Sensitivity of eddy current signals to probe's tilt and lift-off while scanning semi-elliptical surface notches
A finite element modeling approach

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Outline

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

Introduction

NDT in transportation industry

Of high importance in Aerospace → Methods evolving due to the sensitivity of application

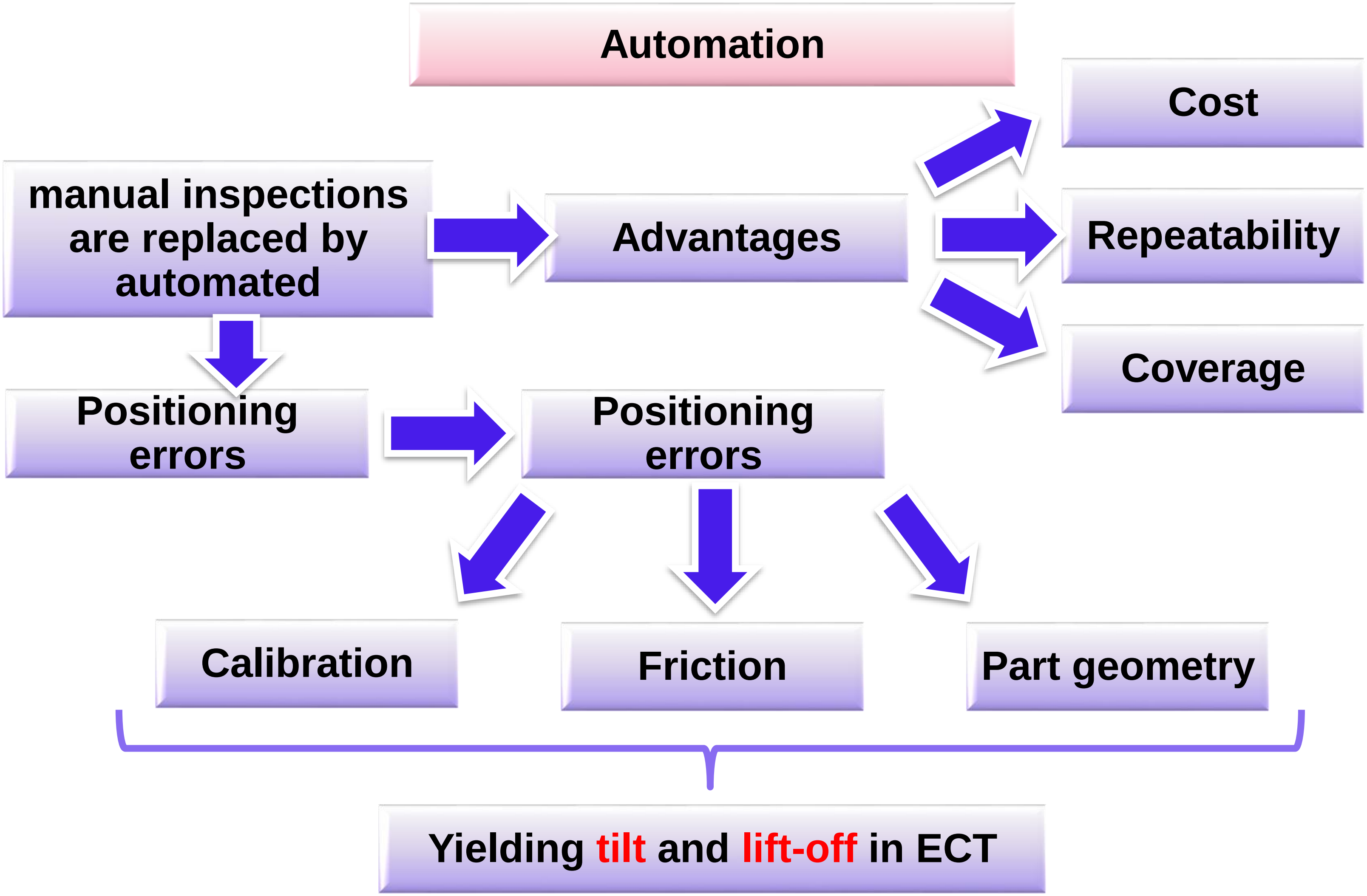
Eddy current testing (ECT)

widely used method for detection of surface-breaking cracks

- Fuselage
- Wheel
- Engine

→ Fatigue cracks → Detect at their early stages → Demanding High S/N → Split-D differential probes

Introduction



Objectives

1

- **Signals acquired from automated ECT robotic scans are fed into an artificial intelligence inversion algorithm for training**

2

- **automated ECT robotic scans are always accompanied by small tilt and lift off variations of probe**

3

- **to explore the effect of small tilt angles and lift-off of the probe on the recorded signals**

- ❑ **Accounting for the errors associated with lift-off and tilt**
- ❑ **Find the uncertainty introduced in inversion**

