Probabilistic analysis of NDT signals for modeling the uncertainty of NDT&E

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Personal profile

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- **Affiliation & Position:**
  Professor,
  Department of Quantum Science and Energy Engineering,
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- **Professional experiences:**
  - 2020-Present Professor, Tohoku University
  - 2009-2020: Associate Professor, Tohoku University
  - 2006-2009: Project Assistant Professor, The University of Tokyo (concurrent)
  - 2005-2006: Assistant Professor, Keio University (concurrent)
  - 2001-2009: Researcher/Director, IIU Corp.
  - 2001: Researcher, Japan Society of Applied Electromagnetics and Mechanics
- **Education:**
  - 2004: Doctor of Engineering, Department of Quantum Engineering and System Science, Graduate School of Engineering, The University of Tokyo
  - 2000: Master of Engineering, Department of Quantum Engineering and System Science, Graduate School of Engineering, The University of Tokyo
  - 1998: Bachelor of Engineering, Department of Quantum Engineering and System Science, Faculty of Engineering, The University of Tokyo

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- Professional experiences:
  - 2020-Present Professor, Tohoku University

Research interests:

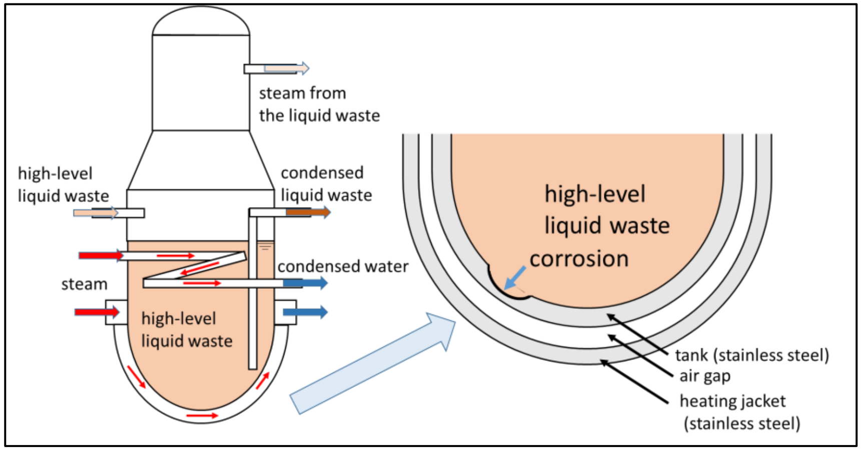
- Development of NDT&E techniques mainly for, but not limited to, large-scale structures such as power plants.
- Designing a system to transmute high level radioactive waste using high-energy neutrons.
- Energy and environmental education, especially from the viewpoint of the public acceptance of nuclear power.

System Science, Graduate School of Engineering, The University of Tokyo

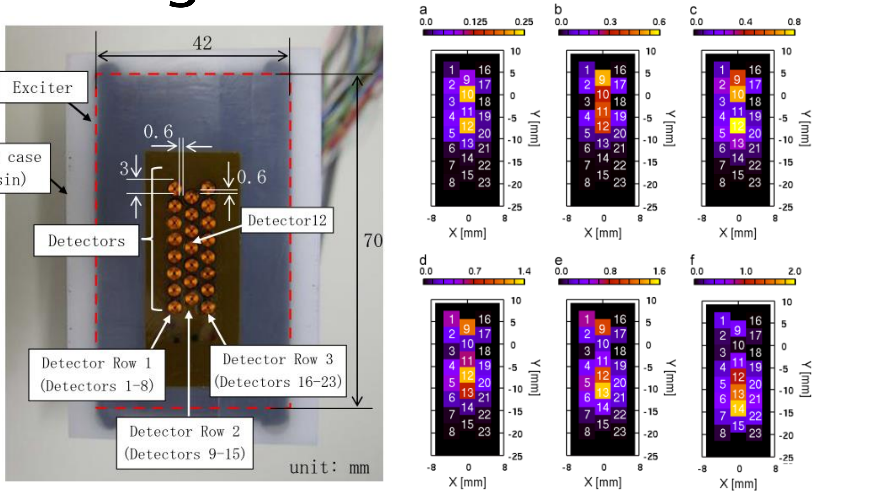
- 1998: Bachelor of Engineering, Department of Quantum Engineering and System Science, Faculty of Engineering, The University of Tokyo

Some of specific researches

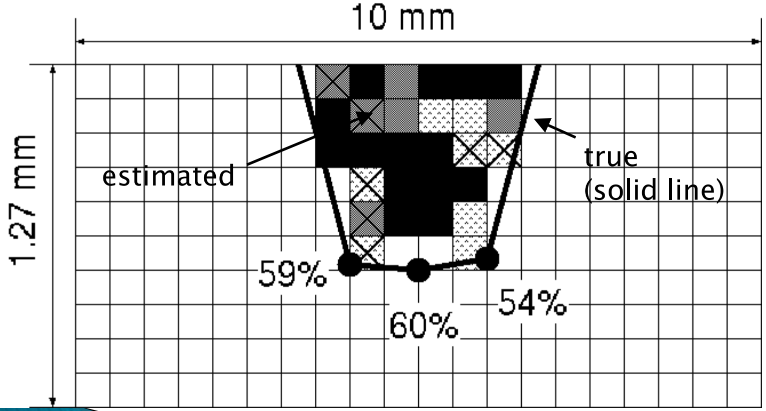
- NDT&E using DC～GHz electromagnetic fields



