Use of Monte-Carlo Methods to Derive Quantitative Probability of Defect Detection Data

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Abstract. The European Network of Inspection and Qualification (ENIQ) Methodology for qualifying inspections is well established within Europe and provides a robust framework for demonstrating that an inspection is capable of detecting specific defects. A key feature of the ENIQ qualification approach is that, at present, it provides only qualitative information on defect detection capability and not any quantitative value. In the absence of any value for the probability of detection or PoD it is not possible to quantitatively evaluate the capability of an inspection or measure its effectiveness in reducing the risk of a component failure. This inability to generate quantitative PoD data is a notable limitation in the current approach to Inspection Qualification and the robustness of NDE reliability models in general.

Previous approaches to deriving PoD data have often relied on direct estimation and have suffered from acceptability by the inspection and structural reliability communities.

This paper develops an alternative idea of deriving quantitative PoD data based on the principles of the ENIQ Essential Parameters.

In contrast to conventional qualification, appropriate statistical distributions are assigned to each of the Essential Parameters and then combined via Monte-Carlo methods to simulate many different configurations of the inspection system. By using an appropriate defect response model it is then possible to identify which of the inspection configurations gives an 'amplitude' exceeding the reporting threshold and a 'hit'. By choosing a sufficiently large number of iterations a quantitative estimate of PoD can be derived.

Results are presented from a case study of a previously validated automated ultrasonic inspection of a nuclear plant component. Parameter distributions have been estimated using expert judgement and combined via a Monte-Carlo simulation performed in MATLAB interfaced with an ultrasonic response model based upon the Geometric Theory of Diffraction and Kirchoff Elastic theory.

The work reported in this paper extends previous work that demonstrated the potential of the Monte-Carlo approach to modelling PoD and supports the validity of the approach.

1. Introduction

Inspections of safety-critical plant items are commonly subject to some form of validation or qualification – particularly in nuclear power related applications. Within the European nuclear industry this is principally performed in accordance with the ENIQ European Qualification Methodology Document (EQMD) [1].

Although the inspection qualification provides high confidence in the reliability of the applied inspection system to achieve specific defect detection and sizing criteria the output is most often expressed in purely qualitative terms and there is no universal agreement how the output from inspection qualification trials can be related to PoD.

In the experimental approach to PoD the inspection system is applied to a test specimen(s) containing a range of synthetic defects and each time a defect is successfully detected, the detection score is incremented. The PoD is then estimated directly by dividing the detection score by the total number of defects. This is the 'classical' approach to deriving PoD data directly from experiment.

Whilst the direct experimental approach has the advantage of providing a quantitative value of PoD it also possesses several technical weaknesses:

- The defect detectability varies as a function of many variables not all of which can be adequately sampled in a practical trial and so what has been determined is not PoD but instead is the Defect Detection Frequency (DDF).
- Commonly the PoD is expressed as a function of a single parameter - the through-wall size of the defect. However, from experience of experimental trials, and from theoretical assessment, it can be seen that inspection performance can be influenced by multiple defect parameters. For instance defect tilt relative to the interrogating ultrasonic beam has a significant effect on signal amplitude.

In the USA and where ASME style inspection verification trials are conducted, it is common to interpret the DDF as the PoD and not necessarily to include the influence of subsequent sizing or characterization inspections. While this may be viewed as not technically rigorous, DDF is likely to be related to the true PoD and a consistent application of this approach provides some means of comparing performance of inspections.

It can therefore be seen that the direct experimental approach to determining quantitative PoD has a number of shortcomings principally related to the practical inability, in most cases, to represent all significant defect parameters in test specimens. This recognition suggests that a more theoretical approach based upon simulating 'many' different experiments may offer benefits.

This idea has been developed and a probabilistic qualification model (PoDMOD) developed that is based upon the established principles and techniques of the ENIQ Essential Parameters, ultrasonic inspection modelling and Monte-Carlo simulation.

2. Principles of the PoDMOD Qualification Tool

2.1 Basis of Pod Calculations

The PoD methodology that has been developed and encoded in PoDMOD relies on simulating a very large number of trials via a Monte-Carlo analysis of the inspection Essential Parameters combined with an ultrasonic inspection/defect response model.

