Title: IMPLEMENTATION OF A ROBUST METHODOLOGY TO OBTAIN THE PROBABILITY OF DETECTION (POD) CURVES IN NDT: INTEGRATION OF HUMAN AND ERGONOMIC FACTORS

Author: Miguel Reseco Bato – AIRBUS OPERATIONS SAS / ICA, CNRS UMR 5312.
Co-Authors: Anis Hor - Institut Clément Ader (ICA, CNRS UMR 5312) / ISAE-SUPAERO
Aurelien Rautureau – AIRBUS OPERATIONS SAS
Christian Bes - Institut Clément Ader (ICA, CNRS UMR 5312) / UPS
Lecturer: Miguel Reseco Bato – AIRBUS OPERATIONS SAS / ICA, CNRS UMR 5312.

ABSTRACT

The performance assessment of non-destructive testing (NDT) procedures in aeronautics is a key step in the preparation of the aircraft's certification document. Such a demonstration of performance is done through the establishment of Probability of Detection (POD) laws integrating all sources of uncertainty inherent in the implementation of the procedure. These uncertainties are due to human and environmental factors in In-Service maintenance tasks. To establish experimentally these POD curves, it is necessary to have data from a wide range of operator skills, defect types and locations, material types, test protocols, etc. Obtaining these data evidences high costs and significant delays for the aircraft manufacturer.

The scope of this paper is to define a robust methodology of building POD from numerical modeling. The POD robustness is ensured by the integration of the uncertainties through statistical distributions issued from experimental data or engineering judgments. Applications are provided on titanium beta using high frequency eddy currents NDT technique.

First, an experimental database will be created from two environments: laboratory and aircraft. A representative sample of operators, with different certification levels in NDT technique, will be employed. Multiple inspection scenarios will be carried out to analyze these human and environmental factors.

This database is used, subsequently, to build statistical distributions. These distributions are the input data of the simulation models of the inspection. These simulations are implemented with the CIVA software. A POD module, based on the Monte Carlo method, is integrated into this software. This module will be applied to address human and ergonomic influences on POD.

Finally, the POD model will be compared and validated with the experimental results developed.
1. INTRODUCTION

The engineering structural design is based on the implementation of the damage tolerance criteria. This criterion assumes the presence of non-detectable defects during their manufacture and their life-cycle maintenance operations without any safety problem [1,2]. Every structure and its assembly are assured during their In-Service life by a design service goal with correspondence selection material, design and specific calculus to airlines due to their requirements. Aircraft inspections during In-Service life are determined by exhaust calculus by different departments based on NDT methods and materials. Nondestructive test (NDT) is a key step inside each part determining a detection capability to meet the specific requirements. Each NDT method involves multiple application parameters and the resultant to quantify detection capabilities varies with each application.

NDT reliability [3,4] is one of the key issues in ensuring safety of structural components. Nowadays in the aerospace field, this reliability is quantified by estimating the Probability of Detection (POD) which is the probability of detecting a flaw as a function of its size. This assesses the ability of the inspection equipment and the inspector ability to detect defects depending on their size, the probe angle or the inspector scanning. This result is valid in a specific geometry, defect type, inspection system and associated procedure. However, one of the largest sources of performance variation in In-Service inspections can be found in the inspector [5]. The inspector will perform the NDT calibration, the NDT scanning and will interpret the signal response provided by the equipment. Therefore, reliability and human factors are directly linked for a better understanding of NDT inspections [6,7,8]. Moreover, environmental conditions, protective clothing, time stress and organizational structure can affect an inspection and indirectly impact in the reliability of POD Curves [9,10].

For Airbus, the experimental determination of POD Curves is challenging because a large number of test must be carried out in order to determine reliable results. Annis and Gandossi [11], as an approach, recommend using at least 60 target flaws to obtain a robust POD Curve. Each inspection has to be performed by a large number of inspectors that will be quite costly and time consuming. On the other hand, the need of POD data is becoming greater since the use of probabilistic methods for safety justifications is being more widely accepted. In addition, the emergence of new materials, designs, and new NDT techniques may require a robust definition of the POD Curve.

