Numerical Modeling of Leakage Magnetic Field Caused by Internal Defects in a Multilayer Ferromagnetic Structure

Non-Destructive Testing of Steel Wire Ropes Using the Magnetic Flux Leakage (MFL) Method

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Problem Relevance and the Physical Basis of Magnetic Testing

- Steel wire ropes are critical load-bearing elements in mining, transport, and lifting infrastructure
- Cyclic loading, abrasive wear, and corrosion cause wire breakage, cross-section loss, and fatigue micro-cracks
- The Magnetic Flux Leakage (MFL) method is based on magnetizing the object to saturation with high-energy permanent magnets
- Near a defect, magnetic field lines are expelled to the surface and detected by high-sensitivity sensors (Hall, inductive coils)

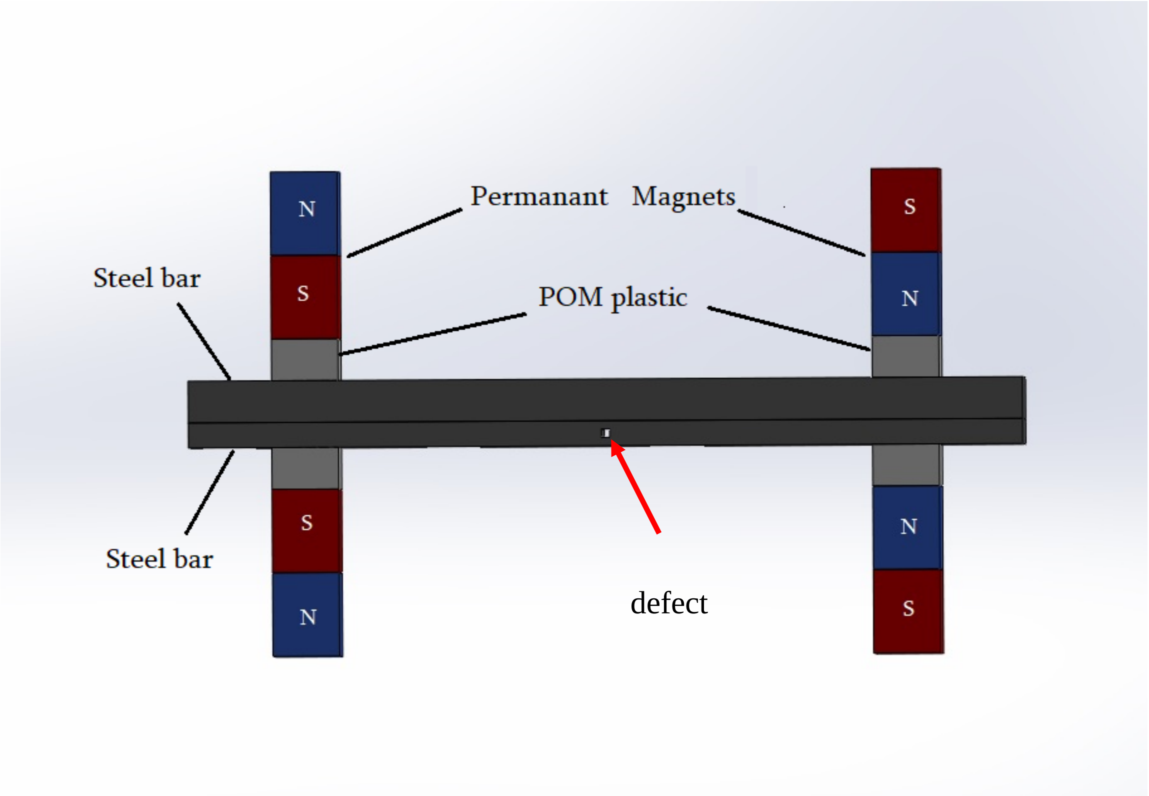


Fig. 1 — Simplified schematic of the magnetic head: permanent magnets, steel core, POM plastic shielding

Specific Challenges of Wire Rope Diagnostics

Discrete structure

A rope is built from wires of different geometries and lay lengths — this creates constant structural inhomogeneity and high-intensity electromagnetic noise

Surface defects — detectable

Modern flaw detectors reliably identify localized flaws (LF) and global loss of metallic area (LMA)

