time 2-D Imaging**

As described in (I. Bolotina, 2012) more explicitly, we took a video of a manual scan on the test-block with the simultaneous presentation of the sector scan as shown in Figure 9. The applied linear array transducer, Olympus (Part Number 5L60-A14), frequency 5 MHz, with 60 elements and 1 mm spacing with an active aperture of 60 mm. We have operated the transducer in the (1,32) mode: the center element
Nr. 30 was used as transmitter, 32 elements as receiver (in parallel). The video demonstrates the capability of real-time high-resolution imaging. Today, we may reach scanning speeds for linear arrays up to 1m/sec. The selectable sector range SR (we cannot longer use the term sweep) was chosen as $-70^\circ < SR < 70^\circ$. The manual scan speed was about 250mm/sec.

The sector scans are reconstructions of raw data. We have not applied any filtering or resolution improvement to illustrate the basic performance of migration. However, the compound scan shown in Figure 10, displays all details of the aluminum test specimen at high resolution.

3-D Cone Scan Imaging

As discussed, we need 3-D imaging by matrix arrays for flaw evaluation. Flaws are three-dimensional and we have to go for high-resolution and high-contrast sensitivity in all space dimensions. Furthermore, for practical and economic reasons we want high-speed imaging by standard line scanning without the need of multiple scanning. EPRI has designed a test specimen to evaluate 3-D reflector imaging that we used for our experiments (Figure 11). The 11 by 11 matrix transducer has a frequency of 2.25MHz; the element arrangement complies with the sampling theorem. Due to the limit of 64 receiving channels of our experimental equipment, we have used only the inner 64 matrix elements. The center 4 elements have been also used as transmitter elements.
The matrix transducer provides 3-D images, which we call Cone Scan. The cone angle can be chosen similar to the sector scan angle. Within the chosen cone angle we can detect the reflector orientations in arbitrary space directions. The reflector detail imaging is limited by the poor depth resolution due to the small effective array aperture of about 9mm by 9mm. However, we could prove the possibility of fast 3-D cone scan imaging at high repetition rate that enables standard scanning speeds. Figure 12 shows the first cone scan image taken on a test specimen with side drilled holes by one measurement in a single position. We can see the side drilled holes, the back wall and the three corners of the test specimen.

**Compound Cone Scan**

During scanning, we may synthesize a growing aperture that enables better resolution. Growing apertures
are also sparse apertures that we can clean from artifacts as outlined above.

Using the matrix array transducer with the small array aperture, we cannot resolve the details of the EPRI 3-D block. However, by scanning we can reconstruct compound cone scans that are already of good contrast and resolution sensitivity even when we use small array transducers. Figure 13 shows the scanner system used. Due to the limited size of the test specimen, we had to also limit the cone angle. A large cone angle would have generated image details caused by the specimen edges that bury the artificial test reflector indications. Therefore we chose a cone angle of 30°.

Certainly, just a conventional raster scan with a standard 0° transducer with a rather well directed beam profile, will give similar results on this test block. However, it will not image misaligned, inclined flat flaws like cracks.

Compound C-Scans and B-Scans are shown in Figure 14 and Figure 15, including the second B-Scan and different 3-D views.
Figure 15 above shows the first results. The image quality has to be improved by standard signal processing, such as distance-amplitude correction. However, migration array measurements offer improvements to a large extent by signal and image processing techniques. One example demonstrates how crack tip signals can be discovered by signal filtering based on stochastic principles.

**Stochastic Phase Filter**

Migration is a position controlled measurement, and Phased Array is phase controlled. Based on simple geometric assumption, we may test the data for the correct phase of each image pixel. The test is viable because of the number of redundant measurement data. This principle enables the elimination of coupling errors and grain boundary noise. Only pixel amplitudes with stable expected phase features will summarize into indications.

Figure 16 shows the effects of the LucidSoft filter algorithm. The filter picks the tip indication of a crack in front of the root of an austenitic pipe weld. After filtering, we see the crack root indication, the crack tip and two weld root indications; the direct reflection and a second reflection caused by reflection in the root geometry itself. The sector scan angle was 0° to 70°. The wide sector produces also wedge echoes imaged at an angle of about 30°.
CONCLUSIONS
We have developed an ultrasonic testing technique based on migration. This technique enables both, high-contrast and high-resolution sensitivity for quantitative flaw imaging and evaluation. The technique is based on advanced IT and efficient computing principles; however, simple multichannel hardware can be used. The development of sparse matrix arrays with stacked elements is still a remaining technical task.

The principles of migration type measurements open up the use of advanced wave physics for ultrasonic testing.

LITERATURE
Electric, Nuclear. *Assessment of the integrity of structures containing defects, R/H/R6 Revision 3.* Barnwood, Gloustershire : Nuclear Electric.


