Effect of fatigue crack orientation on the sensitivity of eddy current inspection in martensitic stainless steels

Hamid Habibzadeh Boukani, Ehsan Mohseni, Martin Viens

Département de Génie Mécanique, École de Technologie Supérieure (ETS)

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Outline

- **Introduction**
- **Experimental procedure and data analysis**
- **FE modelling and analysis**
- **Results and discussion**
- **Conclusions**

Introduction

Risk assessment programs

material properties

loading conditions

flaw characteristics

Damage tolerance models

Nondestructive testing (NDT) methods

Reliability quantification by probability of detection (PoD)

$\hat{a}$ **versus** a

Introduction

Martensitic stainless steels

- **High strength, hardness, and toughness**
- **Moderate resistance to corrosion**
- **Low cost**

→

- **Bearings**
- **Shafts**
- **Compressors**
- **gas generators**
- **valves**

→

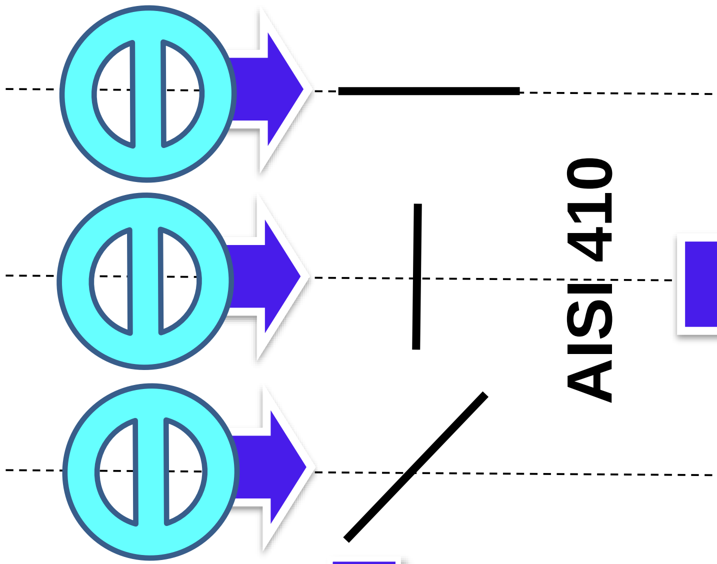
Principal degradation
FATIGUE

Eddy current testing (ECT)

widely used method for the detection of surface-breaking cracks

→ **High S/N** → **eddy current split-D probe**

Objectives



In the framework of a PoD study of automated ECT, $\hat{a}$ versus a at 3 different crack orientations with respect to the scan direction, as the influential parameters for the PoD evaluation, is studied

1st

Due to limitations in crack length interval in experiments

finite element modelling (FEM) is employed to expand the extent of our study to larger sizes and thus to gain a better insight into this observation

2nd

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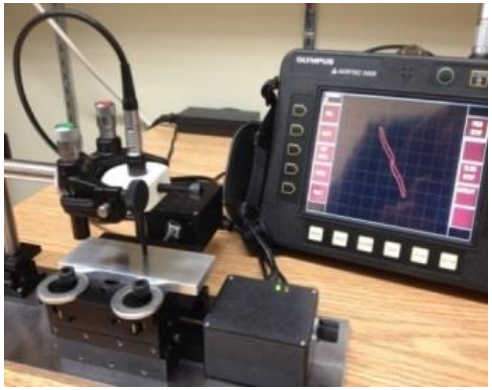
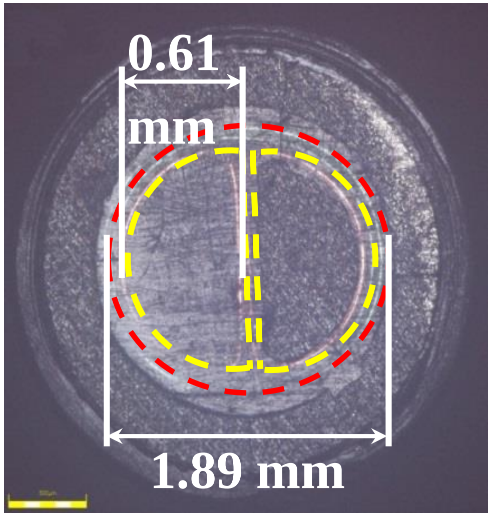
Test unit and samples used in the study

- **Nortec 500S along with a reflection differential split-D probe are used**
- **The probe's frequency range is 500kHz-3Mhz**
- **Starter flaws using electrical discharge machining (EDM) process on the surface of samples**
- **cyclically loaded in order to grow fatigue cracks out of the starter flaws.**
- **Samples containing fatigue cracks of 0.76 to 2.95 mm in length**
- **According to destructive tests, Their depth linearly increases with their length.**

