SIMULATION ASSISTED POD OF A HIGH FREQUENCY EDDY CURRENTS INSPECTION PROCEDURE

N. Dominguez[1], F. Jenson[2]

[1] European Aeronautic Defense and Space Company (EADS), Innovation Works Dept., 18 rue Marius Terce, 31025 Toulouse, France
[2] CEA, LIST, F-91191 Gif-sur-Yvette, 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. High costs of POD campaigns combined with continuous increase in configurations needing POD determination make cost reduction of POD campaigns a major issue. Development and maturity of NDT modelling tools is today a credible prospect for low cost NDT data generation useable in the context of POD studies.
This paper presents first results of simulation assisted POD 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.

Introduction

Structure reliability is a major care in air transportation. It is ensured by application of NDT in accordance to maintenance manuals defined by the aircraft design. Hence NDT performances must be evaluated in order to ensure the desired level of safety. Probability of Detection (POD) evaluation is a meaningful approach to do so and is the rule in aeronautics. It considers 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. This probability integrates as a whole the sources of uncertainties, from the material, the structure, the defect or the NDT itself.
Traditionally POD data are the result of expensive and long experimental campaigns in order to match the requirements for consistency of the statistical POD analysis[1]. To this respect the use of models and/or simulations is seen as a great prospect to make POD evaluation more affordable. The concept of Model Assisted POD has been introduced first in the US in 2004 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. In the model assisted POD, two approaches are usually distinguished. The transfer function approach which consists in using POD data from a configuration A and apply it to a configuration B which is a cousin of A via application of a transfer function mapping data from A to B. The full model POD, which we also name simulation-based POD, uses simulated NDT data as input for evaluation of POD. Most of the reported works concern the transfer function approach [1-3], but [3] also shows an example of full-model assisted POD on an eddy currents inspection for fatigue cracks in aluminium lap-joints. This paper deals with simulation-based POD evaluation. It presents a practical implementation of the approach to a High Frequency Eddy currents Testing (HFET) for fatigue cracks detection in Titanium alloys.

[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)

Comparison with experimental data and POD results are presented, showing good agreement and yielding good hope for the future of this approach.

1. HFET case description

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:

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

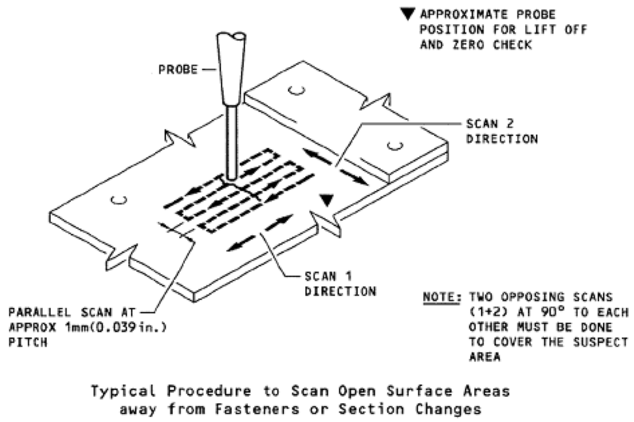


Figure 1: HFET scanning procedure

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.

2. Methodology for POD evaluation using simulation

The POD quantifies the ability of an NDT procedure for detection of defects of given sizes. The essence of the probabilistic approach is to consider that the operated NDT is subject to uncertainties which are the cause of scattering in NDT results and diagnoses. Uncertainties may be due to the NDT itself or to environmental factors such that "secondary" defect features, material properties scattering…

In order to be as representative as possible of the reality of the operated NDT, simulation-based POD approaches must integrate uncertainties description in the computation process.

In the absence of uncertainties in the simulation process, the simulated signal response is a deterministic function of the defect size, which depends on the physics of the considered NDT. However this deterministic relation cannot be regarded as fully representative of the reality of the operated NDT since it does not account for the sources of scattering in the results. Here is the fundamental difference between a lab sensitivity study and a POD study.

Practically, accountancy for uncertainties in the NDT simulation process can be done by

- identifying input parameters of the software as "uncertain"
- characterizing the statistics of each uncertain parameter
- running the simulation software with a set of input parameter values picked up following the described statistics
- Applying diagnosis rules on each simulation result, possibly with uncertainty on this latter step also

Figure 2 presents a schematic view of NDT simulation including uncertainties for simulation-based POD evaluations.