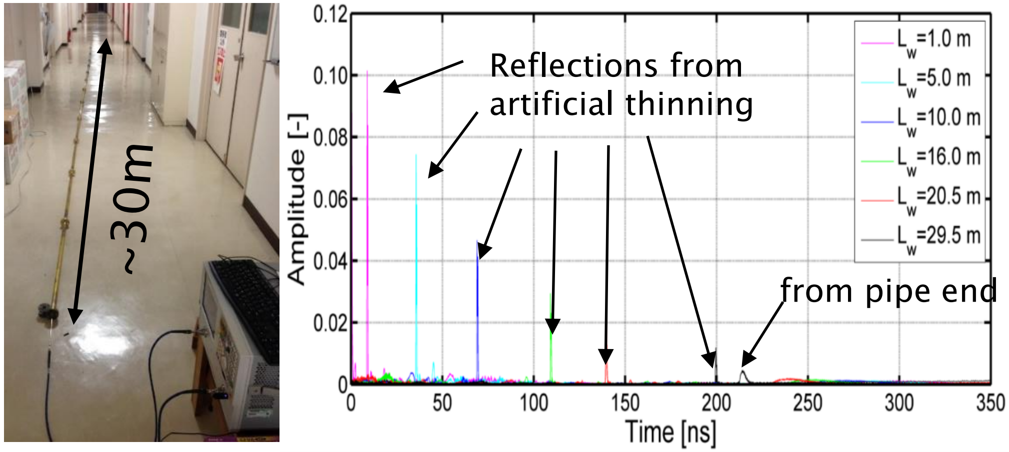
Low frequency eddy current NDT for the evaluation of corrosion of double-layered structures (Nondestr. Test. Eval. 33 (2018), 189-197)



Development of an arrayed eddy current probe and its application to on-line monitoring of fatigue cracks (NDT&E Int. 61 (2014), 127-132)



Development of computational inversion techniques to size flaws (profile evaluation of natural stress corrosion cracking at heat exchanger pipes, NDT&E Int. 36 (2003), 449-459, etc.)



Long-range inspection of pipe wall thinning using microwave (NDT&E Int 96 (2018), 45-57, etc.)

Form maintenance’s viewpoint

Assigning resources properly is one of the most important issues for assuring the safety of large-scale structures. Detecting a tiny flaw is not always welcomed.

