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# Potential new approaches to ultrasonic quantitative NDE (QNDE) by combining high speed defect reconstruction procedures based on sampling phased array techniques with probabilistic failure assessment

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## Abstract

An optimized phased array transducer with sector scan or compound scan in medical application obviously provides tomographic images of hidden objects in the human body which are nearly comparable with photographs. Solid state materials of technical components - the objects of NDT - have other elastic properties compared with the human body. Therefore the imaging task is more difficult. However, to increase the inspection speed for scanning including an online reconstruction is a general enhancement task for both of the applications. In medicine the doctor want to see, for instance, the pumping of the heart of the foetus in real time, in nuclear industry we want to reduce the inspection time in order to safe costs and to reduce the irradiation dose of personnel. New computing facilities like FPGA, DSP, and high-speed graphic plug-in boards allow to reconstruct inspection images in NDT now also in real time. Combining these possibilities with the integration of the SAFT technique using the sampling phased array (SPA)[1] approach has as result a virtual focusing by computation on each individual pixel in the image sector space. Compared with the classic phased array the SPA has the advantage of the much smaller near field length of the given point source. As far as the stochastic distribution of the material properties (yield and tensile strength, fracture toughness) are known[2] as well as the probability of detection of an individual defect[3] the failure assess diagram allows the probabilistic prediction of the risk of failure.

**Keywords:** Inservice inspection, high speed, online and real time reconstruction, sampling phased array, failure assessment diagram

## 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.
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.

## 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 1).

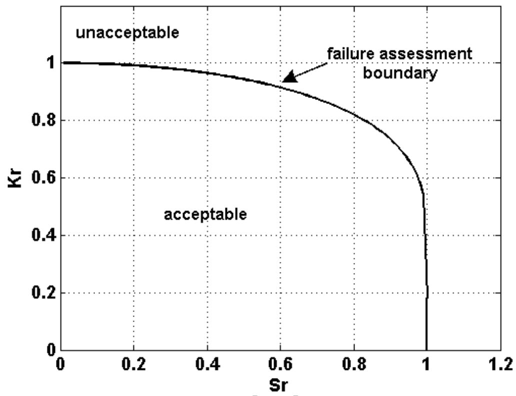


Figure 1: Failure Assessment Diagram (FAD)[5, 6] (strip yield model). Failure occurs when the calculated assessment point (Sr, Kr) reaches the failure assessment boundary. If the assessment point lies within the acceptable area the component is considered as safe.

The FAD 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 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.

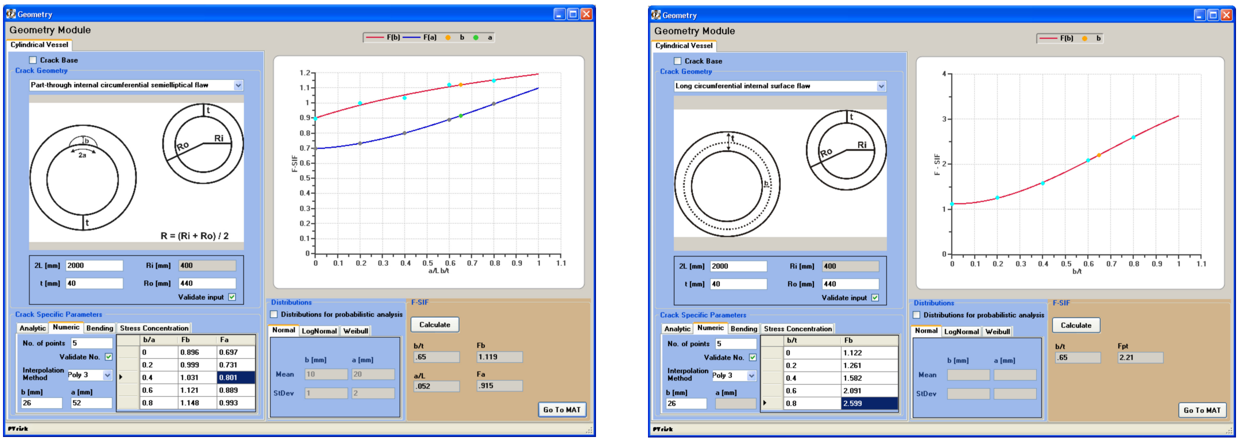


Figure 2: Left: Model of a semi-elliptical internal surface crack in a cylindrical pressurized shell [9]. Right: Model of a circumferential internal surface crack[9].

