Simulation-Supported POD for Ultrasonic Testing – Recommendations from the PICASSO Project

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Abstract

The objective of the European project PICASSO (Improved reliability inspection of aeronautic structures by simulation-supported POD) was to build a new and original concept of simulation-supported Probability of Detection (POD) curves based on Non Destructive Testing simulations. This new methodology is based on the replacement of some of the experimental data with simulation results to obtain accurate and reliable POD curves with significantly less personnel and material costs. The present paper presents the main results of the PICASSO project for ultrasonic testing and addresses the most crucial aspects of the new approach, e.g. the definition of the noise level, the validation of the modeling tools, the combination of experimental and numerical data, and the specification of the uncertainty parameters and their statistical distribution. From the results recommendations for the practical use of simulation-supported POD curves are given.

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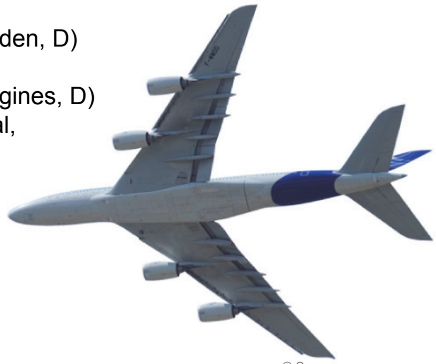

PICASSO

Improved Reliability Inspection of Aeronautic Structure through Simulation Supported POD

Fraunhofer IZFP

Co-Funded by the European Community's Seventh Framework Programme (FP7/2007-2013)

Outline

- **PICASSO Project**
- **Simulation-Supported POD Methodology**
  - Description of UT Configuration – Model Building
  - Determination of Uncertainty Parameters
  - Statistical Distribution of Uncertainty Parameters
  - Model Validation and Verification
  - POD Estimation from Simulated Data
  - Combination of Empirical and Simulated Data
- **Benefits and Limitations of Simulation-Supported POD**

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PICASSO – Improved Reliability Inspection of Aeronautic Structures by Simulation-Supported POD

- SEVENTH FRAMEWORK PROGRAMME
- THEME 7: TRANSPORT
- COLLABORATIVE PROJECT:
  Small or medium-scale focused research project
- BUDGET: 6,5 Mill. €
- DURATION: 3.5 Years (1.7.2009 – 31.12.2012)
- **www.picasso-ndt.eu**

Co-Funded by the European Community's Seventh Framework Programme (FP7/2007-2013)

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Partners

Research Institutes

- BAM, Berlin
- Chalmers, Göteborg
- CEA LIST, Gif-Sur-Yvette
- IZFP, Dresden
- TWI NDT, Swansea

Industry

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- Safran-Turboméca, Bordes
- Volvo Aero, Trollhättan

SMEs

- HTS, Coswig
- PHIMECA, Paris
- Technic Control, Stettin

Simulation Tools

Eddy Current Testing

- VIC-3D (HTS)
- VAC (Chalmers, Volvo)
- CIVA-ET (CEA)

Radiographic Testing

- CIVA-RT (CEA)
- aRTist (BAM)

Ultrasonic Testing

- CIVA-UT (CEA)
- EFIT (IZFP-D)

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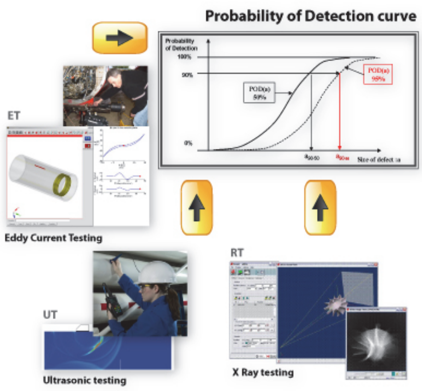
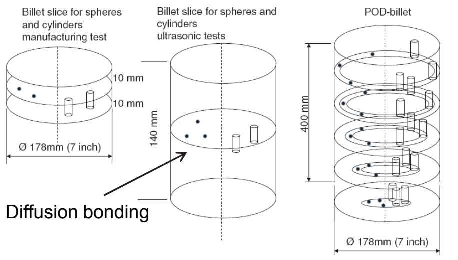
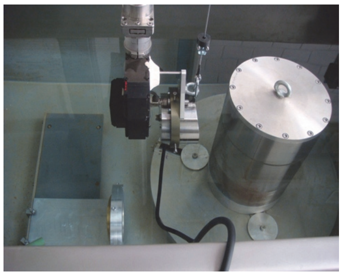


