Magnetic Response Field of Spherical Defects within Conductive Components

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1. Examples of different electromagnetic NDE Problems to detect inclusions using dc or ac currents

2. FEM – Modelling and influence of
   - different conductivity of matrix and inclusion
   - sensor-to-inclusion separation
   - inclusion size
   - Development of an analytical description

3. Experimental results

4. Summary and outlook
Inclusion Detection in Microwave Cavities

- Accelerating microwave cavity made from high purity niobium.
- Tantalum inclusions are common defects, which must not be larger than 100 µm in diameter.
- Methods to be used: Eddy Current Testing, Current Injection and thermomagnetic methods.

(Courtesy W. Singer, TESLA-Accelerator, DESY, Hamburg)
- Testing electrical contacts
  - usually tested by measuring the electrical resistance

- The injected current can be used to detect the magnetic field variation due to additional geometrical changes within the contact
Testing Al-laser welds and its porosity

arising of pores

sheet: AlMg3 [3% Mg], 1 mm thick pore-Ø average ~300 μm

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MR- linear-array

- 64 single sensors
- 50 μm strips Permalloy
- Sensitivity 1 nT / √Hz
- Spatial resolution 125 μm

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r_{def} = 300 μm: SNR: 69

r_{def} = 100 μm: SNR: 7.5
Technical Application of Superconducting Wires

**Magnetic Resonance Tomograph (MRI)**
Cu/NbTi: 45 Filaments, 0.6 - 2.4 mm, 2 - 5 Tesla at 4.2 K, ΔI < 1.5 ppm/year

**NMR- and Lab-Magnets**
Cu/NbSn: 6000 - 18000 Filaments, 0.7 - 1.4 mm, 10 - 15 Tesla at 4.2 K

**High Energy Physics, Magnets for particle accelerators**
Cu/NbTi: 8670 Filaments, 1.065 mm, I_c = 540 A (7 Tesla at 4.2 K)
Testing the SC-Wire using 4 GMR-Sensors

Magnetic field strength of the radial component of each GMR sensor as function of the axial position of the wire.

defect size: about 60 µm diameter in 200 µm depth below the surface.
High intrinsic accuracy requires large FEM-mesh with sufficient number of elements (> 2.5 Mio, > 1 Mio nodes).

Substraction method of reference model and defect model for a better determination of the inclusion’s tiny field variation up to nine orders of magnitude smaller than the excitation field.

Circular excitation coil located above a metal plate containing inclusions with sizes between 50 µm and 800 µm.
FEM-Modelling as a Suitable Tool for Current and Magnetic Field Calculations

Example for a gradiometric current excitation
Spherical tantalum inclusion within a metal plate with eddy current distortion in cross-section plane. FE-mesh composed of several nested spheres.
Spherical tantalum inclusion within a metal plate with eddy current distortion in cross-section plane. FE-mesh composed of several nested spheres.
Current Density in the vicinity of the defect

Inclusion diameter: 200 µm, z = 0, uniform current flow passes along x-axis.
Conductivities: Ti: 2.34 MS/m, Cu: 59.6 MS/m, Al: 37.7 MS/m.

If \( \sigma_I > \sigma_M \): increased current flow within the inclusion

If \( \sigma_I < \sigma_M \): increased current flow outside the inclusion
Perturbation current flow generates a 2D magnetic flux distribution above the surface, inclusion conductivity $\sigma_i$ is zero, location: 1 mm below the surface, diameter: 100 µm, hosted in Al-alloy-matrix ($\sigma_M = 20$ MS/m)
Magnetic Flux Density Response for Different Conductivity of Inclusion and Host

Inclusion diameter: 200 µm, located 2 mm below the surface, sensor-to-inclusion separation: 5 mm

Simulation shows:

\[
\lim_{\beta \to \infty} B_z(\beta) = -2
\]

with \( \beta = \frac{\sigma_I}{\sigma_M} \)
Response for Different Conductivity of Inclusion and Host – error function of the fit

![Graph showing magnetic field $B_z$ vs. inclusion conductivity $\sigma_I$ and host conductivity $\sigma_M$.]

Inclusion diameter: 200 µm, located 2 mm below the surface, sensor-to-inclusion separation: 5 mm

Fit function:

$$B_z \sim \frac{\sigma_I - \sigma_M}{\sigma_I + 2\sigma_M} = \left(\frac{\beta - 1}{\beta + 2}\right)$$

(FEM: red, green, blue dots)  
(Fit: solid lines)
Fall-off characteristic for the flux density calculated for different inclusion diameter \( r \) and separations \( z \)

Inclusion with zero conductivity (air) located in a titanium matrix (conductivity: 2.34 MS/m).

\[
B(z) \sim \frac{1}{z^2}
\]
Current distribution at the vicinity of the inclusions calculated for different inclusion diameter $r$

Inclusion with zero conductivity (air) located in a titanium matrix

![Graph showing current distribution for different inclusion sizes]
Fall-off characteristic calculated for different inclusion diameter $r$ and separations $z$

Inclusion with zero conductivity (air) located in a titanium matrix

$B(z, r) \sim r^3$
Despite the high dynamic flux range between 30 pT and 7 µT, the constant $k = \frac{\mu_0}{1.354}$ varies in a range of a few percent only.
For dc current flow $j_0$ describes the current density at the defect. This is also the case for ac applications including the skin effect. In our case the distortion field caused by the defect is attenuated on its way back to the surface. This makes $j_0$ a frequency dependent property variation of $k(f)$ as a function of the frequency and as a function of the normalized penetration depth).

\[ k(f) = \frac{\mu_0}{1.354} j_0(f) \]

$k(f)$ is an universal function for the frequency dependence.
Experimental Results
Tantalum inclusions in Nb-plates

Current distortion of a 2 mm-deep circular tantalum inclusion (dia. of 800 µm) in a planar niobium sheet (FEM simulation),

Low perturbation effect due to similar conductivity:
Tantalum: 7.6 MS/m
Niobium: 6.9 MS/m

Eddy current distortion along the dashed line in the left figure.
Experimental Results
Tantalum inclusions in Nb-plates

- Eddy current response of a 1 mm-deep, 200 µm dia. circular inclusion with varying conductivity in a planar niobium sheet

- FEM simulations, Sensor-to-sample separation: 1 mm). The maximum achievable magnetic field 1 mm above the sample is about 1.7 nT for a tantalum inclusion (0.8 mT excitation field)

![Graph showing magnetic induction Bzpp against electrical conductivity σ]
11 Tantalum spheres each about 100 µm in dia. were embedded into a 30 cm x 30 cm niobium sheet. EC field distribution above the niobium plate shows a field amplitude in the order of 20 pT.

\[ B_z = 1.7 \text{ nT (FEM)} \]

for \( z = 2 \text{ mm} \) and \( r = 100 \mu \text{m} \)

In case of \( r = 50 \mu \text{m} \) -> 1/8

and \( z = 7.9 \text{ mm} \) -> 1/16

We thus expect a signal strength of 14 pT