Today, the aerospace industry is trying to replace some of the experimental data with simulated results for estimating POD Curves [12]. Few years ago, in 2004, a new concept “Model Assisted POD” was created through the constitution of the MAPOD working group [13]. Afterwards, a French project called SISTAE started in 2006 [14] in relation with the same topic and subsequently it was followed by an European project called PICASSO [15]. This notion, known as simulation-based POD or MAPOD approach, consists on the use of simulated NDT inspections to build POD Curves.

In this study, the experimental analysis and simulation of the high frequency eddy current control was performed on fatigue cracks to quantify the human and environmental factors using POD curves.
This paper is organized as follows; the 2nd section presents the main statistical concepts used to perform a POD analysis. The 3rd section describes an Airbus POD analysis using high frequency eddy currents on titanium beta. To show the impact of the human and environmental conditions, laboratory and aircraft scenarios are considered as well as different inspector skills and human behavior. The 4th section is dedicated to POD analysis using numerical experiments, where the human and environmental variations are taken into account using random variables. In the 5th section, comparisons between experimental and numerical POD curves are presented. Finally, 6th section draws conclusions and addresses further research works.

2. POD

The probability of detection is used to determine the reliability and the capacity of the inspection equipment to detect defects according to their size. The principle of the inspection method will be the selection of the method to build the POD analysis. In general, there are several possible methods to perform a POD analysis: 29:29-Method, Berens hit miss Method, Berens signal response Method, Berens signal response Method with non-central t-distribution and other methods agreed between the customer and supplier. Berens [3] defines "the probability of detection as the proportion of defect's size that would be detected in a particular NDT inspection". This definition lends to take into account an average estimation of the detection and also a large number of data per size and per inspector. In practice, POD analyst shall select one of the previous mentioned methods [16]. The USA Department of Defense Handbook [17] recommends a POD hit miss or a POD signal response method obtained by parametric regression using the maximum likelihood method [4,18], as a function of the nature of the data. The Berens hit miss method is used for binary control data (flaw detected $\rightarrow$ 1 or flaw not detected $\rightarrow$ 0). This method is mainly used in visual inspection, penetrant test, magnetic particle test or RX test. The Berens signal response method is used for amplitude control data. They contain more information than 1 or 0 (detected the defect or not) and it is mainly used in eddy currents or ultrasounds.

![Figure 1. Defect detection during the High Frequency Eddy Current inspection](image)

In this study, the POD data are amplitude signals, therefore Berens signal response method will be the choice. The flaw characteristics can be correlated with the peak value of the signal from the high frequency eddy currents. Consequently, three areas, in function of the amplitude signal, can be distinguished [19] (see Figure 1):
- First area, small defects in which no significant signal amplitude is shown ($\hat{a} < \hat{a}_{th}$), where, $\hat{a}_{th}$ is the threshold signal to obtain valid data. Usually this threshold signal corresponds to the structure noise threshold ($\hat{a}_{noise}$).

- Second area, $\hat{a}_{th} < \hat{a} < \hat{a}_{sat}$, where $\hat{a}_{sat}$ is the saturation signal and is directly related with the calibration procedure (see Section 3). In this second area, a relationship between the response signal $\hat{a}$ and the media response signal of a crack size $a$ is expressed.

- Third area in which the signal saturates and normally concerns the bigger defects ($\hat{a}_{sat} < \hat{a}$).

Berens signal response method uses, firstly, the statistical analysis for the second area. This statistical analysis uses a linear correlation between the signal inspection response $\hat{a}$ and the real flaw size $a$, and consequently a linear regression as:

$$\hat{a} = \beta_0 + \beta_1 * a + \delta$$

Where, $\beta_0$ and $\beta_1$ are regression parameters and $\delta$ is the error term.