Throughout the remainder of the paper the discussion is essentially limited to a consideration of ultrasonic inspection. However, the methodology embodied within PoDMOD could be extended to any inspection method for which a suitable deterministic response model is available and the Essential Parameters are well understood – for instance eddy current and radiographic examination.

2.2 ENIQ Qualification Methodology (Essential Parameters)

The ENIQ approach to Inspection Qualification [1] aims to demonstrate highly reliable inspection system performance by a combination of written and practical evidence. A key input to the qualification process is the validation defect detection and sizing requirements that defines the range of defects for which reliable detection and sizing is required. Principally, the written evidence (Technical Justification [2]) demonstrates that the inspection system is capable of producing a recognisable signal from the defect, with the experimental evidence (Open and/or Blind Trials) considering the reliability of the inspection team in applying the system to produce the signal and subsequently recognise it as significant. A fundamental principle supporting this approach is that of the ENIQ Essential Parameters [3] which are defined as:

' those inspection parameters…whose change in value would actually affect a particular inspection in such a way that the inspection could no longer meet its defined objectives…'

Within the current ENIQ methodology the Essential Parameters are treated in a deterministic manner. Each parameter is assigned a range of validity, such that, provided they are maintained within their specified limits then the required inspection capability is delivered. The inference being that a successfully qualified inspection system and personnel delivers a very high PoD.

In the current approach to inspection qualification no attempt is made to quantify the 'margin of detection' or what is meant by 'highly reliable'. It is essentially a deterministic process that results in a 'pass' or 'fail'. However, in reality, the Essential Parameters vary. Therefore if it is possible to attribute appropriate distributions, rather than just upper and lower bounds, to the Essential Parameters then these could be sampled via Monte-Carlo analysis and a probabilistic/statistical model of the inspection system developed. This is the principle underpinning the PoDMOD qualification tool.

2.3 Monte-Carlo Analysis

Monte Carlo simulation can be viewed as 'experimental' calculation, in which random numbers are used to conduct numerical experiments.

In the current work the Monte-Carlo principle has been applied to the inspection system Essential Parameters. Each Monte-Carlo 'sample' represents a single realisation of the inspection system - essentially it is a snapshot deterministic view. For each realisation the defect response amplitude is calculated using an appropriate ultrasonic response model or models and compared with the reporting threshold. If the amplitude exceeds the reporting threshold then this particular configuration of the inspection system corresponds to successful detection and a 'hit' would be recorded, if not, then a 'miss' would be attributed to this particular inspection system realisation. The proportion of 'hits' then provides an estimate of the probability of the inspection system to produce a signal that exceeds the reporting threshold.

2.4 Essential Parameter Distributions

Three types of distribution functions have been used in the current modelling work.

- Normal distributions.
- Truncated normal distribution functions – this type of distribution has been utilized to model the variation of parameters for which there is no practical likelihood of taking any value outside a certain range. Truncation has been used in the defect orientation distribution– Figure 1.

- Truncated Rayleigh distribution functions – this is an asymmetric distribution function which is bounded at particular values. It is useful for description of 'random' parameters such as probe coupling which can only reach 100%, but which can have a continuous distribution of values less than that – Figure 2.

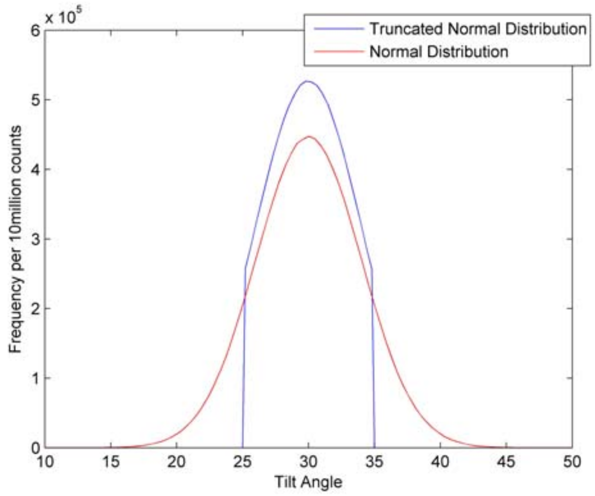

Figure 1 – Comparison of normal and truncated normal distribution of defect tilt angles (mean 30°; truncation ±5°)

