ADVANCES IN IMAGING OF NDT RESULTS

N. Pörtzgen[1], F.H.D. Dijkstra[1], A. Gisolf[2], and G. Blacquière[3]
[1] RTD bv, Rotterdam, Netherlands, [2] University of Technology, Delft, Netherlands, [3]TNO TPD, Delft, Netherlands

Abstract: Several developments in the past have greatly helped to enhance ultrasonic detection and sizing. An important step forward was the introduction of Time of Flight Diffraction (ToFD), making sizing considerably less dependent of defect orientation. Optimized pulse-echo techniques, advances in transducer technology and software support combined with ToFD now enable the relatively high reliability and accuracy of Automated Ultrasonic Testing (AUT). However, despite advanced imaging techniques, even the most advanced AUT approach still uses a series of one-dimensional measurements. This is even the case when phased arrays are used, because these 'emulate' the conventional zonal concept. Apart from the development of the Synthetic Aperture Focusing Technique (SAFT), the basic principles of AUT have not changed in more than 50 years.

RTD bv, together with Delft University of Technology, are working on a concept that uses a phased array in combination with so-called 'inverse wave field extrapolation'. This concept is based on fundamental wave theory and has not yet been used for NDT applications. The principles have been used in applications outside NDT, such as seismic exploration.

This development in fact goes a step further than SAFT. By taking all possible reflections, diffraction’s and wave mode conversions into account, this real-time imaging technique will present a true image of the defect, without being restricted by defect shape or orientation. The image will present the maximum possible amount of information on defect nature, shape, orientation and size. The only limitation is presented by physics.

In this paper, the principles and first results will be presented.

Introduction: Phased array technology has been applied in the field of non destructive testing (NDT) for several years. Mostly these applications were in the medical and nuclear field, but phased array technology is becoming more attractive for industrial applications such as pipeline girth weld inspections.

Girth weld inspection with phased array technology makes use of the same inspection method as a conventional multiple probe inspection. This method is based on zonal discrimination: the cross section of the weld is divided into several zones and each zone is inspected with a corresponding ultrasonic beam configuration.

The beam configurations can be generated with a phased array transducer. Since the beam generated by a phased array transducer can be controlled by the computer, one phased array transducer can be used for the inspection of each zone on one side of the weld. This flexibility provides great benefits in preparation time and probe ‘consumption’.

Despite these benefits, the results and data display are almost identical compared to conventional inspection, because the same inspection method is used. In the following we introduce another inspection method developed in the field of seismic exploration of the subsurface of the earth or ocean. Seismic exploration is based on measurements of echoes caused by acoustic reflection from layers in the subsurface. The acoustic signals are generated at the surface for example by a dynamite explosion or an air gun at sea. The responses from the subsurface are then recorded by an array of microphones. With the data and basic wave theory (such as inverse wave field extrapolation), a reconstruction of the layers in the subsurface can result in an image.

RTD b.v., TU Delft and TNO TPD carried out a joined research project to apply the imaging concept used in seismic exploration on girth weld inspection. The research has been subsidised by the Dutch government.

In the following, the imaging principles based on the already patented inverse wave field extrapolation (IWEX) method are explained. Differences with the zonal discrimination concept will be explained and also the benefits. Similarities and differences with other ultrasonic inspection methods will be discussed. Finally the first results will be shown and conclusions will be drawn.

Principle of creating an image using inverse wave field extrapolation (IWEX): Generating a beam with a phased array transducer is done by firing adjacent elements with a given time delay (phase shift) corresponding to a desired angle and focal spot. As opposed to beam generation, the elements for the imaging process are used without time delays. A data set is created by firing one single element and receiving the response on all the available elements. For example, if two phased array transducers are used with 64 elements each, a data set with 128 x 128 A-scans (or traces as they are called in the field of seismic exploration) can be acquired. The data can be stored in a three dimensional matrix, the co-ordinates of the transmitters, the co-ordinates of the receivers and the recorded time base, see figure 1. Usually, the data in the matrix is transformed to the frequency domain, so that the third dimension represents all the frequency components rather then the time base.

