SIMULATION SUPPORTED POD: METHODOLOGY AND HFET VALIDATION CASE

F. Jenson[1], E. Iakovleva[1] and N. Dominguez[2]
[1]CEA, LIST, F-91191 Gif-sur-Yvette, France
[2]EADS, Innovation Works Dept., 18 rue Marius Terce, 31025 Toulouse, France

ABSTRACT. Structure reliability guaranty requires prior evaluation of non destructive testing methods. The concept of Probability of Detection (POD) is generally used to quantitatively assess performances and reliability of testing operations. Such probabilistic approaches take into account the uncertainties that appear during inspections and that are responsible for the output variability. POD curve determination is based on costly and time consuming experimental campaigns. Increasing demand of NDT configurations requiring POD evaluation makes cost reduction of POD campaigns a major issue. A new trend is to apply simulation in the context of probabilistic approaches in order to replace some of the experimental data required to determine the POD with simulation results.
This paper presents results of simulation based POD curves of a high frequency eddy current inspection procedure obtained with the new POD module of CIVA. The methodology used for describing uncertainties on the input simulation parameters is described and comparisons with experimental results are presented and discussed.

Keywords: POD**,** Eddy Current Inspection, Model Assisted.
PACS: 43.20.Fn, 43.35.Cg, 43.35.Zc, 43.50.Ed

INTRODUCTION

Inspection reliability is one of the key issues in ensuring safety of critical structural components. Among the various methods dedicated to NDE performance evaluation, probabilistic approaches have been increasingly used. They are based on probabilistic criteria such as the Probability Of Detection (POD) which relates the detectability of a flaw to its size. NDE performance evaluation using Probability of Detection (POD) curves is a meaningful approach and is the rule in aeronautics. The properties of the POD curves are related to the uncertainty sources that impact inspection results. In this approach, it is considered that the NDT operation is a repeatable process submitted to uncertainties. As a consequence a flaw of a given size is associated to a probability of being detected by application of the specified NDT. The determination of such curves is currently empirical. It is thus the result of very costly and time consuming experimental campaigns which are performed in order to match the requirements for consistency of the statistical POD analysis[1].

The current trend is to replace some of the experimental data with simulation results. The concept of Model Assisted POD has been introduced first in the US in 2004

[1] MIL-HDBK-1823 recommendations [3]: at least 60 flawed sites for binary (Hit/Miss) data and at least 40 flawed sites for quantitative data (Signal Response)

through the constitution of the MAPOD working group [1]. A French national funded project called SISTAE started in 2006 [2] on this subject and is now followed by a European funded project called PICASSO. The full-model assisted POD, which we also name simulation-based POD, is a MAPOD approach which uses simulated NDT data as input for evaluation of POD. [5] shows an example of full-model assisted POD on an eddy currents inspection for fatigue cracks in aluminum lap-joints. The terminology simulation-supported POD introduces the possibility of using a combination of experimental and simulated data for estimating POD.

This paper deals with POD evaluation using simulations. It presents a practical implementation of the approach to a High Frequency Eddy currents Testing (HFET) for fatigue cracks detection in Titanium alloys. Comparison with experimental data and POD results are presented, showing good agreement and yielding good hope for the future of this approach.

DESCRIPTION OF THE HFET APPLICATION CASE

As a first trial of running a simulation-based POD campaign we have chosen an NDT configuration meeting the two following criteria:

- Simulation of the NDT configuration is possible with existing tools.
- Experimental data are available for calibration and for POD comparisons.

Selected case description

The main features of the selected application case are the following:

- NDT technique: High Frequency Eddy currents Testing (HFET).
- Probe: absolute pencil probe at 2 MHz.
- Material/geometry: Titanium alloys TA6V / Flat surfaces.
- Defect: fatigue cracks.

The operating procedure is depicted in Figure 1. It is an in-service procedure, the inspections are made manually.

Diagnosis/Thresholds

Lift-off signal phase is set to the X axis. Diagnosis is made on the amplitude of the signal response on the Y channel. Calibration is made on a 1 mm depth x 0.1 mm opening EDM notch of “infinite” length machined in the same material. Gains are set such that the Y signal amplitude on this EDM notch is 100% Full Screen Height (FSH).
The detection threshold is set to 20% FSH considering electronic and structure noises.