- Uncertainty of detection

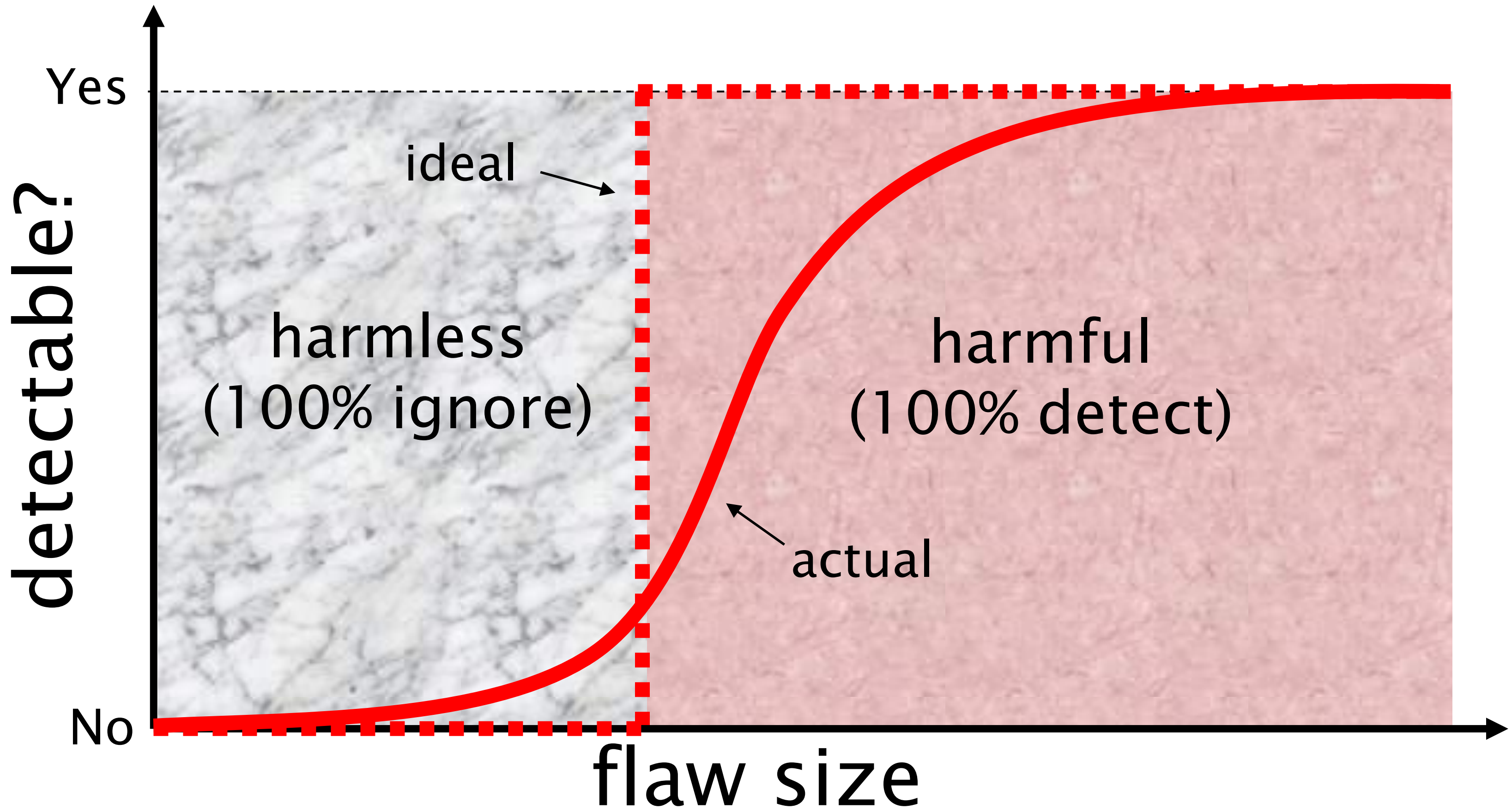
  →Probability of detection

- Uncertainty of evaluation

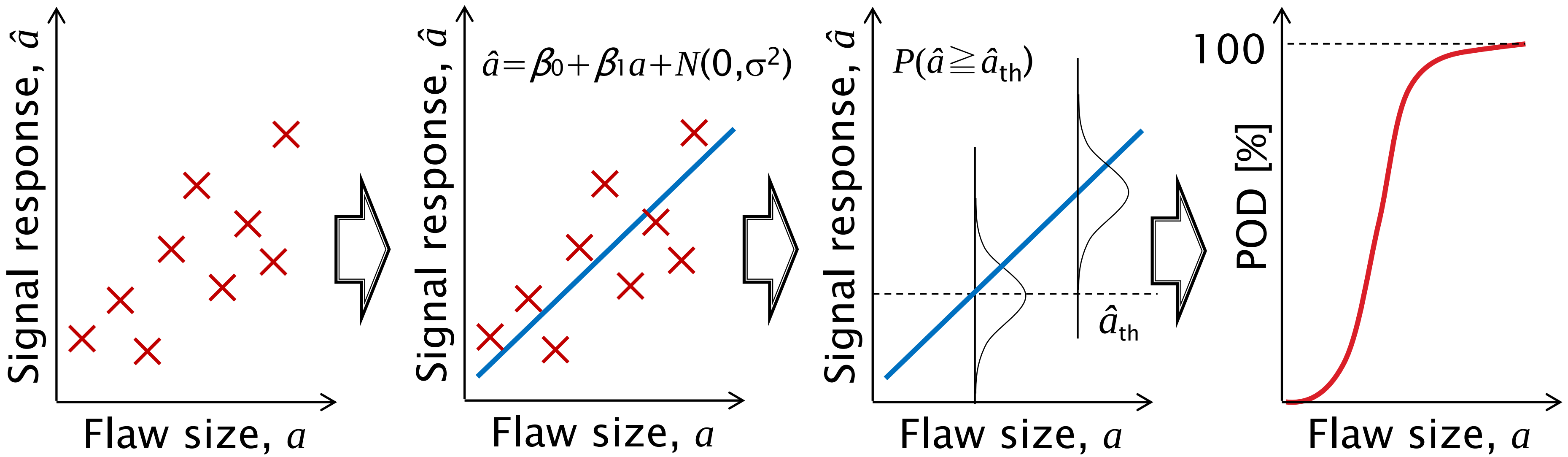
  →Interval estimation

Probability of detection (POD)

We should detect what we must detect.



Probability of detection (POD)



How to construct POD in conventional models

- A flaw is characterized just one parameter, a (flaw size).
- Many signals are necessary (huge resource to prepare samples).
- Signals should have “constant variance.”

Our basic approach

- Finding a proper mathematical model to correlate flaw profiles and signals;
  - Using not a simple linear regression but a more reasonable model based on physics.
- Combinational use of numerical simulation and experiments;
  - Evaluating non-polluted signals by simulations, and uncertainty by experiments.
- Monte-Carlo simulation for evaluating complicated joint probability distributions;
  - Enabling taking consideration of the effects of various factors.

Simulation+Experiment

- Eddy current inspection of a surface breaking crack

Combinational use of simulations and experiments:

Measured signal　　Normal distribution　　Simulated signal

$$V(d,l) = N(\mu_1, \sigma_1^2) \times V^{sim}(d,l) + N(\mu_2, \sigma_2^2)$$

crack depth　crack length　　Normal distribution

Log-likelihood function to estimate the four parameters:

$$\ln L = \sum_{i=1}^{M_l} \ln \Phi\left(\frac{V_l - \left(\mu_1 V^{sim}(d_i, l_i) + \mu_2\right)}{\sqrt{V^{sim}(d_i, l_i)^2 \sigma_1^2 + \sigma_2^2}}\right)$$
$$-\frac{1}{2} \sum_{i=M_l+1}^{M-Mr} \left[\ln\left\{2\pi\left(V^{sim}(d_i, l_i)^2 \sigma_1^2 + \sigma_2^2\right)\right\} + \frac{\left\{V_i - \left(\mu_1 V^{sim}(d_i, l_i) + \mu_2\right)\right\}^2}{V^{sim}(d_i, l_i)^2 \sigma_1^2 + \sigma_2^2}\right] + \sum_{i=M-M_r+1}^{M} \ln\left(1 - \Phi\left(\frac{V_r - \left(\mu_1 V^{sim}(d_i, l_i) + \mu_2\right)}{\sqrt{V^{sim}(d_i, l_i)^2 \sigma_1^2 + \sigma_2^2}}\right)\right)$$