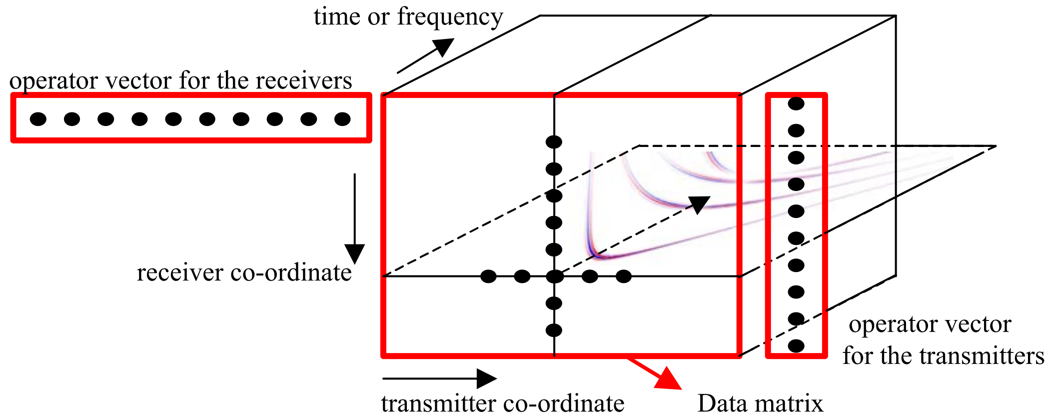

figure 1: Three dimensional data matrix for all transmitter and receiver combinations. The vectors V_s and V_r operate on a slice of the data matrix.

Because all available transmitter and receiver combinations are used, the data matrix contains all the possible information available with the chosen transducers. When a beam is generated by a phased array transducer, for example 16 elements are chosen as both transmitter and receiver at the same time. The A-scans are time-shifted and added, the final result will be a single A-scan, presented on the monitor. If the A-scans in the data matrix corresponding with the same 16 elements are selected, time shifted and added in the same way *after* the measurement is done, the same result is obtained. The difference is that the with IWEX imaging A-scans can be used again for other time shifts corresponding to other beam angles and focal spots. In fact, time delays (or phase shifts in the frequency domain) can be applied corresponding with any number of positions or focal spots in the volume to be inspected. Also, we do not have to restrict ourselves to 16 'active' elements, the responses from all 128 elements can be used.