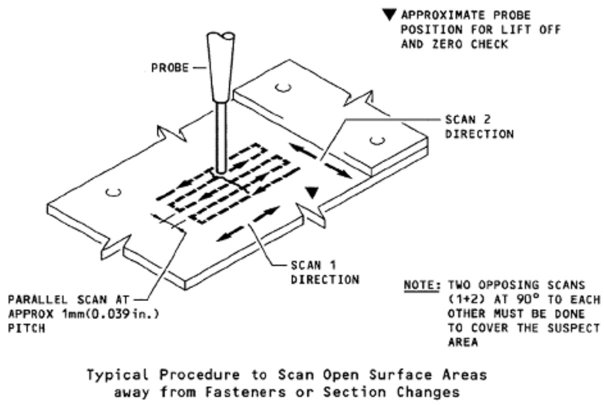


FIGURE 1. HFET scanning procedure.

DESCRIPTION OF THE METHODOLOGY

Selection and description of variability sources

When performing an inspection, the probe signal response due to a flaw is affected by factors related to the NDI system (transducer, scan plan, electronic device), to the part (geometry, material properties, surface roughness) and to the flaw itself (size, shape, orientation, position). Some of these factors or inputs may be seen as uncertain if there is insufficient knowledge related to them, if they are not well controlled during the inspection or if they imply physical phenomena with inherent randomness.

The first step consists in identifying the parameters which are susceptible of being sources of variability in the NDT results. Once identified, a statistical description of each uncertain input parameter must be done in order to feed the NDT computation code. In order to manage this step, a questionnaire has been proposed to a panel of "experts" who are used to practice the particular NDT. For our HFET application case, four parameters have been identified as strongly influent on the signal amplitude response:

- Start scan position in the incremental direction
- Scanning increment (manual operation)
- Crack height (fatigue cracks)
- Angle of the probe (pencil-probe)

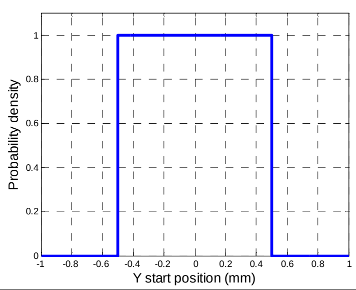
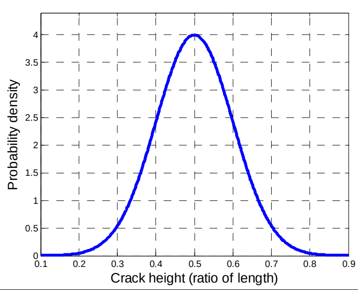
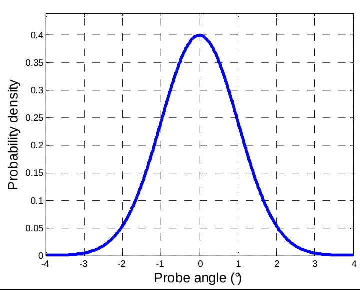
An additional flaw related parameter has been considered in a second step: the occurrence of electrical contacts which are randomly positioned on the crack surface.

Other parameters were first identified (e.g. conductivity, lift-off) but a deeper analysis showed that their potential variations were very well compensated by the application of the procedure (balance and lift-off phase settings) and were of negligible influence on the signal amplitude response.

Expert's interviews lead to statistical description of each influent uncertain parameter. The distributions used as inputs for the simulation study are described in Table 1.

It should be noted that start scan position and scanning increment uncertainties are taken into account thru the start position in the incremental scan direction. Since nominal scan increment is 1 mm, a uniform distribution between two scan path [-0.5mm;0.5mm] has been considered to model the probe position uncertainty.

TABLE 1. Description of uncertainties on a selection of input parameters.

Start scan position	**Crack height (mm)**	**Angle of the probe (°)**
Uniform in [-0.5;05] (scan increment=1mm)	Gaussian with dependency to the crack length (fatigue crack) 0.5*length +$\mathcal{N}$(0,1)*0.1*length	Gaussian(0°;1°)
		

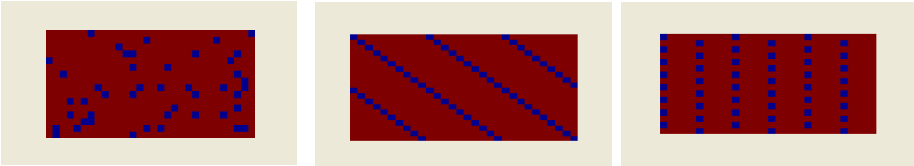


FIGURE 2. Illustration of the three possible electrical bridge descriptions in the software. The filling rate is the only input parameter that is user defined.