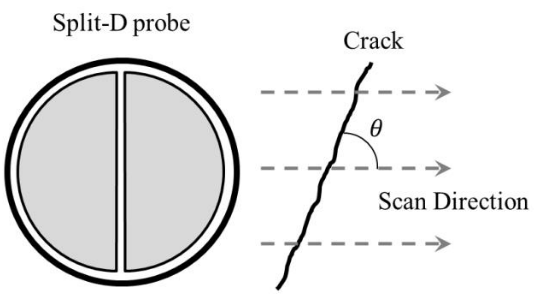




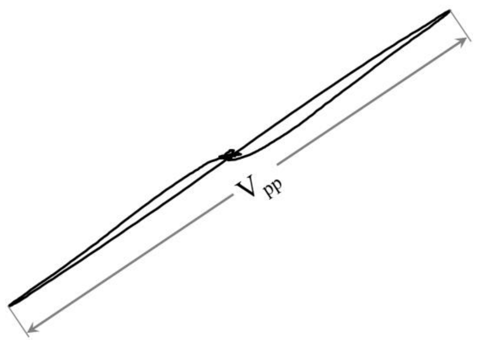
$$Depth = -0.0006 + 0.3475\, Length\, ,\, r^2 = 0.9845$$

ECT automated scans and signal analysis

- **Calibration on a reference flaw:**
  - **device gain**
  - **the impedance plane angle**
  - **perpendicularity of the probe to the sample's surface**



- **Initial lift-off of 0.03 mm**
- **Raster scans at frequencies of 500 kHz and 1 MHz**
- **Scan index of 0.5 mm**
- **Gains are compensated for each axis**
- **signals' characteristics are extracted**
- **ECT signal length (V_{pp}) : main parameter under study**



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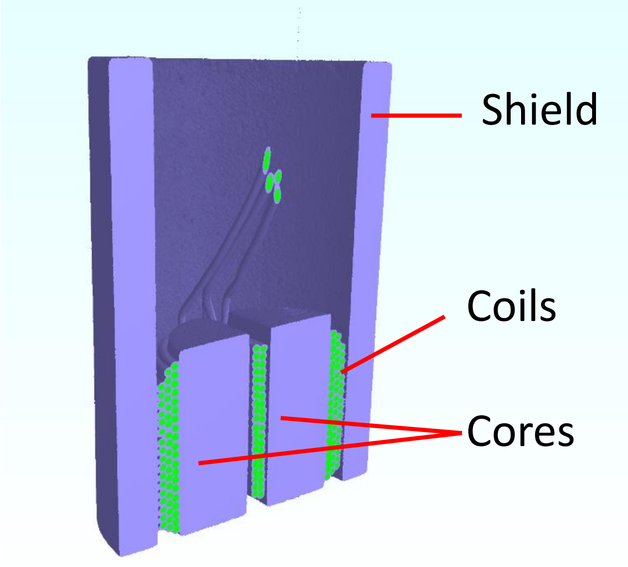
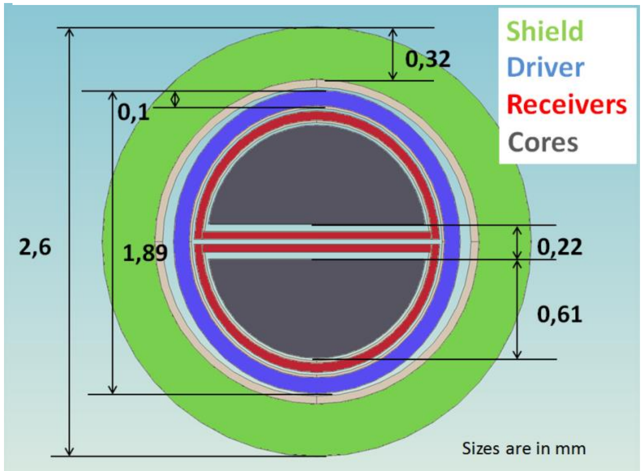
3D model and material properties used for the assembly of the probe and sample

- **3-D modeling in Comsol multyphysics:**
  - **A half-scaled CAD model for orientations of 0° and 90° owing to their plane symmetry**
  - **Full model for orientation of 45°**
  - **Cracks represented by semi-elliptical notches having 0.02 mm opening**
  - **Dimensions of the probe's Interior components according to X-ray tomography reconstruction**
  - **Initial lift-off of 30 µm**



- **Material properties:** **measurements and data sheets**

Component	Relative permeability	Electrical conductivity
Cores and shield	2500	1(S/m)
Sample	300	1.9e6(S/m)



Physics, mesh and solver

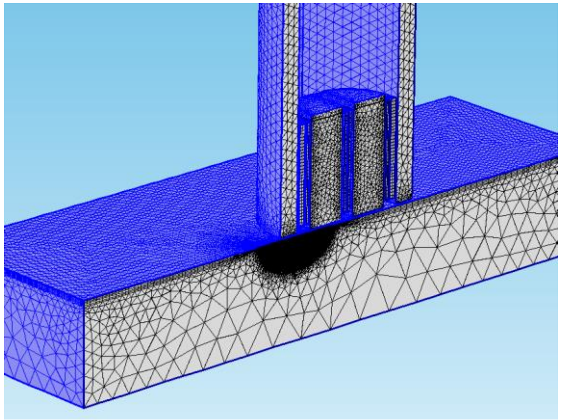
- **Physics:**
  - **MF physics within AC/DC module**
  - **Multi turn domains for coils**
  - **Magnetic insulation boundary condition for encompassing air domain**