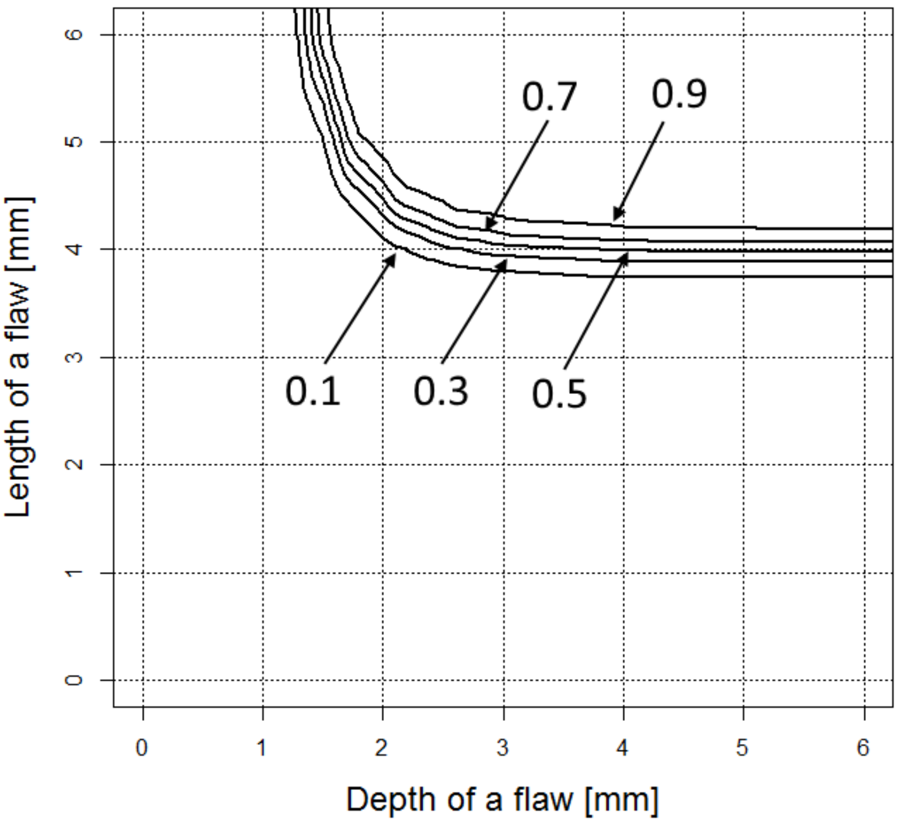
POD as a function of the depth and length:

$$POD(d,l) = \Phi\left(\frac{\left(\mu_1 V^{sim}(d,l) + \mu_2\right) - V_{th}}{\sqrt{V^{sim}(d,l)^2 \sigma_1^2 + \sigma_2^2}}\right)$$

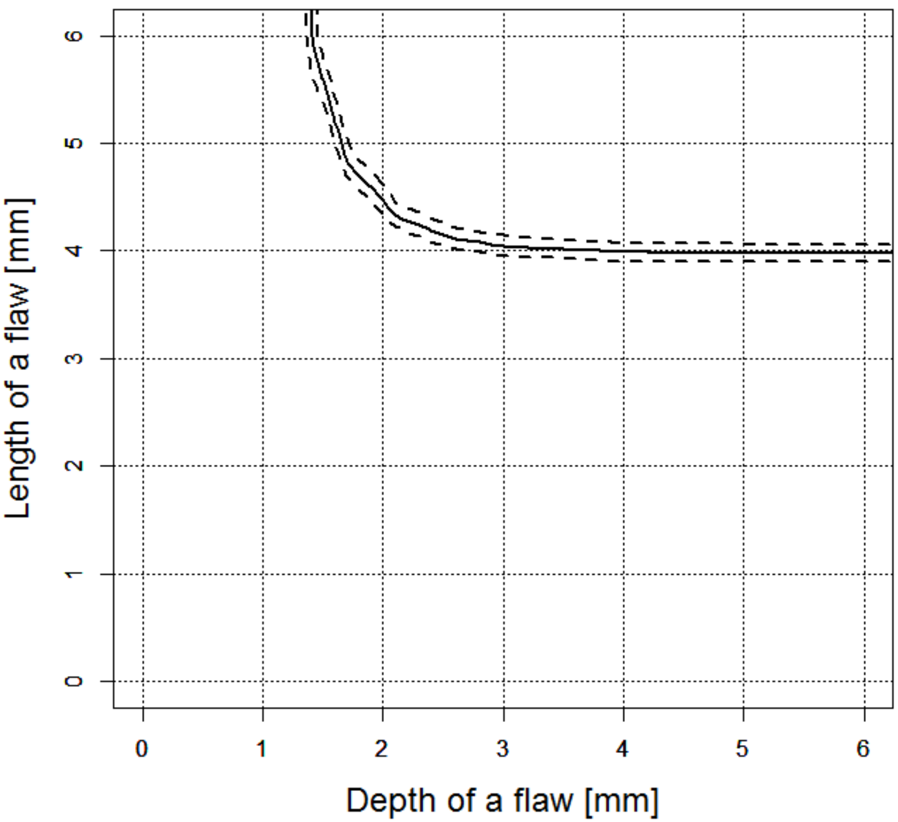
NDT&E Int. 81 (2016), 1-8. etc.