Investigated cracks are fatigue cracks known to be of semi-elliptic profile with, in average, a height of half the length of the crack. A Gaussian distribution centered on this value with a standard deviation of 20% the average height has been considered. The probe angle tilt has been affected a Gaussian distribution centered on the nominal angle with a standard deviation of 1°. The 1° standard deviation may be seen as a very small value but it appeared that applying the setting procedure, a small tilt angle on the probe yielded an obvious displacement of the spot on the X axis of the impedance plane, which is easily identified and corrected by the operator.

To account for the “non-ideal” nature of fatigue cracks we have considered that a certain amount of electrical contacts exist along the crack surface. Three different possibilities are proposed in the software CIVA to describe electrical contacts on the crack surface. These possibilities are described in the Figure 2. Here, we described the contacts in a random way (see Figure 2 on the left). The filling rate has been taken as increasing in average and variance with the crack length (re-closing crack phenomenon).

Uncertainty propagation step and determination of the POD curve

Once the statistical distributions for uncertain input parameters are determined, the NDT simulation tool must be fed with this new type of input data. This is done using dedicated tools that have been implemented in CIVA for POD analyses. The characteristic defect feature (e.g. crack length) against which the POD curve will be plotted must also be selected and described. The GUI panels are shown in the Figure 3.

Simulated data are then computed following a simple Monte Carlo approach and the value of interest for each result is extracted in accordance to specific settings (i.e. the quantity to be considered plus, for instance, phase shift and gains to apply automatically to all data). Monte Carlo is a sampling method that consists in randomly generating values for the uncertain entry parameters according to the statistical distributions selected by the user. Then, the model is computed for each n-tuples of values of the uncertain inputs (in the case where n unknown inputs have been selected by the user). Practically, for each flaw size a set of values for the entry parameters is fixed.

In a final step, the POD curve is computed based on the Berens maximum likelihood estimation technique [6] implemented and validated by EADS IW for Hit/Miss and censored Signal Response data (see Figure 4).

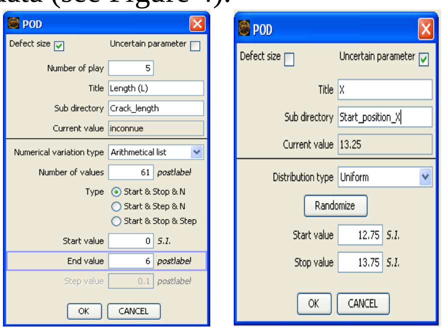


FIGURE 3. Panels for parameter variations in a POD analysis. **Left:** Characteristic defect size, **right:** Uncertain parameter.