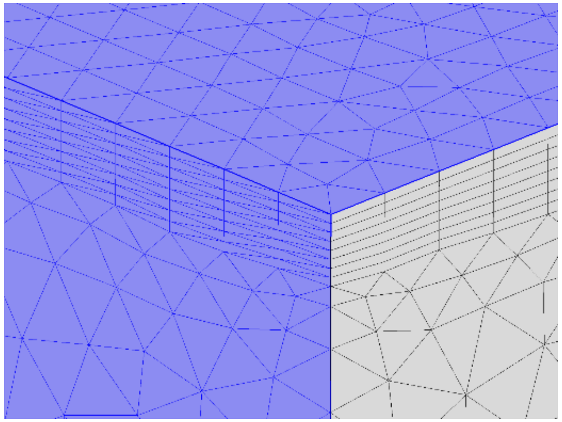
$$(\nabla \times (\nabla \times \boldsymbol{A}))/\mu_0\mu_r + (j\sigma\omega - \omega^2\varepsilon_0\varepsilon_r)\boldsymbol{A} = \boldsymbol{J}_e \quad j = \sqrt{-1}$$

- **Mesh:**

$$\Delta \boldsymbol{Z} = (\boldsymbol{V}_{R2} - \boldsymbol{V}_{R1}) / \boldsymbol{I}_D$$

  - **Second order tetrahedral elements**
  - **8 boundary layer mesh on the surface of the sample**
  - **Each layer has the thickness of first standard penetration depth**
  - **Finer elements for the notch geometry**



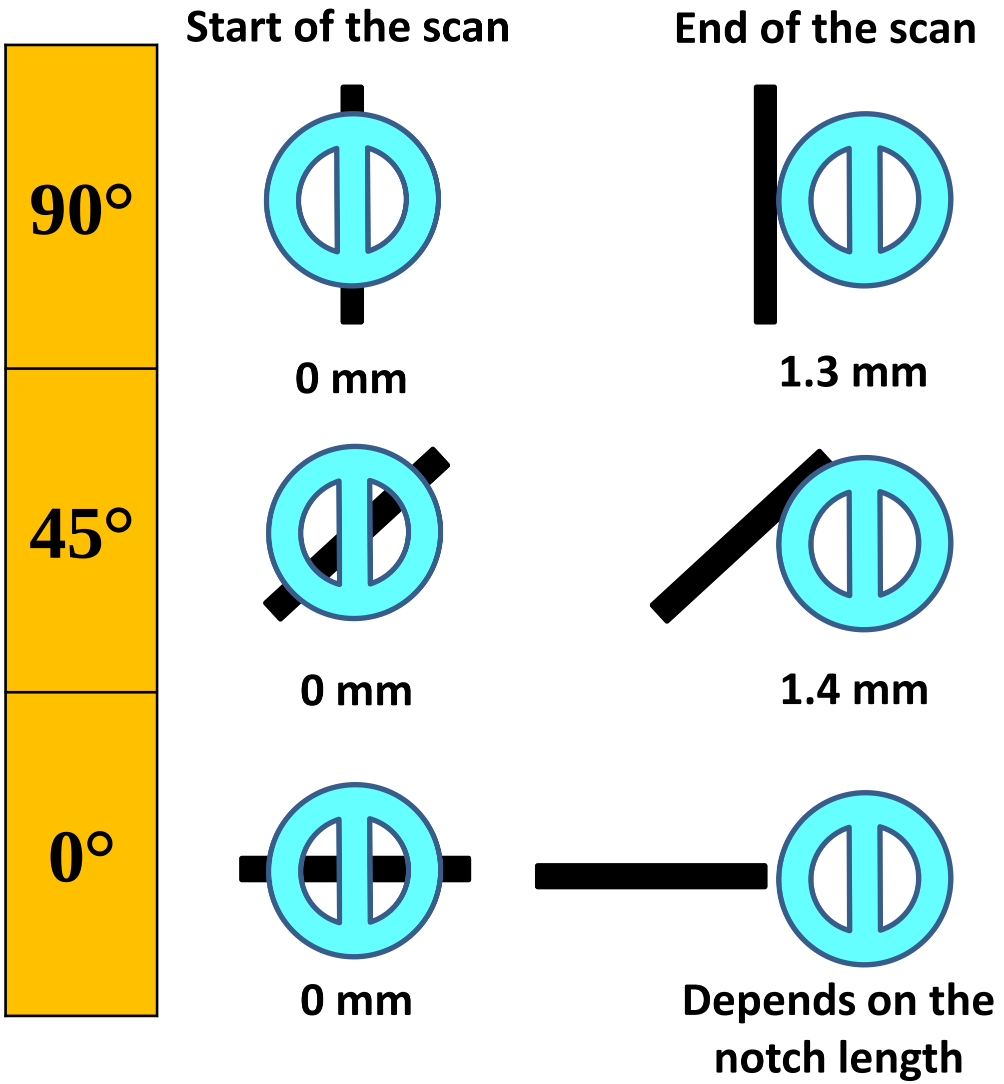


- **Solver:**
  - **Iterative stationary solver**

Details of simulated scans

- 1.3 mm displacements of the probe along the scan path
- Probe's displacement increments of 0.1 mm
- Probe is centered by the notch at the beginning of the scan

