QUANTITATIVE NDE – NEW TECHNOLOGIES FOR DETECTION, CLASSIFICATION AND SIZING OF DEFECTS IN COMBINATION WITH PROBABILISTIC FAD-APPROACHES

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ABSTRACT

Starting with the damage tolerance design of structures in aerospace applications [1] it became obvious: NDT procedures, utilized according to standards in the regulated area and according to technical reports, guidelines and handbooks in non-regulated applications have to take into account the uncertainties of the techniques. These are system features influenced by the type of product to be inspected, more over its individual design and manufacturing techniques, the type of non-conformity or irregularity to be detected, the type of ND technique selected, the hardware (transducer and system electronics), the software reliability and – the human factor influence of the inspector.

All of the influences are summarized in a feature which is called POD – probability of detection. If there is a certain probability of detection, then there is also a PND, a probability for non-detection. As each technical system is not complete and not ideal the indication of a 'finding' or an 'alarm' by the system can be a real hit but also a false indication, or also called, false alarm. In the same way, in the case of a 'calm' system, i.e. no alarm is observed and no finding is indicated, the system' answer can be true or false. For each of the four cases the knowledge of the probability has to be known.

So far as a probabilistic approach is applied [2] POD distributions as function of the size of an individual material irregularity are relevant influencing parameters concerning the probability of the failure of a component evaluated according to a failure assessment diagram (FAD).

The contribution introduces into the state of the art of a software development which will be applied to evaluate components integrity after performing in-service inspections. Special emphasis is on the description of the state of the art concerning a NDT-technology newly developed. The flexible "Sampling Phased Array Technique" [3] combines a high speed hardware approach with an interpretation software which online also analyze complex structures like austenitic and/or dissimilar-multi-layer-metal-welds and allows the representation of defects at its original position, even if complex, anisotropic microstructure is disturbing the inspection task. Procedures like SAFT (Synthetic Aperture Focusing Technique) are integrated. They allow the refocusing of the inspection data sensed in an inspection aperture into a pixel space for imaging. The image allows visualizing defects in order to predict the size. Whereas conventional ISI-procedures are based on fixed angular probe UT, Phased Array probes allow a flexible multiple-angle-inspection. This procedure is optimal when – as in the case of sampling phased array – by fast computing each position in 3D-space can be allocated with a focus spot.

1. INTRODUCTION

An inspection task in NDT (non-destructive testing) concerning the examination of components for irregularities, also called nonconformities or defects, generally can be divided into the two subtopics: Detection and sizing. Depending on the type of defect (slag inclusions in welds, cracks, etc.) and, so far oriented, its orientation to the surface of the component to be examined NDT-techniques are more or less suitable and reliable, i.e. have a certain probability for detection and a certain accuracy for sizing. So it is principally known that techniques based on irradiation of X- or gamma-rays and using the film as detector are more suitable to detect slag inclusions and porosity where as ultrasound is better adjusted to detect oriented defects like lamination or cracks [4].

Concerning the fracture mechanical point of view – depending on the microstructure state in terms of strength (yield and tensile strength) and toughness (fracture toughness) and on the service loads critical defect sizes can be described deterministically initiating the failure of a component. The precise description of the defect geometry embedded in the geometry of the component allows the calculation of the stress-intensity factor so far the actual loads are known. However, everybody knows: Materials and components in service are not homogeneous. Its characteristic mechanical properties vary with position (for instance base material, heat affected zone, weld material) or as a function of degradation influences like thermal and/or neutron degradation. Furthermore, NDT-techniques applied according to given standards cannot provide inspection data comparable to a 3D computing tomography (CT) image as it is well known from medical application of X-ray- or UT-CT and documented in pictures like in figure 1.

New developments in NDT discussed in the here presented paper therefore are following two objectives:

- Take probabilistically into account the statistical distributions of material data and data of service loads as well accept that NDT-data are individual samples of statistical distributions concerning detection (probability to detect a certain defect size) and sizing (statistical scattering of defect size determination). Calculate the risk of failure under these assumptions in the failure assessment diagram (FAD).

- Enhance the development of NDT which tomographically can image 3D-defect geometries with high precision even in inhomogeneous and anisotropic microstructures.