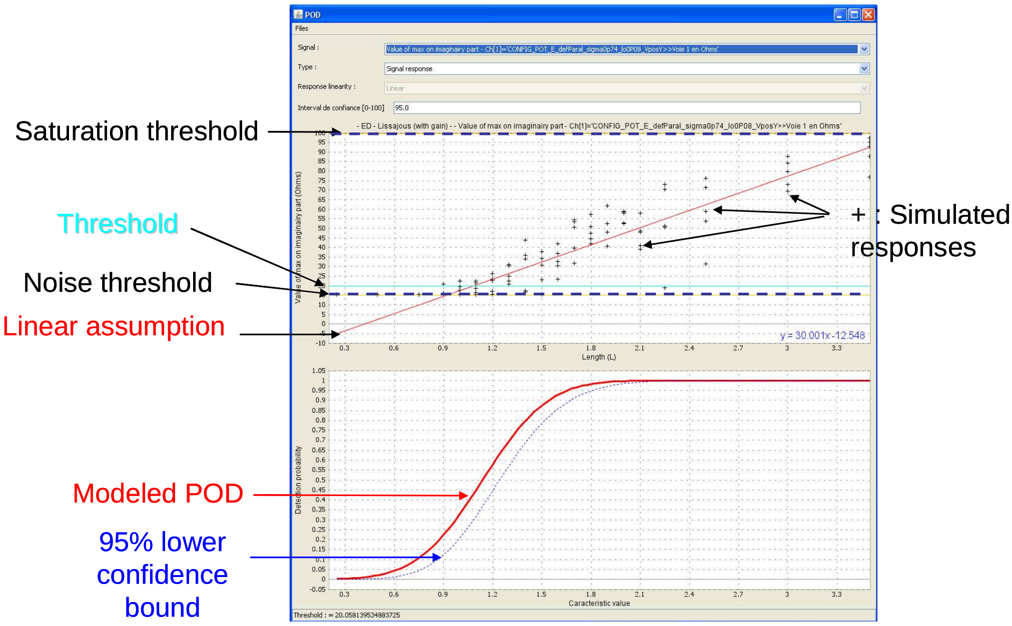


FIGURE 4. CIVA result panel for Signal Response analysis and corresponding POD.

The general scheme of the approach is proposed in Figure 5. The underlined blue parameter is the characteristic parameter of the POD study (the quantity to plot the POD against); typically the crack length. Red parameters are parameters which have been identified as potential sources of uncertainties, considering the NDT procedure, operational conditions, the type of investigated defect, the material…

SIMULATION-BASED POD RESULTS & COMPARISON WITH EXPERIMENTAL POD

The methodology presented above has been applied to the HFET application case. Signal results as well as POD results are compared in this paragraph to the available experimental data.

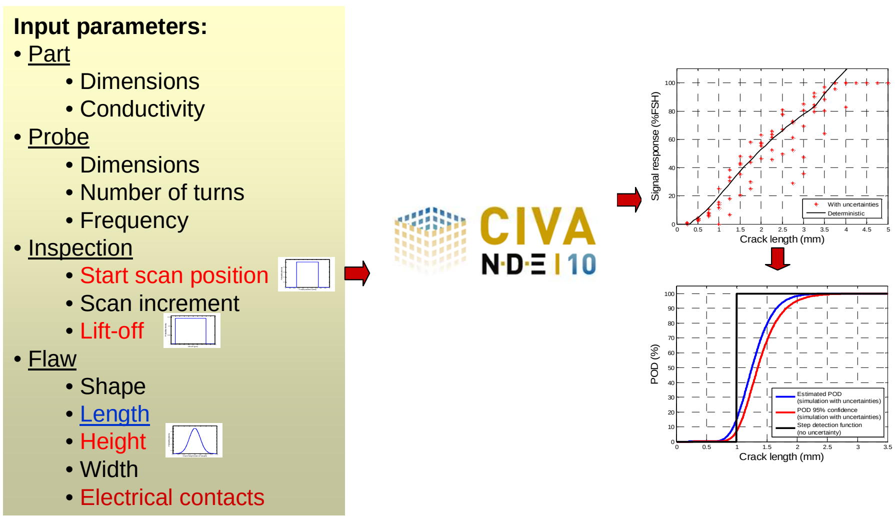


FIGURE 5. General scheme for uncertainties propagation through CIVA for simulation-based POD evaluation (example on ET).

Signal response data analysis

Figure 6 presents signal response results of the experimental campaign, the simulation with uncertainties campaign and the deterministic simulation study. Two simulated datasets have been tried. The difference between the two is the presence or not of electrical bridges on the crack. It is first noticeable that good agreement between experimental and simulated signal amplitude data is observed in the [0mm; 4mm] range. In particular detection and saturation thresholds are passed through at very close crack lengths in experimental and simulated datasets, as depicted in Figure 6. The only data feature that is not represented on the simulated data when no electrical bridges are taken into account is the relatively high scatter of data above 4 mm. One hypothesis for this experimental scatter may be due to the complex crack shapes with possible electrical contacts between the two sides of the crack aperture, then lowering the signal amplitude response of the HFET. When electrical contacts are taken into account (plot on the right in the figure 6), the high scatter of data above 4 mm is better reproduced. In the crack length range of highly increasing detection (between 1mm and 3mm), signal amplitude and scattering agreement are both very good.

Experimental signal response data do not allow for proper signal response POD computation since experimental data in the « noise threshold to detection threshold » have not been reported. Consequently, data have been converted into Hit/Miss (binary) data for POD estimation and comparison. The estimated POD curves are shown in Figure 7.