Orientation	Notch length Variations(mm)	Steps (mm)
90°	2 - 6	0.5
45°	1.5 - 4.5	0.5
0°	0.5 - 3	0.5



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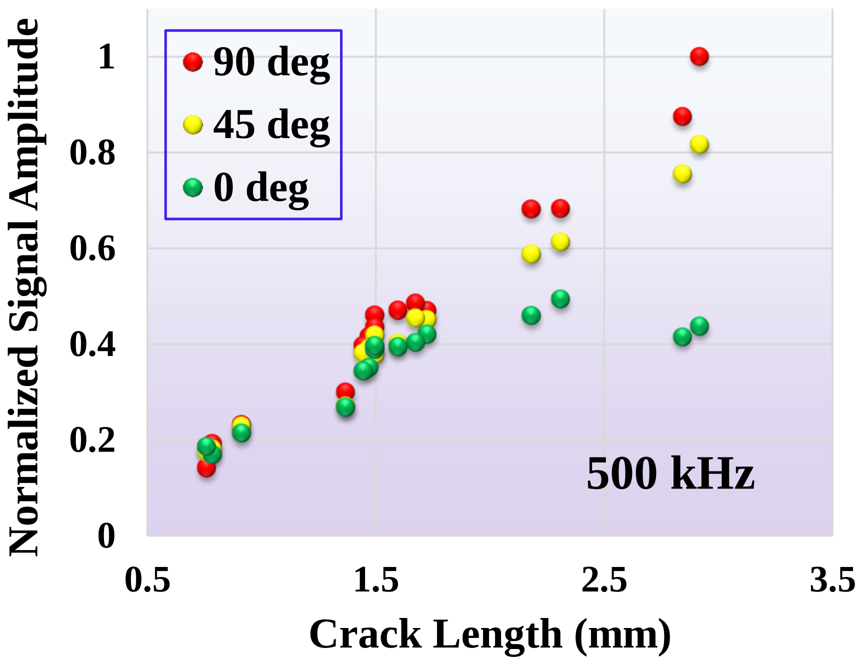
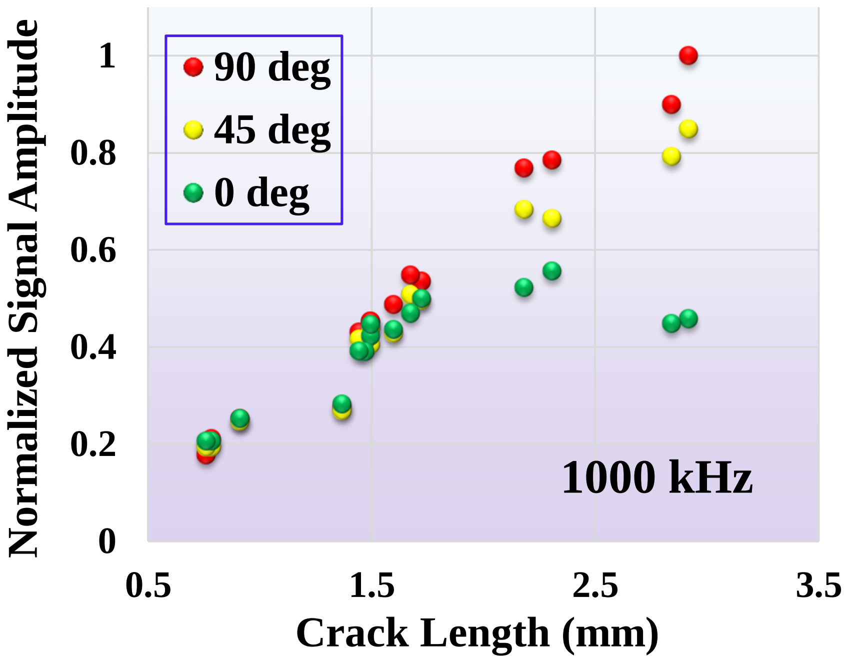
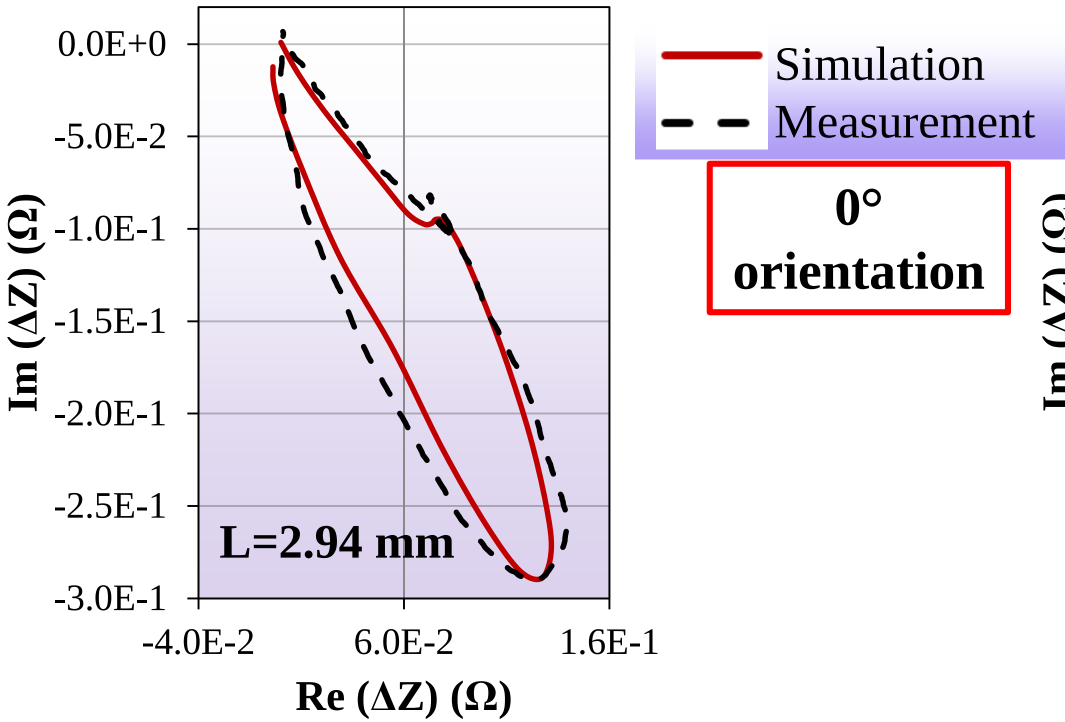
Measured signal amplitude versus crack length