Summary of the study

FEM

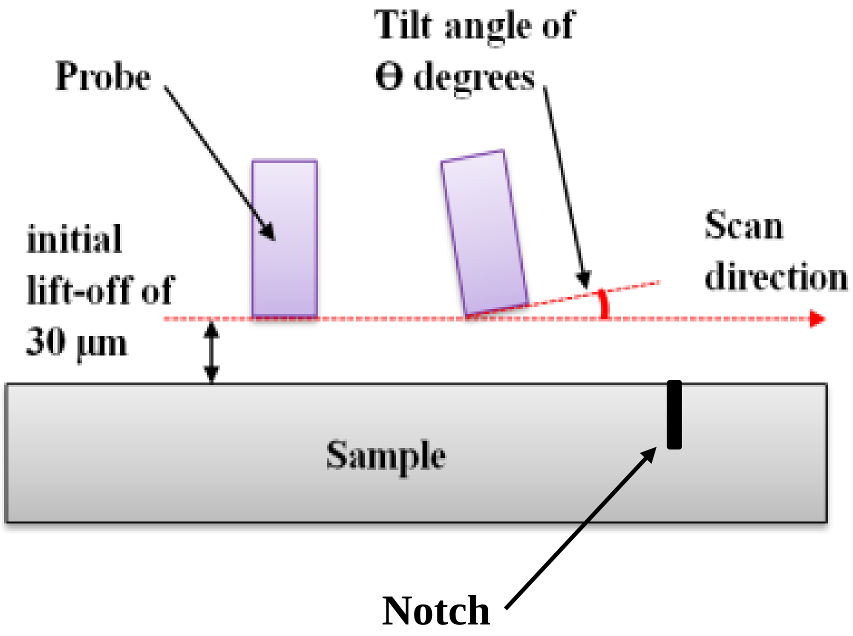
Effect of probe lift-offs of 30, 60, 80, 100, 120 and 140 µm on the ECT signal is studied

Effect of probe tilt angles of 1°, 2° ,3° and 4° on the ECT signal is studied

Validation

Effect of lift-offs of 30, 100 and 140 µm on the ECT signal is measured

Effect of probe tilt angles of 2° and 4° on the ECT signal is measured



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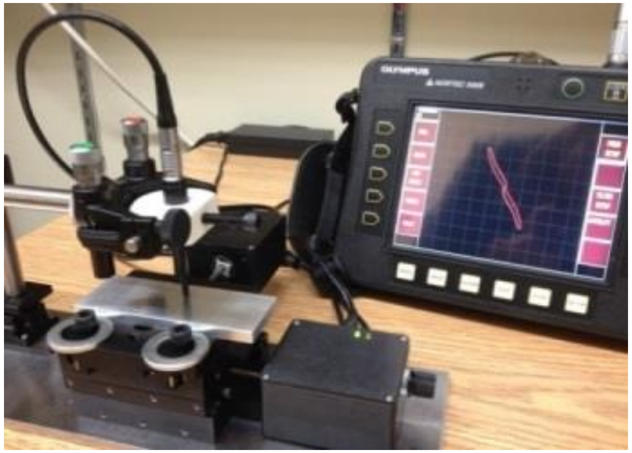
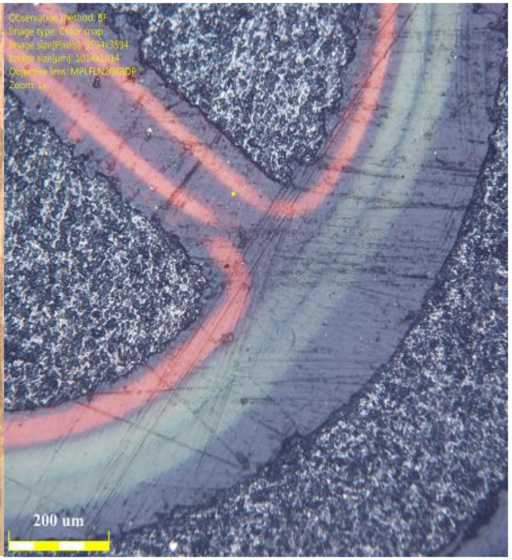
Test unit and samples used in the study

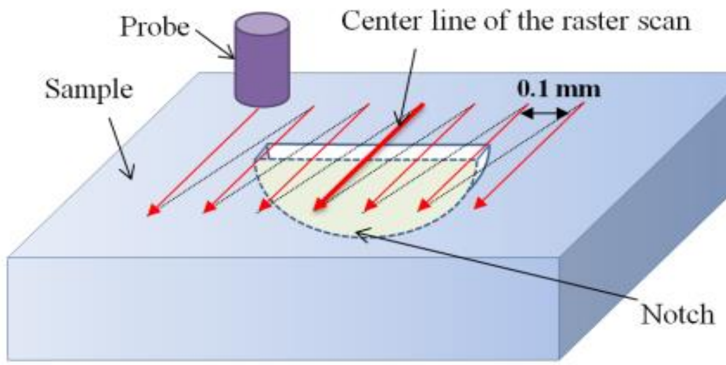
- **Nortec 500S along with a reflection differential split-D probe are used**
- **The probe's frequency range is 500kHz-3Mhz**
- **Initial probe lift-off of 30 µm during all scans**
- **frequency of 500 kHz**
- **Calibration on a reference flaw for perpendicularity of the probe to the sample's surface**



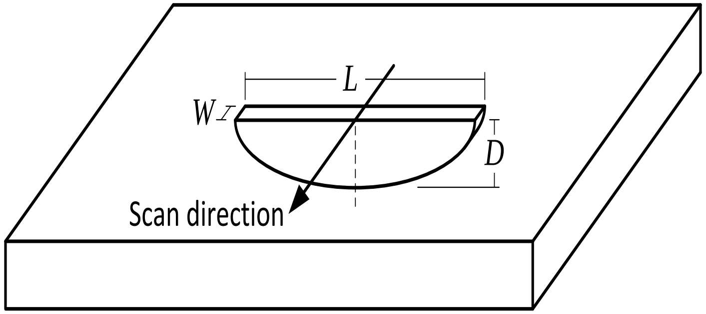


ECT automated scans

- **aluminum-7075 sample containing 3 semi-elliptical electrical discharge machined (EDM) notches**
- **Raster scan with a scan index of 0.1 mm**
- **Lift-offs of 30, 100 and 140 µm**
- **Tilt angles of 2˚ and 4˚**
- **ECT signals are recorded by a LabVIEW® application**
- **Gains are compensated for each axis**