Figure 1: A medical UT-image of a human fetus

2. PROBABILISTIC DETERMINATION OF THE RISK OF FAILURE

For metals the Failure Assessment Diagram represents a tool which summarizes, in the deterministic case, the results in the form: failure or no failure [5, 6] (figure 2).

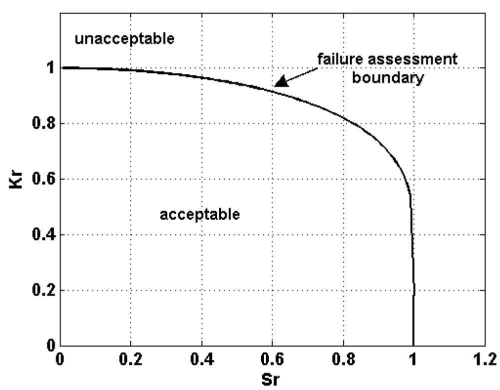

Figure 2: Failure Assessment Diagram [5, 6] (strip yield model): failure occurs when the calculated assessment point (Sr, Kr) reaches the failure assessment boundary. If the assessment point lies within the acceptable area the component is considered as safe.

The failure assessment diagram as shown in figure 2 was developed for deterministic input values. It has become an accepted tool for failure analysis and is part of several standards and norms [7, 8, and 9]. However, the FAD was originally designed for deterministic input information and, as already mentioned, realistic assumption requires the consideration of uncertainties. Therefore, the fracture mechanical approach was associated with Monte Carlo simulation which takes directly into account the uncertainties from statistical distributions. The result of such an analysis is a quantitative assessment in terms of probability of failure.

The main field of application for the probabilistic approach is pressure vessel and piping assessment [10, 11, 12, 13, and 14]. Some applications can also be found in the aerospace industry [15, 16].

The probabilistic evaluations described in these examples are focused on the distributions of the material parameters. The scattering of fracture toughness, yield strength and tensile strength values are usually represented by one of the three distributions: Normal, Log-Normal or Weibull distribution. However, the geometric input parameters representing the type of crack or flaw considered in the analysis have also got a severe influence on the result of the analysis. If methods from the field of non-destructive testing are used for crack size determination, the measurement error and the probability of detection (POD) of the used method itself have to be considered.

2.1 NDT Influences

Each fracture mechanical analysis needs information about the geometry of the investigated crack. Then a fracture mechanical model can be allocated and the corresponding stress intensity factor can be calculated. If the geometry of the crack or flaw is determined using a non-destructive testing method, e. g. ultrasound or X-ray, the gained values for crack depth and crack length are affected by certain errors. A realistic analysis should consider these measurement errors. The determined crack geometry values can be treated as mean values and the corresponding errors as standard deviations.

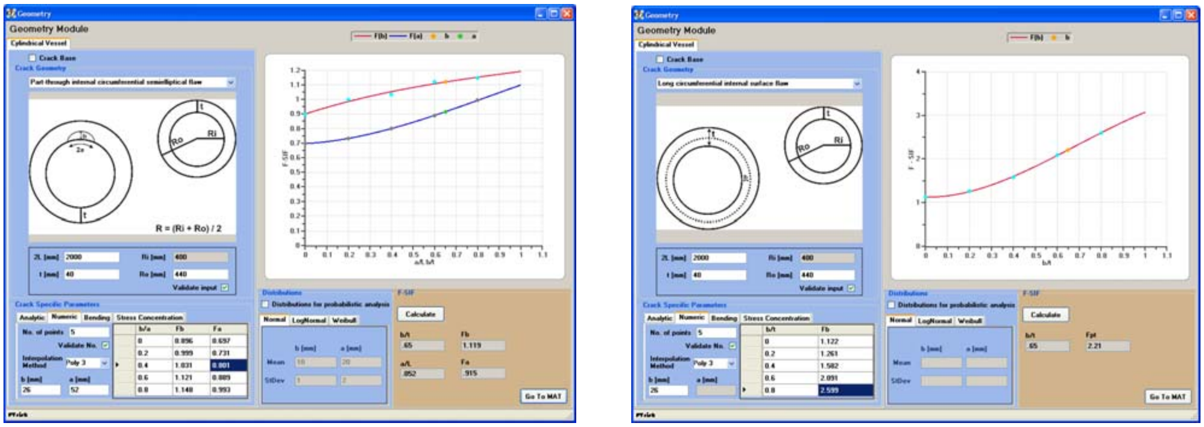

Figure 3: Left: Model of a semi-elliptical internal surface crack in a cylindrical pressurized shell [9]. Right: Model of a circumferential internal surface crack [9].