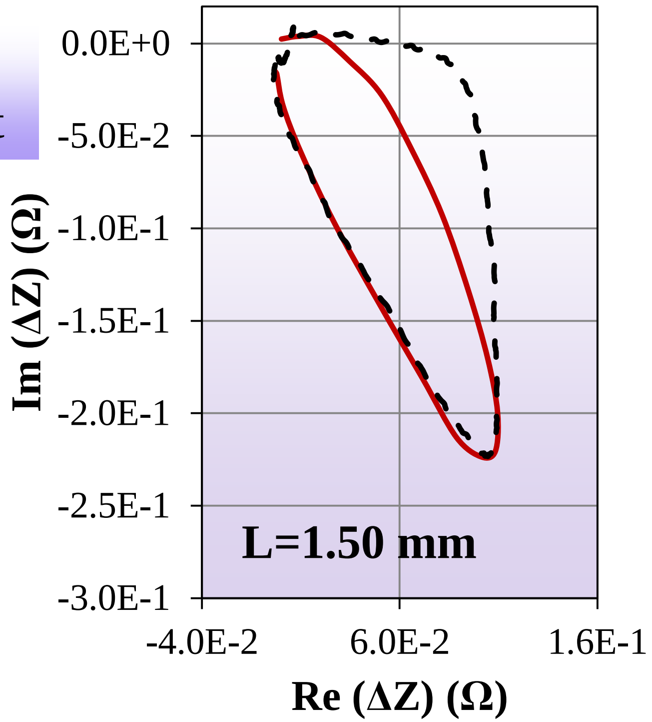


- **The same behaviour at both frequencies**
- **Amplitude is independent of the orientation for crack length below 1.8 mm**
- **Amplitude changes versus length variation becomes plateau after 1.8 mm for 0° orientation**