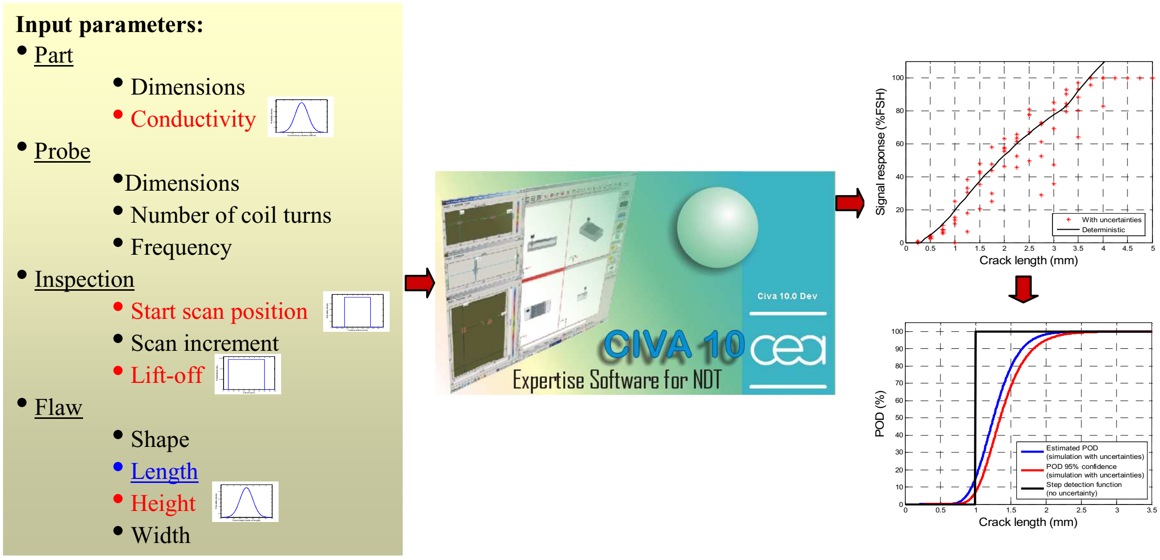


Figure 2: General scheme for uncertainties propagation through CIVA for simulation-based POD evaluation (example on ET)

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…

3. Statistical description of influent NDT parameters

As mentioned above, the first step consists in identifying the parameters which are susceptible of being sources of uncertainties in the NDT results. Once identified, a statistical description of each uncertain parameter must be done in order to feed the NDT computation code.

Identification:

Identification of uncertain parameters and statistical description is strongly related to the operated NDT (procedure, operational conditions, defect type, material…). 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 the HFET on titanium case described in paragraph 1, 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)

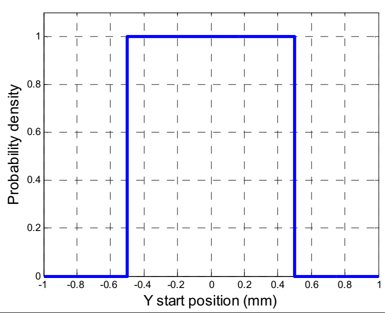
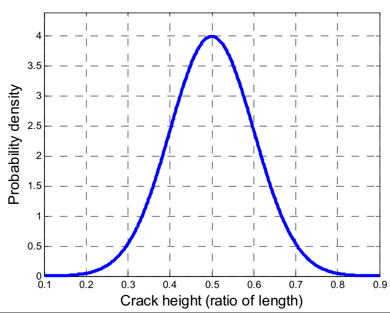
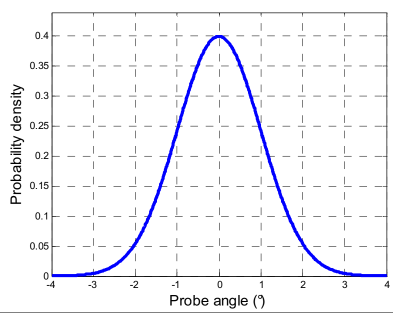
At the first glance more parameters were identified (e.g. conductivity, lift-off) but a deeper analysis showed that their potential variations were very well compensated by the application of the procedure (balance and lift-off phase settings) and was of no influence on the signal amplitude response.
Moreover the “start scan position in the incremental direction” and the “scanning increment” can be put together under only one uncertain parameter which represents the spatial position of the probe for recording of the maximum amplitude signal. Therefore in the following the scanning increment variation will be dropped.

