Modelling of a Differential Sensor in Eddy Current Non-destructive Evaluation

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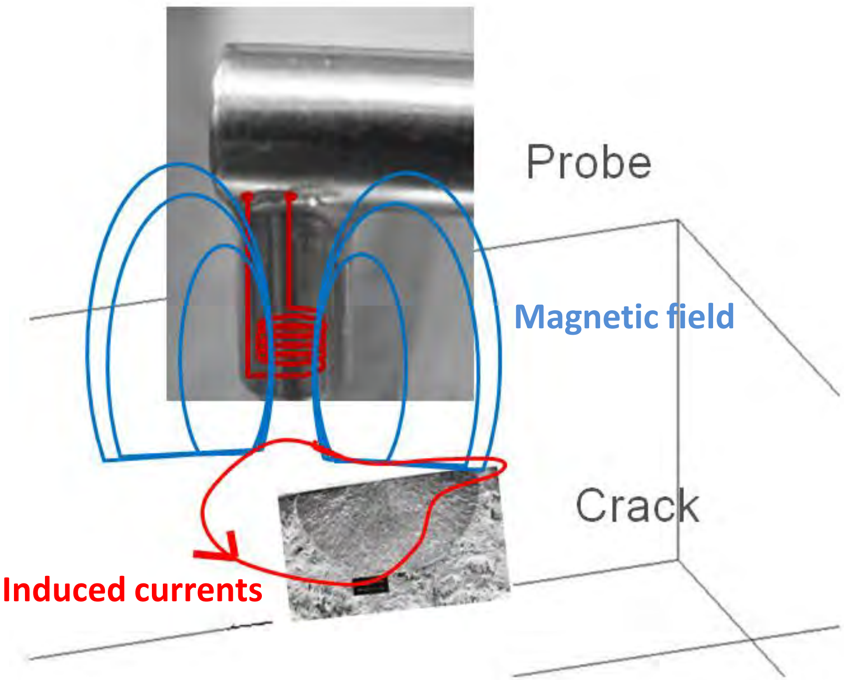
Presentation outline

- Introduction to eddy current NDE & modelling
- Objectives
- Model description
- Simplified axisymetric model
- TEAM 8 benchmark in 3D with a differential eddy current sensor (TEAM - Testing Electromagnetic Analysis Methods)
  - Set up in COMSOL
  - Results
- Conclusions

Introduction – *eddy current NDE*



A probe is put in proximity to a conductive material, induced currents respond to material characteristics.

Eddy current is used in order to detect near surface defects (skin depth limited).

The method capability is estimated with a statistical approach (within aero-space) and the probability of detection is established.

To assess capability in models it is needed to have results that reflect changes due to small variations in the configuration.