Verifying simulated signals by comparing them to measurements



0° orientation

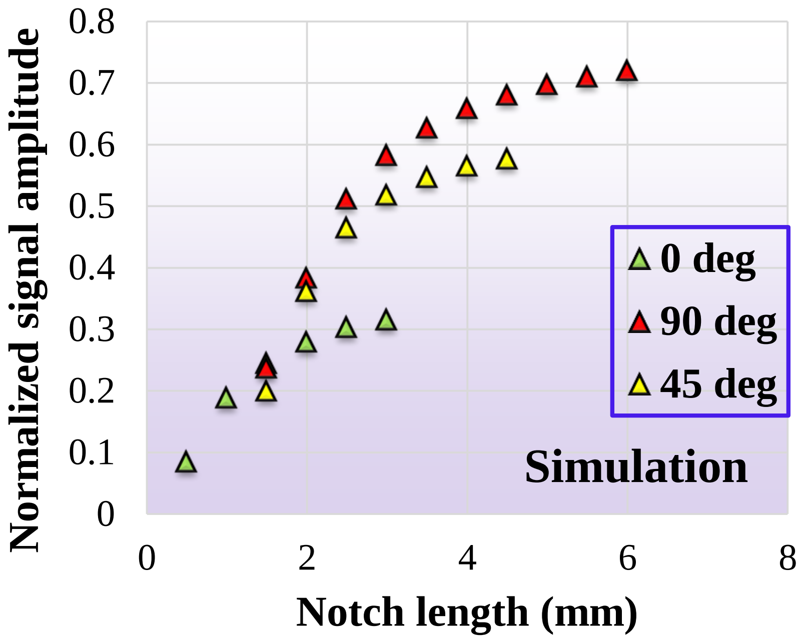


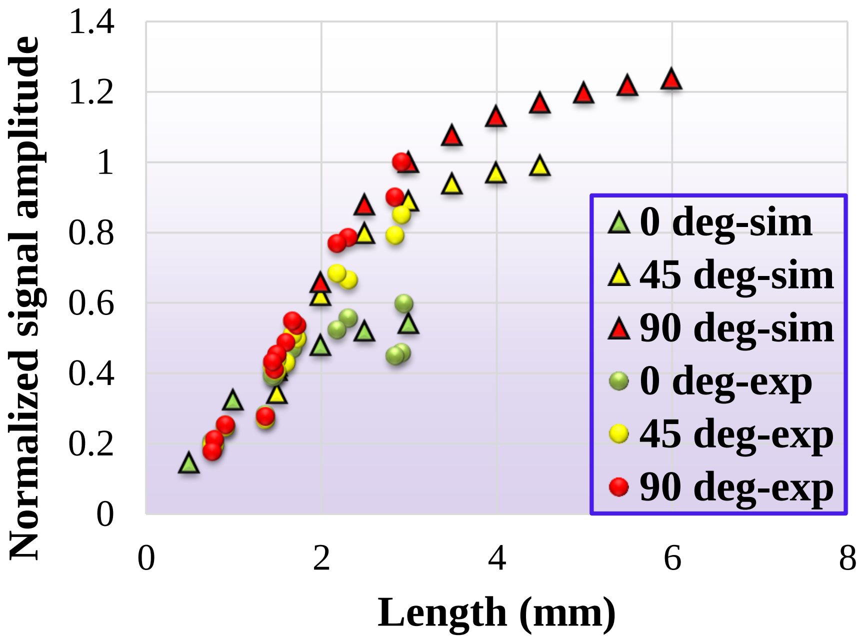
Good amplitude agreement

Shape discrepancies :

- **Deviation of notch geometry from the fatigue crack**
- **Material properties**
- **Probe manufacturing imperfections**