Notch	Length, L (mm)	Depth, D (mm)	Opening, W (mm)
A	2.84	1.11	0.1
B	1.62	0.63	0.1
C	0.81	0.31	0.1



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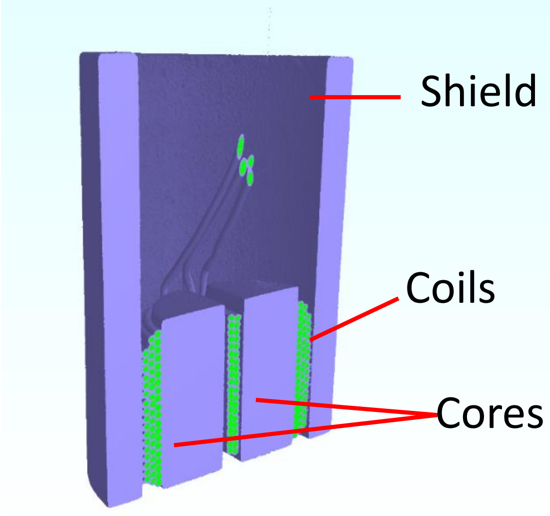
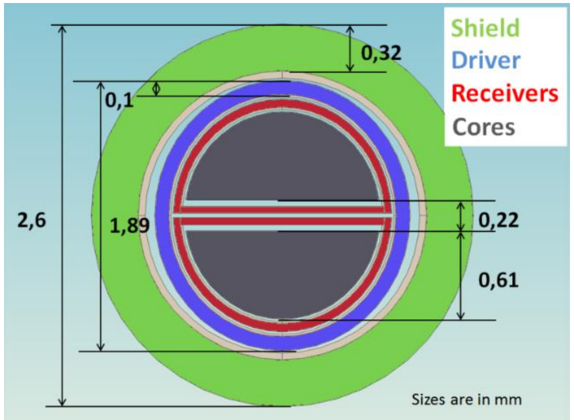
3D model, material properties and physics in FEM

- **3-D modeling in Comsol multyphysics:**
  - **A half-scaled CAD model owing to the plane symmetry**
  - **Dimensions of the probe's Interior components according to X-ray tomography reconstruction**
  - **Initial lift-off of 30 µm**
- **Material properties: data sheets**
- **Physics:**
  - **MF physics within AC/DC module**
  - **Multi turn domains for coils**
  - **Magnetic insulation boundary condition for encompassing air domain**

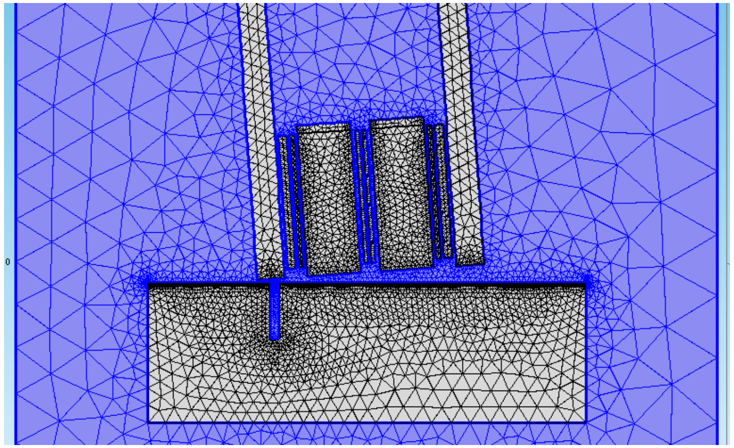


Component	Relative permeability	Electrical conductivity
Cores and shield	2500	1(S/m)
Sample	1	1.87e7(S/m)

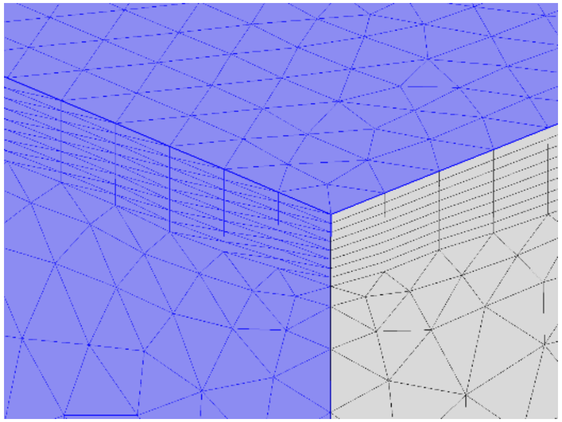


Mesh and solver

- **Mesh:**
  - **Second order tetrahedral elements**
  - **8 boundary layer mesh on the surface of the sample**
  - **Each layer is half of the thickness of first standard penetration depth (δ)**
  - **Finer elements for the notch geometry**