Figure 3 (left) shows the model geometry of an internal semi-elliptical crack (length 52mm, depth 26mm) in a cylindrical pressurized shell (inner diameter 800mm, wall thickness 40mm) and in figure 3 (right) the crack is assumed to be circumferential with the same depth. The material selected for the shell was according to the steel 22NiMoCr 37 a pressure vessel material according to early NPP design in Germany. In the model calculations the yield strength was selected as YS=500MPa, the tensile strength as UTS=640MPa, the fracture toughness was Kc=89.79MPa $\times\sqrt{}$m. These values represent a martensitic microstructure which according to the codes is not acceptable. The internal pressure was selected to be 150bar=15MPa and the temperature to 280°C. The stress intensity factors (SIF) are calculated by FE-codes [9] and the geometry dependent factors F-SIF also are represented in figure 3.

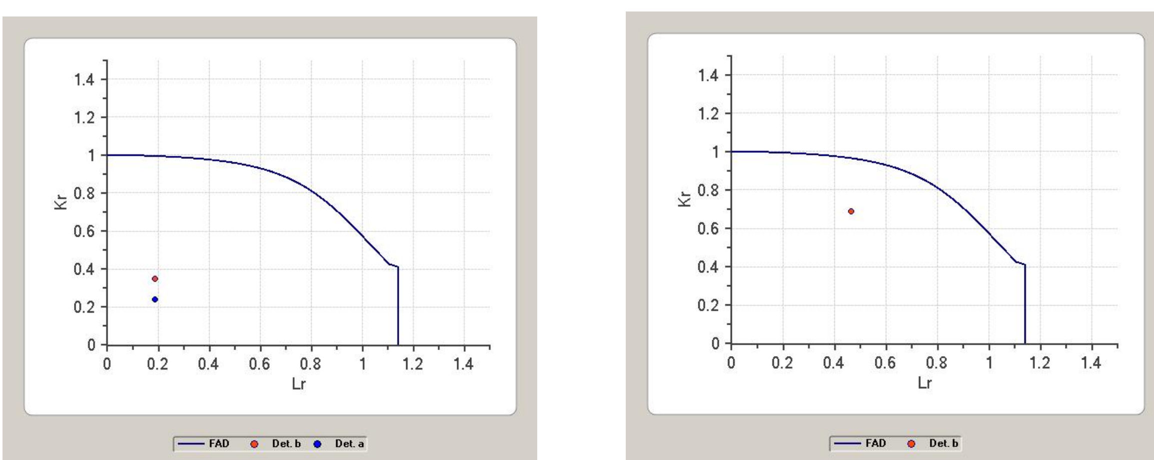

Figure 4: Deterministic FAD evaluation, Left: semi-elliptical crack (assessment point for crack depth, red and for crack width, blue), Right: circumferential crack (assessment point for crack depth, red)

In figure 4 the FADs are presented for the two model assumptions. Obviously, the circumferential crack is more critical. Only this second model was then utilized to demonstrate the probabilistic approach. The Monte Carlo simulation for failure assessment is able to use the information about the geometry parameters and the material values in form of distributions. Especially the consideration of non-destructive testing results offers the possibility to use inspection data for probabilistic failure risk assessment. However, performing such an assessment requires a broad knowledge about the POD associated with the method used for crack detection. The standard deviations assumed were σ_{Kc}= 5MPa×√m, $\sigma_{YS}=\sigma_{UTS}$=10MPa, and σ_b=2mm.

2.2 Probability Of Detection

A further often neglected factor of influence for performing a realistic fracture mechanical analysis which is based on NDT data is the probability of detection (POD). POD is an important part of the damage tolerance design procedure. Extended investigations were carried out during the space shuttle program and during damage tolerance assessments in response to structural failures in jet aircrafts [18].