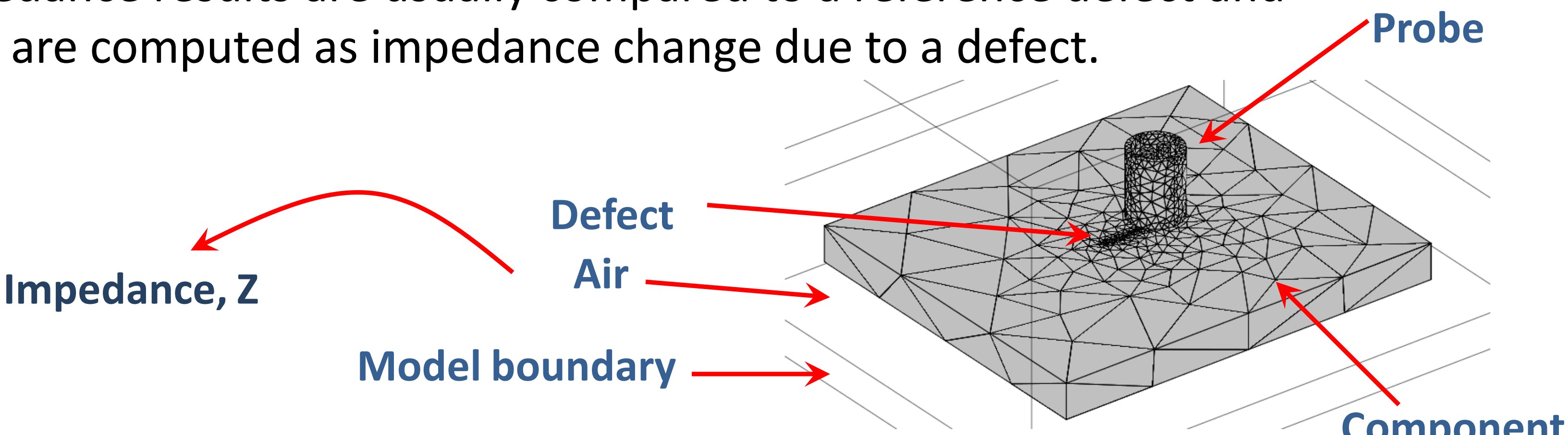
PICASSO

Introduction – *modelling eddy current*

- The goal is to use the FEM for computations to display impedance variations due to small variations in input parameters, such as sensor position or defect size.

- FEM has the possibility to include complex parts and defects. But a consistent model set up must be used in order to produce comparable results between models.

- Impedance results are usually compared to a reference defect and signal are computed as impedance change due to a defect.



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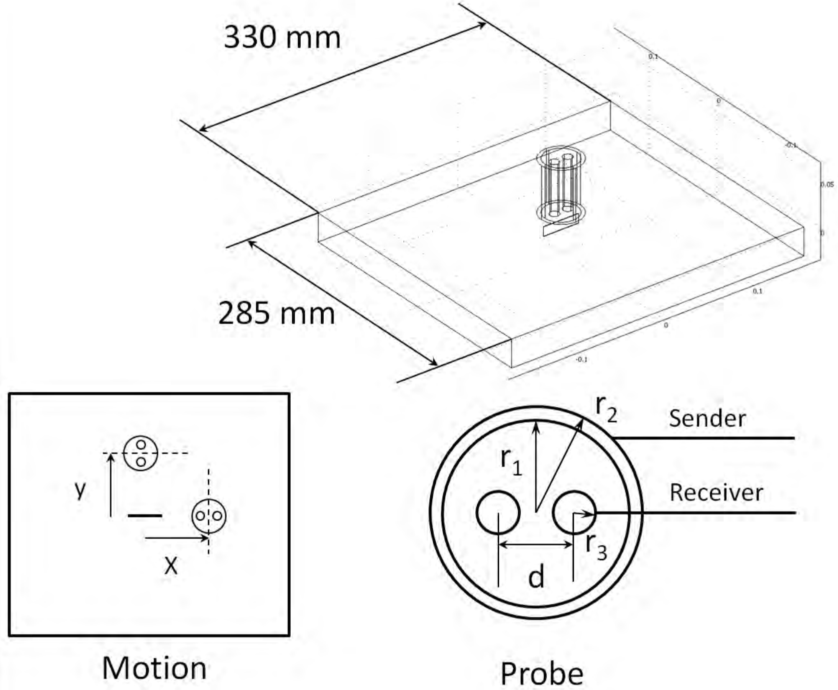
Objectives with presented study

- Build model for calculation of accurate impedance results for a differential eddy current sensor
  - Strategy for selecting model dimensions
  - Evaluate the needed mesh densities in different regions
  - Efficient computations of impedance variations including the edge effect
- Evaluate results against benchmarks in literature (Testing Electromagnetic Analysis Methods TEAM problem 8)

Model description

TEAM 8 Benchmark



Considerations

- *Truncation at the outer boundaries?*
- *Mesh, density of sensor and defect?*
- *Edge effect, as the sensor approaches the metal block boundary?*
- *Accurate results and low number of degrees of freedom?*