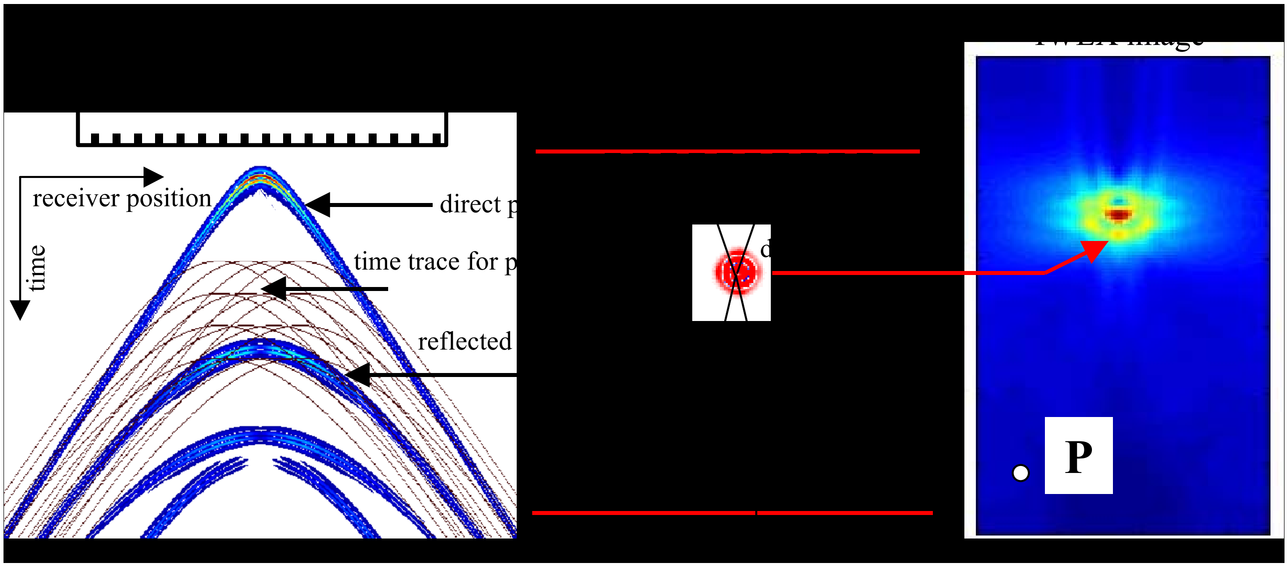

figure 2: (left) Response (simulated) caused by a cylindrical reflector, the reflector is assumed to be a source. (centre) Possible paths form the reflector(red dot) to the receivers. (right) Result of the IWEX image, when all points in the area are imaged. Point P does not contribute to the image, because no corresponding values can be found in the data at the left.

To illustrate the imaging process step by step, we start from the data matrix (128x128 A-scans) transformed to the frequency domain and we select one frequency. The data matrix is now reduced to a two dimensional matrix. Now we select a point P in the volume of interest. This point will be imaged using two matrix-vector operations. The first operation is to multiply the reduced data matrix with a row vector V_r. This vector contains the amplitude and travel time corrections for all 128 receivers to point P. The amplitude and time corrections are calculated with the Rayleigh integral and therefore directly related with the wave equation. In the first step, all wave field responses measured at the receivers are inverse propagated or 'pushed' back to point P, so that all receivers 'listen' to point P. Because of reflection at the back wall, more paths are possible to propagate back to point P. By calculating in the frequency domain, all possible paths (also paths via mode converted waves) are taken into account. The result of this first step is a row vector. The second operation is to multiply this result with a column vector V_s. This vector contains the amplitude and time corrections for all 128 transmitters to point P. In this step, all transmitters are propagated towards point P, thus all transmitters are focussed at point P. If a reflector was present in point P, the value at time zero of the above operations will strongly contribute. This value can now be plotted at the position of point P as part of a colour scale, see figure 2. The procedure should be repeated for each relevant frequency component and each point in the area of interest. Since each point in the weld volume is imaged, no prior knowledge from the weld preparation is needed for reliable detection.

Vectors V_r and V_s are called the (focus) 'operators' because they operate on the data matrix. The operators are comparable with the time delays according to the focal law. In addition, the operators also contain amplitude corrections. Many studies have been done to obtain operators in the seismic application field, the so called 'migration' methods, see [1] and [2]. The concept of inverse wave field propagation is earlier introduced in this field, see also [1] and [2] .

In practice, all operators need to be calculated before the inspection of a girth weld and stored on the computer. During the inspection, the data matrix as described above is filled for the present position on the circumference. Then the operators are applied and the 2D image corresponding to the position is acquired. One can imagine that a 3D picture can be obtained with the same method, if the operators contain the amplitude and time corrections of the third dimension.

The quality of the image is dependent on parameters such as the number of transmitters and receivers (thus the size of the data matrix), the area covered by the transmitters and receivers (aperture) and the band width of the signals received. These parameters have to be optimised for the best results.

The principles of IWEX imaging can also be used for other geometry's and materials. The essence of the technique is the use of operators containing the information of the arrival and amplitude of all possible signals. As opposed to the geophysical application, fortunately in the case of girth weld inspection many parameters such as sound velocity and wall (or layer) thickness are a priori known. In that case the operators can also be calculated in advance.

In seismic exploration, methods are developed (such as the common focal point method or CFP) to image unknown subsurface structures with unknown material constants, see [3]. These methods are based on iterative update algorithms. The operators are made by an estimated model of the inspection volume. Then the model can be update by looking at the difference between the measured data and the operators. The same methods can also be applied on ultrasonic NDT, however iterative updating consumes time.

In the following we will discuss similarities and differences compared to other known imaging techniques.

Imaging and other techniques: In the following, four commonly used (imaging) techniques will be discussed:

- Sector scans
- Time of Flight Diffraction (ToFD)
- (Multi) Synthetic Aperture Focussing Technique (SAFT)
- Strip charts.