First of all, a model which distributes data in a proper way has to be selected in order to obtain a linear regression. There are 4 possible models; $\hat{a}$ vs $a$, log ($\hat{a}$) vs $a$, $\hat{a}$ vs log ($a$) or log ($\hat{a}$) vs log ($a$). Actually, it is considered that a defect is detected when the signal $\hat{a}$ exceeds the decision value $\hat{a}_{th}$, which enables the definition of the probability of detection as:

$$POD(a) = p(\hat{a} > \hat{a}_{th})$$

From a linear regression hypothesis,

$$POD = \Phi \left( \frac{\beta_0 + \beta_1 * a - \hat{a}_{th}}{\delta} \right)$$

Where, $\Phi$ is a Gaussian law. In this case, a cumulative normal law is applied. Now, $\beta_0$, $\beta_1$ and $\delta$ have to be estimated using the linear regression where the likelihood function $L$ is maximum. The likelihood function $L$ of inspection data is defined as the probability of observing $\{\hat{a}_1, \hat{a}_2, \ldots, \hat{a}_n\}$ when inspecting the defects $\{a_1, a_2, \ldots, a_n\}$ knowing the probability of detection defined above POD. The likelihood function is $L = L_1 * L_2 * L_3$, where:

- For a signal response $\hat{a}$ less than the decision level $\hat{a}_{th}$:

$$L_1 = \prod_{\hat{a} < \hat{a}_{th}} \Phi \left( \frac{\hat{a}_{th} - (\beta_0 + \beta_1 * a)}{\delta} \right)$$

- For a signal response $\hat{a}$ greater than the saturation level $\hat{a}_{sat}$:

$$L_2 = \prod_{\hat{a}_{sat} < \hat{a}} \left( 1 - \Phi \left( \frac{\hat{a}_{sat} - (\beta_0 + \beta_1 * a)}{\delta} \right) \right)$$

- For a signal response $\hat{a}$ ranging from $\hat{a}_{th}$ to $\hat{a}_{sat}$:

$$L_3 = \prod_{\hat{a}_{th} < \hat{a} < \hat{a}_{sat}} \frac{1}{\delta} * \Phi \left( \frac{\hat{a} - (\beta_0 + \beta_1 * a)}{\delta} \right)$$

The next process step aims to obtain $\beta_0$, $\beta_1$, and $\delta$, directly maximizing the likelihood function, by finding the solution to the system of partial differential equations:

$$\frac{\partial \log L}{\partial \beta_0} = 0 \quad ; \quad \frac{\partial \log L}{\partial \beta_1} = 0 \quad ; \quad \frac{\partial \log L}{\partial \delta} = 0$$
After this calculation each parameter obtains a parameter estimator $\beta_0$, $\beta_1$, and $\delta$: $\hat{\beta}_0$, $\hat{\beta}_1$, and $\hat{\delta}$. They are used to plot the function POD (see Figure 2). However, an associate confidential interval through the POD function is missing. To give sense to this confidence with the estimated parameters, it has been agreed to adopt the following terms:

$$\hat{\mu} = \left(\frac{\hat{\beta}_0 - \beta_0}{\beta_1}\right)$$

(5)

$$\hat{\sigma} = \left(\frac{\delta}{\beta_1}\right)$$

(6)

Where,

\(\hat{\mu}\) is the defect size for a 50% of probability of detection

\(\hat{\sigma}\) is inversely proportional to the slope of the linear regression

Finally, POD (at a given confidence level) is a cumulative standard normal distribution $\Phi$ calculated from $\hat{\mu}$ and $\hat{\sigma}$ using the likelihood function. See equation below:

$$POD = \Phi(\hat{x} - h)$$

(7)

Where,

$$\hat{x} = \frac{x - \hat{\mu}}{\hat{\sigma}}$$

(8)

$$h = \left\{\frac{\gamma}{nk_0} \left(1 + \frac{(k_0\hat{\beta}_0 + k_1^2)^2}{(k_0^2 + k_1^2)^2}\right)\right\}^{0.5}$$

(9)

Where,

\(x\) corresponds to the choice of the four possible models \((a \text{ or } log (a))\).

\(\gamma\) is the convergence parameter of the model

\(n\) is the defect size number inspected

\(k_0, k_1\) and \(k_2\) are link to the variance-covariance matrix

To conclude with the process, $\hat{\beta}_0$, $\hat{\beta}_1$, and $\hat{\delta}$ as estimator parameters are already known, obtained by maximum likelihood, they converge asymptotically towards a multivariate normal distribution. The variance-covariance matrix of this process can be obtained from the second partial derivatives of the likelihood function. To obtain $k_0$, $k_1$, and $k_2$ the following relation is used:

$$\begin{bmatrix} k_0 & -k_1 \\ -k_1 & k_2 \end{bmatrix} = \frac{\hat{\sigma}^2}{n} \begin{bmatrix} \text{var}(\hat{\mu}) & \text{covar}(\hat{\mu}, \hat{\sigma}) \\ \text{covar}(\hat{\mu}, \hat{\sigma}) & \text{var}(\hat{\sigma}) \end{bmatrix}^{-1}$$

(10)
In this study, CIVA software is used with the POD module developed by CEA [20] for the statistical analysis during the evaluation of the probability of detection in different scenarios.

