**3D Ultrasonic Imaging by Cone Scans and Acoustic Antennas**

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**Abstract**

In this paper we present real time 3D imaging with multi-channel ultrasonic equipment using matrix array transducers. This provides several advantages including improved contrast sensitivity for planar reflectors that are arbitrarily aligned in space. Real time imaging is realised using efficient computing algorithms optimised for both CPU and GPU. This technique can be applied on arbitrary surface geometries and wedge shapes interfaces by migrating of wave field data measured at the specimen surface for high resolution reflector imaging. Migration or focusing is limited by the aperture of array. Increasing the aperture at any given frequency increases the number of elements to keep the spatial resolution constant. This requires an increased number of ultrasonic channels and data to be processed. We have used two techniques to overcome this problem. First is to compound the ultrasonic data using the scanning information of the sensor. Second is to organize the sensor elements in sparse arrangement. The disadvantage with this technique is the migration artefacts arising out of the sparse nature of the element distribution. We have developed special techniques to overcome this problem and to reduce the cost of equipment and data storage and transfers.

We demonstrate these advancements using two test blocks, one with 3D scan on plate surface with oriented defects and the second with a sensor as acoustic antenna on a fixed position on a shaft. Since the imaging is done on a cone this also offers the possibility to synthetically reconstruct A-scans for arbitrary skew and beam angles. This will help in complying with the existing standards for evaluation.

**Keywords:** Ultrasonic sparse arrays, quantitative flaw imaging, high resolution and contrast sensitivity

**1. Motivation**

Ultrasonic testing (UT) methods applied for material inspections are especially sensitive for the detection of planar discontinuities that pose risk of structural failure. Therefore structural high loaded materials and their joints must be inspected by UT according to most of the applicable codes. However, there are two limitations that ask for improvements of the applied UT techniques:

Planar defects can be detected generally only when the applied sound field is reflected back to the transducer (when pulse-echo method is used). The sound pulse must hit the face of the planar discontinuity (e.g. lack of fusion or crack) at an angle of 90° or be caught by a corner trap (for surface cracks). We may define the specific contrast sensitivity for planar discontinuities as a function of the number of angles of incidence. For the maximum contrast sensitivity we would have to cover the full 3-D space for pulse propagation. Until now, for practical reasons, the contrast sensitivity is limited by an optimized and required set of insonification angles and directions. As a result, when we apply inspection procedures with limited contrast sensitivity we have to assume likelihoods of possible defect geometry and position that may exist due to manufacturing problems or operational loads. The assessment of risk of failure of loaded technical structures depends on the probability of detection (PoD) (1) that is limited by the physics of defect detection in addition to human or performance errors.

The second problem is posed by the flaw evaluation procedure. We detect reflectors that are commonly evaluated by reference to standard model reflectors (notches, side drilled and flat bottom holes). The correlation between reference reflector type and dimension and flaw features is rather weak. More advanced UT techniques take advantage of reflector image evaluation to assess flaw type and dimension. Crack tip evaluation has become an important procedure for flaw sizing (2). However, the reflector image does not represent the corresponding flaw image. Reasons are complex phenomena of the interaction of wave field with the material discontinuity. Especially for wide divergent sound beams the reflected signal is composed of different types of reflection
including interference phenomena. For example, the diffracted signal from the tip of a notch can be identified easily but crack tip signals from cracks of varying depth can be only identified by experienced practitioners when for a specific transducer position the contributing diffraction signals sum up by interference to detectable amplitudes. Therefore, reflector imaging may inform about flaw geometry when the sound field is well focused in space. We define this feature of ultrasonic testing techniques 3-D resolution sensitivity.

In conclusion we have to improve both the 3-D contrast and resolution sensitivity for quantitative ultrasonic flaw detection and evaluation. Further, we consider high resolution and contrast sensitivity a precondition for future de-convolution of flaw geometry and sound field by taking into account their (simulated) interaction.

2. Technical Demands

We have to consider technical requirements for advanced systems with improved contrast and resolution sensitivity: real-time imaging at scanning speeds of m/sec as required by industry and applicable complexity of inspection system expressed by the number of ultrasonic channels. Both demands are still barriers for quantitative 3-D flaw imaging. The Phased Array technique (3) controls the angle of incidence and the focal zone by phase delay sets of the individual array elements. For fast scanning only some angle of incidence or focal zones can be chosen. The phase array transducer operated in such a way is replacing a set of standard transducers. For better contrast sensitivity we may sweep the full angle. The image is called sector scan. For improved resolution in 2-D we would have to control phase settings of several sector scans with different focal zones. Just for a 2-D measurement set with improved imaging quality we would need about 500 measurements in one array transducer position or about 1 sec measurement time.