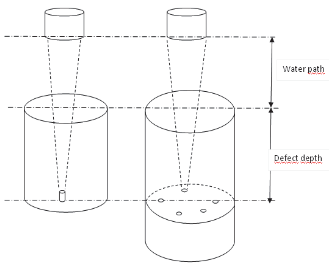
Goals:

- Calculation of simulation-supported POD curves for eddy current, ultrasonic and radiographic testing of metallic aircraft components
- Extension of experimental POD data
- Faster, more accurate & cost-effective POD studies
- Reduction of operating costs (weight reduction, less fuel consumption, reduced maintenance costs, longer time between inspections etc.)

POD Methodology Step 1: UT Configuration – Model Building







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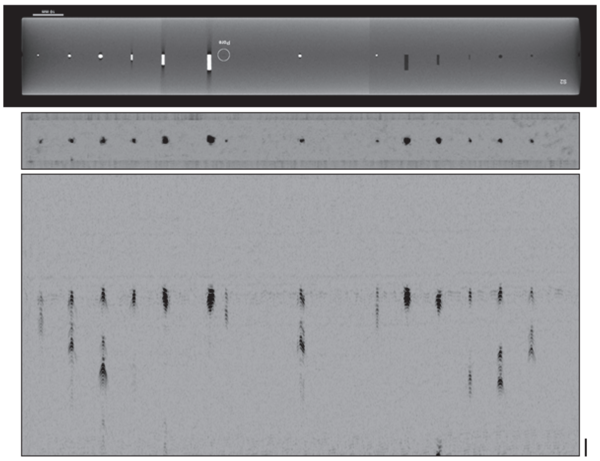
POD Methodology Step 1: UT Configuration – Model Building



X-Ray CT

UT C-Scan

UT B-Scan

Reference measurements of artificial flaws by X-Ray CT and ultrasonic B- and C-Scans at 20 MHz.

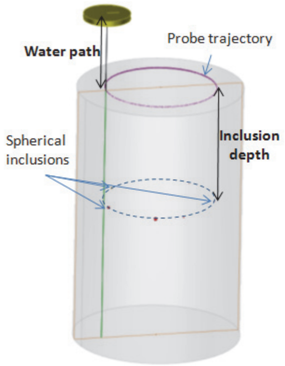
POD Methodology Step 1: UT Configuration – Model Building

Example: Alumine inclusions in forged Titanium billets

- Tested part: cylindrical titanium blocks, c_L = 6228 m/s, c_T = 3146 m/s, ρ = 4400 kg/m^3, α_L = 0.054 dB/mm @ 10 MHz, α_T = 0.062 dB/mm @ 10 MHz.
- Flaws placed at various depths by diffusion bonding, Al_2O_3 spherical inclusions with $2.5 \leq kR \leq 20$ (where $k = 2\pi/\lambda$ is the wave number, λ is the wavelength inside the matrix medium and R is the radius of the inclusion). c_L = 10845 m/s, c_T = 6350 m/s, ρ = 3900 kg/m_3.
- NDT technique: multi zone inspection with conventional UT transducers
- Probes and inspection zones: cylinder is divided in seven zones, each zone being inspected with a given probe. The beginning and end depths of the zones are in mm: zone 1: (surface, 12.7), zone 2: (12.7-25.4), zone 3: (25.4, 38.1), zone 4: (38.1, 50.8), zone 5: (50.8, 63.5), zone 6: (63.5, 88.9) and zone 7: (88.9, 139.7).

POD Methodology Step 1: UT Configuration – Model Building

Example: Alumine inclusions in forged Titanium billets



Probe Diameter (")	Center frequency (MHz)	Band-width (%)	Phase (°)	Crystal diameter (mm)	Nominal Focal Lenght (MHz)	Radius of curvature (mm)
6	10	70	0	25.4	152.4	155.5
8	10	70	0	25.4	203.2	210.5
10	10	70	0	25.4	254	268.5
13	10	70	0	25.4	330.2	363.5
16	10	70	0	25.4	406.4	472

Configuration description: Probe characteristics

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POD Methodology Step 1: UT Configuration – Model Building

Example: Alumine inclusions in forged Titanium billets

Inclusion depth (mm)	25.4	38.1	50.8	50.8	63.5	63.5	76.2	88.9	101.6	114.3	127	139.7
Probe diameter (")	6	8	8	10	10	13	13	13	16	16	16	16
Water path (mm)	76.7	45.2	45.2	41.3	41.3	58.6	58.6	58.6	44.5	44.5	44.5	44.5