The term 'imaging' is not unambiguously defined in the application field of NDT. Mostly the term 'image' refers to a series of stacked A-scans, with the amplitudes mapped to a colour scale. Examples are the sector scan and TOFD. Characteristic is that the data is not processed before the image is made. As opposed to sector scans and TOFD, the synthetic aperture focussing technique (SAFT) makes use of a processing step on the data before the image is generated.

Sector scans are obtained by steering a beam with small increments in the angle (for example from –30° to 30° with increments of 1°) see figure 3.

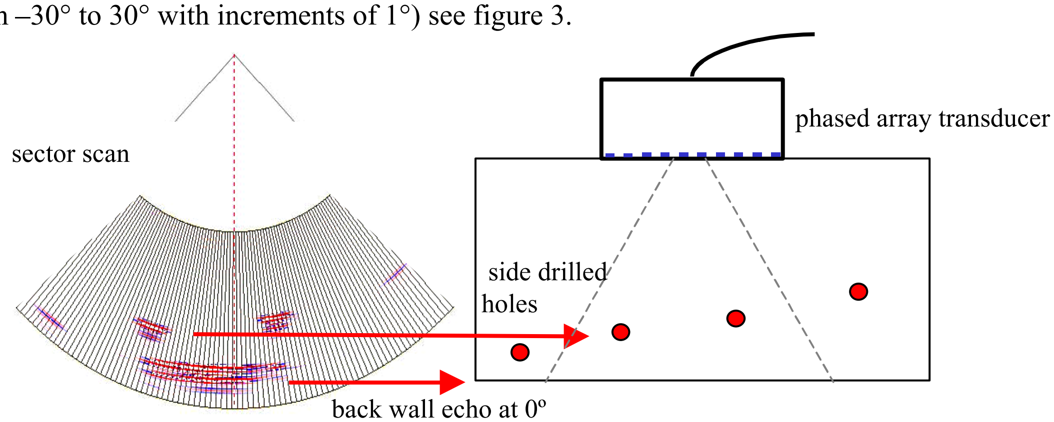

figure 3: Sector scan made on a block with side drilled holes.

The result appears to be an image of a cross section of the inspected volume (baby in womb effect). It is important to realise that these images can not contain all the information of the inspected volume. The orientation of a planar defect can cause the ultrasound to reflect in a direction, such that it can not be detected with the configuration of the sector scan. Also, all the beams originate from the same index point, causing the sector shape. Not all positions in the volume are covered. Thus not all directions and beam positions are incorporated in sector scans.

Another technique which produces an image by stacking A-scans is Time of Flight Diffraction or ToFD. A ToFD scan is obtained with two single element transducers with a large beam width, placed on each side of the weld (pitch-catch method).