Further, focusing depth depends on the array aperture. For the inspection of heavy wall components we would need large apertures with a high number of array elements since we have to design the array in compliance with the Sampling Theorem. However, with increased number of array elements the electronics and the transducer, wiring and cables will become rather complex and expensive. For 3-D imaging the complexity is increased to the second with a number of array elements much too high for realization.

The requirements for fast scanning and a reasonable low number of array elements even for 3-D high resolution and high contrast imaging ask for a different technical approach of image generation and reconstruction. Phased Array with phase controlled data acquisition is not viable for practical technical reasons.

3. Migration Arrays

Phased Arrays summarize the RF A-scan data of the individual array elements after they have been shifted by the phase settings. Only the resulting signal has to be processed further. The requirements for signal acquisition, processing and data management no longer challenge standard computing systems. Moreover, modern computing offers the possibility for processing the RF A-scan data of all the array elements in parallel. We have called this type of array technique migration array because we may apply position controlled reconstruction of reflectors known for example in Geophysics as migration (4). The processing of RF A-scans of array elements with known position data is the viable gate to improve contrast and resolution sensitivity but in compliance with reasonable technical complexity of the data acquisition system called migration transducer. The complexity is shifted to signal processing and the codes applied.

3.1. Engineering Approach

Quantitative Ultrasonic Testing (QUT) is a (mandatory) part of codes and procedures related to safety engineering of technical structures. The value of these procedures is the engineering experience acquired over a period of almost 50 years and must be considered. Therefore, the use of new procedures and technologies must comply with existing approved procedures but also realize significant advantages. Migration is no longer a technique that is based on directed wave propagation and the related A-scan imaging. However, we can synthesize A-scan data out of the migration data to demonstrate the equivalency.
Figure 1 shows RF A-scans with crack tip signals both from Phased Array and synthesized from migration data (5). As can be seen, the signals are the very same. The equivalency and the possibility for migration A-scan reconstruction enable the use of migration arrays in compliance with existing codes and procedures.

Fig. 1a. Test Specimen with Fatigue Crack (numbers in mm)

Fig. 1b. Phased Array A-Scan

Fig. 1c. Migration A-Scan

Fig. 1d. Phased Array Crack Tip Signal

Fig. 1e. Migration Crack Tip Signal

Fig. 1. Proof of Equivalency (Transducer: 16 element linear array, 5 MHz)

3.2. Basics of Migration

When we measure wave field data of an (infinite) cross section of the wave field we can compute the further propagation (forward problem) and the wave propagation to the measurement plane (backward problem). Therefore we can migrate backwards to the sources of the wave field. For technical application we can afford limited apertures but the migration asks for accurate position data. When exciting the sources as reflectors by highly divergent sound fields, for example by elementary waves, in different positions we can reconstruct most of the reflecting geometry. The migration itself can be considered a combination of Synthetic Aperture (SAFT) and Array Technique. With at least one array element we excite the sources. The reflected waves are received by all array elements and processed. For point reflectors one transmitter element is sufficient, for shaped reflectors
we have to take care that all the reflector faces contribute to the migration. This can be achieved either by using all or several array elements as transmitters or by compound scans. Crack tips are point-like reflectors. For that reason there is almost no difference (beside noise) between synthesized crack tip A-scans with one transmitter or with all 16 elements used as transmitters in serial pulse mode operation (6) as shown in Figure 2.

![Fig. 1a. 16 transmitter pulses by 16 array elements](image1)
![Fig. 1b. 1 transmitter pulse by array element Nr. 6](image2)

![Fig. 2. Source Generation by Transmitted Pulses](image3)

3.3. Basics of Applied Code

We have developed the code LUCID SynFoc® with the following objectives: Real time data processing for 2-D and 3-D reflector imaging comprising data filtering, migration, image processing, and evaluation. Further, the software can be used for system operation according to the requirements for automated ultrasonic systems including transducer and system calibration and recheck procedures. For migration, most commonly used codes are based on the Kirchhoff algorithm.