Configuration description: Water paths used for the different probes

- Physical quantity considered: maximum amplitude reflected by the flaws.
- Calibration to the experimental 0 dB is made by a 0.4 mm flat bottom hole located in an N18 block (powder metallurgy) located at the same depth as the respective spherical defect.
- Noise is not explicitly taken into account in the simulations. However, the mean noise level that is typically needed for POD calculations can be determined from the corresponding experiments.
- Attenuation law used to compute the inclusion echoes given by SNECMA: exponential attenuation law, 0.054 dB/mm for the P wave, proportional to f^2, center frequency: 10 MHz.

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POD Methodology Step 2:
Determination of Uncertainty Parameters

1) Consider all factors that influence the outcome of a non-destructive test

2) Categories of influencing factors are for example:
   - *Defect*
   - *Equipment*
   - *System settings*
   - *Environment or external*
   - *Procedural*
   - *Human*

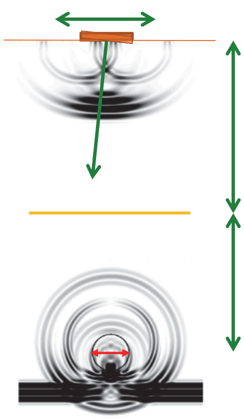
3) Ensure that experimental study to determine the POD curve is representative for conditions during the inspection of actual components

4) All factors significantly affecting the inspection results are uncertainty parameters of the POD study (MIL – HDBK-1823 , Section 4.5). The remaining factors are “controlled” parameters.

POD Methodology Step 2:
Determination of Uncertainty Parameters

Example: Uncertainty parameters for multi-zone inspection of Titanium billets

- Radial and angular position of the inclusion relatively to the probe
- Probe orientation
- Water path
- Inclusion depth
- POD parameter: radius of inclusion



POD Methodology Step 3:
Statistical Distribution of Uncertainty Parameters

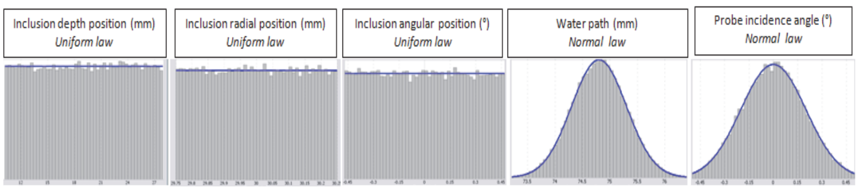
Methods to quantify the variation of the uncertain parameters include, but are not limited to:

- Direct understanding – when variation lies within known limits e.g. scan pitch, where the defect would be situated within +/– half the scan pitch from the probe.
- Measurement – possibility to measure the variation of uncertain factors e.g. aspect ratio of defects or equipment parameters such as probe central frequency.
- Engineering knowledge and experience – Discussions with inspectors, engineers, etc can be a very useful tool in understanding a process.
- Procedural controls – Procedures often give specific tolerances for parameters that influence the inspection. This can allow for a straight forward quantification of variation.
- Comparison with measurements – when it is not possible to understand all uncertain parameters the response from real defects can be used to aid the quantification.

POD Methodology Step 3:
Statistical Distribution of Uncertainty Parameters

Example: Multi-zone inspection of Titanium billets

- Radial and angular position of the inclusion relatively to the probe: The scanning step value in both directions is 70% of the beam effective diameter measured on a simulated C-scan. Then the radial and angular scanning uncertainties are taken as half of the scanning steps Δθ and ΔR. The associated distribution laws are uniform.
- Probe orientation: the orientation uncertainty given by SNECMA is +/– 0.5° around 0°. The associated distribution law is Gaussian.
- Water path: it can vary from +/– 1.6 mm around the nominal water path value. The distribution law is Gaussian.
- Inclusion depth: uniform probability function across the given inspection zone.