3. EXPERIMENTAL POD CURVES

The application of damage tolerance design rules requires assessment of NDT procedure performances. Such performances have to be given under the form of Probability of Detection (POD) to evaluate the reliability of NDT procedures. POD analyses include reproducibility, repeatability and sensitivity to source of uncertainty in the NDT process, including the defect itself. Nowadays, POD is estimated through a statistical analysis of an experimental campaign.

In 2007, Airbus worked in the development of an adequate internal procedure describing the rules to determine an experimental POD Curve for the NDT procedures. This procedure was developed in such a way that it had to be representative of an In-Service procedure focused on every instrument and material. In this paper, we deal with the high frequency eddy currents NDT method. First of all, the procedure provides the standard requirements to inspect surface breaking cracks in different non-ferrous metals/alloys and glare material. Concretely, the experimental NDT procedure is used for the possible damage detection (fatigue surface cracks) in a flat plate made of titanium beta. This inspection is performed using an absolute mono-coil probe as the procedure specifies. This probe is connected directly to the equipment with an accuracy depending directly of each human as a result of being an In-Service inspection. The NDT control system is constituted as follows:

- An eddy current generator capable of operating with an absolute probe at a frequency of 2 MHz.
- An absolute probe of a fixed diameter (Ø 2 mm) with a particular shape for a suitable detection using the procedure.
- A calibration block, used for an accurate measurement of surface crack. The calibration block have certain dimensions and material specifications similar to the inspect area in maintenance. In Airbus standards, the calibration block contains three different types of defects. Each defect consists of an "open" sleeve with three different depths respectively, machined by EDM (Electro Discharged Machining) from titanium beta. The sleeve constitutes an infinite defect.
For this study case, the experimental test will be ran with 70 samples enclosing (or not) surface fatigue cracks, non-crossing thickness of a length ($l_s$) between 1 mm and 7 mm and variable depth. Defects should be as realistic as possible (fatigue defects) and moreover a size distribution should be considered depending on the NDT method and the POD scope. The rule is to provide the majority of defects having a size which is contained between a lower limit (defect size which can be detected with a very low occurrence) and an upper limit (defect size which is a priori considered as always detected). Notice that samples with defects which are never detected and defects which are always detected are also needed. These cracks are characterized with accuracy using microscopy to be sure of inspector detection and measurement.

After identifying the defect size as a function of its surface length, defects are characterized in 60 specimens. Inside the experiment campaign, each sample has different defect type to cover the POD scope except 10 of them, which are free defect to prevent false calls. Probability of false calls (POFC) is a key parameter to take into account as part of reliability in POD Curves [3,4]. In total, NDT inspection experiment is composed by 70 samples.

Seven inspectors carried out the POD study during the experimental campaign. The number of inspectors carrying the tests is an important parameter as reliability is directly linked with the amount of results provided by the inspectors [6,7,8]. Table 1 presents some human performances taken into account for the POD Curve evaluation. The selected human performances are based on criterions analyzed in other studies [22] or psychological recommendations affecting the NDT activity:

- Experience, being one of the most important parameter.
- Their certification level directly implies experience and knowledge on the fundamental parts of the method.
- Their mechanical knowledge implies a better understanding of each NDT inspection process. The marks assigned to each inspector were set up with an internal Airbus survey for this study.
- Right or left handed has an influence in the probe angles due to the view position during the inspection.

The inspector performances with their correspondence marks are described in Table 1.

