Overview of the Simulation-Supported POD Approach in the CIVA Software

Frédéric Jenson, Philippe Benoist
CEA, LIST, 91191 Gif-sur-Yvette, France

Evaluation of POD Curves Based on Simulation Results

Background

- **Inspection reliability:** one of the key issues in ensuring safety of critical structural components
- Increasing use of probabilistic approaches based on statistical criteria such as **POD curves** and **PFAs**
- Are currently obtained thru **expensive and time consuming** experimental campaigns

Objective

- To propose tools to replace some of the experimental data with **simulation results** such as those obtained with the software CIVA

Outline

POD curves evaluation based on a sampling approach

- Definition of the uncertainty sources
- Uncertainty propagation thru the physical model
- Extraction of the output (the variable of interest)
- Computation of the POD curve and the lower confidence bound

Validation case

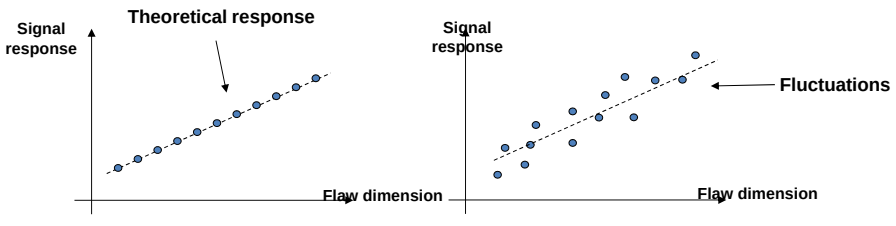
- HFET of fatigue cracks in Titanium

Validity of the simulated POD curve : error sources

Future work and objectives for CIVA

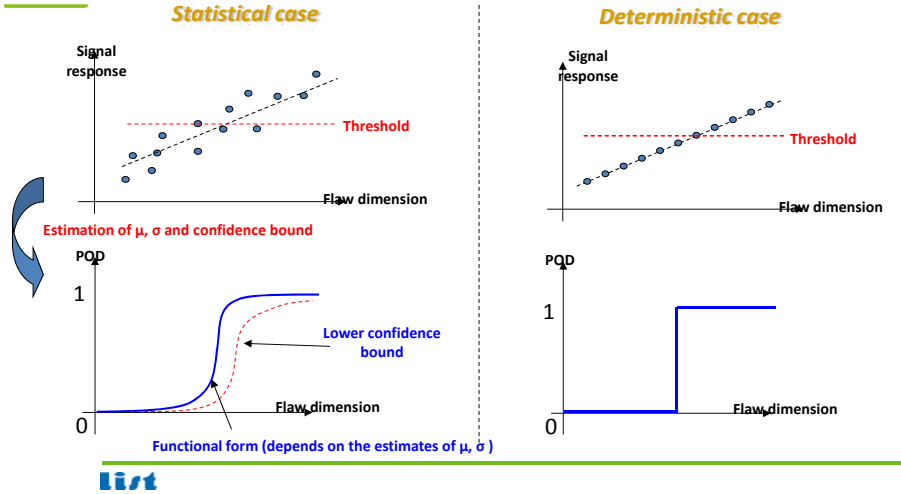
Aim of the approach: first, simulate a set of "realistic values" for the NDI system response

• **« realistic values»:** values that take into account uncertainty and noise sources and thus reflect fluctuations around the theoretical responses

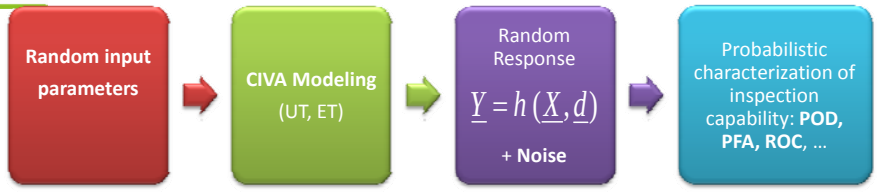


Deterministic approach → ***Statistical approach***

… then, perform an estimation of the POD curve using a functional form



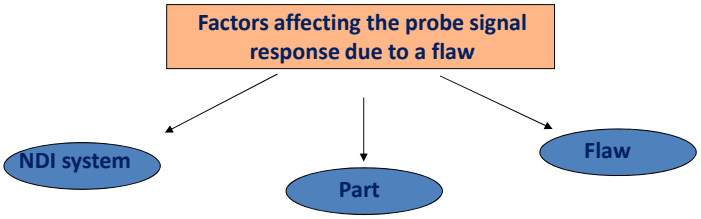
POD's in CIVA Software: a sampling approach based on existing physical models