Simulation+Experiment

- Eddy current inspection of a surface breaking crack



POD contour lines

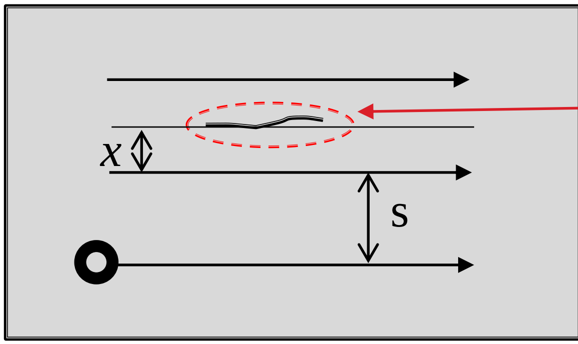


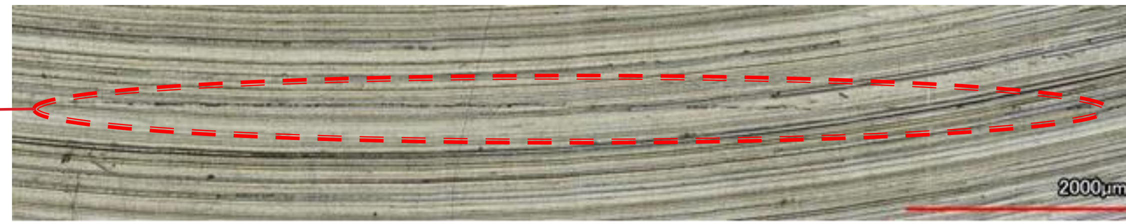
POD=0.9&Confidence interval

NDT&E Int. 81 (2016), 1-8. etc.

Considering various factors

- Effect of the distance between two scanning lines on the probability of detection of ECT against a crack



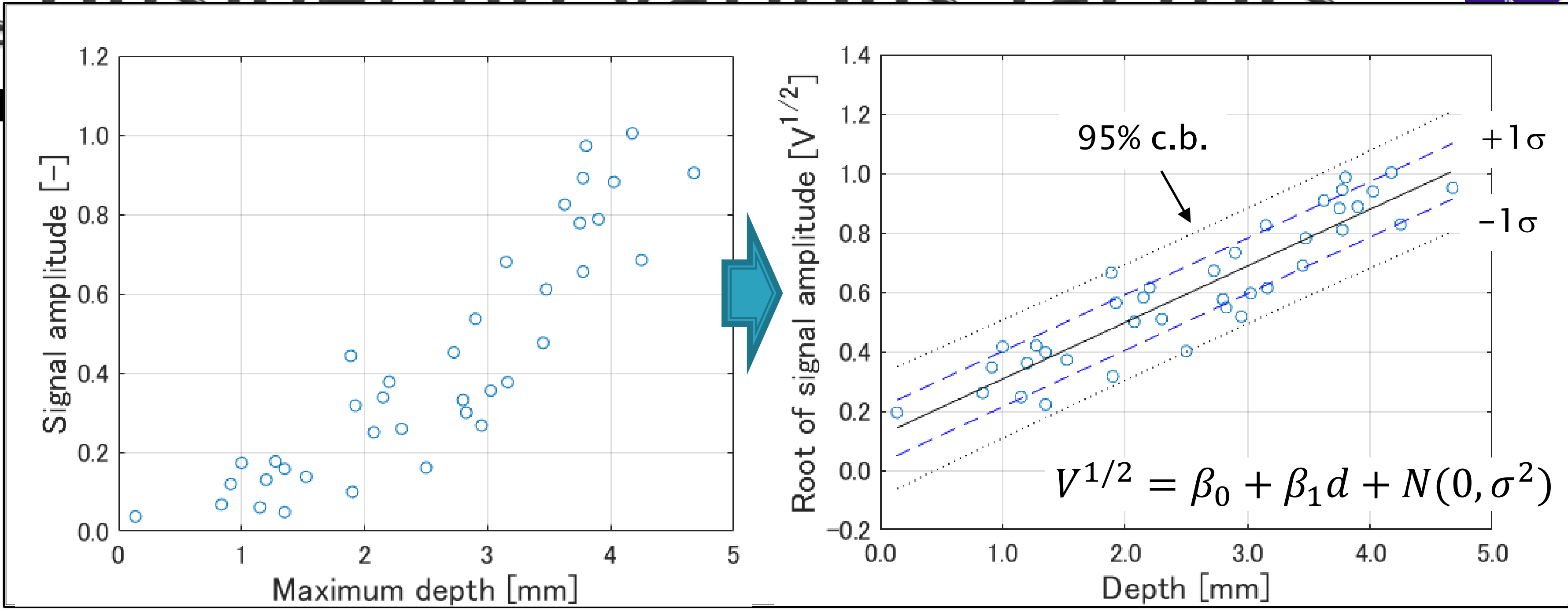


Artificial fatigue crack (38 cracks prepared)