Statistical description:

Expert’s interviews lead to statistical description of each influent uncertain parameter. The questions for each parameter are about:

- Range of possible values
- Shape of the statistical law (symmetrical or not)
- Statistical law (uniform, Gaussian, log-normal, triangular, Rayleigh, …)
- Mean value (most probable value, 50%-quantile if necessary)
- Deviation from most probable value
- Dependency with another parameter

The technique used to choose among possible statistical distributions is the maximum entropy principle which claims that in case of doubt it is better to say nothing (uniform distribution) than to say wrong things (too specific distribution). More precisely, entropy of the distributions mentioned above is easily computed and provides quantitative values for decision.
We end-up with the following distributions:

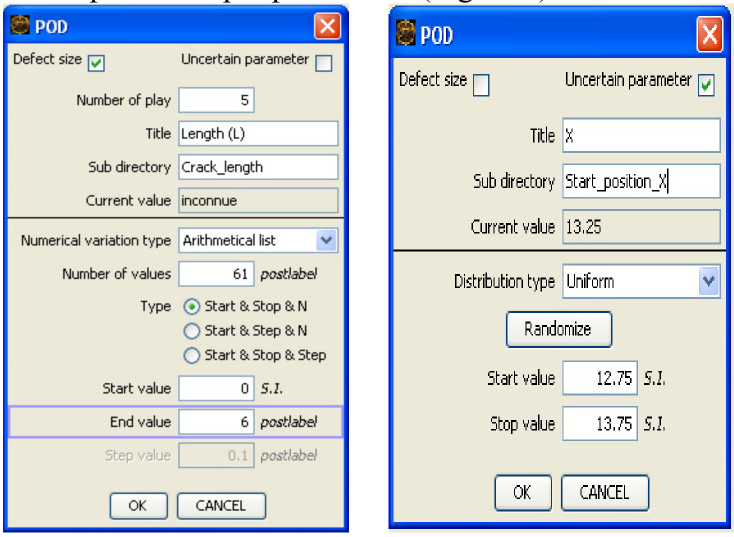
Start scan position	Crack height (mm)	Angle of the probe (°)
Uniform in [-0.5;05] (scan increment=1mm)	Gaussian with dependency to the crack length (fatigue crack) 0.5*length +$\mathcal{N}$(0,1)*0.1*length	Gaussian(0°;1°)
		

- The start position in the incremental scan direction amalgamates the start scan position and the scanning increment uncertainties. 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.
- 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 seem very small 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, then easily identified and corrected by the operator.

4. Running simulations for POD analysis with CIVA

Once statistical distributions for uncertain input parameters characterized, the NDT simulation tool must be fed with this new type of input data. To do so the following tools have been implemented in CIVA for POD analyses:

- Definition of values taken by the characteristic defect feature (e.g. crack length)
- Statistical description of input parameters (Figure 3)



(a) (b)

Figure 3: Panels for parameter variations in view of POD analysis. (a) characteristic defect size, (b) Uncertain parameter

- Setting of automatic data extraction: quantity to be considered plus, for instance, phase shift and gains to apply automatically to all data
- Computation of POD curves: uses Berens maximum likelihood estimation technique [4,5] for Hit/Miss data and for censored Signal Response data from validated EADS IW sources