Simple Kirchhoff migration algorithm (7) (8) is described with:

\[ C(t) = \sum w_i A_i(t) \]

Where \( C(t) \) is the computed RF echo return, \( w_i \) is the weight assigned to returned signal \( A_i(t) \) from element \( i \) and \( t_i \) is the time delay for element \( i \). Kirchhoff Migration methods use surface-related coordinates known by scanning. The Kirchhoff equation assumes that the wave-field \( W \) at a given point \( (x,y,z,t) \) is a summation of waves propagating from other points at earlier times. This technique suffers from the noise induced because of the summation process, especially when the aperture is limited and \( i \) is small. Our solution extends this by introducing an operator \( G \) which enforces goodness for fit on \( C(t) \):

\[ G \]

is function of distribution at time \( t \). In perfectly focused condition all values of should be in phase and the amplitude should be same. By taking advantage of this information algorithmic noise caused by limited bandwidth of the ultrasonic signals can be eliminated or reduced. Various parameters are possible to enforce this fitness rule like deviation, entropy etc. We used standard deviation as the enforcing parameter. This technique works well when coverage is good and inversion is well conditioned. Even though this condition theoretically leads to unity, in practice because of the measurement errors it requires a certain band. Tighter conditions give better resolution in general, but can lead to suppression of weak indications - a consequence that apodization enhances resolution if it is applied to detected images but with the unfavorable
effect of a loss of contrast sensitivity and an increasing level of the side-lobes of the point-spread function (9).
The advantage of this solution is the calculation of $G$ is independent of neighborhood points and can be
calculated in-line with the summation. This technique is well suited for parallel computing of migration images.
The images shown in Figure 8 are sector scans from sampling phased array (10) but the technique can be applied
on simple SAFT or 3D cone scans, too.

Simple Migration  Weak Enforcement  Tight Enforcement

**Fig. 3.** Enforcement of Goodness of Fit of Different Strength

The idea of migration is very close to the Synthetic Aperture Focusing Technique SAFT as shown in figure 4.

**Fig. 4.** Principle of Migration (10)
3.4. Sparse Aperture Arrays

As outlined above migration type array technique offers advantages: There is no need for phase control electronics – we just need quite simple multi-channel electronics, and we can implement algorithmic advanced signal processing like entropy filters for processing measurement data with stochastic errors. Most relevant advantage however is the use of arrays with sparse aperture. Arrays with sparse aperture do violate the Sampling Theorem as it is required for Phased Arrays.

Figure 5 and Figure 6 illustrate the effect of migration and filtering of phased array data taken on a test specimen with point-like reflectors (side drill holes).

![Simulation of beam directivities](image)

**Fig. 5.** Simulated beam directivities (f=5MHz, 16 elements of λ/2 element aperture)

We have simulated longitudinal wave beams for the angle of incidence of 45° (fig. 5a) and for 0° (fig. 5b). The linear phased array transducer with 64 elements has a frequency of 5 MHz and a plane wedge for 0° center angle of incidence (5). Only 16 elements have been used. In Figure 5a we activated the 16 center elements, in Figure 5b each fourth element with a skip between the active elements of two wavelengths. The distribution factor DF is defined for homogeneous sparsing of elements as:

\[ DF_{ij} = \frac{2 S_{ij}}{\lambda} \]

(With λ the wave length and S_{ij} the skip between two active elements; for phased array transducers DF = 1)

Experimental data measured on a test specimen with side drilled holes (Figure 6a) are presented in Figure 6. As expected, arrays with sparse aperture cannot be used for phased array instruments due to the multi-lobe structure of the ultrasonic beam (Figure 6b). Applying the migration code LUCID SynFoc© we can image all reflectors with high resolution sensitivity (11).
We can get clean migration images up to distribution factors of 4. For sparse apertures with higher distribution factors we have to optimize the arrangement of elements. Nonhomogeneous distribution of elements also suppresses the reconstruction artefacts by some kind of averaging.

Figure 7 shows the effect of the application of advanced filtering. Figure 8 results of non-uniform distribution.

Diffraction-caused reconstruction noise can be eliminated further as demonstrated by the images 8a, c, and d. Figure 8b shows for comparison the best possible migration with full information of wave field data measured by the 64 array elements. For the non-uniform distribution of elements we have used a reducing procedure “multiples of two” starting from the array center (x2AC) and starting from the array end sides (x2TC).

Sparse apertures are especially useful for 3-D imaging by matrix arrays. Because we can focus only into the near field of the array aperture with \((\lambda/2 \times \lambda/2)\) elements of 3 MHz we need for a full array aperture of about 20 mm \((20 \times 20)\) array elements – a number that is no longer technically viable or reasonable. A sparse aperture with a distribution factor of 4 would reduce the number of array elements to 100, and by an optimized element arrangement we may reduce the number to 32 or 64, number of elements that can already be controlled by existing multi-channel systems.

The challenge at the moment is the manufacturing of matrix transducers with distributed \((\lambda/2 \times \lambda/2)\) elements. We call these elements P-elements. For a resolution sensitivity close to the Rayleigh Criterion of half a wavelength we need element apertures less than half a wavelength. Therefore, we have to stack 3 piezo-layers for
effective transmitter pulse generation and sensitive receiver performance. The technical task was handed over to experts for micro-assembling and packaging. For that reason we can present experimental results for 3-D imaging only applying a full matrix array with 8x8 active P-elements. However, we may configure already acoustic antennas with large apertures to migrate 3-D images over a long distance.