- Sensors are measuring the difference of magnetic flux through the receivers.
- Defect is a rectangular slot, length ~ sender diameter length x depth = 40 x 10 mm

Skin depth (penetration depth) 19 mm and material thickness 30 mm

Sender – external current load

Receiver impedance proportional to flux

$$\phi = \int_A \boldsymbol{B} \cdot \hat{n} dS$$

Quasi-static magnetic analysis with harmonic fields (freq 500 Hz)

High conductivity and low frequency approximations (ε_0=0)

$$\nabla \times (\mu^{-1} \nabla \times \boldsymbol{A}) + j\omega\sigma \boldsymbol{A} = \boldsymbol{J_s}$$ with ***n x A=0*** at outer boundaries

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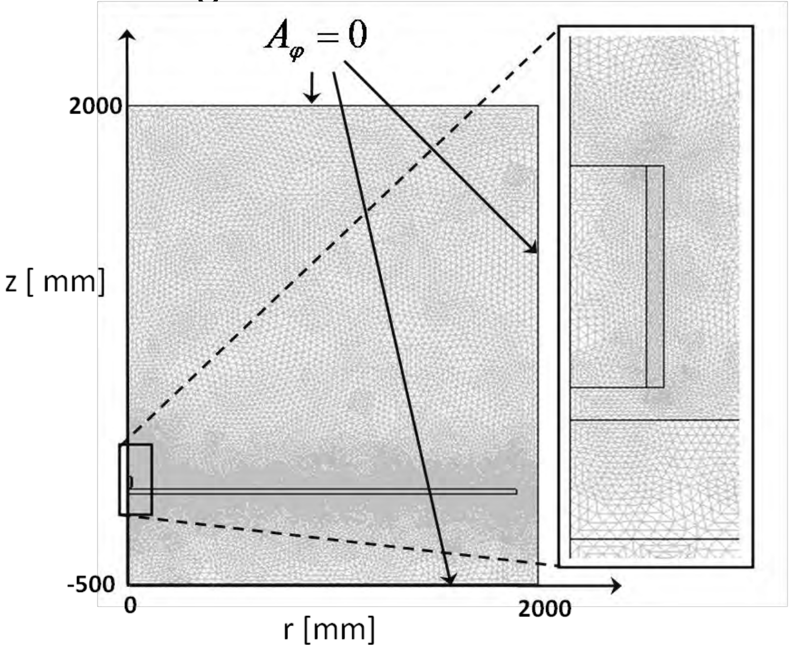
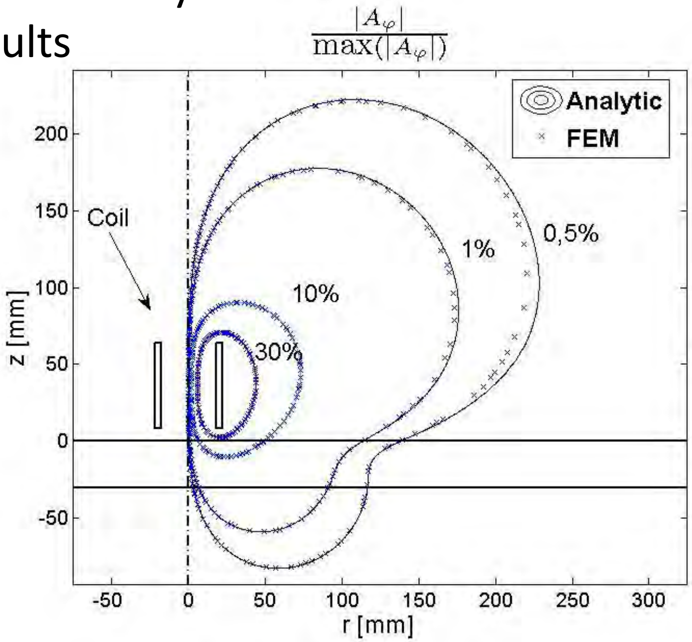
Simplified axisymmetric model