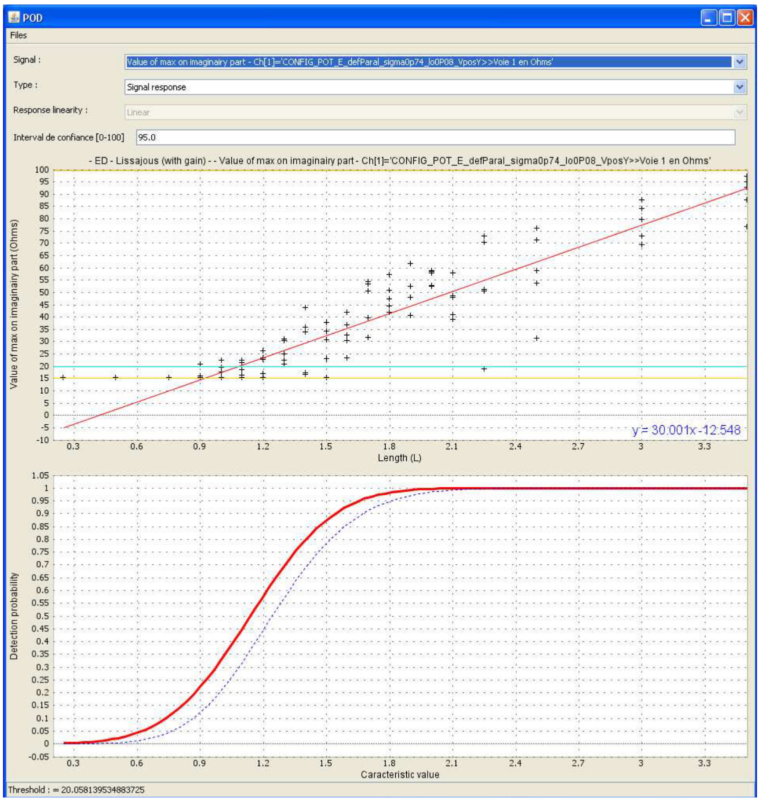


Figure 4: CIVA result panel for Signal Response analysis and corresponding POD

5. Simulation-based POD results & comparison with experimental POD

The methodology presented in paragraph 2 has been applied with the input data of paragraph 3 using the CIVA software POD tools (paragraph 4). Signal results as well as POD results are compared in this paragraph to the available experimental data.

Signal response data analysis:

Figure 5 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 being the number of data (100 data and 600 data respectively), in order to see the effect of this parameter on POD results. 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 on Figure 5. The only data feature that is not represented on the simulated data 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. This phenomenon may be mixed with other highly influent factors for smaller cracks, hence not appearing under 4mm. Anyway in the crack length range of highly increasing detection (between 1mm and 3mm), signal amplitude and scattering agreement are both very good.