<table>
<thead>
<tr>
<th>Inspector number</th>
<th>Exp. Years in EC</th>
<th>EC Level</th>
<th>Mechanics Knowledge 0-10</th>
<th>Right / Left handed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inspector 1</td>
<td>5</td>
<td>1</td>
<td>5</td>
<td>R</td>
</tr>
<tr>
<td>Inspector 2</td>
<td>26</td>
<td>2</td>
<td>9</td>
<td>R</td>
</tr>
<tr>
<td>Inspector 3</td>
<td>26</td>
<td>3</td>
<td>9</td>
<td>R</td>
</tr>
<tr>
<td>Inspector 4</td>
<td>10</td>
<td>2</td>
<td>7</td>
<td>R</td>
</tr>
<tr>
<td>Inspector 5</td>
<td>27</td>
<td>2</td>
<td>7</td>
<td>R</td>
</tr>
<tr>
<td>Inspector 6</td>
<td>20</td>
<td>3</td>
<td>7</td>
<td>L</td>
</tr>
<tr>
<td>Inspector 7</td>
<td>13</td>
<td>2</td>
<td>6</td>
<td>R</td>
</tr>
</tbody>
</table>

Table 1. Inspector parameters in High Frequency Eddy Current inspection.

As a matter of fact, In-Service inspections should take into account human and environmental factors to provide reliable POD Curves. Therefore, to reach this objective two inspection scenarios have been established: the first is called the "laboratory scenario" and
the second is called the "aircraft scenario". In the following paragraphs, these two scenarios will be described.

3.1. Laboratory Scenario

This scenario is developed inside of the Airbus Non-destructive laboratory, where all specific inspections are done due to their facilities and the availability of equipment. This way to perform a POD Curve study is so common in the aerospace sector, therefore being the easiest and quickest process. Inspectors begin their inspections sitting down in a chair, with a high degree of comfort, without noise surrounding (laboratory environment) and standard temperature (see Figure 3(a)). Each inspector has to follow the specific procedure, in this case called “HFEC NDT Instruction for TA6V Beta”. This document provides the standard requirements for sample inspections in titanium beta alloy for the POD process.

![Figure 3. Inspector performing a High Frequency Eddy Current inspection in flat plates (a) in laboratory scenario (b) in aircraft scenario](image)

3.2. Aircraft Scenario

Inside Airbus, a specific building stores all structures from dismantled aircrafts or even In-Service aircraft pieces. As a result, a huge number of structures are available to perform any tests and especially non-destructive inspections. In the experimental campaign, the aircraft scenario was developed inside the cargo part of an A321 (Figure 3(b)) with a change in the sample orientation and human position, quite different from the situation in the laboratory.

The experimental campaign consists in gripping each sample inside the aircraft, concretely in some different frames of the aircraft cargo side, to change their accessibility and specially their comfortable human position. Additionally, inspectors carried the equipment and they were obliged to change their position every singular sample to continue the inspection. This specific place was chosen from different inspector feedbacks with different experience in In-Service inspections.

3.3. Experimental POD Curves

In this section, POD Curve development is described step by step. The POD programmer manager has to follow carefully this process to build an accurate POD Curve. This process is valid for each scenario previously described.

First of all, the specific NDT procedure (HFEC inspection) describes the component or area to inspect as fatigue test samples. Secondly, the procedure provides a description of
possible damage as fatigue cracks starting in the top surface of the fatigue test sample. Thirdly, equipment and materials needed for inspection are detailed (e.g. instrument, probe, calibration standard, etc). Before starting the test, inspectors have to verify the calibration date and conformity of the equipment; identify the area on the fatigue test sample to be inspected and check if it is clean and smooth. Another inspection is carried out in order to check the lack of visible damages or discontinuities. In addition, an instrument calibration step has to be performed using the probe and the reference standard related to the inspection requirements.

As it was shown previously, the inspector has to adjust the instrument parameters of the system to obtain a 100% FSH (Full Screen Height) for the infinite defect at 1 mm depth on the calibration block. Then, this value is used to set up the 100% value in the POD process which corresponds to the saturation threshold ($\hat{a}_{sat}$). The other important parameter is the detection threshold ($\hat{a}_{th}$) at 10% FSH as indicated in the NDT HFEC procedure. Finally, the inspector passes the probe slowly along the area to inspect and make sure that the coil scans the whole surface. All indications, which are vertical and exceeds $\hat{a}_{th}$, in this case, 10% FSH (Full Screen Height) shall be marked as cracks (see Figure 1).