The POD is defined as the fraction of detected defects in the total number of all defects. It has to be determined individually for each NDT technique and technical application. So far, the irregularities of flaws are small in size, NDT techniques are very near the physical limit of detectability, i.e., the more the data to evaluate are in the range of electrical noise the less is the detectability [19].

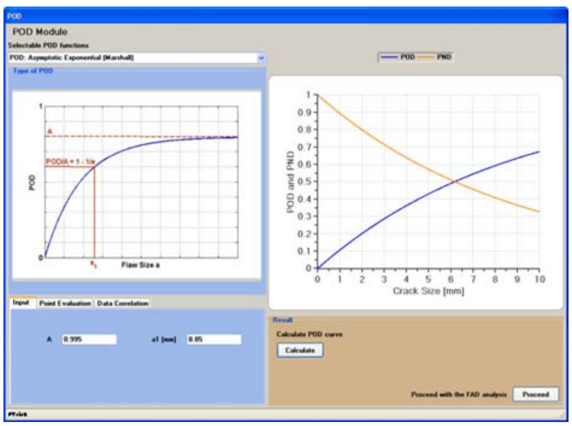

Figure 4: Asymptotic exponential POD [20]

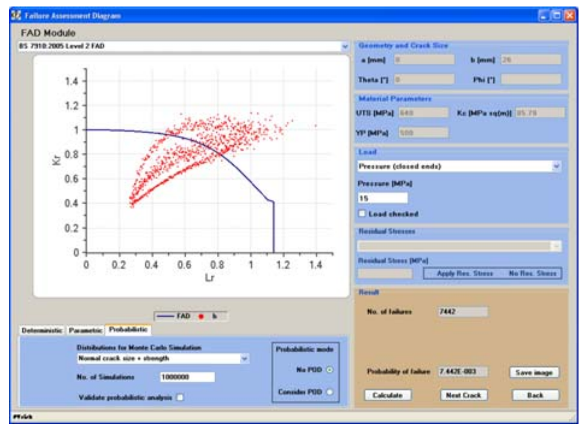

Figure 5: No NDT applied (assessment points for crack depth, red)

In many cases the relationship between the gained hit/miss POD and the size of the crack is linearly related on a logarithmic scale. Therefore, the corresponding POD functions can be gained by a linear fit of the POD values corresponding to a certain crack size. The POD values have to be acquired during appropriate tests. Owing to the binomial statistics of hit/miss tests a large number of trials are required (minimum of 29 successful trials per crack length interval to obtain 90 % POD). Different mathematical models can be assumed to fit POD functions on the base of appropriate data. The asymptotic exponential POD function (Figure 4) is based on the results of round robin test data of pressure vessels [20] according to the OECD-programme PISC with value A=0.995 and a_1=8.85. In a probabilistic fracture mechanical analysis with the POD information the non-destructive testing method is directly considered. Using the POD model the analysis procedure is refined since it can be assumed that a detected non-acceptable crack which does not lead to failure is repaired or the corresponding component is replaced.

2.3 Probabilistic Assessment Using PVrisk

The software PVrisk [21] is designed for a deterministic, a parametric and a probabilistic fracture mechanical analysis of pressure vessels using the FAD. The software is of modular composition. Therefore, the user has to specify at first the crack or flaw geometry parameters and in a second module the materials parameters before the actual fracture mechanical analysis can be performed. This last module for calculating the FAD also contains as a sub module the POD module.

The result of the deterministic analysis as shown in figure 4 is a safety index which indicates the position of the state of a flawed component under considered loading relative to the FAD boundary. Therefore, the criticality of the presence of the crack can be determined. The parametric analysis allows the determination of the critical pressure, the critical fracture toughness or the critical crack length for the deterministic case. Using the probabilistic procedure the probability of failure is calculated by a Monte Carlo simulation (MCS) whereas the user can additionally specify a POD function, if values are available.