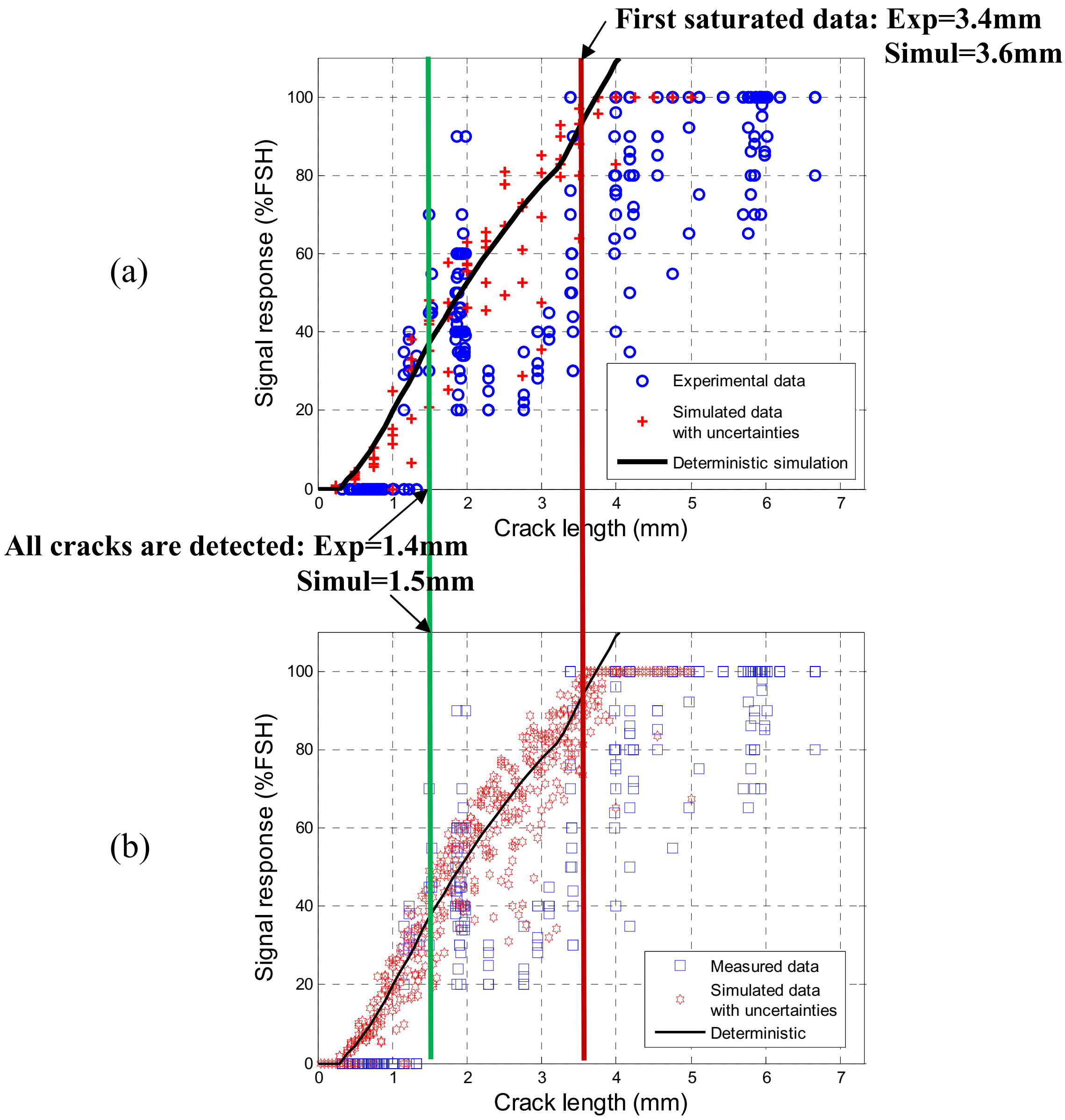


Figure 5: Signal Response analysis: comparison simulation – experimental. (a) Simulated dataset with 100 data, (b) Simulated dataset with 600 data

Figure 5 also gives the opportunity to highlight the importance of considering uncertainties in the simulation process. Even a simple comparison between "nominal" simulations and experiments would be made difficult and could lead to biased conclusions on the adequacy of the model to the experiments without consideration of uncertainties. As for POD analysis using simulation, it becomes mandatory in order to avoid over optimistic results. Indeed, if some uncertainties yield responses symmetrically distributed about the deterministic curve (e.g. crack height), some others systematically decrease the signal amplitude value since their nominal values are actually the best values (e.g. probe position for maximum amplitude recording and tilt angle of the probe), thus decreasing the POD. In other words, some uncertainties just add scatter while others add biased scatters.

POD analysis:

The available experimental data being unsatisfactory for Signal Response POD estimation, Hit/Miss analysis has been carried out.

Figure 6 presents POD results obtained from the experimental dataset and from the two simulation datasets with uncertainties.

(a)

(b)