Hidden internal breaks — more or less unresolved problem

The internal defect's field decays exponentially and is shielded by the outer layers — the useful signal is often below the noise level

Research gap: *the interaction of internal defects in neighboring, undamaged multilayer discrete structures — and how it manifests in the surrounding space — remains poorly studied*

Aim and Scientific Novelty of the Study

Aim

- **Numerical simulation is used to investigate the spatial distribution of the leakage magnetic field caused by an internal defect in a simplified two-layer ferromagnetic structure**
- **The influence of the defect's geometric parameters (depth, width) on the MFL signal topography is analyzed, both in the ferromagnetic body and in the air gap**
- **Using these activities, let's explore ways to increase the accuracy of the method**

N Scientific Novelty

- A homogenized description of the **Interlayer Contact Zone (ICZ)** is proposed for the first time, using equivalent effective magnetic parameters
- A Magnetic Transmission Coefficient and a **Leakage Field Transmission Factor (LFTF)** are introduced, linking microstructure to the surface signal

ANALYTICAL MODEL

Geometry and Assumptions of the Layered Rod Model

A five-layer ferromagnetic rod model is considered, with a rectangular air-filled defect placed in the central layer, symmetric about the model's vertical axis.

The layer material is assumed to be an isotropic ferromagnet under uniform longitudinal magnetization H0 = H0 ex.

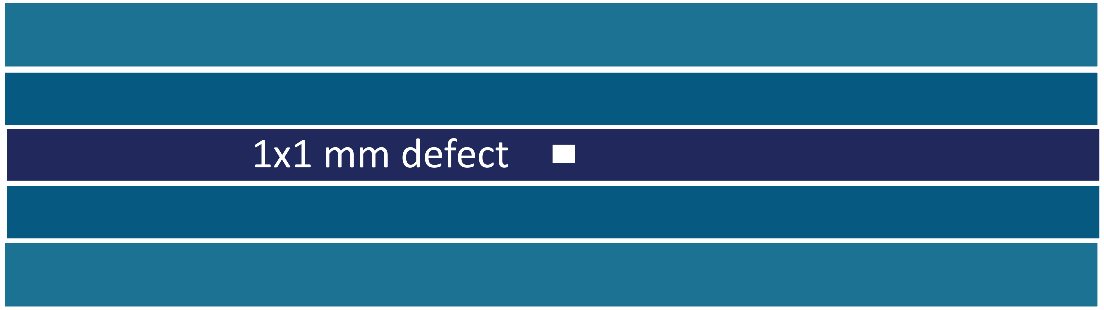


Fig. 2 - Five-layer steel rope model with an internal defect (schematic)

L = 100 mm
Total length

T = 25 mm
Total thickness

mu_r = 500
Relative magnetic permeability

2a x 2b = 1x1 mm
Defect size

Layer thicknesses: t1=6 mm, t2=5 mm, t3=3 mm, t4=5 mm, t5=6 mm

Homogenization of the Interlayer Contact Zone (ICZ)

In real multilayer systems, metallic contact between layers is not continuous - contact and non-contact regions alternate periodically.