What happens if no NDT is applied is presented in figure 5. By MCS the material parameters and the crack geometry were varied according the assumed distribution functions and standard deviations. Within a number of 10^6 cases a number of 7442 failures are registered, the probability of failure is 7.442×10^{-3}. The scatter plot of the assessment points resulting from the Monte Carlo simulation is graphically filtered. Therefore, only the shape of the original scatter plot is displayed. This makes the performance of the software more efficient but has no influence on the calculated results since the raw values are certainly used for calculating the probability of failure. If a NDT-technique is applied with a POD as documented in figure 4 the number of failures is reduced to 264 with a probability of failure of 2.64×10^{-4}. If the POD is enhanced by use of a more reliable NDT technique - the parameter a_1 in figure 4 is reduced to a (hypothetical) value of 2.85 – then the probability of failure can be reduced to a value of 4.5×10^{-5}.

3. MULTIPLE ANGLE QUANTITATIVE UT BY THE SAMPLING PHASED ARRAY TECHNIQUE

3.1 The Basic Principles

The phased array technology provides test data via an array of individual transducers which transmit and receive as directed by the electronics and software [22]. The implementation of phased array systems for material testing and evaluation utilizes only a small portion of the overall data acquisition capability since the acoustic transmissions for specific incidence angles are time-phased and the received signals are then summarized. This means that the entire array acts as a single transducer in accordance with the sampling theorem which asks for a distance of the point sources $< \lambda/2$ (λ-wavelength). However, if the time-domain signals from the individual transducer point elements are acquired, the resulting data can then be summarized with arbitrary phase information to permit data processing of all possible incidence angles and all physically available focus points from a single data set. This concept is referred to as the sampling phased array system (Figure 6).