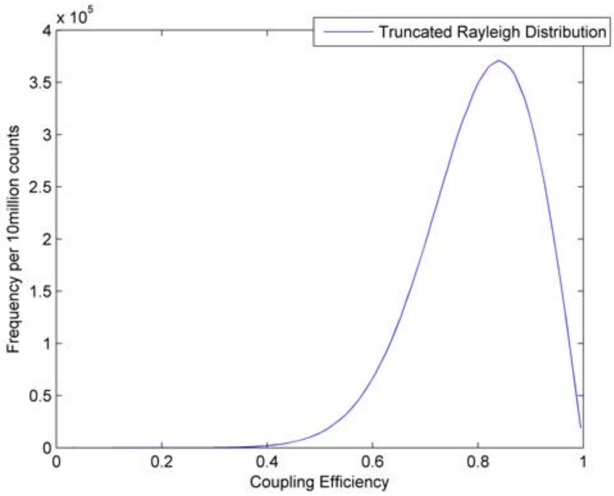

Figure 2 - Rayleigh distribution used to simulate 80% coupling efficiency.

2.5 Modelling the Inspection Process – Estimating Signal Amplitudes

To achieve both reliable prediction of amplitudes and computational efficiency bespoke models have been developed based upon well established and validated algorithms.

Two semi-analytic methods have been developed to predict echo amplitude based upon the Geometric Theory of Diffraction (GTD) [4] and Kirchhoff Elastodynamic (KED) theory [5] (KED). The inspection model could also treat 'corner trap' response of inner surface breaking defects using a modified version of the Kirchoff Elastodynamic Theory algorithm by use of a lookup table containing data generated by running British Energy's Corkirch model.

2.6 Description of PoDMOD

PoDMOD utilises a MATLAB platform that allows the model to be configurable at runtime to treat a variable number of scans and different defect orientations. A schematic of the operation of PoDMOD can be seen in Figure 3.

The algorithm in PoDMOD firstly establishes a fixed defect population that is stored in a matrix. When the code is run, the amplitudes of all beams incident upon a particular 'defect realisation' are calculated but with only the maximum amplitude is stored. At the end of the model runs, the matrix is then analyzed to determine whether the maximum amplitude for a particular defect realisation equates to a 'detection'. From this information the proportion of the overall defect set that has been detected provides information both on global PoD and also PoD at locations within the inspection volume.

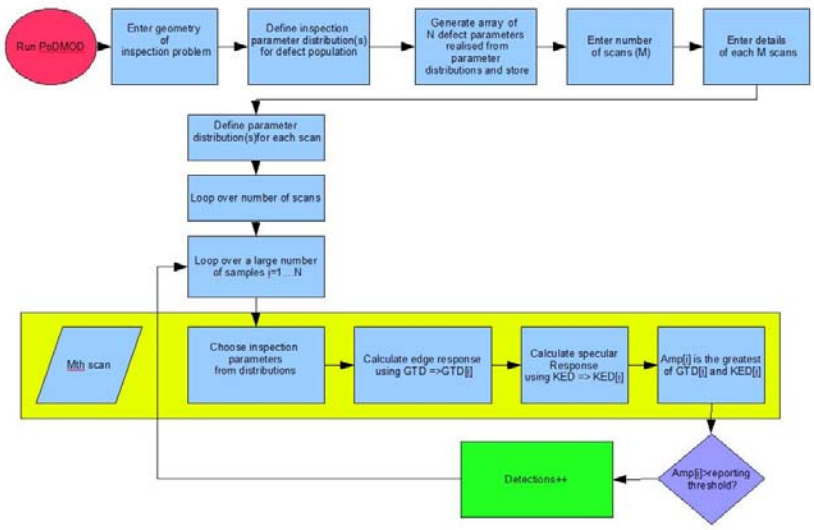

Figure 3 – Schematic diagram of the operation of the PoDMOD model.