Contact fraction

$$\lambda = l_c / (l_c + l_g)$$

lc - length of metallic contact,
lg - length of the air gap

ICZ period

$$p = l_c + l_g$$

Total length of contact plus gap

Homogenization condition

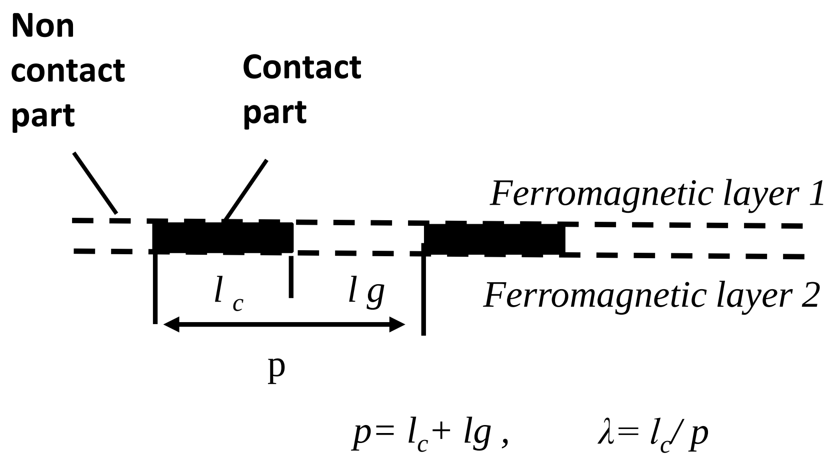
$$p << 2a$$

Period is much smaller than the defect's transverse size

Equivalent permeability

$$\mu_{eq} = \mu_0[\lambda^*\mu_r + (1-\lambda)]$$

Average microstructural effect as a homogeneous parameter



Magnetic Transmission Coefficient and LFTF

Magnetic Transmission Coefficient τ

$$\tau = [1 + (\mu_r - 1)*\lambda] / \mu_r$$

Describes how the equivalent ICZ affects the efficiency of leakage-field transmission between layers.

E.g.: when λ =0.5, μ_r =100 -> τ ~ 0.505

Leakage Field Transmission Factor (LFTF)

$$LFTF = B_{surf} / B_d = \tau^N * e^{-k1*h}$$

k1 = pi / L, N - number of ICZs between the defect and the surface at distance h. The lower the LFTF, the weaker the signal reaching the surface.

Physical meaning: as the leakage field propagates from the defect to the surface, it undergoes both spatial attenuation and interlayer transmission losses simultaneously - both effects are combined in the LFTF expression, which is used to validate the FEM results.

Model Setup in the EMCoS Studio 2025 Environment

- A two-layer composite ferromagnetic body is constructed with a homogenized boundary condition
- External saturating static magnetic field H = 1.9 T, applied longitudinally
- The leakage field is studied in the ferromagnetic medium, in the homogenized boundary layer, and in the surrounding space
- 9 zones near the defect are scanned (X= -5 mm ... +5 mm), parallel to the longitudinal layers