- To give the model state at the boundary and use this to select positions of the model truncation in 3D
- Possible to use large volume model with dense mesh
- The sender coil with external current is considered only
- Good agreement between FE and analytic results



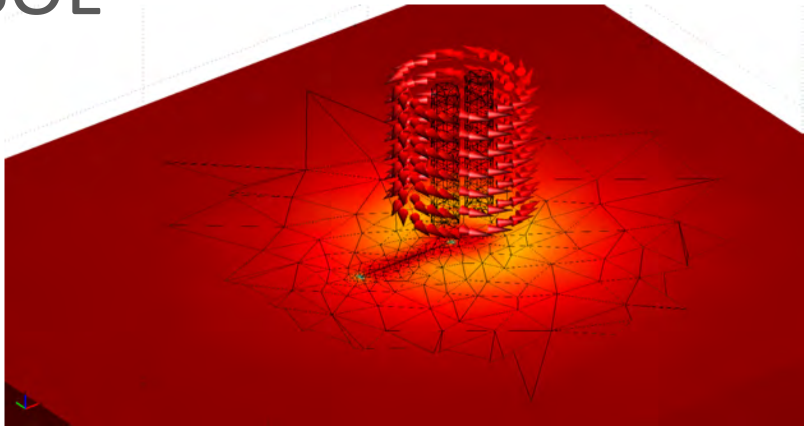


$$|A_\varphi| = \sqrt{A_\varphi \cdot A_\varphi^*}$$

*Analytic model implemented in Matlab® based on Dodd, C. and Deeds, W., *Journal of Applied Physics*, ***39(6), 2829 - 2838 (1968)***

Set up of TEAM 8 in COMSOL

Comsol version 3.5
Pardiso OOC solver
Quadratic vector elements
Speed ~ 0.5 - 3 minutes/sensor position



External current in sender coil and induced current on the surface of the material

External current applied in circumferential direction in the sending coil

appl.equ.Je = {'J0*((-yl/sqrt(xl^2+yl^2))' 'J0*((xl/sqrt(xl^2+yl^2)))' '0'}
xl, yl – are the local coordinates of the probe with origo at the axis

Calculation of flux (proportional to impedance) of the receivers

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
    %Flux difference between the two receivers
    ra=postint(fem,['Bx*coil_AXISx+By*coil_AXISy+',...
           'Bz*coil_AXISz'],'Dl',receiver1_subnr);
    rb=postint(fem,['Bx*coil_AXISx+By*coil_AXISy+',...
           'Bz*coil_AXISz'],'Dl',receiver2_subnr);
    FLUX1=ra-rb;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

Here, for a general direction of the sensor axis

$$\Delta\phi = \left(\phi_b^{(2)} - \phi_b^{(1)}\right) - \left(\phi_a^{(2)} - \phi_a^{(1)}\right)$$