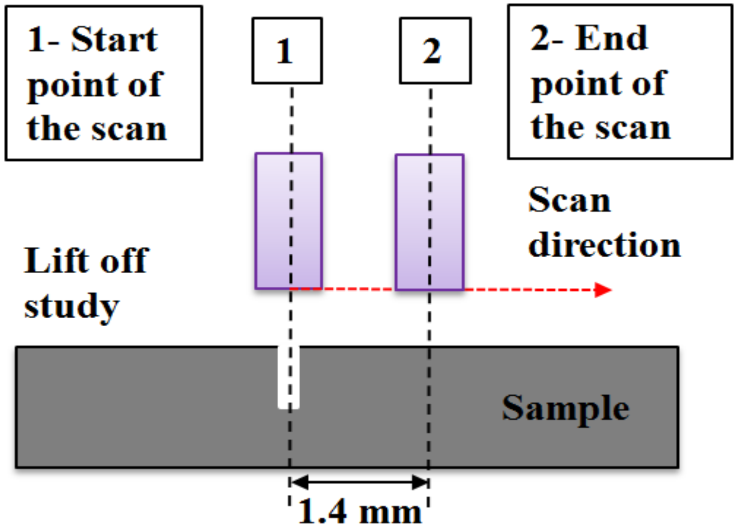
- **Solver:**
  - **Iterative stationary solver**



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

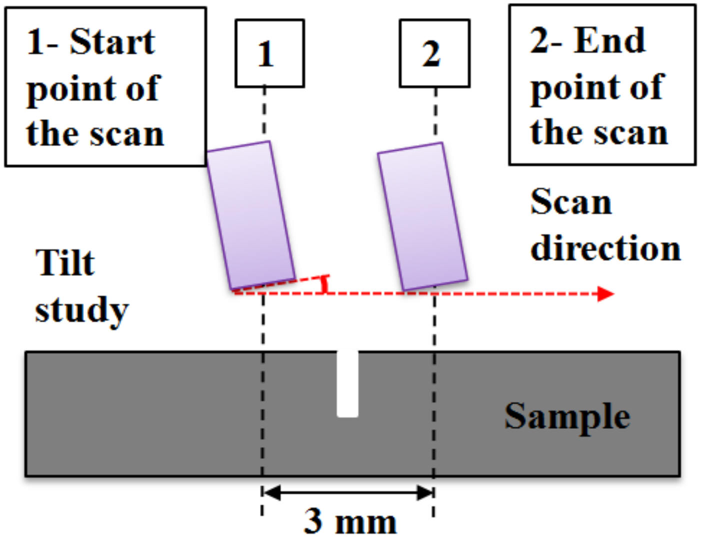
$$\Delta \boldsymbol{Z} = (\boldsymbol{V}_{R2} - \boldsymbol{V}_{R1}) / \boldsymbol{I}_D$$