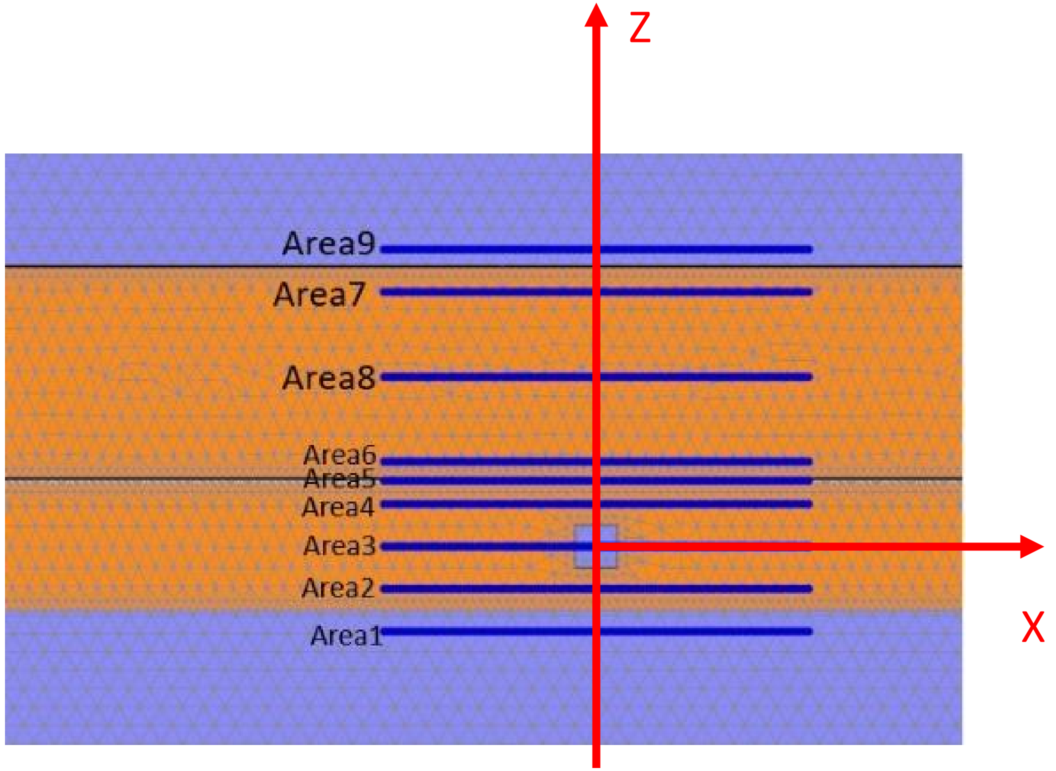
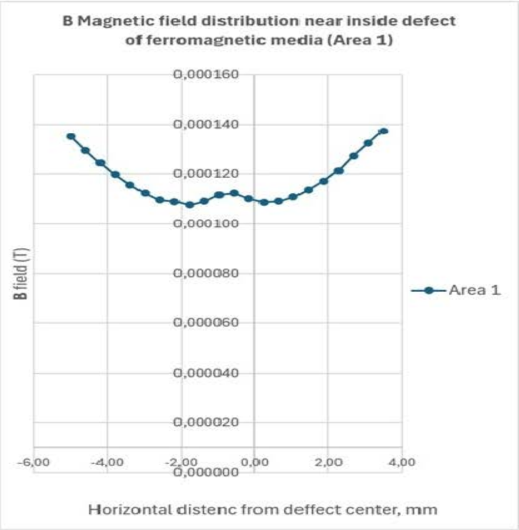
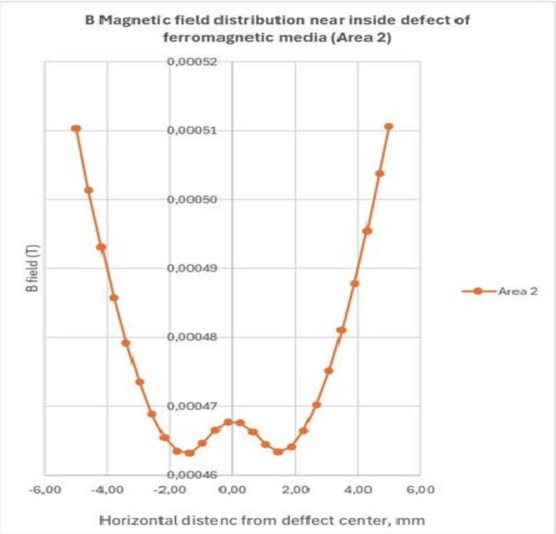
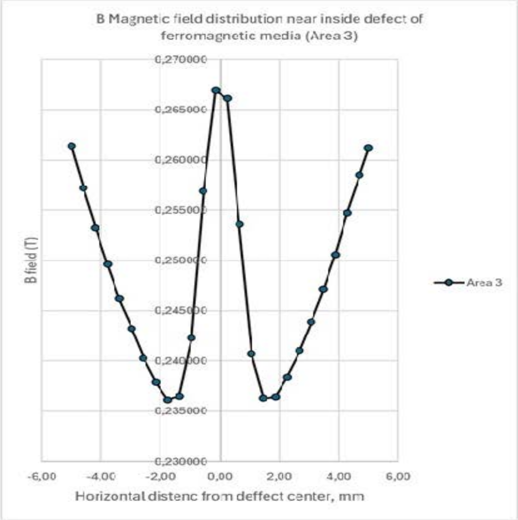


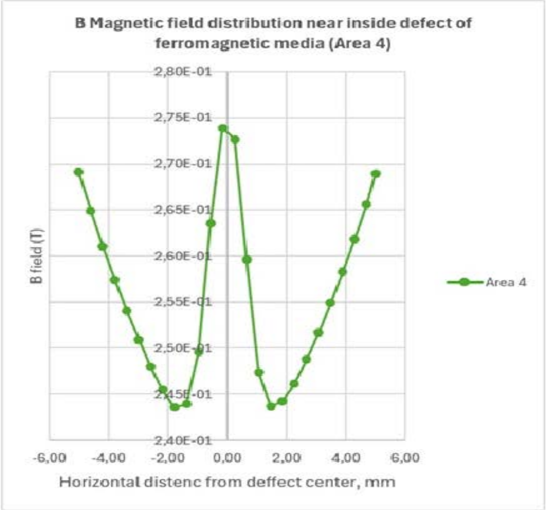
Fig. 1 - 9 scanning zones near the defect

Field Distribution Near the Defect (Area 1-4)