b – with defect, *a* – without defect
1 – first receiver, 2 – second receiver

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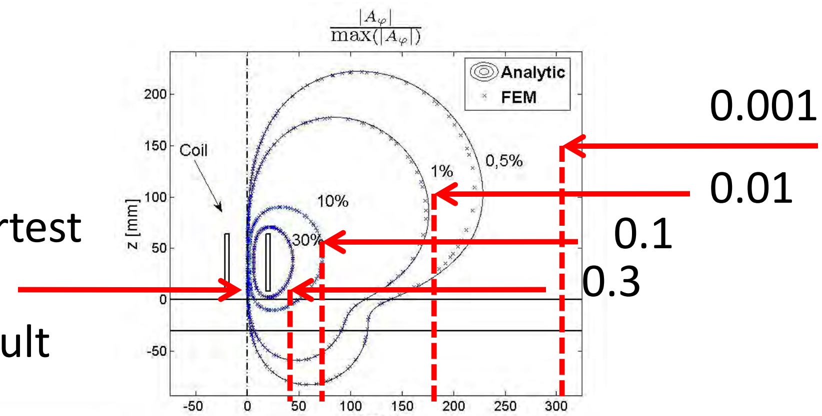
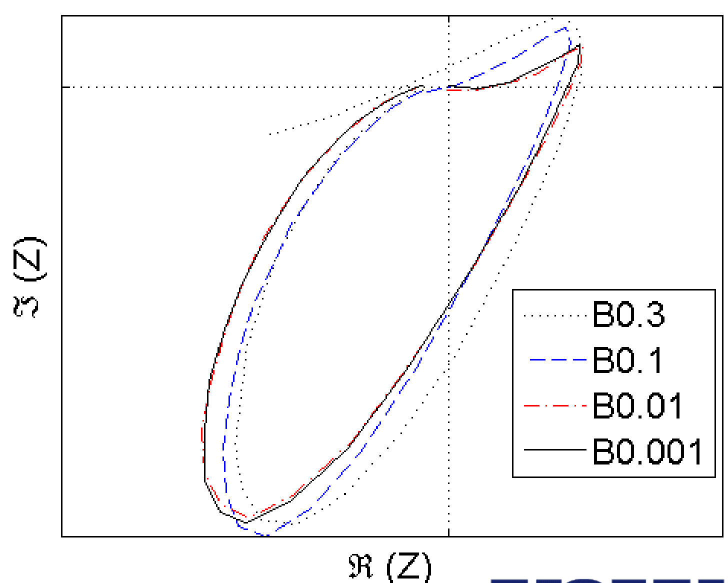
Results - *truncation of outer boundary*

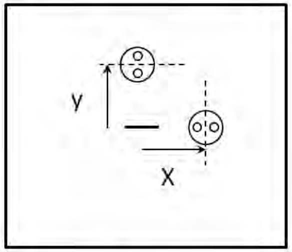
- 4 models truncated at positions where $|\boldsymbol{A}|/|\boldsymbol{A}_{max}| < 0.3, 0.1, 0.01, 0.001$ at the shortest distance to boundary
- Relative signal change considered in the result