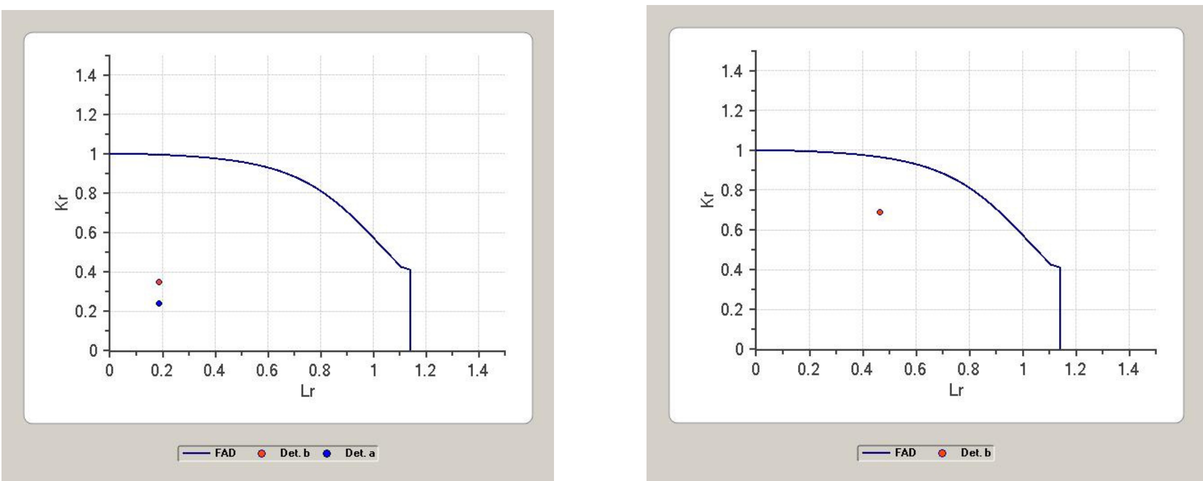


Figure 3: Deterministic FAD evaluation, Left: semi-elliptical crack (assessment point for crack depth, red and for crack width, blue), Right: circumferential crack (assessment point for crack depth, red)

Figure 2 (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 2 (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 ×√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 2.

In figure 3 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.

## 2.2 Probability Of Detection

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.

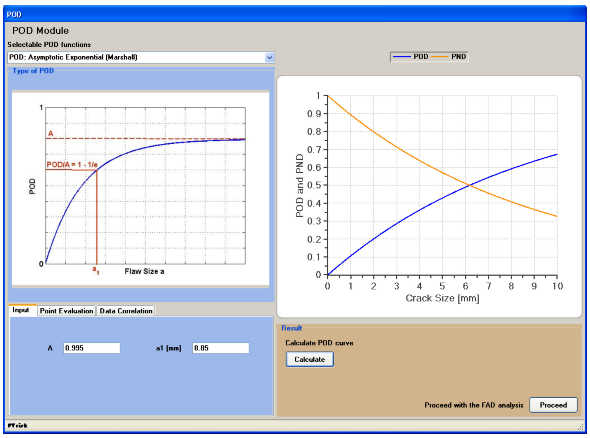


Figure 4: Asymptotic exponential POD

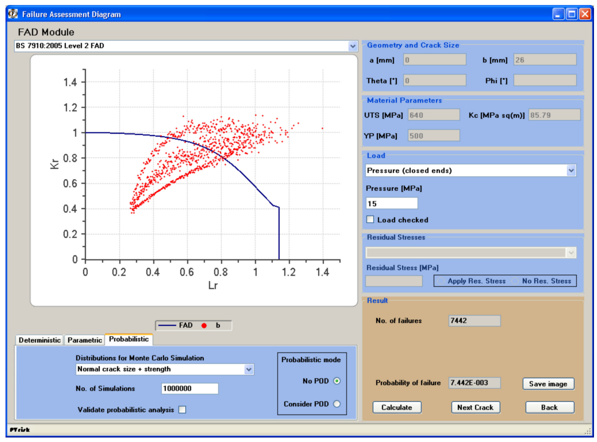


Figure 5: No NDT applied (assessment points for crack depth, red)

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 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[10] is designed for a deterministic, a parametric and a probabilistic fracture mechanical analysis of pressure vessels using the FAD. The result of the deterministic analysis as shown in figure 3 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.

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. The standard deviations assumed were $\sigma_{Kc}$= 5MPa×√m, $\sigma_{YS}=\sigma_{UTS}$=10MPa, and $\sigma_b$=2mm. 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 $7.442\times10^{-3}$. If a NDT-technique is applied with a POD as documented in figure 5 the number of failures is reduced to 264 with a probability of failure of $2.64\times10^{-4}$. 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 $4.5\times10^{-5}$.

## 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. 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 < $\lambda/2$ ($\lambda$-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[1, 11].


Figure 6: Near field characteristic of a conventional (left, middle) and the sampling phased array (right)

In figure 6 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 6 in sector scans. In the unfocused sector scan with the conventional phased array (figure 6 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.

**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. 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.

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