Storing only the maximum amplitude at each location avoids possible 'double counting' which may occur when several beams result in responses exceeding the reporting threshold for a single defect realisation. If this is not taken into account then there is the potential to produce an optimistically high estimate of PoD in situations where there are redundant beams. Note this means that the matrix ends up containing a result for a specific flaw size.

An interesting feature of the Monte-Carlo approach is that PoD variation can be assessed as a function of defect size but also any other or inspection parameter such as tilt or skew.

3. PoDMOD Case Study

The selected case was a previously qualified automated ultrasonic inspection of a typical small pressurized water reactor (PWR) component. The inspection system and personnel had already been successfully validated in accordance with the ENIQ EQMD [1] and the PoD analysis has been based upon the documentation contained within the qualification dossier (Inspection Procedure [IP] and Technical Justification [TJ]).

3.1 Overview of Inspection Situation

3.1.1 Description of Weld Geometry

The component of interest is the ferritic attachment weld joining a nozzle to a large attachment pressure vessel (PV) on a typical small pressurized water reactor (PWR). The component is a cylindrical section tube in the region of the weld and the locations from which the inspection is performed. The dimensions are typical of an example plant item.

The fusion faces of the weld are 30˚ and 0˚. The base material is fine-grained ferritic forging and the weld is fine-grained ferritic material deposited by manual-metal arc welding. The inside of the PV and nozzle are unclad.

3.1.2 Validation Defect Description

The validation defect is defined as having a through-wall extent of 10mm and a length of 20mm. Defects are anticipated to be smooth, planar (buried:elliptical and surface breaking:semi-elliptical) and orientated circumferentially and aligned with the weld fusion boundaries.

Defect tilt is taken to be within 5˚ of the fusion boundaries for the circumferential defect (that is 30˚±5˚ or ±5˚).

Credible skew angles are bounded at ±5˚.

3.1.3 Inspection System Description

A range of transducers and beam angles were raster scanned along the weld axis with automated data collection – Figure 4.

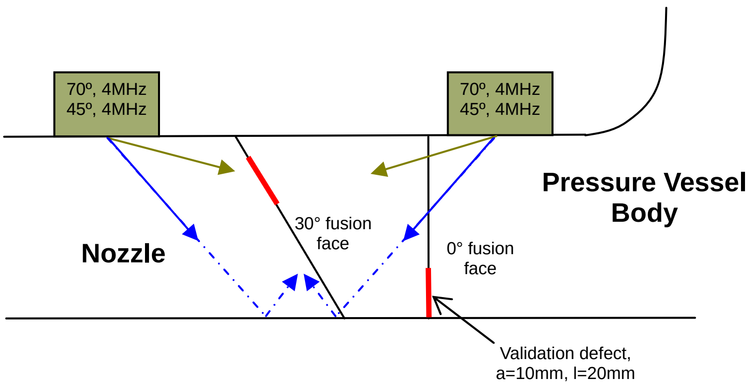

Figure 4 – General inspection configuration (axial beams)

Sensitivity for the inspections was set as follows: 100% Distance Amplitude Correction (DAC) is for an echo from a 4.8mm side drilled hole (SDH). An additional 6dB is added to account for variations in coupling efficiency.

The reporting thresholds for the 45° and 70° shear wave transducers were 20% DAC and 14%DAC, respectively.

4. PoD Modelling Performed

A series of PoD calculations has been performed using PoDMOD based upon the inspection situation described above. In each case the defect is treated as being in the transducers' far field for simplicity. All transducers are scanned in pulse-echo mode in a single line that passes directly over the centre of the defect and in the same plane as the normal to the defect surface. This is reasonable based upon the 'real' inspection was automated and rastered over the defect on a fine pitch.

For the inspection situation under consideration there are a significant number of Influential/Essential Parameters. For the illustration presented here, the study has been limited to: defect orientation parameters (skew and tilt); probe beam angle; calibration errors and coupling variation.

The 'random' effect of the variation in probe coupling was simulated using a truncated Rayleigh distribution. All other parameters were assigned truncated normal distributions about their nominal values.