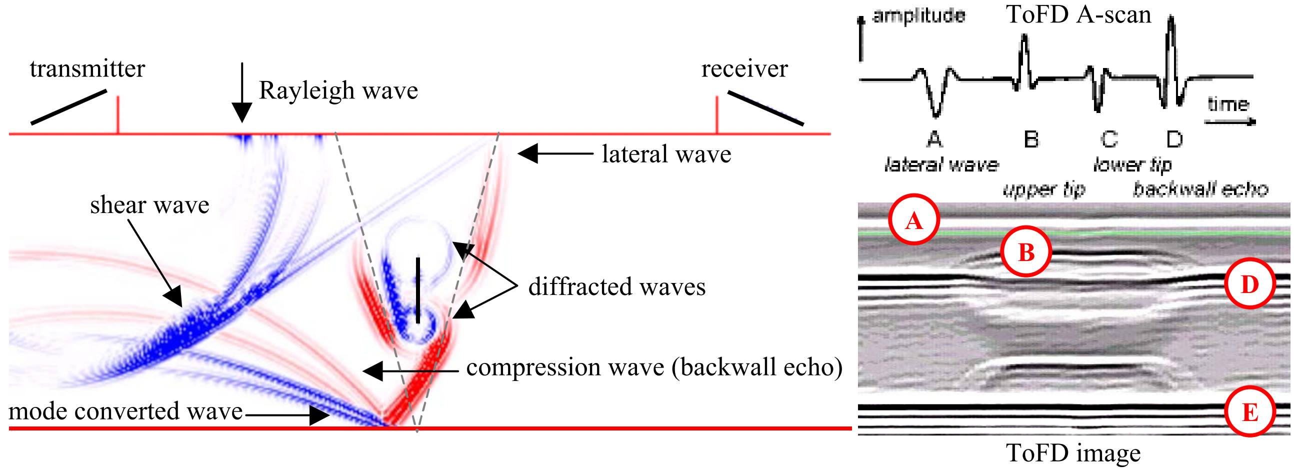

figure 4: Elastic finite difference simulation of the ToFD principle, showing all the important events: A) lateral wave, B) diffraction of the upper defect tip, C) diffraction of the lower defect tip, D) reflection at the back wall, E) signal caused by the mode converted wave.

Because of the beam width, most of the volume of interest is covered with ultrasonic energy. The A-scan of a ToFD scan is built-up by the arrival times of the different events see figure 4. The first signal is caused by the lateral wave, running just under the surface. The second wave is caused by the reflection of the back wall, the third is caused by waves that are mode converted at the back wall. Signals caused by a defect appear between the signals from the lateral wave and the back wall reflection. A-scans from subsequent positions are stacked, the result is a characteristic pattern, the image. The defect shows as a disturbance in the pattern. As opposed to sector scans, the image is less dependent on the defects orientation. However, a ToFD scan is a 2D side view picture of a 3D scanned volume. The position of the defect in the cross section is therefor not fully known.

A SAFT image is also obtained with two single element transducers, a transmitter and a receiver both placed on the same side of the weld and both faced to the weld volume (tandem method). A-scans are made by varying the positions of the transmitter receiver combination along the aperture. The data is stored in a data matrix in a similar way as discussed earlier. The image is obtained after a processing step on the data, see figure 5. The processing step is a focussing method, compensating only the travel time of the first arrived signals for each point in the inspection volume. MultiSAFT takes more possible arrival times into account, however no amplitude corrections or signals caused by mode conversion are taken into account for both SAFT and MultiSAFT see [4]. Again, the larger the aperture measured, the better the quality of the image. As opposed to IWEX, SAFT takes only half the possible aperture into account.

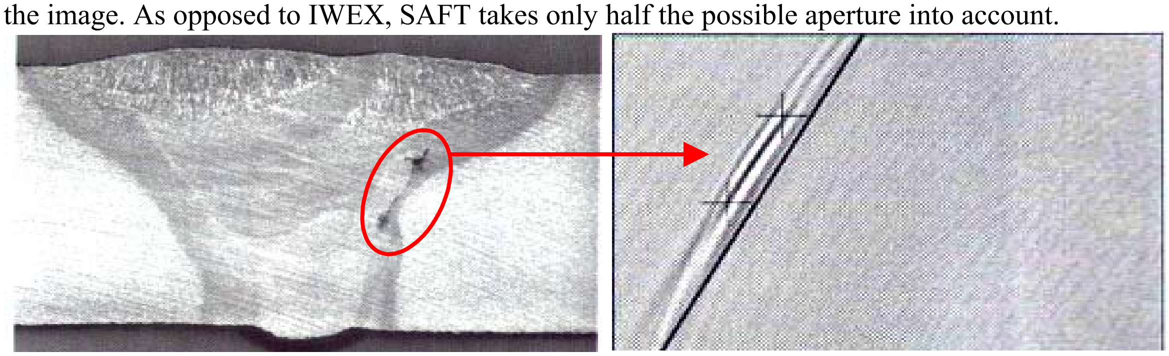

figure 5:Multi SAFT image (right) showing the result of a lack of fusion defect (left). Courtesy Maarten Lorenz (Shell Global Solutions International).

Strip charts are mostly used for the display of automated ultrasonic testing (AUT) data from girth welds, inspected with the principle of zonal discrimination. With this method, a cross section of a girth weld is divided into several zones, depended on the wall thickness. Each zone is inspected from both sides of the weld, with an ultrasonic beam aimed perpendicular to the weld preparation. The ultrasonic beams for the zones can be made with both single element probes (one probe is needed for one zone) and with phased array probes (than only one probe is needed for all the beams on one side of the weld). The assumption is made that defects caused by lack of fusion will have the orientation of the weld preparation (or fusion line). Strip charts do not represent the defect information in direct relation to the measured area. The information of a single strip represents the amplitude and transit distance in a time gate corresponding to the position of the expected signal. In the event of a defect, the signal will appear precisely in the time gate, see figure 6. The amplitude is calibrated with the amplitude of a known reflector, usually a flat bottomed hole. Defect sizing is done by referring the amplitude caused by a defect with the amplitude corresponding with the known reflector.