Simulated and measured signal amplitude versus crack length

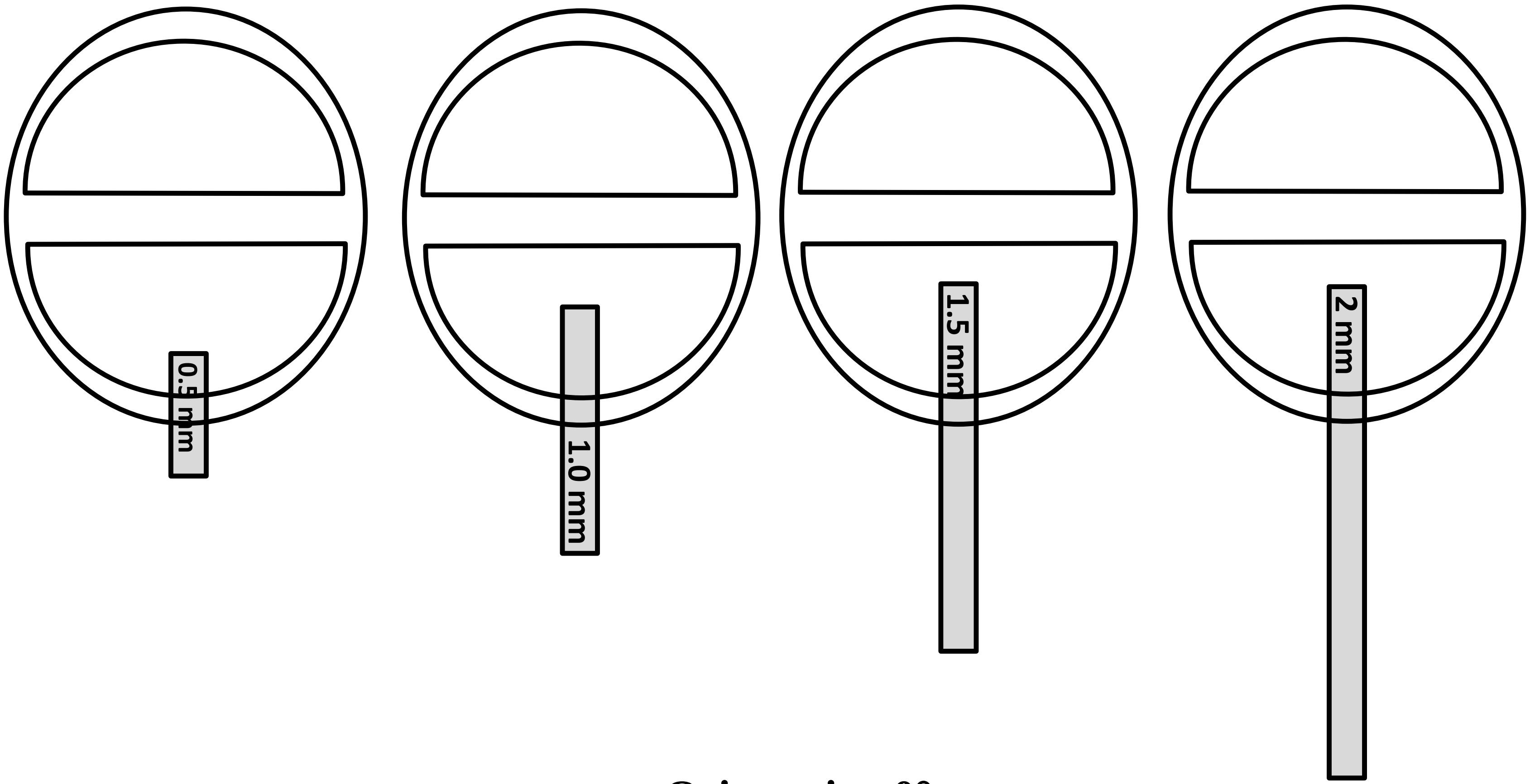




For each orientation, Amplitude variations becomes less than 5 % after a certain notch length:

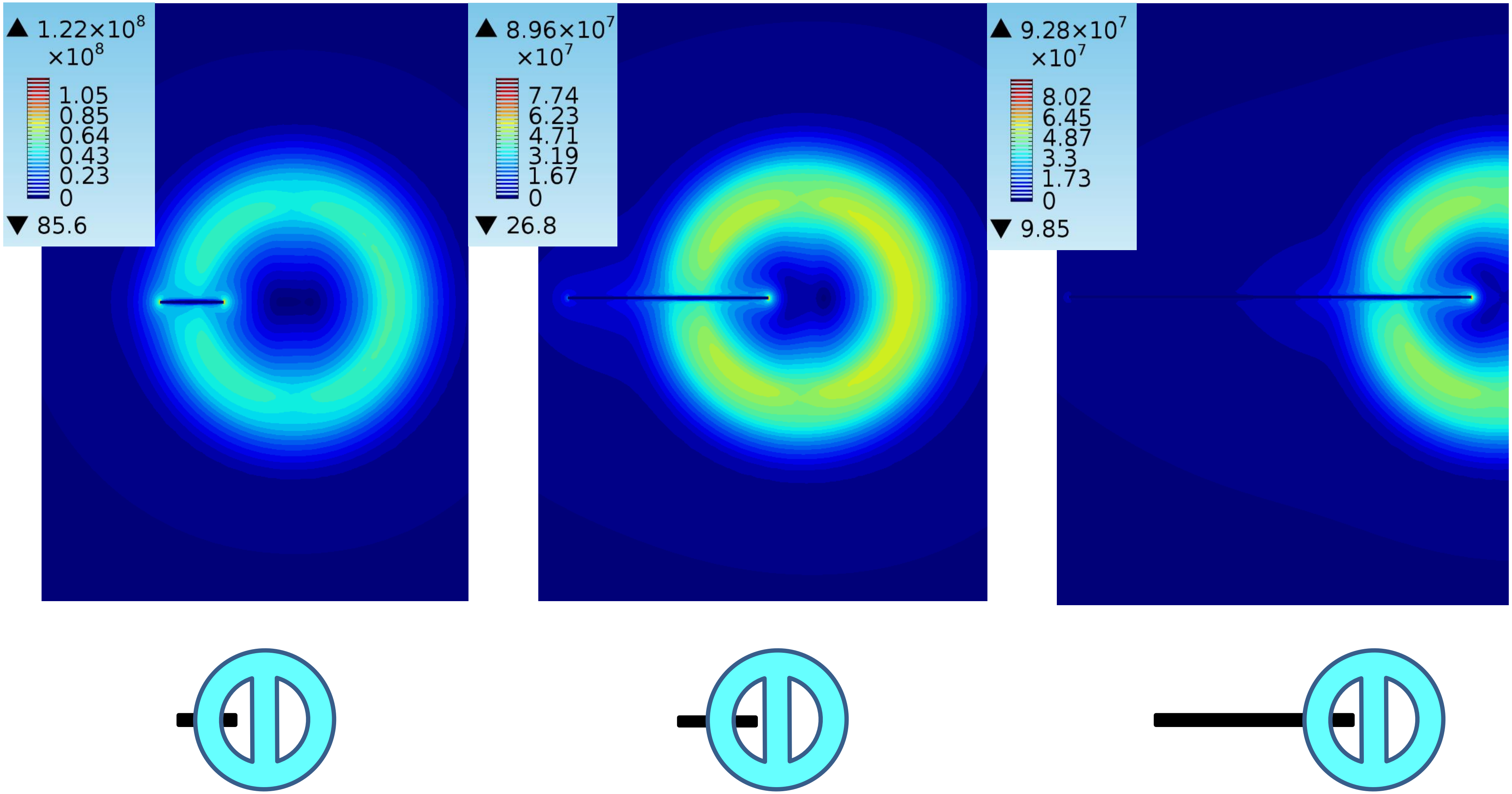
- **0°- 2.5 mm**
- **45°- 3.5 mm**
- **90°- 4 mm**