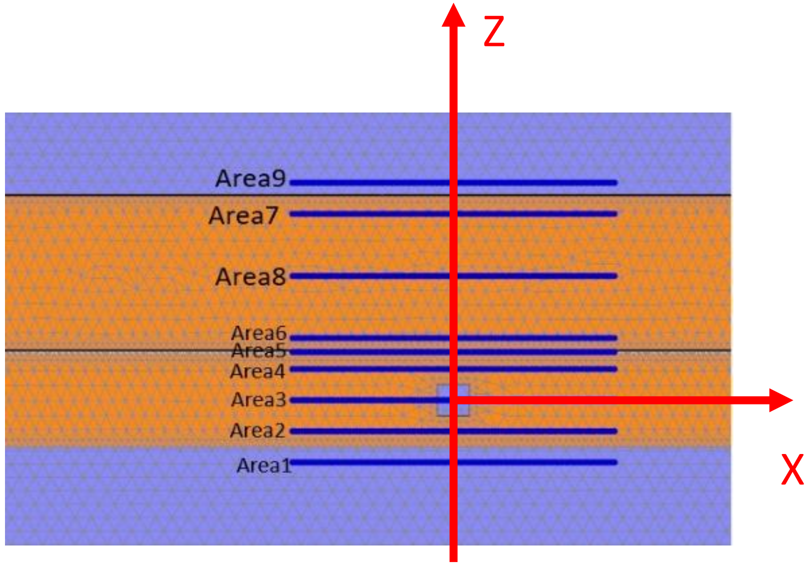




At the center (0 mm), the minimum field value corresponds to the air-filled defect - a deficit of magnetic flux

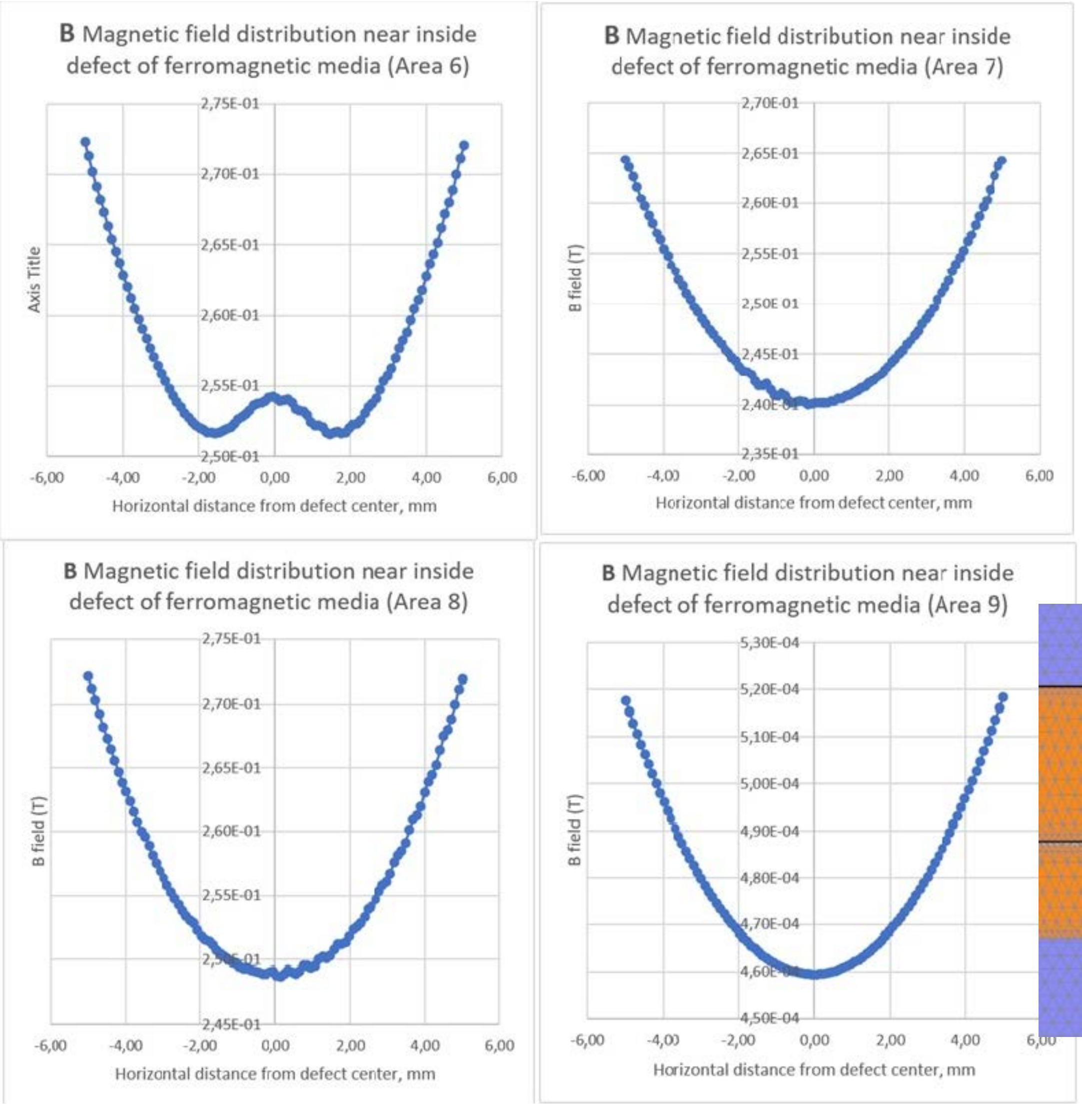
Area 1-2 (deep, far from defect): smooth, low-amplitude U-shaped profile