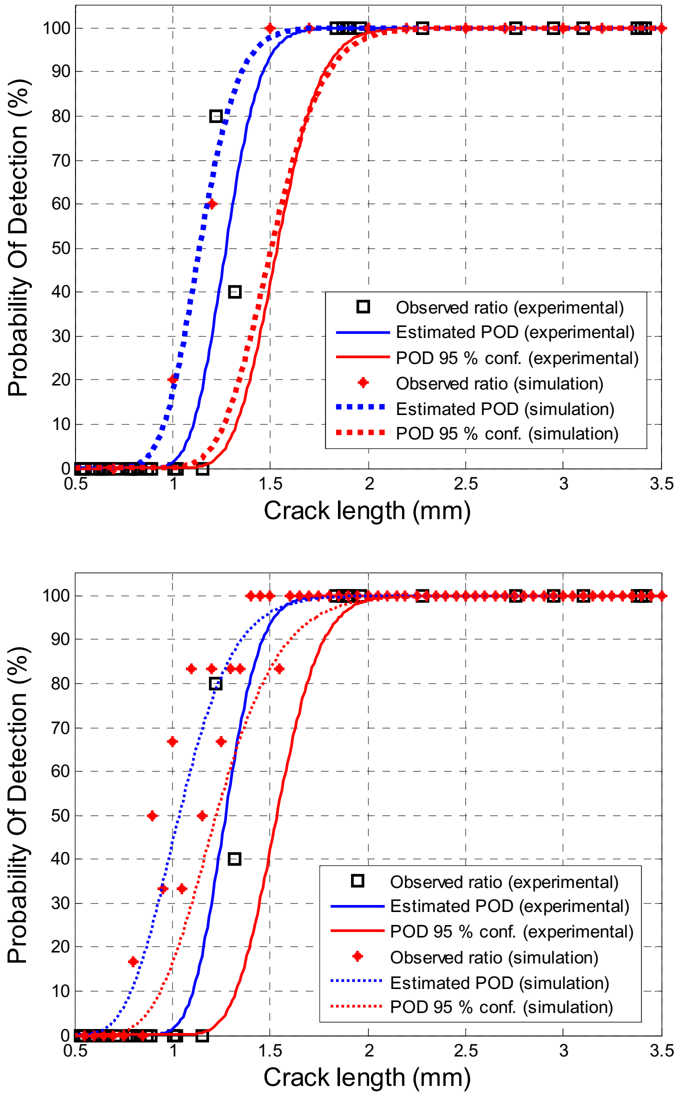


Figure 6: Comparison experimental POD / simulation-based POD.
(a) Simulated dataset with 100 data, (b) Simulated dataset with 600 data

It shows that the steep slope areas of the POD curves are well situated between 1 mm and 2 mm for both simulations and experiments. This is typically the feature we wanted to validate when starting with this study.
For the first simulated dataset (100 data, see Figure 6 (a)) the obtained experimental and simulated POD curves are really similar: they have the same slopes, the confident curves are almost superimposed, and the values of interest are very close:

$$\begin{cases} a_{90}^{\exp} = 1.5mm \\ a_{90/95}^{\exp} = 1.8mm \end{cases}, \begin{cases} a_{90}^{simu,100l} = 1.4mm \\ a_{90/95}^{simul,100} = 1.8mm \end{cases},$$

where a_{90} denotes the crack length that is detected with 90% POD, and $a_{90/95}$ is the a_{90} with 95% confidence.

For the second dataset (600 data, see Figure 6 (b)) the simulated POD curves look a bit different, the slope is smoother, but the values of interest remain very close from the experimental ones:

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

This “aspect” change of simulated POD curves is actually related to the number of data. Indeed by repopulating the defect size range in the highly increasing POD area, the probability of having more “partially detected” defects (red crosses) is increased, and therefore the POD curve aspect in this region is refined (and modified). Instead of two “partially detected” defect sizes in the experimental and in the first simulated dataset, one have twelve such defect sizes in the second simulated dataset.

It is also 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.

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 preserved by increasing the number of data. This result validates the approach of simulation based POD for this NDT configuration and strengthens the confidence into the previously obtained experimental POD.

Notice that estimation with confidence is still meaningful for the present simulation-based POD estimation since the total number of simulated data used for the POD analyses are 100 (20 crack length, 5 data per length) and 600 (100 crack length, 6 data per length) respectively, with 345 experimental data (69 cracks, 5 data per site). For such dataset sizes the sampling errors are not negligible and the smaller the dataset, the poorer the confidence (Figure 6 (a) & (b)). To this respect application of the signal response POD analysis decreases a lot the confidence margin, as depicted on Figure 7.

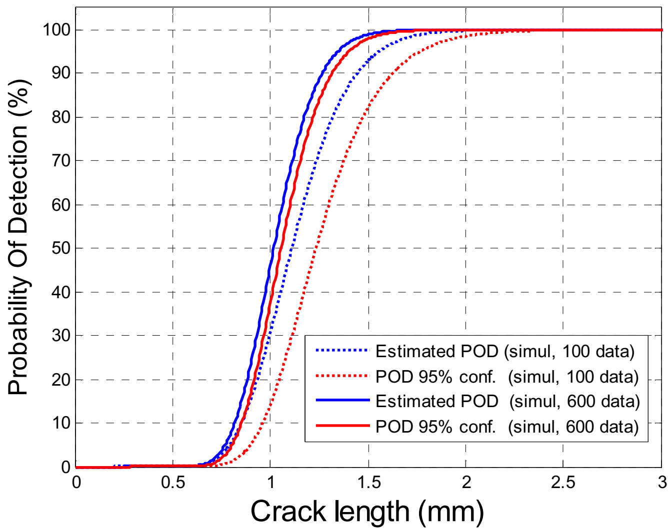


Figure 7: Simulation-based POD with signal response data with 100 data and 600 data

Conclusion

First results of simulation-based POD have been presented on a High Frequency Eddy Currents Testing of fatigue cracks in flat Titanium parts. The results have been obtained using the POD module of the CIVA development version 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. 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.

Acknowledgements

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