After all, a statistical analysis of experimental data has been carried out to reach an accurate POD Curve in each scenario. Figures 4 and 5 shows the amplitude measured by each inspector for the samples set used during the experimental campaign. Notice two horizontal cursors, the upper black one indicates the saturation threshold ($\hat{a}_{sat}$) and the lower red one, the detection threshold ($\hat{a}_{th}$).

![Figure 4](image1.png) (a) ![Figure 5](image2.png) (b)

Figure 4. Data distribution from NDT inspector in laboratory scenario with different scales: (a) linear and (b) logarithmic

![Figure 5](image3.png) (a) ![Figure 5](image4.png) (b)

Figure 5. Data distribution from NDT inspector in aircraft scenario with different scales (linear and logarithmic)
In the following steps of the study, the POD Curve is computed using the method described in Section 2. According to this method, the first step consists in choosing the best model which allows a linear correlation between $a$ and $\hat{a}$ to satisfy the Berens’ hypothesis. In this case, the linear model ($a$ vs $\hat{a}$) is the best choice (see Figures 4 and 5) for providing the best linear correlation coefficient ($R^2$) value. For each POD Curve, the selected parameters to analyse are:

- $a_{50}$ is the defect length for a 50% of probability of detection;
- $a_{90}$ is the defect length for a 90% of probability of detection;
- $a_{90/95}$ is the defect length for a 90% of probability of detection obtained with 95% of confidence level.

For confidential reasons, these POD parameters are normalized by the $a_{90/95}$ obtained from the POD Curve corresponding to the laboratory scenario. Additionally, the same normalization is applied in the POD Curve axis. This value is the Airbus baseline which is taken into account in aircraft intervals inspections. Finally, the normalized value of $a_{50}$, $a_{90}$ and $a_{90/95}$ will be noted, respectively, $a_{50}^*$, $a_{90}^*$ and $a_{90/95}^*$.

![Figure 6. POD Curve for (a) laboratory scenario and (b) aircraft scenario using titanium beta samples](image)

According to this normalization, the laboratory POD results are: $a_{50}^* = 0.45$, $a_{90}^* = 0.92$ and $a_{90/95}^* = 1$ by setting the horizontal cursor to 50% and 90% for the red (True POD Curve) and blue line (95% of confidence level) in Figure 6(a). Consequently, the aircraft POD results are: $a_{50}^* = 0.58$, $a_{90}^* = 0.97$ and $a_{90/95}^* = 1.11$ in Figure 6(b).

This last POD results have been carried out only with four instead of seven inspectors due to some problems with their availability. Therefore, this POD curve could be less robust than the previous one. However, as the amount of data collected is quite significant, the result will not present major differences as previously expected.

However, some caution should be taken. This POD study assumes that the inspector is respecting the procedure, specially the calibration written in the document. Furthermore, the procedure could be greatly enhanced by adding a simple tool to help the positioning of the probe or by changing it for better inspection performances.
4. NUMERICAL POD CURVES

The CIVA software is a digital platform of expertise for non-destructive testing developed by CEA and its NDT simulation partners. It can be used to simulate ultrasonic controls, X-ray, Gamma ray and eddy current, as well as the use of associated image and signal processing modules on simulated or experimental data. The software also provides a statistical analysis tool for the construction of probability of detection curves based on maximum likelihood analysis. The methodology used to obtain variability in inspection results, as in In-Service inspections, is based on the introduction of uncertainty on different input parameters for control (sensor frequency, position, inclination, defect parameters, etc.) [14,26].

4.1. Eddy currents configuration by CIVA

In this section, CIVA model is presented for a better understanding of High Frequency Eddy Current inspections. In accordance to the experimental data base, the material in this model is titanium beta (TAV6 Beta). The simulation geometry shape is a flat plate (250x40x5 mm) and concerning the defect, it will be consider a semi-elliptical flaw, close to real case. Finally, the simulated probe consists of 1 coil. The model is described in Figure 7.

![Figure 7. CIVA model of a High Frequency Eddy Current inspection](image)

The simulated model has a semi-elliptical defect shape to be as close as the experimental samples. The model chosen for the corresponding defect mesh will be the BEM (Boundary Element Method) because it is more representative to a real defect response (narrow flaws).