1. Definition of the inspection setup
2. Description of **uncertainties** on a set of input parameters
3. Propagation of uncertainty thru existing models (Monte Carlo)
4. Extraction of the output (the variable of interest)
5. Evaluation of probabilistic criteria such as the **POD**, PFA

Evaluation of POD Curves Based on Simulation Results

Factors that can be adressed using physical models



- **NDI system:** transducer, scan plan, electronic device, probe orientation
- **Part:** geometry, material properties, structural properties, surface roughness
- **Flaw:** size, shape, orientation, position, material properties

Factors that are difficult/impossible to address using physical models

Some "human factors" : psychological factors, physiological factors

Evaluation of POD Curves Based on Simulation Results

These factors are either deterministic or random during the inspection

Factors that are thought to be deterministic

A signal-determining factor is taken to be deterministic if either the factor can be controlled in the inspection operation or if it is desired to estimate POD as a function of the level factor (flaw size for instance).

Factors that are thought to be random or uncertain

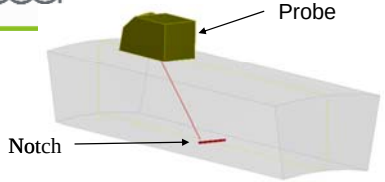
The factor is thought to be random during the production/field inspection if there is insufficient knowledge related to it, if it is not well controlled or if it implies physical phenomena with inherent randomness.

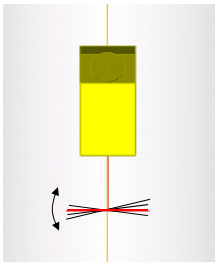
Evaluation of POD Curves Based on Simulation Results

Examples of random (uncertain) factors:

- ***Detail of metallurgical macro and microstructure***: structural noise, beam distortions, beam deviations
- ***Flaw morphology***: for a fixed size, various parameters such as shape, orientation, position, elastic properties, and conductivity can vary in a random manner
- ***Probe positioning***: Lift-off variations and/or probe orientation during a manual inspection using an eddy current pencil probe
- …

Modeling uncertainty sources using statistical distributions





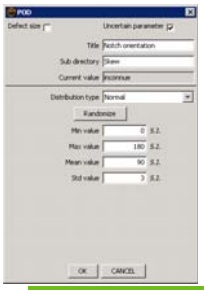
Simulated responses

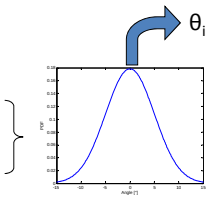
$\theta_{nominal} \rightarrow S_{nominal}$

$\theta_1 \rightarrow S_1$

$\theta_2 \rightarrow S_2$

$\theta_n \rightarrow S_n$





Statistical distribution for the skew angle

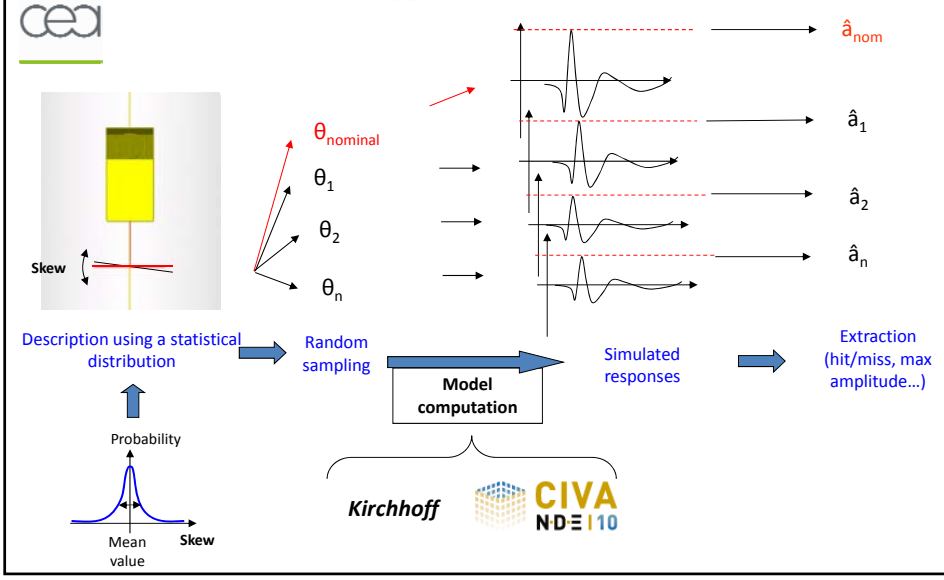
Proposed parametric distributions:

Uniform
Normal
Log-normal
Rayleigh
Exponential
…

Defined using engineering judgment

Dedicated GUI

Performing uncertainty propagation using a sampling approach (Monte Carlo)



Simulations are based on existing physical models

Physical models :

- UT beam modeling using ray tracing (pencil method)
- UT beam-defect modeling using Kirchhoff approximation, Geometrical Diffraction Theory, Born approximation
- ECT field modeling using Finite Integration Technique, Analytical expressions
- ECT defect response modeling using Volume Integral Method

Estimation of the POD curve using a functional form

• POD curves relate the detectability of a flaw to its size (or to another geometrical characteristic)

• Usual approach (MIL HDBK 1823) consist in:
- assuming a functional form for the POD curve
- estimating the parameters of the function from the inspection results
- estimating the associated confidence bound

Berens

• Hit/miss data format: $POD(a) = \left\{1 + \exp\left(-\frac{\pi}{\sqrt{3}}\left(\frac{\ln a - \mu}{\sigma}\right)\right)\right\}^{-1}$

Log-odds function

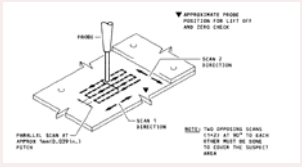
• Signal response data format: $POD(a) = \Phi\left[(\ln a - \mu)/\sigma\right]$

Cumulative log-normal distribution function

Cheng

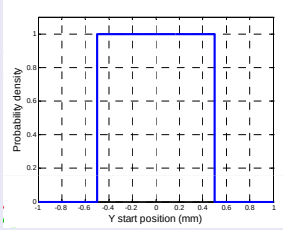
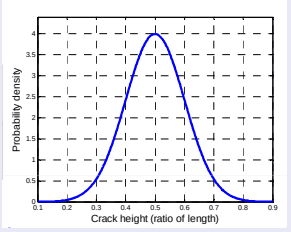
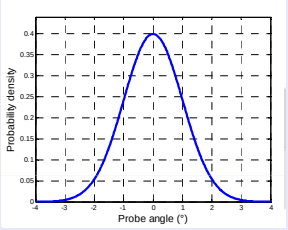
• Estimated from a finite size data sample ⇒ sampling uncertainty ⇒ confidence bound

Validation case: HFET of fatigue cracks in Titanium

Part	NDT
Material: Titanium (TA6V) **Geometry:** Flat areas **Defects:** Fatigue cracks	**Configuration:** High Frequency Eddy Currents Testing (HFET)  **Probe:** Pencil probe (2MHz)  **Conditions:** In-service (manual)

Design of Numerical Experiments HFET on Titanium

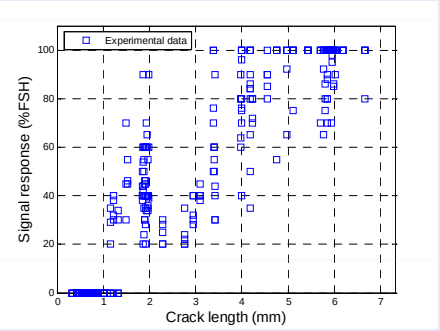
- **Characteristic variable**: crack length (mm)
- **Uncertain parameters**:

Start scan position	Crack height (mm)	Angle of the probe (°)
Corresponds to the position of the probe for picking the maximum amplitude signal	Fatigue cracking is subject to many uncertainties	Translated into an additional lift-off using geometrical rule
		
Uniform in [-0.5;05] (scan increment=1mm)	Gaussian with dependency to the crack length (fatigue crack) 0.5*length +N(0,1)*0.12*length	Gaussian(0°;1°)

Sampling strategy: Monte Carlo

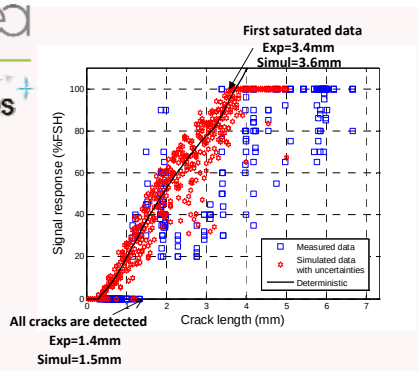
Simulated vs. Experimental data

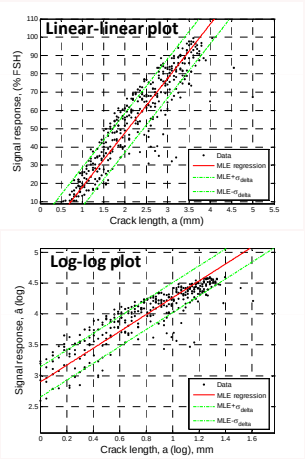
- **Experimental database**
  - 69 cracks from 0.33 mm to 6.66 mm
  - 5 operators