1. Evaluating $\mathrm{V}(d)$, the distribution of signal due to a flaw with a depth of d.
2. Evaluating $\mathrm{F}(x)$, the effect of positional deviation on the decrease in $\mathrm{V}(d)$.
3. Evaluating not $\mathrm{P}(\mathrm{V}(d) > \mathrm{V}_{\mathrm{th}})$ but $\mathrm{P}(\mathrm{F}(x)\mathrm{V}(d) > \mathrm{V}_{\mathrm{th}})$ on the assumption $x \sim U(-0.5s, 0.5s)$.

IJAEM 64(2020), 11-18

Considering various factors



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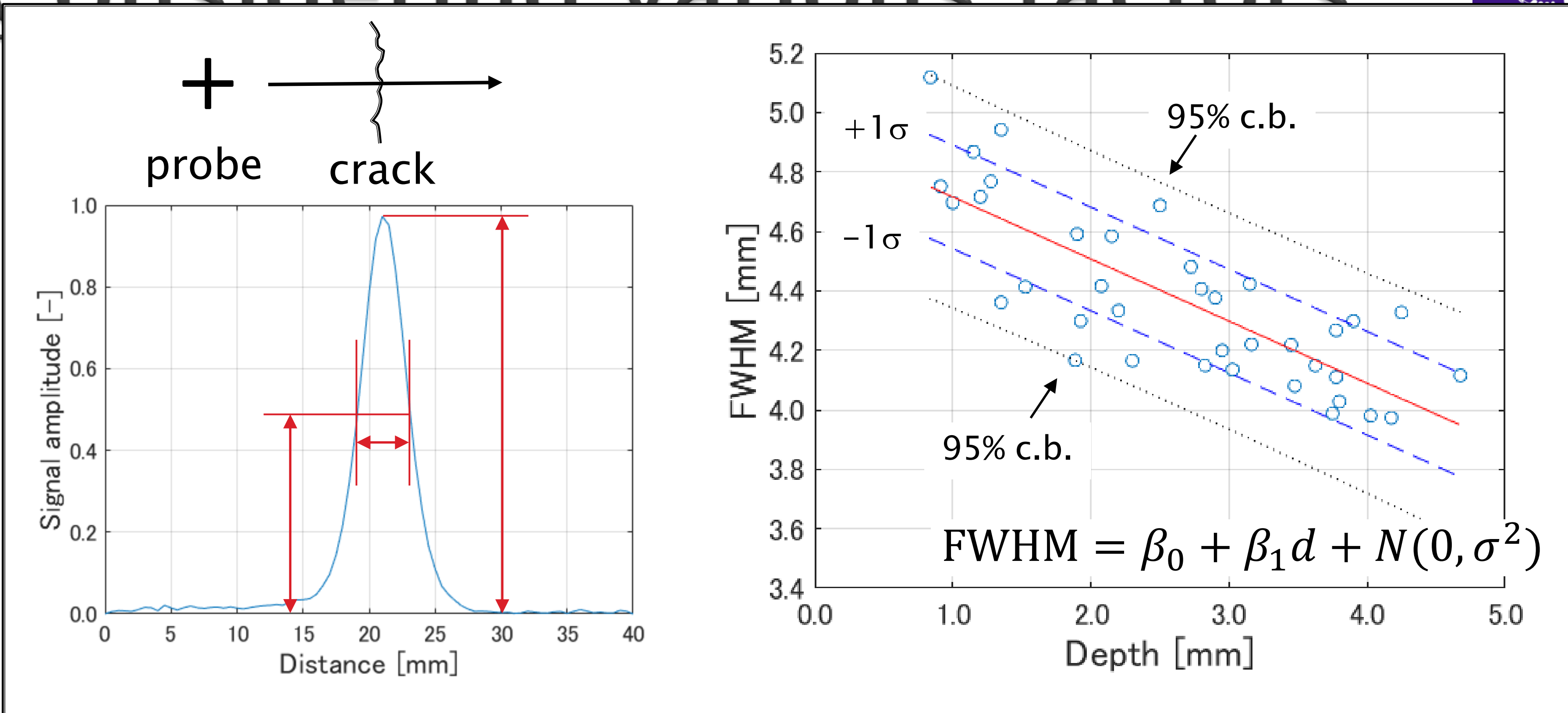