5. Modelling Results

Results for the complete qualified inspection system demonstrated high capability (100% PoD) for all validation defects within the original inspection scope. This was in line with expectation for a successfully 'qualified' inspection system where very high PoD is expected. No results are presented for this case.

However, the inspection requirement is delivered using a series of scans designed to supply capability for different portions of the inspection volume. To illustrate the manner in which the overall inspection capability is built up from the individual scans and elements of the expected scattered responses PoD results are presented for a validation defect on the inclined fusion face – Figures 5 and 6.

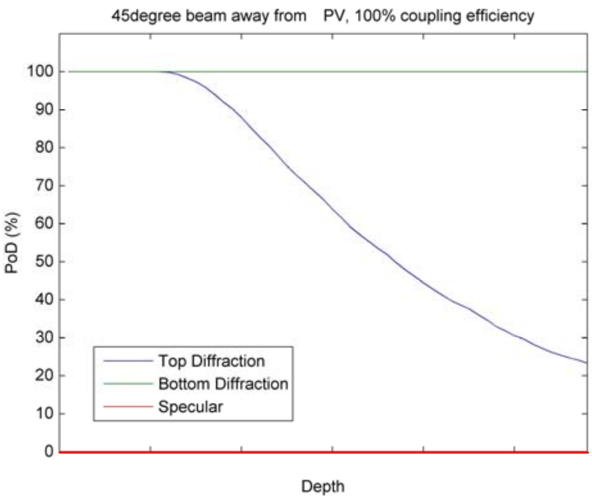

Figure 5 – PoD vs. Depth plot (specular and edge signals) of a validation defect via 45° half-skip beam firing away from PV.

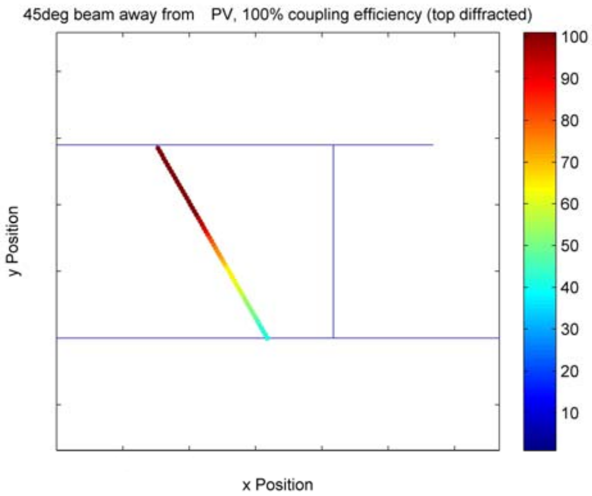

Figure 6 – Geometry plot showing PoD (top edge diffracted signal) of a validation defect via 45º half-skip beam firing away from PV.

5.1 Random effects – Coupling Efficiency

Figures 7 and 8 show the predicted effect of coupling efficiency variations which has been modelled through making realisations from a Rayleigh distribution and DAC calibration errors which are modelled by a truncated normal distribution. The overall effect is to reduce the expected probability of detection. This happens because while the DAC error function is distributed symmetrically about zero, the coupling efficiency will always be ≤100%.

It can be seen that the prediction of high reliability detection is robust against moderate changes in coupling efficiency (80% mean value), but that more extreme variations (60% mean value) start to have more significant reliability consequences. This can be seen quite clearly in the effect of 60% coupling efficiency on the combined qualified system. Whilst initially the inspection system performance gives 100% PoD and highly reliable inspection this is seriously degraded if realistic variations in probe coupling are proposed.