Area 3-4 (near the defect): sharp double-peak structure - local field increase at the defect edges

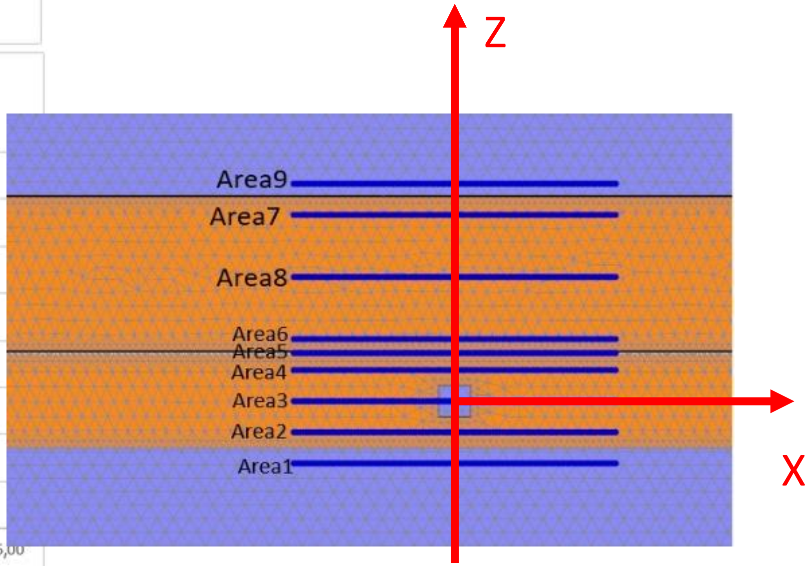


Field Distribution Approaching the Surface (Area 6-9)