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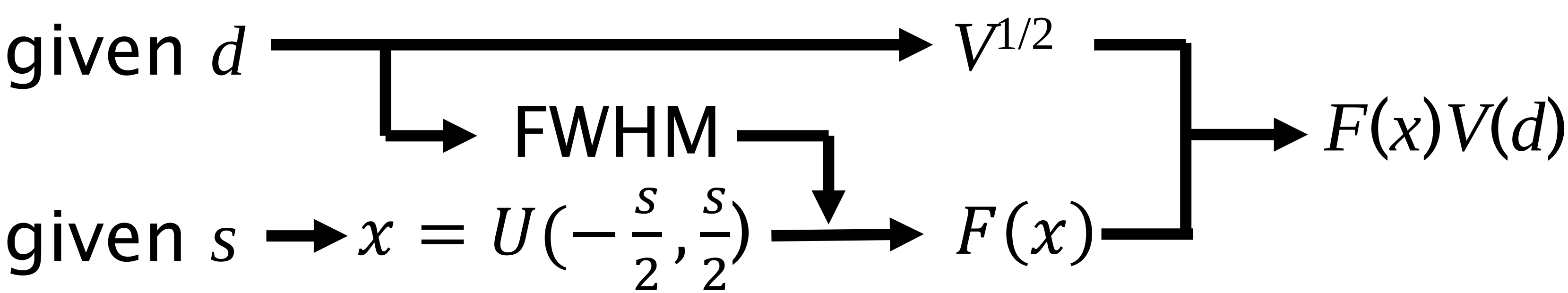

then, count the number of trials satisfying $F(x)V(d) \geqq \mathrm{V_{th}}$ by Monte-Carlo simulation

with a depth of d.

2. Evaluating $\mathrm{F}(x)$, the effect of positional deviation on the decrease in $\mathrm{V}(d)$.
3. Evaluating not $\mathrm{P(V(}d\mathrm{)> V_{th})}$ but $\mathrm{P(F(}x\mathrm{)V(}d\mathrm{)> V_{th})}$ on the assumption $x \sim U(-0.5s, 0.5s)$.

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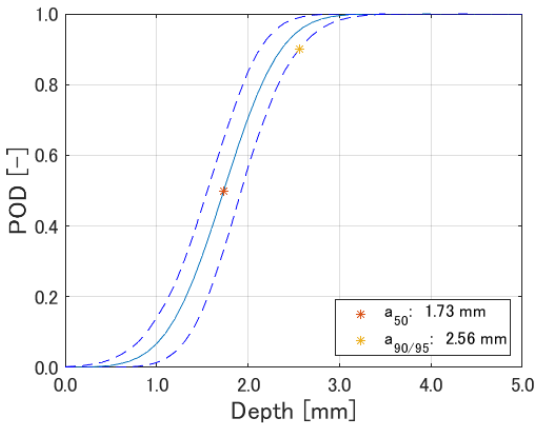
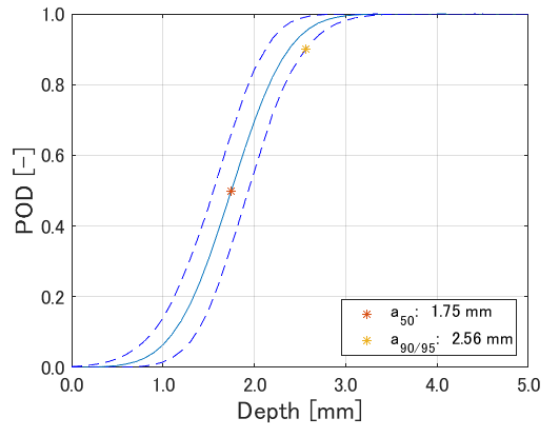
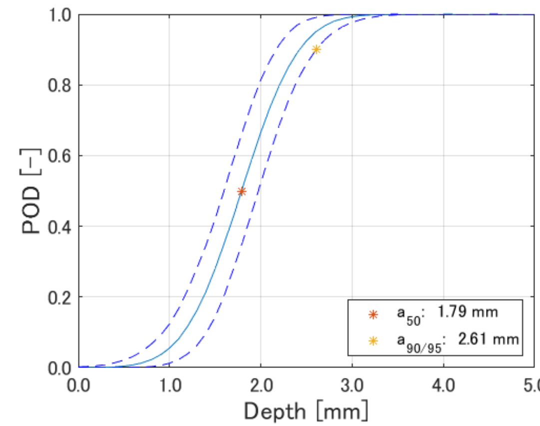