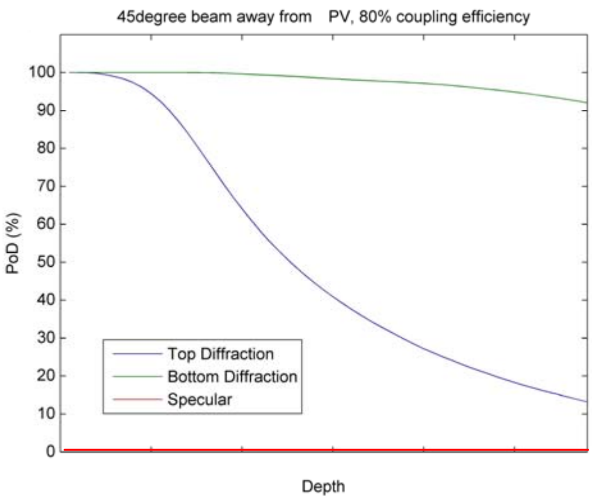

Figure 7 – PoD vs. Depth plot (specular and edge signals) of a validation defect via 45º half-skip beam firing away from PV – 80 % coupling efficiency.

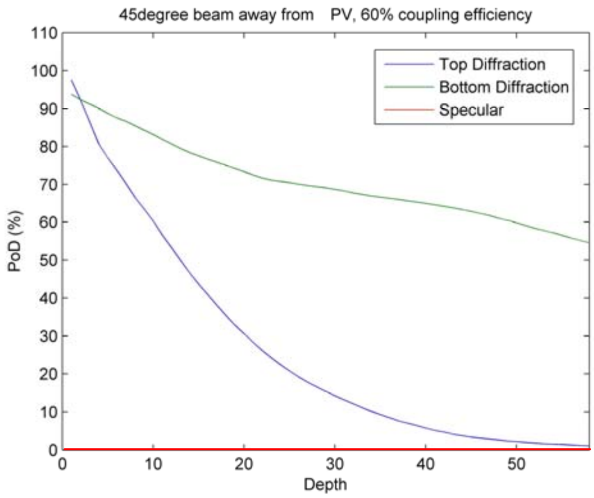

Figure 8 – PoD vs. Depth plot (specular and edge signals) of a validation defect via 45º half-skip beam firing away from PV – 60 % coupling efficiency.

6. Discussion

The results generated via the use of Monte-Carlo simulation of the Essential Parameters embodied in the probabilistic qualification tool PoDMOD have essentially been generated from ‘first principles’ with no predetermination of the shape of the curves or the values of PoD. The results themselves are in accord with experience, exhibiting the expected form and characteristics, and this provides a level of qualitative validation.

An important feature of the Monte-Carlo approach is that it relies directly on the established ENIQ principle of the Essential Parameters that is embodied in the ENIQ qualification process and hence circumvents much of the subjectivity of other alternative approaches to PoD. Despite this there is still a degree of judgement required in the selection of robust credible distributions for input into the analysis.

In the present study the distributions have been generated from information contained in the qualification dossier (inspection procedure and technical justification) by staff with considerable experience in qualification and NDT. Considering the generic application of PoDMOD in qualification it could be foreseen that the derivation of the distributions could be performed once the TJ has been accepted by the Qualification Body (or even in parallel) and undertaken as an expert elicitation involving the Qualification Body, the Inspection Development Team plus other experts as appropriate.

At present it is acknowledged that there are limitations in terms of the ability of PoDMOD to simulate all aspects of the inspection situation. Firstly, it does not consider the whole of the data interpretation process. Currently, successful detection is defined as a signal exceeding the reporting threshold. However, recognising a significant signal is only the first stage in the data analysis process, to get a full picture it will be necessary to extend this to consider the reliability of the subsequent sizing and characterisation. This is important and would need to be addressed in further versions of PoDMOD.

Although PoDMOD and the Monte-Carlo approach have been developed with the purpose of generating quantitative PoD data the method has other benefits. The Monte-Carlo/Essential Parameter facilitates an alternative approach to ENIQ style inspection qualification. It is possible to perform sensitivity studies on possible variations to the Essential Parameters and also to investigate the influence of so called 'worst case' defects having high levels of misorientation. These are currently the focus of much effort during qualification yet are potentially highly unlikely. Using the Monte-Carlo approach the real effect of these types of defect on overall PoD could be assessed. Another benefit of PoDMOD is its potential to quantify the redundancy of the inspection system. This arises through the generation of a matrix of all possible defect realisations and the testing of the inspection system on each realisation in turn. It is then possible to record the number of beams that 'detect' each defect and provide a 'redundancy index' indicating the robustness of the inspection system as applied to the defect population.

References

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