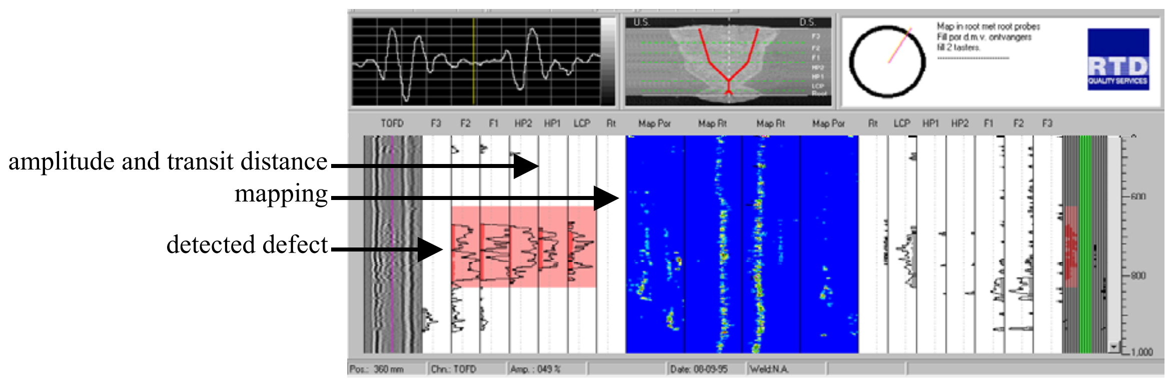

figure 6: Strip chart display, commonly used AUT. Each column represents the information of a single zone.

Advantages and disadvantages compared to the other techniques: A summary of the performance of the different techniques is illustrated in table 1. The following characteristics are compared: volume coverage, inspection speed, processing speed, data interpretation, dependence on the orientation and shape of the defect and accuracy.

	IWEX	ToFD	SAFT	sector scan	strip chart
volume coverage	++	+	++	-	+
inspection speed	+	++	-	+	++
processing speed	+	++	+	+	+
data interpretation	++	-	+	+	-
orientation, and shape	++	+	+	-	-
accuracy	+	+	+	+	+/-

table 1: Comparison of different imaging techniques.

Volume coverage: Sector scans cover the least inspection volume compared to the other techniques, caused by the origin of the sector image. All the beams originate from only one point at the surface. A larger volume can be inspected by varying this point. ToFD covers a larger volume, however because of the lateral wave, a dead zone appears in the near surface area. The volume coverage of the IWEX method is complete, because effectively a focal spot is made for each point in the volume. SAFT also covers the complete volume. Except in the case when two defects block eachothers reachability for the ultrasound, the volume coverage can not be completed. Strip charts cover only an small area round the fusion line. More charts with longer time gates are used to cover the complete weld volume. These charts or map gates display the complete digitised A-scan within the gate and use a higher sensitivity to detect indications such as porosity and slag inclusions

Inspection speed: Compared to ToFD, sector scans and strip charts, IWEX and SAFT have a lower inspection speed, due to the amount of data collected. The aim is to reach the same inspection speed with IWEX by reducing redundant data. For example, according to reciprocity only half the data matrix is sufficient (above or below the diagonal). Of all the techniques, ToFD images are made with the least of data.

Processing speed: ToFD, sector scans and strip charts do not require any processing, since the raw data is displayed directly. Sometimes sector scans are made with so called dynamical depth focussing. The A-scans displayed are then compensated for depth, in which case processing is required. IWEX and SAFT do require processing before the image can be displayed. The speed of the processing depends on the amount of preparation and the desired resolution. If all the operators are available, the only processing step is the multiplication of the data matrix with the operator for each point.