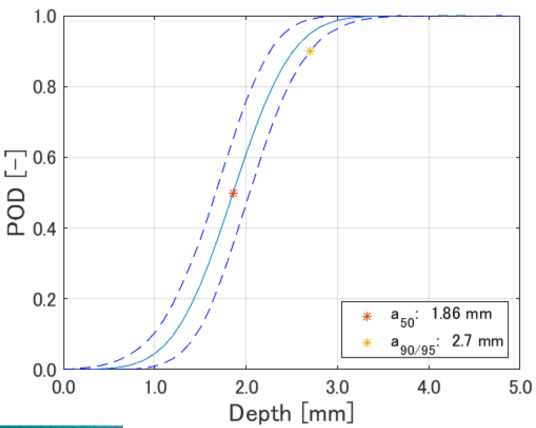
s=0 mm



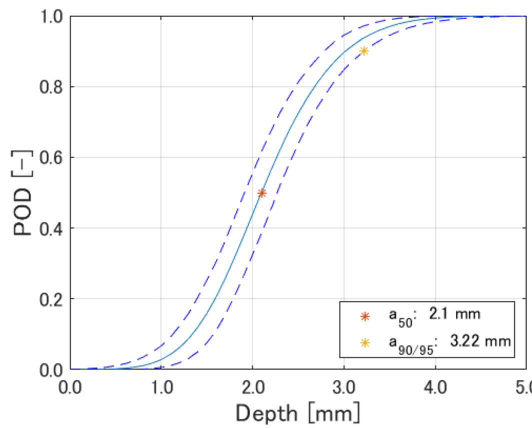
s=1 mm



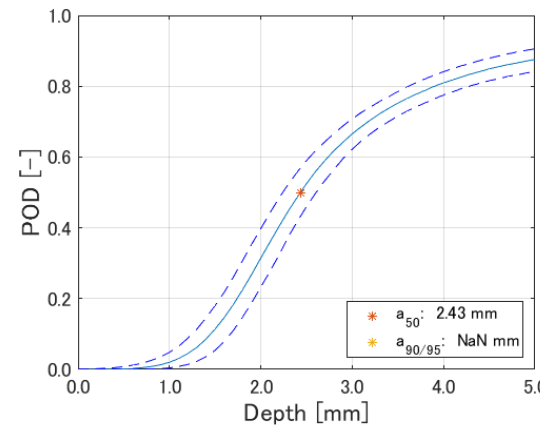
s=2 mm



s=3 mm



s=5 mm



s=7 mm

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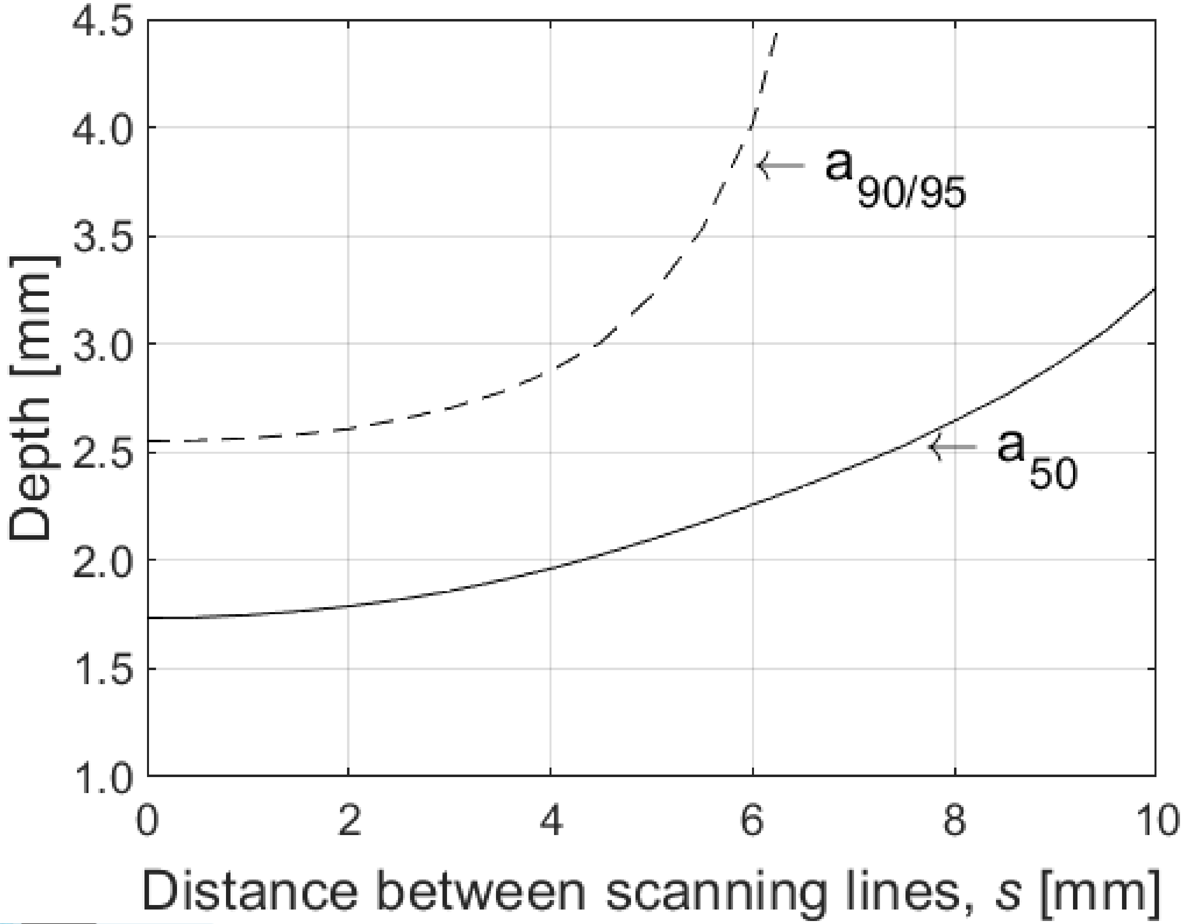

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Summary

- Quantifying the uncertainty of NDT&E is an important issue especially for optimizing the maintenance of large-scale structures.
- POD is a well-known, and well-established, method for quantifying the detection uncertainty. However, there are many challenges in its application.
- Quantifying evaluation uncertainty (not like ±4.4mm, but more quantitatively) is yet quite challenging.