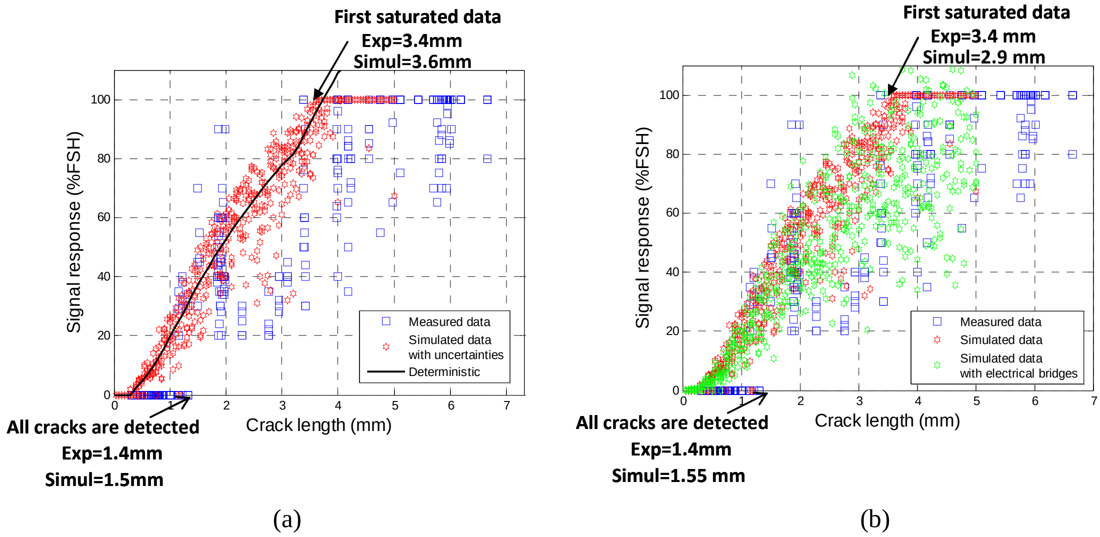


FIGURE 6. Signal Response analysis: comparison simulation – experimental.
(a) Dataset with 600 simulation results without electrical bridges, (b) Simulated dataset with electrical bridges.

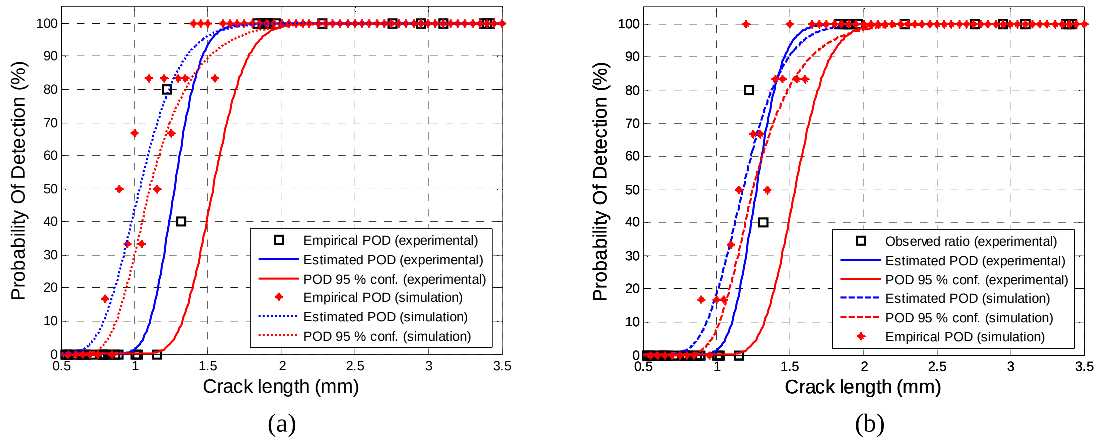


FIGURE 7. Comparison of experimental and simulation-based POD. (a) Simulated dataset with 600 points and no electrical bridges on the cracks, (b) Simulated dataset with electrical bridges.

POD curves analysis

Plots in Figure 7 show that the steep slope area of the experimental POD curve is located in the 1 to 1.6 mm range. The steep slope area of the simulated POD curve is located in the 0.6 to 1.6 mm when no electrical contacts are included in the study and in the 0.8 to 1.7 mm range when electrical contacts are included in the simulation campaign. The simulated crack length range of strong POD variation is thus very close to the experimental one in the latter case. This is one of the main features we wanted to validate in this study.