4.2. Statistical description of CIVA uncertain parameters

When performing an NDT inspection, the probe signal response due to a flaw is affected by mainly 3 factors related to the inspection procedure specifications (transducer, scan plan including transducer angles, electronic device), to the inspected part (geometry, material properties, surface treatment) and last but not least the flaw (size, shape, orientation). Some of these parameters 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 all parameters, key issue inside the process, which is 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 survey has been proposed to a huge number of “experts”, who are used to practice NDT inspections as a different way (quality, final assembly line, engineering, suppliers, etc.) from different sites. In addition, the engineering judgment is used to perform an accurate simulation model in terms of uncertain parameters. This step is essential in terms of obtaining a reliable POD Curve.

For High Frequency Eddy Current (HFEC) application case, ten parameters have been identified as strongly influential on the signal amplitude response. However, an experimental verification was performed; therefore finally eight parameters were selected. Two other parameters were identified (conductivity and Z rotation) but a deeper analysis showed that their potential variations were very well compensated by the application of the procedure and were of negligible influence on the signal amplitude response. Expert's interviews lead to statistical description of each uncertain parameter. The distributions used as inputs for the simulation study are described in Table 2.

For the numerical POD Curves development a methodology will be follow to reproduce the impact of the variability of each parameter inside the model. These parameters correspond to uncertain sources that are really influential in the response of the NDT system. The variability represented on the NDT results from the simulation is post-treated statistically and used to calculate the POD Curve. This process is really key inside the development of a POD Curve and often known as “propagation of uncertainties”. This model allows reproducing NDT results observed in experimental cases with real equipment driven by a certified inspector.

In this section, the numerical POD Curves development is described as a key step for all different NDT methods. As it was mentioned before, identifying uncertain sources and attribute a statistical law will be the principal scope. All reliable process follows an algorithm.

<table>
<thead>
<tr>
<th>HFEC Parameters</th>
<th>Statistical description</th>
<th>Statistical moments</th>
<th>Sampling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lift-off (µm)</td>
<td>Uniform</td>
<td>[0mm,0.5mm]</td>
<td>10</td>
</tr>
<tr>
<td>Angular position</td>
<td>Gaussian</td>
<td>[0°,5°]</td>
<td>10</td>
</tr>
<tr>
<td>of the probe – Y rotation (°)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Angular position</td>
<td>Gaussian</td>
<td>[0°,5°]</td>
<td>10</td>
</tr>
<tr>
<td>of the probe – X rotation (°)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scanning increment – Step X (mm)</td>
<td>Truncated Gaussian</td>
<td>[1mm,2mm]</td>
<td>10</td>
</tr>
<tr>
<td>Scanning increment – Step Y (mm)</td>
<td>Truncated Gaussian</td>
<td>[1mm,2mm]</td>
<td>10</td>
</tr>
<tr>
<td>Flaw</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Depth (mm)</td>
<td>Truncated Gaussian</td>
<td>[1mm,0.5mm]</td>
<td>10</td>
</tr>
<tr>
<td>Skew (°)</td>
<td>Gaussian</td>
<td>[90°,10°]</td>
<td>10</td>
</tr>
<tr>
<td>Width (mm)</td>
<td>Truncated Gaussian</td>
<td>[0.2mm,0.11mm]</td>
<td>10</td>
</tr>
</tbody>
</table>

Table 2. Statistical description for uncertain parameters introduce in the model for a high frequency eddy currents inspection.

4.3. Numerical POD Curves by CIVA

For the numerical POD Curves development a methodology will be follow to reproduce the impact of the variability of each parameter inside the model. These parameters correspond to uncertain sources that are really influential in the response of the NDT system. The variability represented on the NDT results from the simulation is post-treated statistically and used to calculate the POD Curve. This process is really key inside the development of a POD Curve and often known as “propagation of uncertainties”. This model allows reproducing NDT results observed in experimental cases with real equipment driven by a certified inspector.

In this section, the numerical POD Curves development is described as a key step for all different NDT methods. As it was mentioned before, identifying uncertain sources and attribute a statistical law will be the principal scope. All reliable process follows an algorithm.
This algorithm was analyzed and treated for usual NDT inspections as eddy currents or ultrasounds methods (Figure 8).