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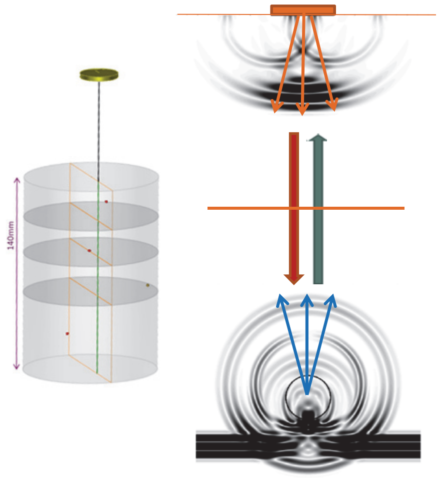
POD Methodology Step 4: Model Validation and Verification



Three different aspects have to be taken into account:

i) Validation of echo response against known artificial defects

ii) Demonstration that the model correctly predicts the change in response due to the uncertainty parameters (model verification)

iii) Sensitivity of the model needs to be matched to the sensitivity of the actual inspection (reference sensitivity)

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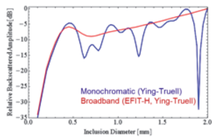
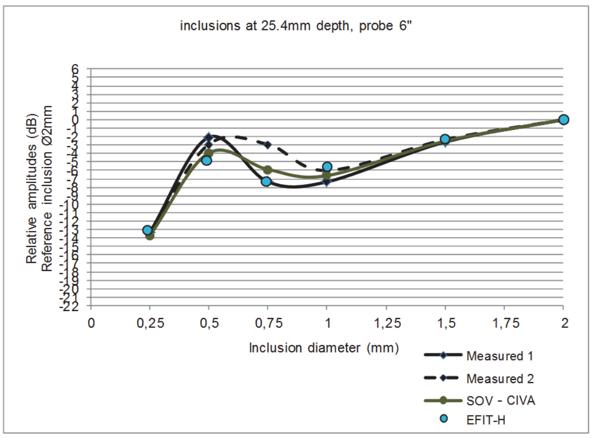
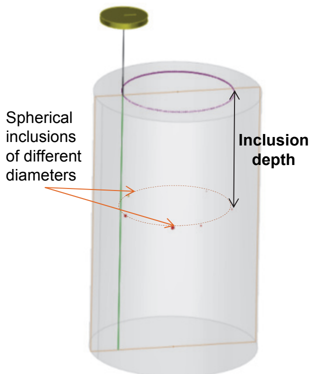
POD Methodology Step 4: Model Validation







Al_2O_3 in TA6V Billet, Comparison between EFIT-H, CIVA and measurements

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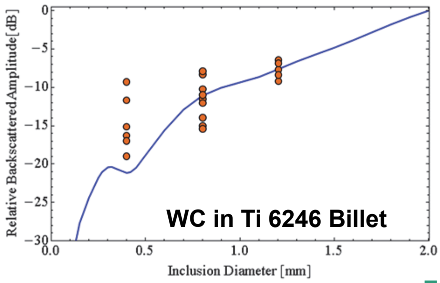
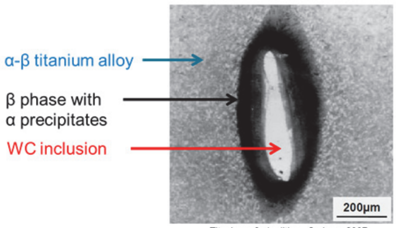
POD Methodology Step 4: Model Validation (negative example)



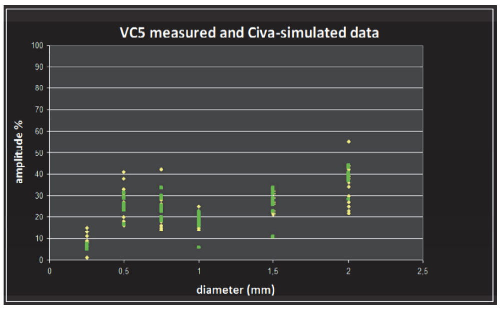
Tungsten carbid
c_P = 6655 m/s
c_S = 3984 m/s
ρ = 15630 kg/m³

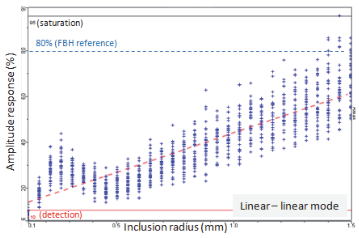


Titanium - 2nd edition - Springer 2007

- Technological problems during manufacturing of the POD-Billet (coarse grain structure, strong ultrasonic attenuation)
- Unknown impacts on the interface conditions of small inclusions (higher porosity?, delaminations? etc.)
- Generation of a strong beta phase around the WC inclusions (interfacial transition zone)
- Model needs to be validated for each individual material system !