It is worth pointing out that the "shape" of the simulated POD curve is strongly dependent on the amount of uncertainty introduced in the simulations. A very low level of uncertainty would yield a step-like POD curve while increasing this level of uncertainty tends to decrease the slope of the rising part of the POD curve.

The confidence bound is closer to the estimated POD for the simulation case because a larger dataset was used than in the experimental case. The total number of simulated inspections used for the POD analyses is 600 (100 crack length, 6 data per length), while it is 345 for the experimental study (69 cracks, 5 data per site). For such dataset sizes the sampling errors are still not negligible and the smaller the dataset, the poorer the confidence. Hence, estimation with confidence is still meaningful for the present simulation-based POD estimation.

For the first simulated dataset (see figure 6(a)) the simulated POD curve differs somehow from the experimental POD curve. The slope is smoother, but the values of interest are nevertheless very close to the experimental ones:

$$\begin{cases} a_{90}^{\exp} = 1.5mm \\ a_{90/95}^{\exp} = 1.8mm \end{cases}, \qquad \begin{cases} a_{90}^{simul,600} = 1.4mm \\ a_{90/95}^{simul,600} = 1.6mm \end{cases}$$

For the second simulated dataset (see figure 6(b)) the slope is corrected and is closer to the experimental POD curve slope than previously. The values of interest are very similar to the experimental ones:

$$\begin{cases} a_{90}^{\exp} = 1.5mm \\ a_{90/95}^{\exp} = 1.8mm \end{cases}, \qquad \begin{cases} a_{90}^{simu,EC} = 1.5mm \\ a_{90/95}^{simu,EC} = 1.7mm \end{cases}$$

What is finally important for aeronautics use is to observe that values at 90% POD, reflecting the defect size which is almost always detected, is well predicted using simulation data. This result validates the simulation-based POD approach for this particular NDT configuration and strengthens the confidence into the previously obtained experimental POD.

CONCLUSION

Simulation-based POD curves have been determined and compared to experimental POD curves for an application case consisting of High Frequency Eddy Currents Testing of fatigue cracks in flat Titanium parts. The simulation results have been obtained using the POD module proposed in the latest release of the CIVA software (CIVA 10) and the methodology of uncertainty management implemented by EADS and CEA in the SISTAE project. Simulation-based POD results are in very good agreement with experimental POD for this simple configuration. It is shown that by taking into account a limited number of variability sources (start scan position, crack high, probe angle and electrical contacts on cracks), a simulation-based POD curve with features very similar to the experimental curve is obtained. From this first successful attempt, the basic methodology and principle is considered with confidence. Hence more challenging NDT configurations are now ready to be considered for increasing confidence on the approach and move towards a well accepted practice for NDT reliability demonstration.

ACKNOWLEDGMENTS

The authors would like to thank the experts who have participated to the definition of the uncertain parameters (L. Fontaine and P. Métayer from Airbus, D. Simonet from EADS IW).

REFERENCES

1. Model Assisted POD working group, http://www.cnde.iastate.edu/MAPOD
2. F. Jenson, H. Ammari, A. Rouhan, N. Dominguez, F. Foucher, A. Lebrun and J. Moysan, "The SISTAE project: Simulation and Statistics for Non Destructive Evaluation", *4th European-American Workshop on Reliability of NDE*
3. USA Department of Defense Handbook, *MIL-HDBK-1823*, NDE system reliability assessment, April 2009
4. J. S. Knopp, J. C. Aldrin, E. A. Lindgren, and C. Annis, "Investigation of a Model-Assisted Approach to POD Evaluation", *in Review of Progress in Quantitative Nondestructive Evaluation*, vol. 26, 2007
5. R.B. Thompson, "A unified approach to the Model-Assisted Determination of Probability of Detection", *Materials Evaluation*, **66**, n°6, June 2008
6. A.P. Berens, "NDE Reliability Data Analysis", *ASM Metals Handbook*, Volume 17, 9th Edition: Nondestructive Evaluation and Quality Control, ASM International, Materials Park, Ohio, pp. 689-701, (1988).