After analyzing the “propagation of uncertainties”, a POD Curve development has to be performed to reach the interesting POD parameters. Based on the previous algorithm, the flaw amplitude is calculated for each flaw length, and then computed using a linear regression. Finally, the POD Curve has been obtained using Berens signal response method due to the NDT inspection response.

A simulation scenario was modeled by CIVA to obtain POD parameters. In this case, the linear-linear MLE estimation also provides a better fit to the estimation hypothesis (linear model) (Figure 9(a)). The normalized POD results obtained from the simulation are: $a_{50}^* = 0.54$, $a_{90}^* = 1.09$ and $a_{90/95}^* = 1.15$ (see Figure 10).

Figure 8. Algorithm to analyse the uncertainties in each NDT inspection

Figure 9. Data distribution from NDT inspector in CIVA with uncertain parameters scenario with different scales: (a) linear and (b) logarithmic.
5. COMPARISON

The comparison between the normalized POD parameters obtained in different scenarios is presented in Table 3.

<table>
<thead>
<tr>
<th>Statistical parameter</th>
<th>POD Laboratory</th>
<th>POD Aircraft</th>
<th>POD CIVA</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a_{50}$</td>
<td>0.45</td>
<td>0.58</td>
<td>0.54</td>
</tr>
<tr>
<td>$a_{90}$</td>
<td>0.92</td>
<td>0.97</td>
<td>1.09</td>
</tr>
<tr>
<td>$a_{90/95}$</td>
<td>1</td>
<td>1.11</td>
<td>1.15</td>
</tr>
</tbody>
</table>

Table 3. Comparative table for statistical values in different scenarios including simulation

The post-analysis of the statistical results obtained from the experimental and simulation campaigns allows differentiation between the scenarios. Nevertheless, this differentiation is not sufficient to demonstrate a high impact of the distinctive factors of the scenarios (human and environmental conditions) as it was mentioned before. In Table 3 simulation and experimental results can be appreciated close to each other. One of the main reasons can be a right selection of uncertain parameter descriptions were successfully performed in the CIVA model.

6. CONCLUSION

The human factor and environment measurements are characterized for their difficult quantification. The post-analysis carried out for the different scenarios (laboratory and aircraft) allow measuring their impact on the POD Curve. In this case, the whole impact is independent of the equipment and the procedure followed because these parameters were fixed for both scenarios.

The future POD Curves calculation will be supported by the simulation validation, however it is necessary to check that the simulation tools are able to properly model the inspection case. Hence, validations have to be performed on this particular case study by covering the range of uncertainties of the POD study. This specific validation step is crucial for the validity of the final study. In particular, the experimental parameters used for validation shall be measured carefully (surveys, engineering judgment and inspection videos). The simulation inspection discrepancies shall be compared to the repeatability deviation.
observed in the experiments. If the simulation inspection discrepancy is within the repeatability deviation then the simulation model's confidence is guaranteed for the particular study.

Reliability is a key question for further use of the obtained POD results. The quantity of data is directly linked with this aspect. In this particular study, experimental campaigns were carried out with a huge amount of data due to the specimens and inspectors used. In the end, POD parameters can be assumed as robust enough and quite representative.

Nowadays, structural integrity programs require empirical POD campaigns with high costs and time consuming. In this study a simulation model, known as MAPOD approach, which integrates the experiment campaigns is presented. Additionally, this simulation tool has been used as the bases of incorporating knowledge of physical effects and providing more reliable inspection results. Finally, this study demonstrates the simulation benefits in terms of costs and time reduction obtaining similar experimental results.

ACKNOWLEDGEMENTS

The authors would like to thank the experts who have participated in the NDT surveys and carried out all inspections during their daily work (J.F. Hugot, E. Malarme, B. Jarry, F. Bertrand, B. Bacque, J.L. Sauleek, J. Proust, ESCMN department and leaders, QBSN department and leaders; and external people).

REFERENCES

[1] NHB 8071.1, Fracture Control Requirements for Payloads Using the National Space Transportation System (NTS), National Aeronautics and Space Administration.