$$|A_\varphi| = \sqrt{A_\varphi \cdot A_\varphi^*}$$

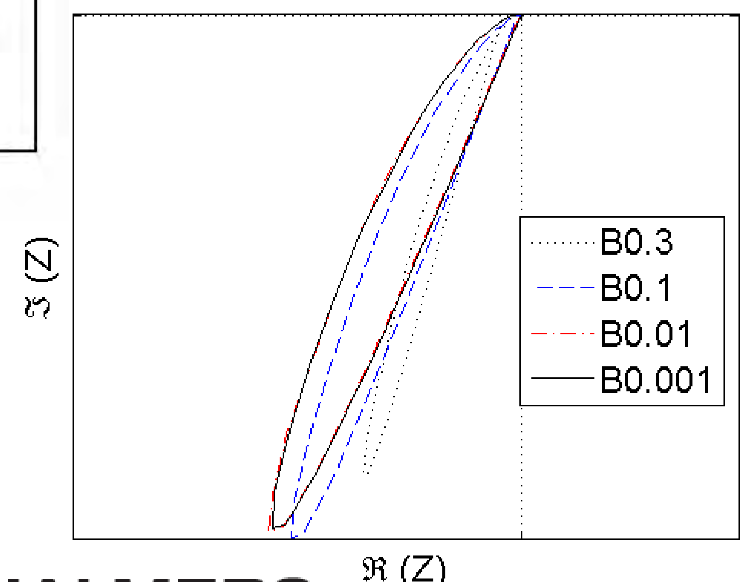
Impedance, X- motion





Motion

Impedance Y- motion



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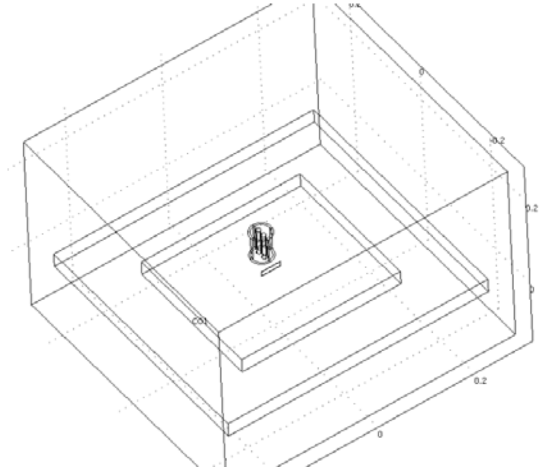
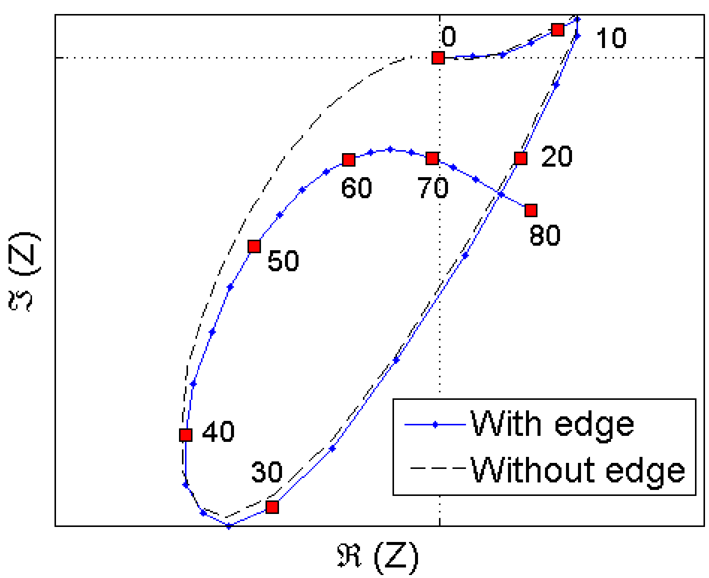
Results - *edges included in model*

Edge treated as defect in calculations
- Impedance variations from a situation without influence from defect or edge is considered

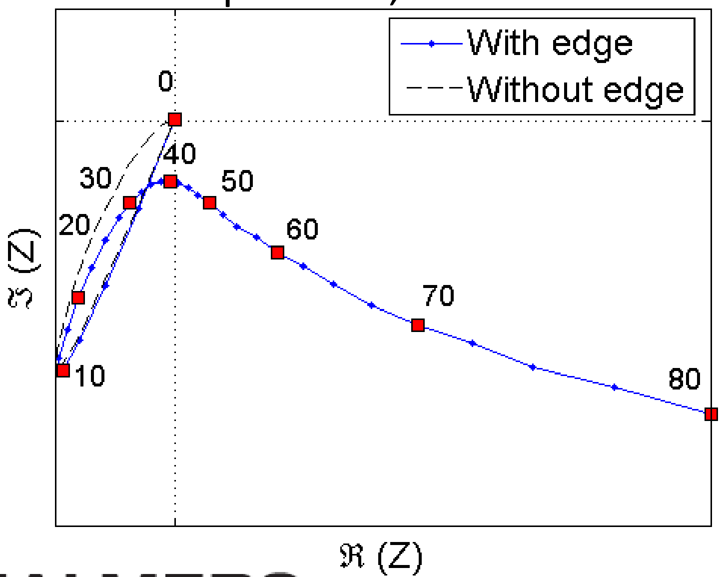


Good agreement with previously published results (numerical & experimental)