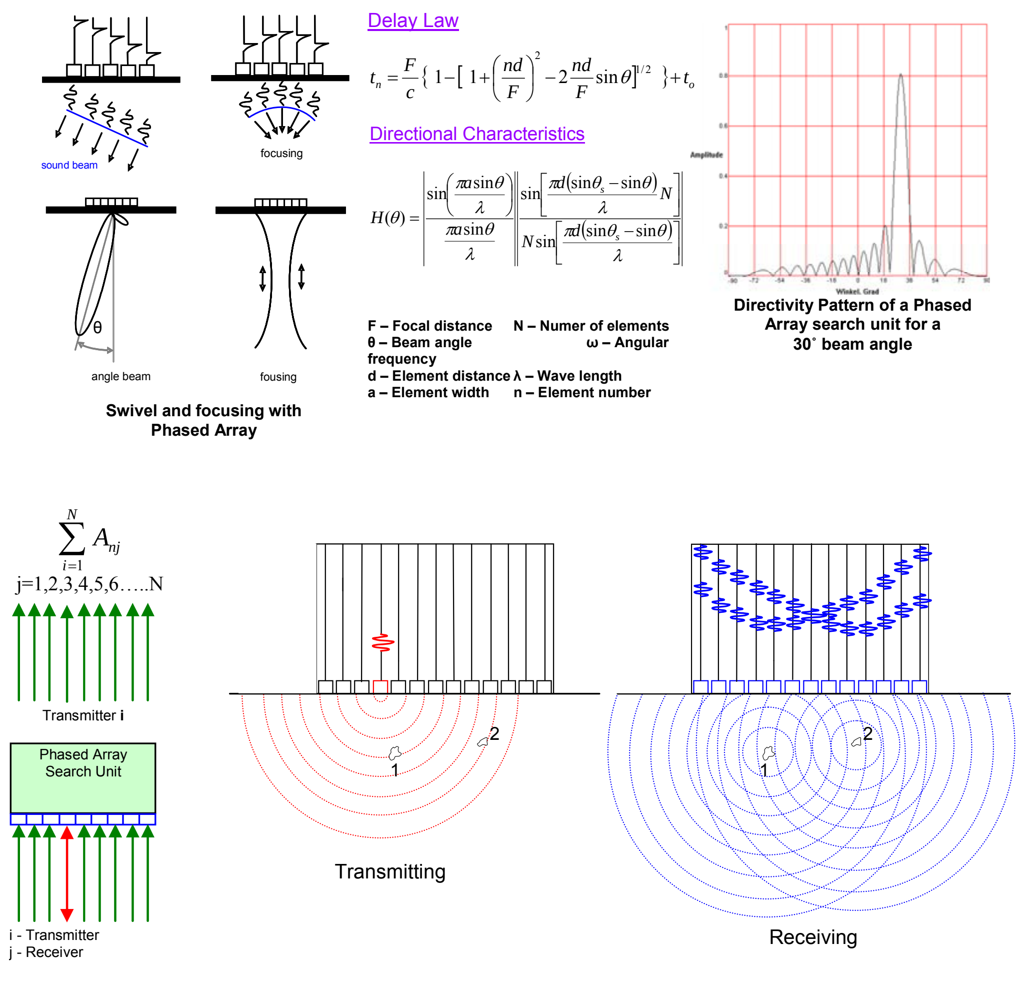

Figure 6: Conventional and sampling phased array principles

The measurement of signals in a time domain $A_{iJ}(t)$ with i = j (i: transmitter elements, j: receiver elements) is the essence of the synthetic aperture focusing technique (SAFT) where one phased array element is virtually steered over the aperture of the array. The additional acquisition of the time domain signals A_{iJ} with $i \neq j$ can be used as a data set for the solution of migration algorithms (e.g. Kirchoff Algorithm), for image reconstruction [23] and [24] In figure 7 the conventional phased array technique is compared with sampling phased array and depicts the advantages of the sampling phased array technology. The data for the sector scan were acquired in a single shot and processed in real-time, where the generation of the same image using conventional phased array with electronically controlled phase shifting requires 161 shots for a density at 1° angular increments. Whereas the near-field length of the conventional technique is determined by the whole array, in the case of the sampling phased array the near field is that of the individual point source. Therefore transducer near regions in the test object can be better inspected. The effect is demonstrated in figure 7 in sector scans. In the unfocused sector scan with the conventional phased array (figure 7 left part) the reflector 1 (side drilled holes, SDH) cannot be detected because of shielding by reflector SDH2. Furthermore the reflector indications are not sharp and a strong near field noise is indicated. In the case of focusing (figure 7 middle part) only the reflector in the focal depth is clearly detected. The application of the sampling phased array and using SAFT (here called SynFo Sampling) as described allows a synthetic focusing in each voxel element and the near field is free of noise.

Figure 7: Near field characteristic of a conventional (left, middle) and the sampling phased array (right)

3.2 Improvements for the inspection of austenitic and dissimilar metal welds

Austenitic and dissimilar metal welds have the characteristic to be acoustically anisotrop and inhomogeneous because of the columnar grain structure. Typically effects can be observed as documented in figure 8 based on theoretical models. In [24] the propagation of a pressure wave (45° incidence) and a shear wave (60° incidence) is modeled by ray tracing at an austenitic weld. In [25] the superposition of Gaussian beams was applied to model the wave propagation in carbon fiber reinforced polymeric material with fiber orientation under 15° and under 75°. Depending on the fiber orientation or the grain orientation respectively more ore less the sound field is deformed.