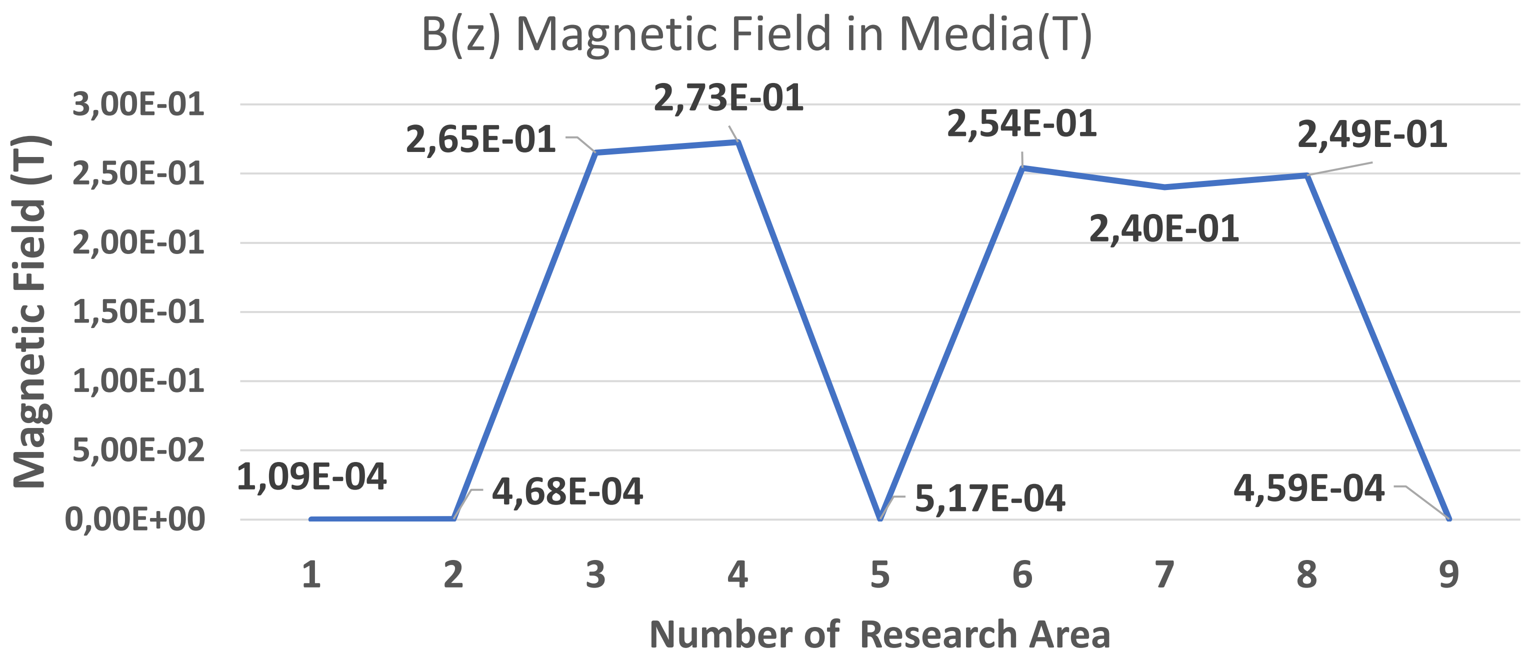
Moving toward the surface (Area 6 to 9), the distance between peaks and the double-peak contrast gradually fade due to interlayer transmission losses



Magnetic shielding: the field amplitude in zones closer to free space is noticeably lower than that recorded within the ferromagnetic body



Numerical modeling of Magnetic field distribution in a longitudinal ferromagnetic body in the transverse direction



Interpretation of numerical modeling results

- Saturation magnetic field of the ferromagnetic medium - **H=1.9 Tesla;**
- Magnetic field magnitude in the ferromagnetic medium - **B_F ≈ 0,1 H Tesla;**
- Magnetic field magnitude in the surrounding medium of the ferromagnetic body - **$B_A \approx 10^{-4}$ H Tesla**

Physical Interpretation of the Results

1. High-gradient local maxima form at the defect edges, while a flux deficit occurs at its center
2. Far from the defect, the profile is a smooth U-shape; close to it, a double-peak structure forms
3. The signal amplitude in free space is significantly lower than in the ferromagnetic body - the magnetic shielding effect
4. The multilayer medium acts as a natural magnetic filter; detectability depends not only on geometry but also on interlayer coupling
5. The numerical results qualitatively agree with the homogenized analytical model - a lower LFTF leads to a weaker surface signal

Main Conclusions

- An internal air defect causes a sharp local redistribution of magnetic flux and a characteristic spatial anomaly of the stray field
- A clear pattern emerges: a U-shape in distant zones, a double-peak profile near the defect
- The multilayer ferromagnetic medium acts as a natural magnetic filter, reducing the signal that reaches the surface
- A homogenized description of the Interlayer Contact Zone (ICZ) with effective parameters is proposed for the first time
- A Magnetic Transmission Coefficient and LFTF were developed, linking microstructure to the surface MFL signal
- The proposed approach reduces computational cost as an alternative to full 3D FEM modeling

Future Work

3D modeling of real spiral-wound steel ropes, accounting for non-linear B-H characteristics, and experimental validation

Acknowledgments

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Thank you for your Attention