![a) Standard Migration - D non-uniform](image)

![b) 64 Element Information Matrix](image)

![c) Filtered Migration – “x2AC”](image)

![d) Filtered Migration – “x2TC”](image)

Fig. 8. Effect of Non-uniform Element Distribution

### 4. Experiments

We have visualized the results of two laboratory experiments that may demonstrate the advances achieved by migration arrays. The first experiment is a manual scan of a linear array on a test specimen with geometric reflectors, side drilled holes and two cracks close to a simulated weld root geometry. This experiment proves the real-time high resolution imaging feature of migration array scans.

With the second experiment we could reconstruct a cone scan the first time by a full array of 8x8 P-elements. Within the selectable cone angle range the matrix array transducer can sense all reflector orientations in space.

#### 4.1. Real-Time 2-D Imaging

Figure 9 shows a series of pictures taken from a video of a manual scan on the test-block seen in the pictures. The applied linear array transducer was from Olympus (Part Number 5L60-A14), frequency 5 MHz, with 60 elements and spacing at 1mm with an active aperture of 60 mm. We have operated the transducer in the (1,32) mode with a distribution factor of 2. The center element Nr. 30 was used as transmitter, 32 elements have received in parallel.

The video demonstrates the capability of real-time high resolution imaging. We may reach scanning speeds for linear arrays up to 1m/sec but looking forward for higher scanning speed. The selectable sector range $S_R$ (we cannot longer use the term sweep) was chosen as $-70^\circ < S_R < +70^\circ$. The rather strong diffraction signal from the crack tips can be used for precise sizing under the given condition of constant crack depth. For cracks with
varying crack depth we would have to identify and focus on the deepest part of the crack or you may find it by fortune by positive interference of contributing backscattered signals.

The images are reconstructions of raw data. We have not applied any filtering or resolution improvement to illustrate the basic performance of migration. Figure 9a shows the details of the Aluminium test specimen used, figure 9b the migration sector scans at selected positions copied from the video. The manual scan speed was about 250 mm/sec.

![Figure 9a. EPRI Test Specimen with cracks, modelled weld root, and side drilled holes](image)

![Figure 9b. Real-time Migration Sector Scans (Sector -70° to +70° longitudinal)](image)

**Fig. 9. Real-time Migration Imaging**

4.2. First 3-D Cone Scan Imaging

For first experimental cone scan measurements we used an EPRI prototype matrix transducer with (8x8) 2,25 MHz elements. The element spacing of 1,1 mm both row and column wise complies with the Sampling Theorem. Figure 10 indicates the operation mode of the matrix transducer. The four elements highlighted in red are used as transmitters for our experiments.
We multiplexed transmitter signals because of two reasons: The array aperture is rather small with less than 10 mm and we cannot focus outside of the near-field of the array. Therefore, at longer distances the resolution is poor because of the loss of focusing. Second, the elements are not very effective transmitter sources and sensitive receivers with the consequence of noisy data which we have averaged by multiple transmitter pulses.

In one position we could image the full space within the selectable cone angle of 60°. We have used the longitudinal wave mode. Figure 11 shows cone-scan images in standard 3-D visualization technique. The test specimen used has got four side drilled holes that can be seen by different views. Further, we see the back wall of the specimen however with poor resolution. If we could apply synthetic focusing to that depth just by a larger array aperture, the back wall image would become much smaller. Same holds for the three corner indications. The specimen faces have been very smooth. Because of the rather poor element sensitivity we cannot see the backscattering from the three specimen faces.

For further optimization we have to develop matrix arrays with sensitive elements distributed in a sparse but large aperture.
5. Conclusion and Outlook

We have proven the advances that can be achieved by migration arrays. The term Migration Array is used in contrast to Phased Array since both transducer and equipment are different. The migration array instrument is less complex but we have to take advantage of advanced computing, especially in respect to fast data links, storage capacity, and optimized pipelining of the data flow. The complexity of the system has been shifted to IT with the expectation of continuing improvements. Our objective is a repetition rate of reconstructed cone-scans close to 1 KHz that would enable reasonable high scanning speeds.

Further, we assume that high resolution and contrast sensitivity as defined above are an essential pre-condition for quantitative ultrasonic testing QUT. Further, the architecture of migration array equipment enables the implementation of various algorithms including data filtering techniques for specific applications and inspection problems. In the mid-term we expect first results that reveal the real geometry of a material discontinuity from the reflector geometry.

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Literature