Impedance, X- motion



Impedance, Y- motion



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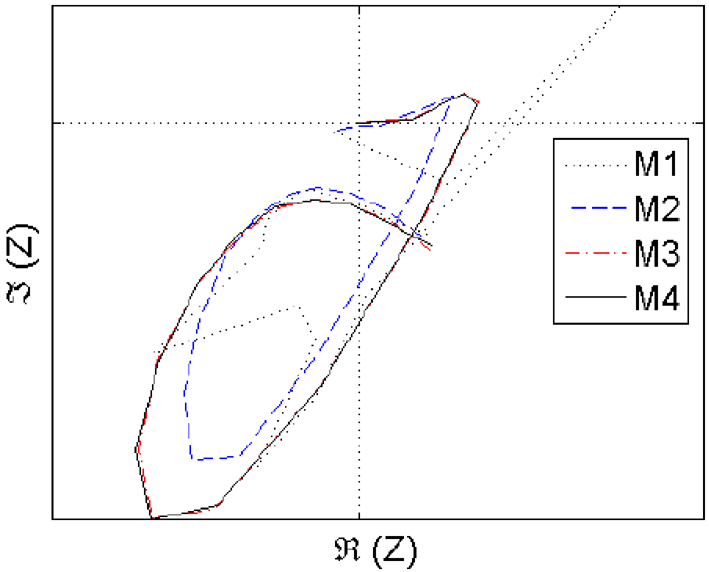
Mesh considerations – *sensor mesh*

- Quadratic vector elements used
- Output signal represent a change in the order of 0.1 – up to a few % of the applied field
- Slight variations in mesh for different positions may have an effect on the result

NOE- Number of elements

Mesh label	M1	M2	M3	M4
NOE coil	350	530	1264	3902
NOE defect	385	385	385	385
NOE receiver	30	104	296	945
NOE total	6037	7181	12121	25827

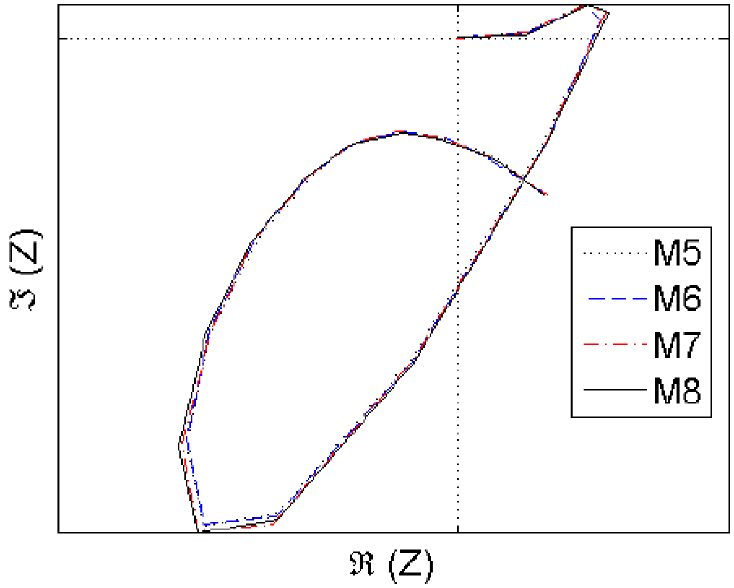
X- motion



Mesh considerations – *defect mesh*

- Skin depth ~ 10 times the element size
-Recommended to use at least two 2nd order elements to resolve the skin depth

X- motion



NOE- Number of elements

Mesh label	M5	M6	M7	M8
NOE coil	1264	1264	1264	1265
NOE defect	385	435	1103	4355
NOE receiver	296	296	296	296
NOE total	12165	12426	15032	26831

Summary and Conclusions

- First an axisymmetric model was compared against analytic results
  - good agreement.
  - We can use simplified/reduced FEM model to give input of the extension of the fields from a sensor.
- Problem TEAM 8 was set up. First an evaluation of different levels of truncation was conducted based on the axisymtric analysis
  - It was concluded to use a truncation where |A| has decreased to 1% at the boundary
- We included the edge of the block in the problem
  - good agreement with published results
  - COMSOL handle eddy current problems effectively and accurately
- Different mesh densities was evaluated
  -Important to keep sufficient mesh density to resolve the probe
  - In this study we had ~10 elements resolving the skin depth around the defect

Thank you for your attention!

Q & A..