POD Methodology Step 4: Model Verification





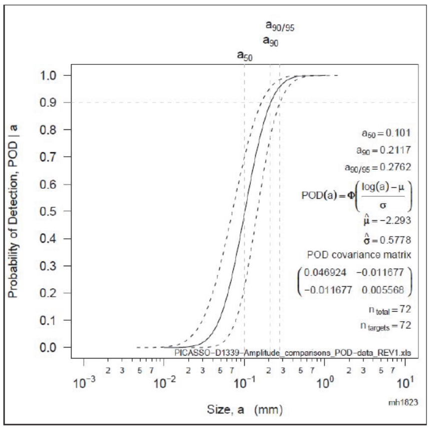
â-vs.-a curve for Al_2O_3 in TA6V Billet; Comparison between measurements (yellow dots) and simulations (green dots).

Reference Sensitivity

Sensitivity calibration was performed by a flat bottom hole of diameter 0.4mm located in an N18 block (powder metallurgy) located at the same depth as the respective spherical defects.

POD Methodology Step 5: POD Estimation from Simulated Data

- First, the range of defect sizes is determined. The majority of defects should be concentrated where the POD curve is steepest, with some defects so small that they will not be detected and some defects so large that they will always be detected.
- A set of test conditions for each defect size is created through Monte Carlo methods to randomly generate values for each of the uncertain parameters from their respective statistical distributions.
- The model is then used to simulate the NDT response for each test.
- The results can be used to calculate standard POD curves using methods already developed and used for empirical studies (e.g. Berens).



	Measurement	Simulation	Difference (mm)
a50 (mm)	0,08563	0,101	-0,02 mm
a90 (mm)	0,2536mm	0,2117	+0,04mm
a90/95 (mm)	0,3535	0,2762	+0,08mm

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POD Methodology Step 6: Combination of Empirical and Simulated Data

Benefit 1: Further understanding of uncertain parameters
If an uncertain parameter is not fully understood combination of empirical and simulated data can be used to aid quantifying the parameter *(e.g.* UT inspection where the interface conditions over a crack influence its acoustic reflectivity.

Benefit 2: Improved reliability and understanding
Adding simulated data to empirical data can reduce the sampling confidence interval, similarly empirical data adds general confidence to a simulated study.

Benefit 3: Complex scenario inspections
Data from a simplified scenario POD study can be used to demonstrate that many of the uncertain factors are correctly simulated. This is useful where it is not possible, or prohibitively expensive, to carry out an empirical POD study incorporating all aspects of the inspection, such as complex geometries.

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Benefits of Simulation-Supported POD Studies

- **Reduced cost of samples**: The use of POD simulations can significantly reduce the number of samples needed for POD measurements and thus, the costs of the samples (by 70-80%).
- **Improved defect size distribution**: In the frame of the POD simulations an arbitrary number of different defect sizes can be considered leading to an improved statistical confidence. In our example we used between 20 and 30 different diameters to accurately describe the echo response of the inclusions.
- **Reduction of sampling based confidence interval**: The confidence interval in empirical POD studies is the result of i) the systematic spreading of the uncertain parameters according to the distribution functions, and ii) the statistical fluctuations around the mean distribution curves due to the finite size of the random samples. By the use of simulations the number of samples can be significantly increased so that the total variation gets closer to the theoretical minimum.
- **Identification and quantification of factors that influence NDT reliability**: Many different factors can affect experimental POD studies. It is usually very difficult if not impossible to estimate the effect of a single factor on the final POD result. Simulations offer the possibility to identify if and how a single parameter affects the POD.

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Current Limitations of Simulation-Supported POD Studies

- **Need to understand underlying physics**: For a POD simulation a so-called forward calculation has to be performed, which means that the model input parameters and boundary conditions that control the final outcome need to be known as precisely as possible. In many cases this knowledge is limited and several - more or less justified - approximations or published values have to be used.
- **Ability to model**: In most cases the computational effort depends on the geometrical size of the model and the ultrasonic frequencies involved. For high frequency 3D problems as typical for ultrasonic POD studies the memory requirements and the calculation time for dozens or hundreds of POD simulations might be too high for practical applications. This problem is tightened if very complex models (e.g. FEM) are required to simulate all aspects of the inspection.
- **Quantification of uncertain parameters**: One of the key experiences of the PICASSO project is the fact that the identification and in particular the quantification of the uncertain parameters could be a difficult and time-consuming task that decreases the overall benefit of a simulation-supported POD study. In the future it is therefore necessary to tackle this so far underestimated aspect in more detail.

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