Details of simulated scans



lift-offs of 30, 60, 80, 100, 120 and 140 µm

- **Half of scan is simulated**
- **Half of 8-shaped signal**



tilt angles of 1°, 2° ,3° and 4°

- **Full scan is simulated**
- **8-shaped signal**

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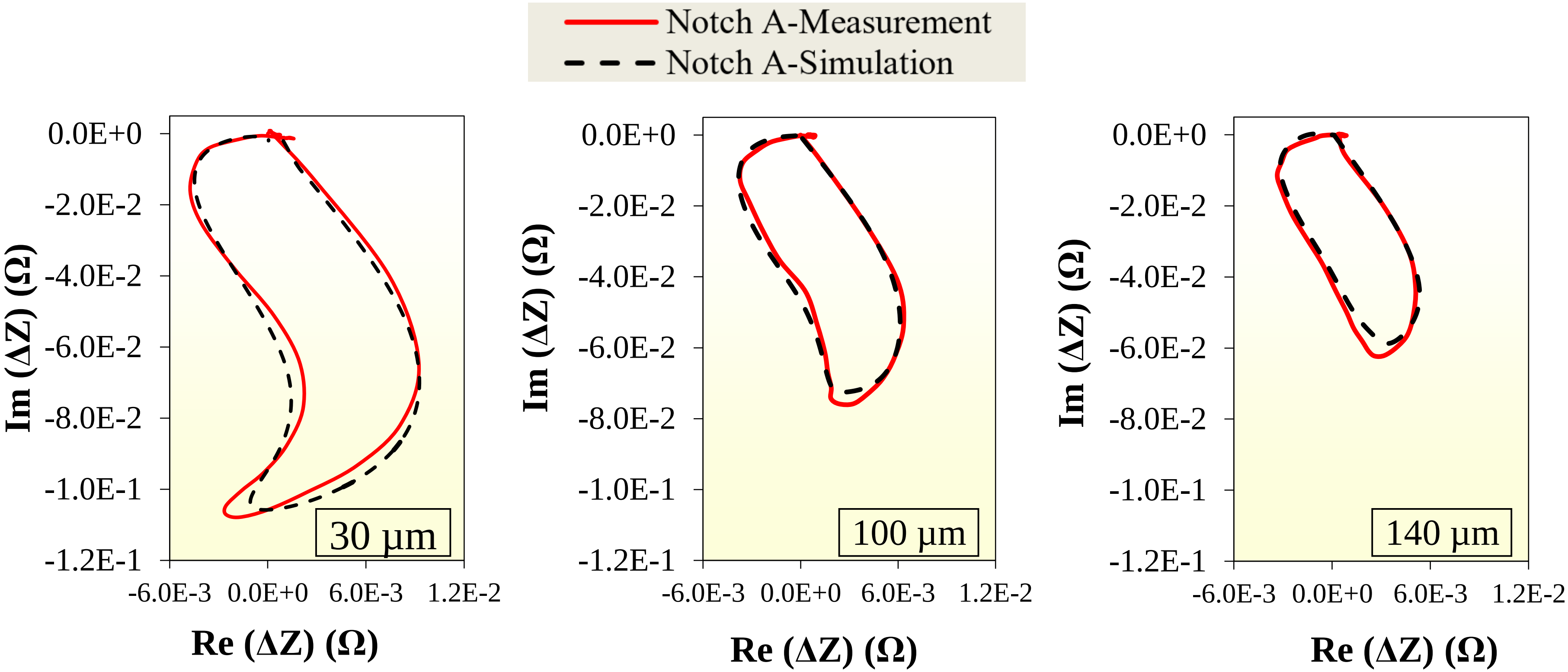
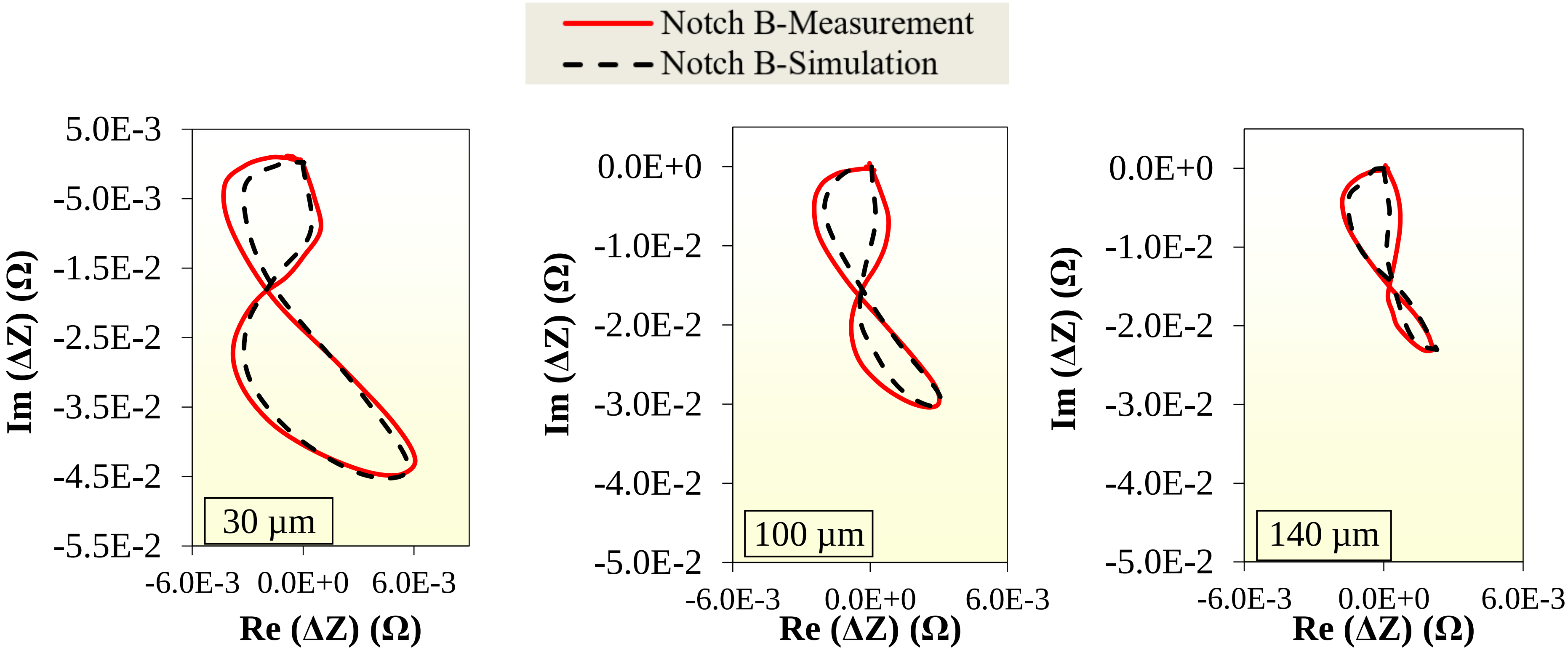
Validation of lift-off signals for notch A



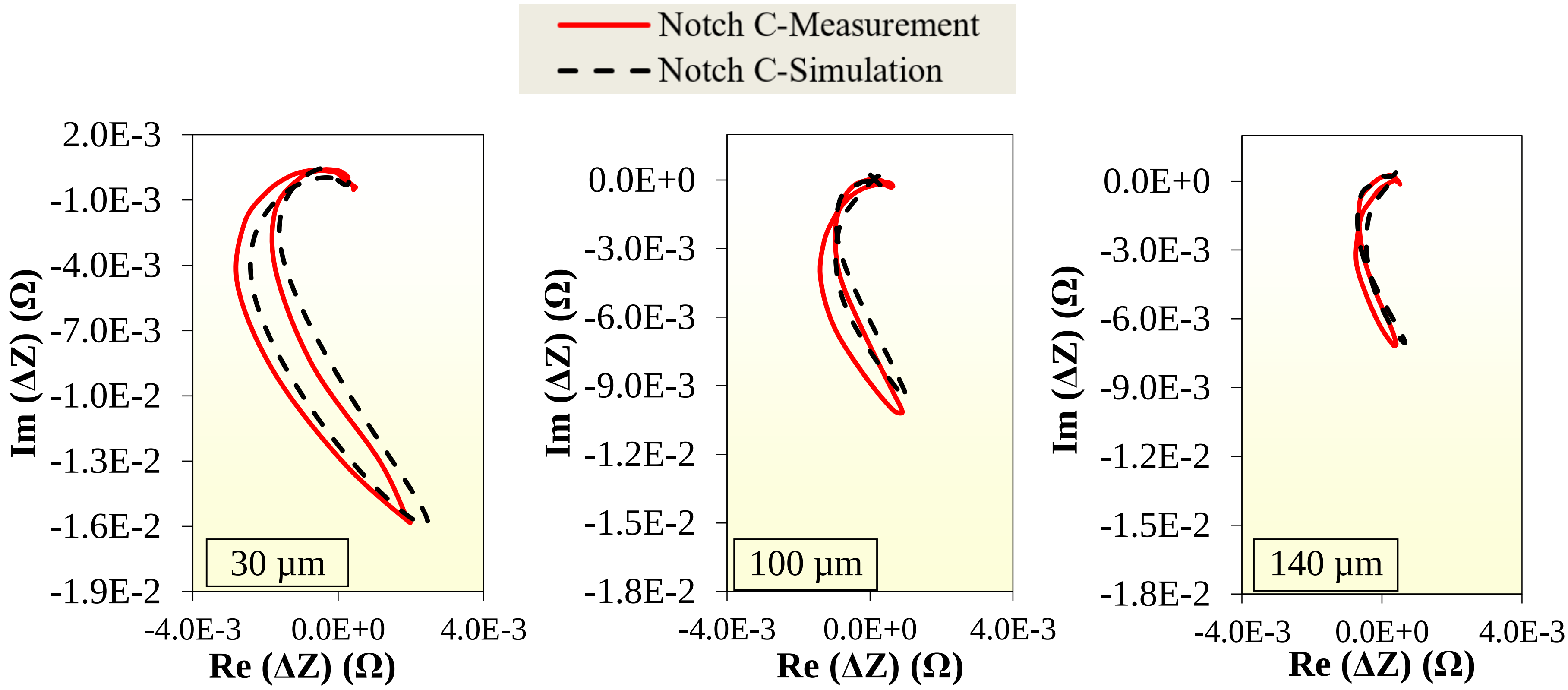
- ❑ **Signal shape matching is good**
- ❑ **Small discrepancies observed in amplitude**
- ❑ **One point initial lift-off calibration causes impedance discrepancies**