Relative position of the probe and notches at which the amplitude is maximum



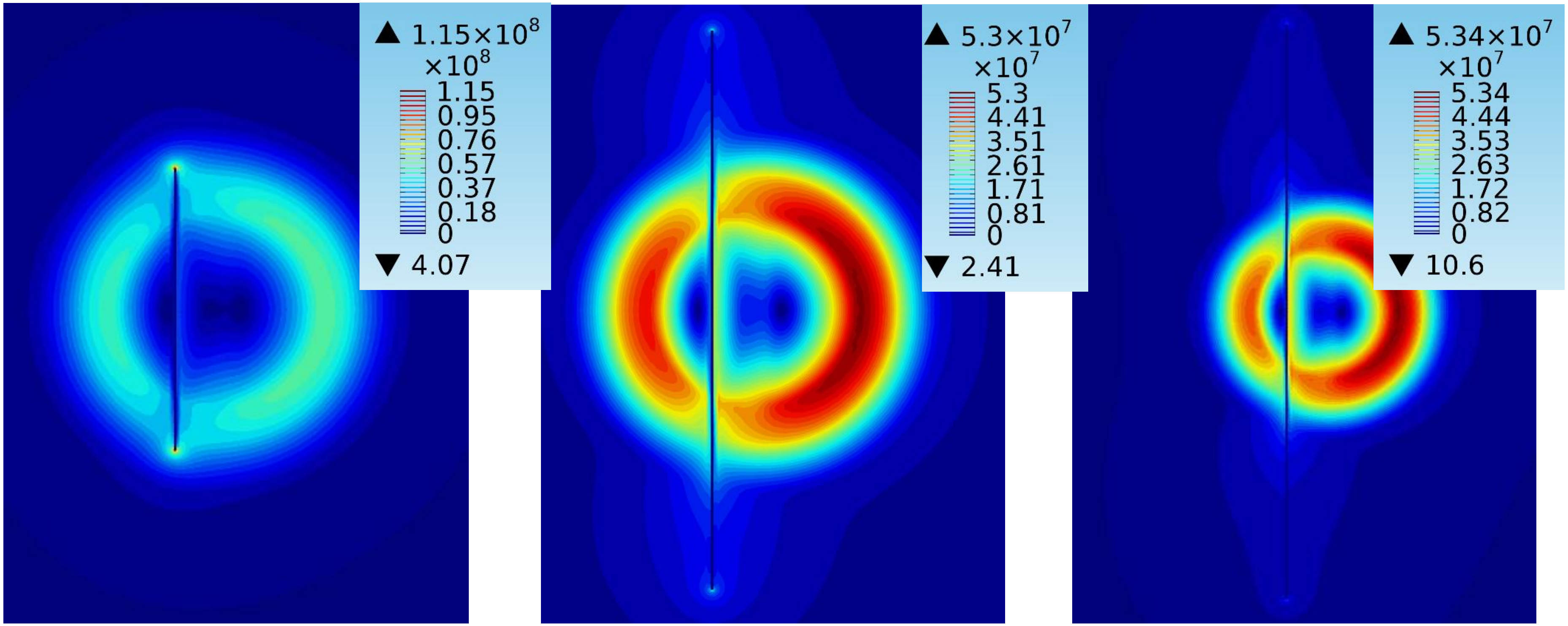
Orientation 0°

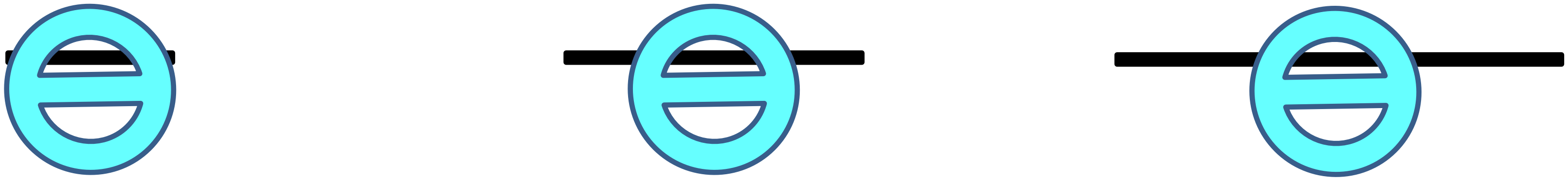
Induced current density distribution as the notch length varies - 0°



Notch length = 0.5 mm **Notch length = 1.5 mm** **Notch length = 3 mm**

Induced current density distribution as the notch length varies - 90°





Notch length = 2 mm **Notch length = 4 mm** **Notch length = 6 mm**

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Conclusions

- Depending on the flaw orientation, the signal amplitude increases with the crack length up to a critical (flaw length)/(drive coil diameter) ratio (L/D) which is specific to the flaw orientation.
- This critical ratio grows as the orientation increases from 0° to 90°
- The variation of the signal amplitude as the crack length increases is almost independent of the crack orientation until a L/D value equal to the unity and then the slope of amplitude versus crack length variations becomes orientation dependent.
- Accordingly, the probability of detection of fatigue is almost independent of crack orientation once the L/D ratio is below the unity.
- The results of our FEM study show a good agreement with the measurements outcome in terms of amplitude. Therefore, this model is a reliable means to carry out model-based studies of probability of detection.

Thank you for your attention