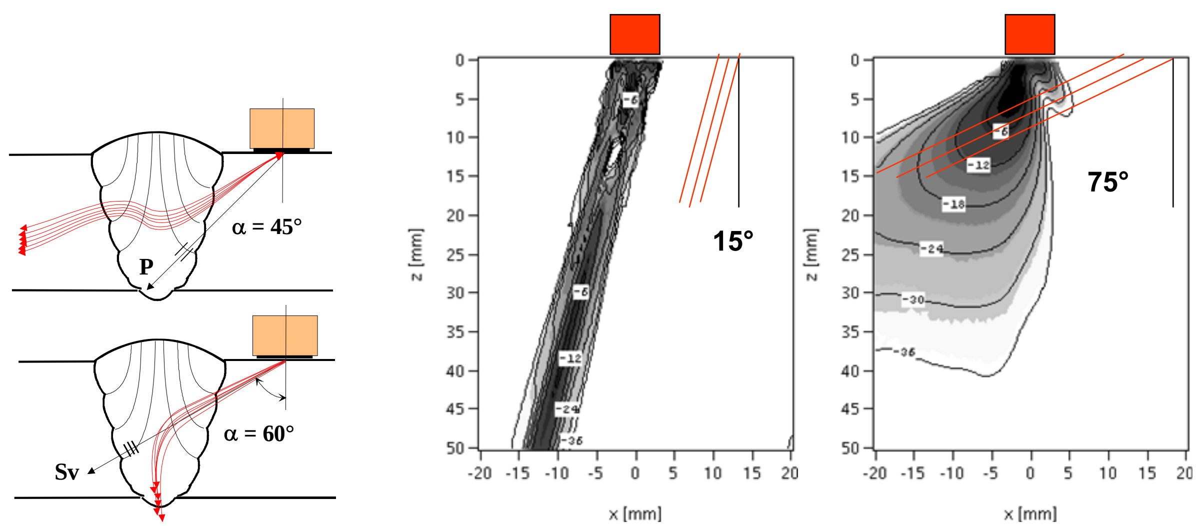

Figure 8: UT of an austenitic weld, modeling by ray tracing (left) [24] and Gaussian beams superposition (middle and right) [25]

To solve the inspection task in an optimal way obviously in a first step an optimal angle of incidence has to be found. In order to learn how the microstructure is, a very flexible and economic inspection using phased array has to be performed. The application of the SynFo technique facilitates extensive improvements for the inspectability of the anisotropic and/or heterogeneous materials. The iterative and voxel-wise adaptation of the elastic properties and the direction of the energy propagation – also called inverse phase matching [26] – is the tool to solve the problem.

Provided that the structure of the material is established, today's technology permits the calculation of the image point to transducer element travel time sufficiently accurate and fast enough to permit a phase-matching reconstruction of the image point from the time-domain signals $A_{iJ}(t)$.

If the material structure information has been established through modelling, reconstruction can principally be improved by varying the model parameters or by using correlators, as used in medical technology. This technique allows not only for successful flaw detection but also delivers a description of the reflector's structure and geometry.

CONCLUSION

In order to apply a quantitative NDT and to take credit of fracture mechanics the reliability of the NDT-techniques has to be improved. Concerning UT phased array techniques provide a flexible tool to perform a high speed multiple angle inspection which will result in better detectability and sizing accuracy. The sampling phased array approach overcomes some drawbacks of the conventional phased array technology, enhances the inspection speed and allows a better inspection of near surface zones.

The implementation of probabilistic features in the FAD procedure taking into account the statistics in the material characteristics, the loads, as well as the uncertainties in NDT observing the POD and the sizing accuracy, will contribute to a safer and less conservative lifetime prediction of components in terms of a risk of failure determination.

REFERENCES

[1] Schmidt H.J., Schmidt-Brandecker B., Tober G., "Design of Modern Aircraft Structure and the Role of NDI", *Proc.Of the 7th ECNDT, European Conference on Non-destructive Testing*, Copenhagen, Denmark, May 1998.

[2] Cioclov D., Dobmann G., Kröning M., "A contribution of Quantitative NDE with ultrasound in combination with probabilistic fracture mechanics for lifetime evaluation of components", *Proc. Of Herausforderungen neuer Werkstoffe an die Forschung und Werkstoffprüfung*, pp 147-156, DVM, Berlin, Germany, December 2005.

[3] Boulavinov A. "Der getaktete Gruppenstrahler", *PhD-Thesis at the Saar University*, Technical Faculty, Saarbrücken, Germany, 2005.

[4] Ultrasonic Test Method. Level I, II, III. *ASNT*, Columbus, Ohio, USA, 1980.

[5] Dowling A. R., Townley C. H. A., "The Effects of Defects on Structural Failure: A Two-Criterion Approach". *International Journal of Pressure Vessels and Piping*, Vol. 3, 1975, pp 77-137.

[6] Harrison R. P., Loosemore K., Milne I., "Assessment of the Integrity of Structures Containing Defects", *CEGB Report R/H/R6 Central Electricity Generation Board*, United Kingdom, 1976.

[7] Nichols R. W., "The Revision to the Structural Integrity Assessment Method CEGB/R6", *Int. J. Pres. Ves. & Piping*, vol.32, 1988, pp 1-327.

[8] Zerbst U., Wiesner C., Kocak M., Hodulak L., "SINTAP: Entwurf einer vereinheitlichten europäischen Fehlerbewertungsprozedur – eine Einführung", *GKSS Report*, 99/E/65.