Validation of lift-off signals for notch B



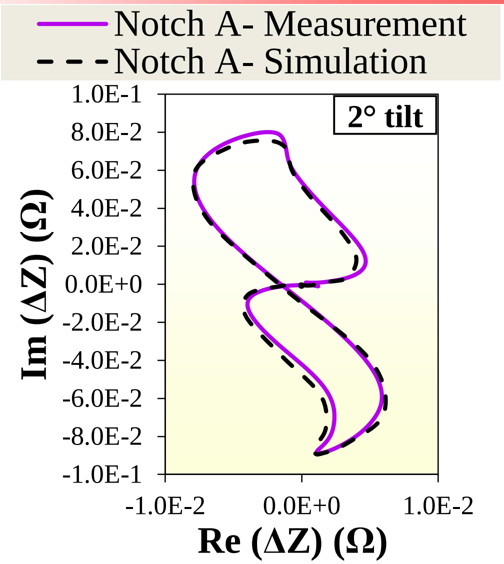
- ❑ **Amplitude matching is satisfactory**
- ❑ **Small shape discrepancies**
- ❑ **deviations of the real notch geometry from the one used in simulations**

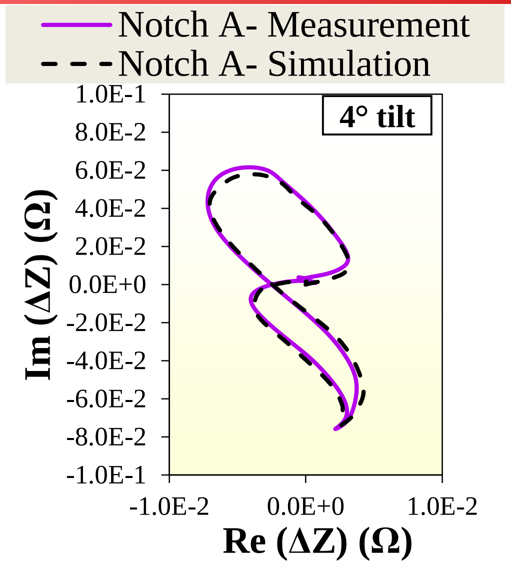
Validation of lift-off signals for notch C

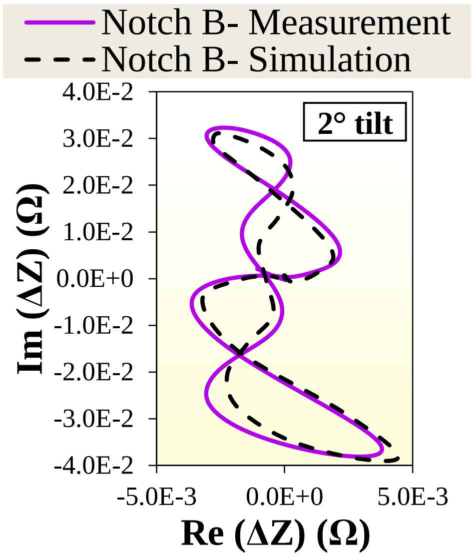


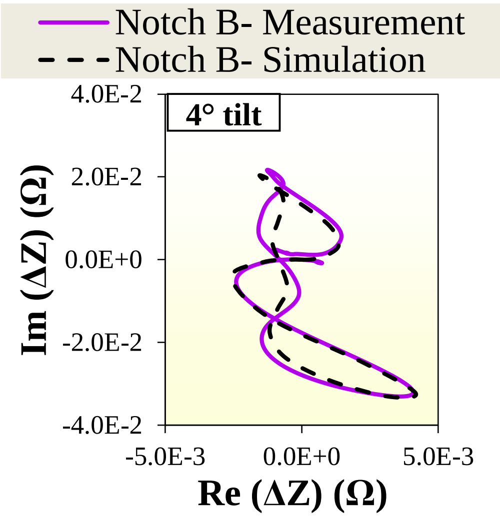
- ❑ **Signal shape and amplitude matching is good**
- ❑ **Signal is slightly displaced**
- ❑ **Nulling process in the simulations + Elevated gains in measurement**