Data interpretation: Data interpretation is very transparent for the IWEX and SAFT method. The image is a cross section of the weld, indications and geometry will appear in the context of the weld preparation. A sector scan also gives a cross section, however not the entire volume is displayed. The ToFD image does not give a cross section but a side view (that is if only the standard non-parallel scan is performed; additional parallel scanning provides additional information). Training is needed to interpret ToFD images. Furthermore, the interpretation of strip charts requires some experience as well. Indications in the strips may not always be caused by defects. For example, reflections caused by the welds geometry (cap and root bead) can appear in the pre-defined time gate. The call of a relevant indication depends on the decision of the experienced inspector.

Shape and orientation: The result of an IWEX and SAFT image is (almost) independent from the shape and orientation of the indication. Information from all possible directions is acquired. IWEX uses information from both sides of the weld, an indication is therefore measured from both sides. Although SAFT uses information from only one side, still the orientation of the indication is not crucial. Orientation and shape play a more important role in a ToFD image. Two different orientations can give a similar ToFD image. Furthermore a ToFD image is based on diffraction rather than reflection signals. When a defect is planar and horizontal, a reflection echo will be detected, giving rise to a much higher amplitude. Amplitude is not related to the severity of the indication. Sector scans are strongly dependent on the orientation of the indication. Some orientations can even not be detected. This also applies to strip charts. An assumption of the orientation and shape of the defect is made, so a defect will be detected with a lower amplitude or not at all if the assumption is violated.

Accuracy: Most important is the accuracy of the image. Sizing of defects (if detected) is for all the techniques mainly based on arrival times rather than amplitude. Amplitude can give a better contrast of the image. Accuracy is dependent on the frequency bandwidth of the signal. For a transducer with a centre frequency of 4 MHz and a bandwidth of 50%, the accuracy can be approximately 0.5 mm. This accuracy can be reached if all other parameters such as wedge angle, element spacing and bandwidth are optimised and if parameters such as probe position, sound velocity and wall thickness are accurate. probe position, sound velocity etc. Variations in those parameters can cause variations in the arrival times and thus in the image. In case of IWEX and SAFT, the image will become blurry because the arrival times for compensation are out of focus. However, in terms of resolution, IWEX images can approach the physical limits better then other methods under practical conditions. Defect sizing with strip charts are partly based on amplitude by referring the defect response with the calibration reflector. The length of defect parallel to the circumference can be measured with the –6 dB drop. No direct sizing relation can be used for data in map gates, because the orientation and shape of channels porosity and slag inclusion are not known a priori and are usually different from the calibration reflector.

Conclusions and discussion: We have seen that the IWEX imaging method offers good potential for future NDT in the industrial field. IWEX imaging makes use of almost all information present in the data which can be measured at each chosen point in the inspection area. Signals caused by shear waves, compression waves and combinations of both (caused by mode conversion) all contribute to the final image. Also the complete inspection volume is covered. The probability of detection will increase because no assumptions of defect shape and orientation are necessary. An IWEX image can be interpreted easily because orientation shape an the relation of the defect within the weld geometry is directly visible. The commonly used strip charts for data display of girth weld may even be replaced by a side view, top view and cross section view of the girth weld. Three dimensional views with rendering can be rotated to give full insight in the shape of defects.

Like each renowned ultrasonic NDT technique, IWEX imaging has to be validated in practice by numerous field studies, trials and evaluations. As part of this research, experiments will be carried out on artificial reflectors and on real defects. Results based on numerical data from finite element simulations of the elastic wave equation are already obtained and show encouraging results. In addition, results from geophysical data have proven to be very useful and reliable.

References:

[1] A.J. Berkhout, '*Seismic migration imaging of acoustic energy by wave field extrapolation*', Elsevier Science Publishers B.V., 1984

[2] C.P.A. Wapenaar, A.J. Berkhout, '*Elastic wave field extrapolation, redatuming of single and multi-component seismic data*', Elsevier Science Publishers B.V., 1989

[3] J.W. Thorbecke, '*Common Focus Point Technology*', PhD thesis 1997

[4] M. Lorenz, '*Ultrasonic Imaging for the Characterisation of Defects in Steel Components'*, PhD thesis 1993