[9] BS 7910:2005, "Guide to methods for assessing the acceptability of flaws in metallic structures", *British Standard Institution*, 2005.

[10] Dillström P., Nilsson F., Brickstad B., Bergman M., "Probabilistic fracture mechanics analysis of a nuclear pressure vessel for allocation of in-service inspection", Int. *J. Pres. Ves. & Piping*, vol. 54, 1993, pp. 435-463.

[11] Rahman S., "Proabilistic fracture analysis of cracked pipes with circumferential flaws", *Int. J. Pres. Ves. & Piping*, vol. 70, 1997, pp. 223-236.

[12] R6, "Assessment of the integrity of structures containing defects", *Appendix 10 Probabilistic Fracture Mechanics Procedure Nuclear Electric Procedure R/H/6 – Revision 3 Nuclear Electric*, vol. A10, 1998, pp. 1-24.

[13] Bullough R., Green V. R., Tomkins B., Wilson R., Wintle J. B., "A review of methods and applications of reliability analysis for structural integrity assessment of UK nuclear plant", *Int. J. Pres. Ves. & Piping*, vol. 76, 1999, pp. 909-919.

[14] Dillström P., Nilsson F., Brickstad B., Bergman M., "Probabilistic fracture mechanics analysis of a nuclear pressure vessel for allocation of in-service inspection", *Int. J. Pres. Ves. & Piping* , vol. 54, 1993, pp.435-463.

[15] Cioclov D. D. Escobedo Medina M. C., Schmidt H. J., "On the probabilistic fracture mechanics simulation of fatigue life and crack statistic for the purpose of damage tolerance assessment". *Proc. Of ICAF 2003 – Fatigue of Aeronautical Structures as an Engineering Challenge,* vol. I, pp. 189-204, Lucerne, Switzerland, March 2003.

[16] Enright M. P., McClung R. C., Huyse L., "A probabilistic framework for risk prediction of engine components with inherent and induced material anomalies", *Proc. Of The 50th ASME International Gas Turbine & Aeroengine Technical Congress,* Reno, Nevada, USA, Paper GT2005-68982, June 2005.

[17] Murakami Y. (Ed), *Stress Intensity Factors Handbook Vol. 2*, Pergamon Books Ltd, 1987.

[18] Rummel W.D., Marietta M., Hardy G. L., Cooper T. D., "Application of NDE Reliability to Systems", *ASM Handbook Volume 17 Nondestructive Evaluation and Quality Control 3rd Edition*, ASM International, USA: pp. 674-688, 1994.

[19] Dobmann G., Cioclov D., Kurz J. H., "The role of probabilistic approaches in NDT defect- detection, -classification, and –sizing", *Welding in the World*, vol. 51 in press.

[20] Marshall W., "An assessment of the integrity of PWR Pressure Vessels". *Summary Report UKEA Authority*, UK, 1982

[21] Kurz J. H., Cioclov D. D., "PVrisk User Manual", Fraunhofer-IZFP, Saarbrücken, Germany, 2006.

[22] Chiao R. Y., Thomas L. J., "Analytic Evaluation of Sampled Aperture Ultrasonic Imaging Techniques for NDE", *IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency control*, vol. 41, No.4, 1994.

[22] Claerbout J. F., "Earth Soundings Analysis: Processing versus Inversion", *Stanford University*, 2004.

[23] Bamber J. C., "Image Formation and Image Processing in Ultrasound", http://www.m-pss.org/1999/pdf/bamber.pdf.

[24] Ogilvy, J., A., "A Model for Elastic wave Propagation in Anisotropic Media with Applications to Ultrasonic Inspection Through Austenitic Steel", *British Journal of NDT*, 1985.

[25] Spies M., "Transducer Field Modeling in Anisotropic Media by Superposition of Gaussian Base Functions", *J. Acoust. Soc. Am.*, vol. 105, 1999, pp. 633-638.

[26] Kröning M., Bulavinov A., Reddy K. M., „Verfahren zur zerstörungsfreien Untersuchung eines wenigstens akustisch anisotropen Werkstoffbereich aufweisenden Prüfkörpers", *German Patent*, Nr. 10 2006 003 978.5, 2006.