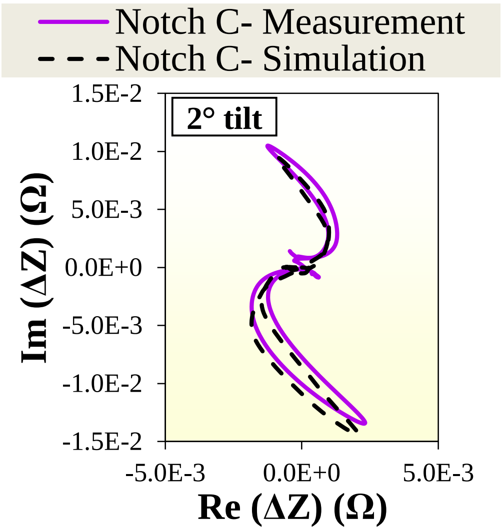
Validating signals for notch A, B and C

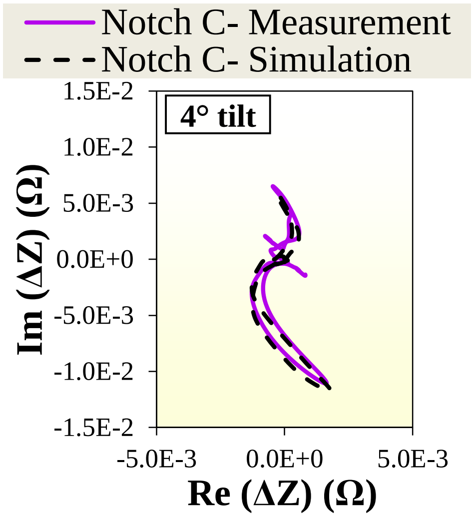




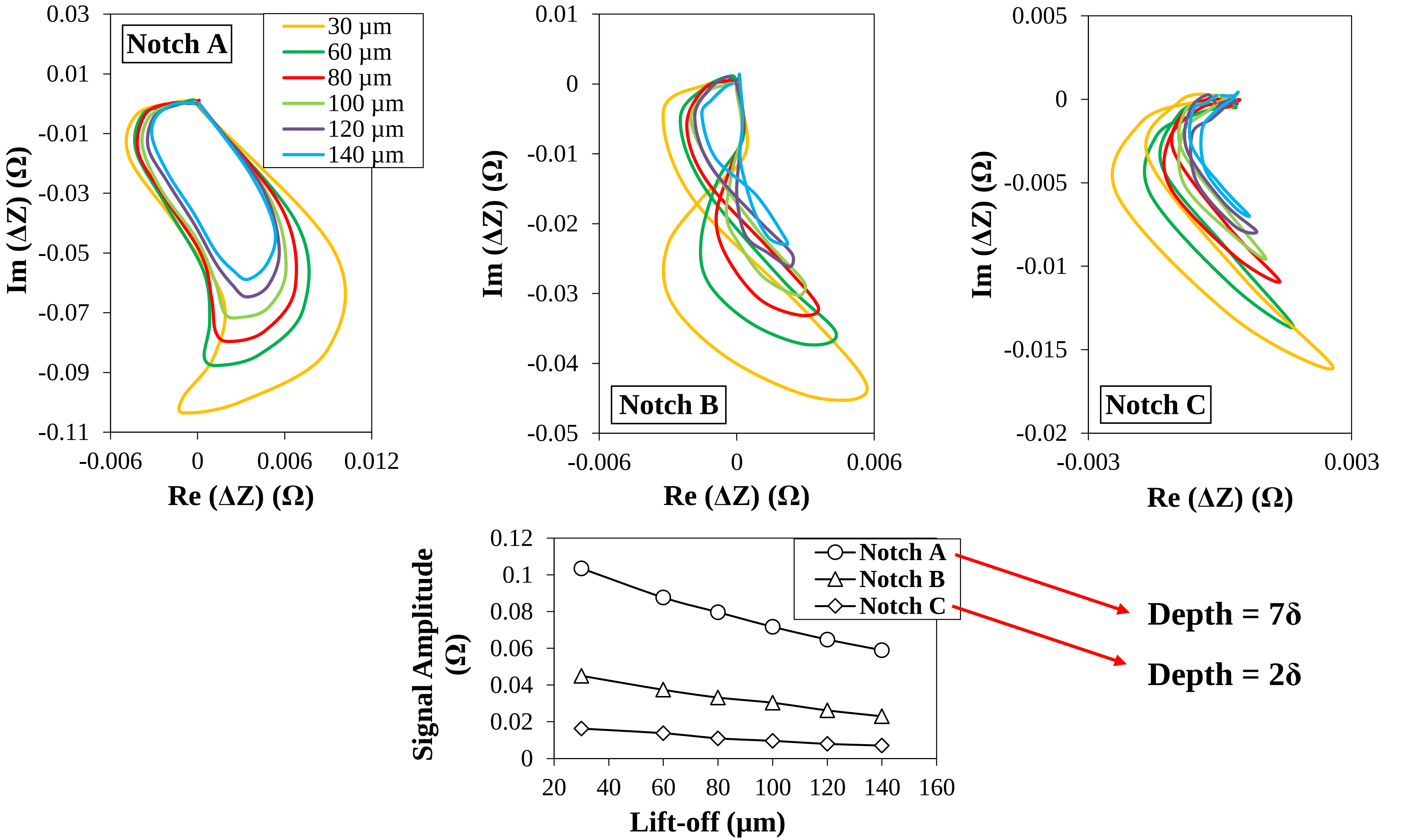




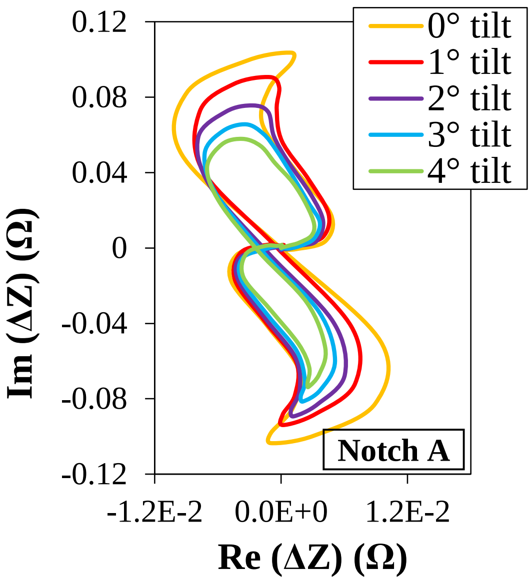


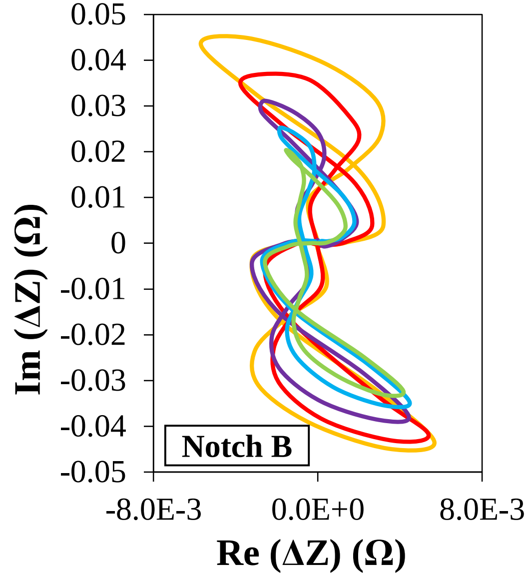


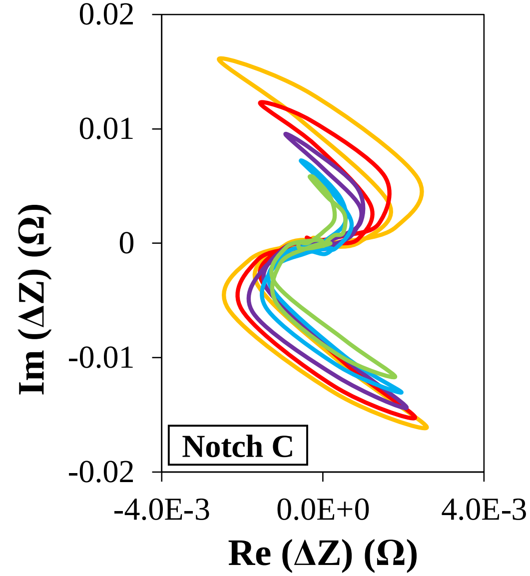
Effect of lift-off on EC signal

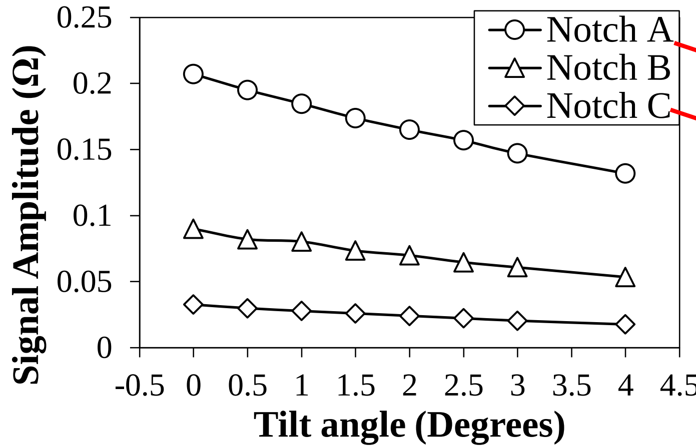


Effect of tilt on EC signal









Depth = 7δ

Depth = 2δ

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Conclusions

- FEM showed a good capability in predicting the effect of tilt and lift-off on the notch signals.
- The small amplitude discrepancies are mainly attributed to the initial one-point calibration used for the probe's lift-off.
- The shape discrepancy is majorly originated from deviations of the real notch geometry from the one used in simulations and also from the unbalance of the receiver coils.
- The origin shift is caused by the nulling process in the simulations. Besides, due to the elevated gains used for the signal recording for the smaller notch sizes, the position of the null point on the impedance plane is more severely affected by the noise.
- The signal amplitude of all the notches decrease as the probe's lift-off increases in the interval of 30 µm to 140 µm. The relationship between the signal amplitude and the lift-off changes in the studied interval is quasi-linear. The amplitude variations versus the tilt angle, changing from 0˚ to 4˚, follow the same behaviour for all notches. The amplitude diminishes more noticeably by the growth of lift-off as compared to tilt.
- The phase of the notch signals remains below 2˚ as either the lift-off or the tilt angle increase.
- The studied amplitude variations caused by small changes in lift-off and tilt will be considered as errors in measurements, utilized to modify training sets, and fed into an artificial intelligence engine designed for EC inversion.

Thank you for your attention