- **Simulations**
  - 100 crack lengths from 0.25 mm to 5.0 mm
  - 6 samples per crack length

Signal response data analysis





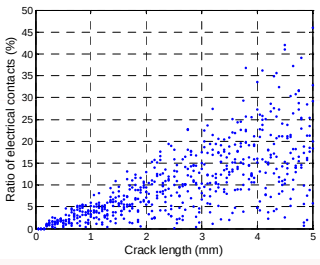
Good agreement on data until 3 mm cracks.

High variability for larger cracks not well represented

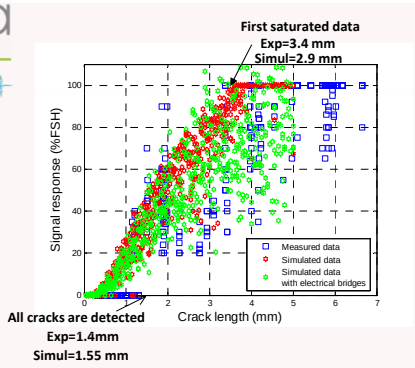
Signal response data analysis

High variability for larger cracks may be due to the complex crack shapes with possible electrical contacts between the two faces of the crack aperture. These contacts are responsible for signal amplitude drops.

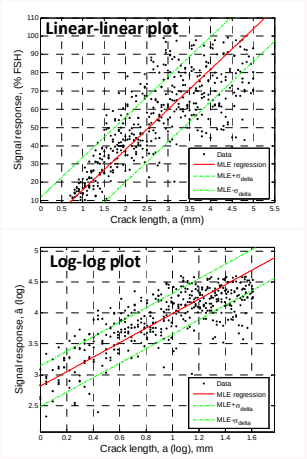
⇒ Dataset is augmented with an additional uncertain input parameter: the rate of electrical contacts along the crack length.



Signal response data analysis

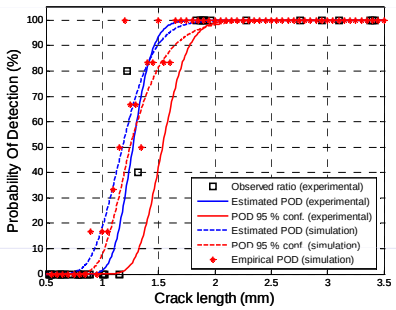


Adding electrical contacts as an uncertain input parameter allows for reproducing the high variability in the whole crack length range.



Hit/Miss POD analysis: 4 input uncertain parameters

- 600 simulated data
- 4 uncertain parameters (start position, crack height, probe angle, elec. contacts)



POD curves very similar

•Slope corrected but still the effect of the number of data

•Confidence band smaller for simulation dataset because more data than in the experimental dataset

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

Values of interest very similar

Validity of the simulated POD curve : error sources

When determining a POD curve from simulation results, various error sources may impact the results:

Sampling uncertainty -> lower confidence bound

Errors on the estimation of the lower confidence bound -> if sample size is to small. Need more simulations.

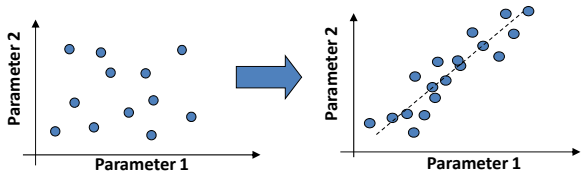
Hypothesis of the POD model: linear relationship, constant standard deviation…

Modeling errors -> systematic error (bias on the estimates of the parameters of the curve). Need validation of the models/ definition of the validity domain.

Errors on the definition of the inputs ->choice of the uncertain parameters of the inspection, of the statistical distributions describing them and of the parameters of the distributions. Need more engineering judgment.

Perspectives

•Additional tools are needed for the modeling of uncertainty sources: take into account **correlations between input parameters**



Example: Correlations between the length and the height of a crack

- Perform **experimental validation** for EC and UT application cases
- New approaches for the modeling of the POD curve

PICASSO Project : European project (FP7), started in 2009

Thank you for your attention

Questions?