Numerical Analysis of the Magnetic Flux Leakage Field Induced by Internal Defects in Longitudinal Ferromagnetic Structures

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https://doi.org/10.29227/IM-2026-02-02-036

Submission date: *2026-12-06* | Review date: *2026-22-06*

Abstract

This paper discusses approaches to improving the magnetic non-destructive testing (NDT) method for longitudinal ferromagnetic bodies, leveraging the advanced simulation capabilities of modern Multiphysics engineering software. The subject of the research is steel wire ropes composed of individual wires of various shapes and cross-sections. Since steel wire ropes do not constitute a homogeneous, continuous body, the application of magnetic NDT methods encounters significant challenges. This is primarily manifested in the difficulty of reliably detecting the magnetic flux leakage (MFL) field generated by wire breakages, as the discrete, multi-wire structure of the rope increases background electromagnetic noise and complicates the extraction of the useful signal. Although modern flaw detectors partially address this issue, the reliable registration of internal wire breaks remains a critical challenge to this day. In this work, the numerical calculation of the MFL field intensity resulting from an internal breakage within a simplified, two-layer steel wire structure is modelled in an engineering software environment. The spatial distribution of the leakage field induced by defects of varying widths and depths is investigated both within the ferromagnetic medium itself and in the surrounding atmospheric environment. The latter is of particular importance for practical NDT applications, given that magnetic sensing devices are typically positioned outside the ferromagnetic component. Based on the obtained results, it can be concluded that the utilization of modern engineering software tools enables a detailed and highly reliable study of the detection and registration processes for internal defects in ferromagnetic wire structures. In the future, developing an accurate geometric model of real steel wire ropes and conducting simulation studies will allow for the precise numerical computation of the MFL field spatial distribution, thereby establishing a foundation for the optimization and refinement of magnetic sensor mechanisms.

Keywords: *Non-Destructive Testing (NDT), Magnetic Flux Leakage (MFL), Internal Defect, Numerical Modeling, Ferromagnetic Wire Rope*

1. Introduction

1.1 The Relevance of the Problem and the Physical Foundations of Magnetic Non-destructive Testing

In modern industrial infrastructure, the mining industry, building structures and transport systems (cableways, lifts, cargo cranes) Steel ropes are critical load-bearing elements whose operational reliability is directly linked to human safety and the prevention of industrial accidents [1]. As a result of long-term cyclic loading, abrasive wear, and exposure to corrosive environments, degradation processes progressively develop within the rope's structure over time, manifesting as the breakage of individual wires, a reduction in the cross-sectional area and the formation of fatigue micro-cracks [2]. Consequently, a paramount task is the periodic diagnostics of load-bearing structures using modern methods of Non-Destructive Testing (NDT). For the inspection of ferromagnetic products

Among the approaches, the Magnetic Flux Leakage (MFL) method stands out for its highest efficiency and practical feasibility. [3]. MFL technology is based on magnetizing the object under inspection to magnetic saturation using high-energy permanent magnets. A simplified physical schematic of the method is shown in Figure 1.

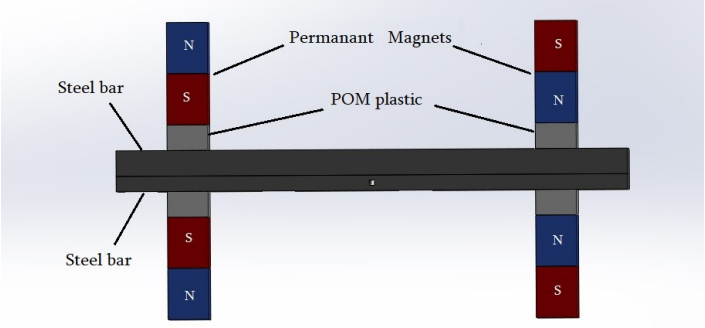


Fig. 1. Simplified physical schematic of the magnetic seamless connection

In engineering practice, to ensure the reliable mechanical protection of the magnetic poles and the sensor system, minimize the overall weight of the structure, and ensure high wear resistance, In the cable's contact area, modern high-tech polymer materials are used (for example, , ultra-high-molecular-weight polyethylene (UHMWPE), or polyoxymethylene (POM)).

Unlike almost all traditional metal protective elements, which significantly increase the mass of the measuring head and are considered a now-obsolete structural approach, These engineering plastics are characterized by a low specific gravity and ideal magnetic permeability ($\mu_r \approx 1$). Furthermore, the dielectric nature of the polymeric structures completely eliminates parasitic eddy currents induced by the high-speed cable (Eddy Currents) excitation in the shielding layer, which fundamentally reduces the level of electromagnetic noise and increases the reliability of the useful signal extraction [4].

In the region of a structural defect, the local magnetic permeability of the medium changes drastically, Consequently, a portion of the magnetic flux lines is expelled from the surface of the component, creating a scattering field which is detected by means of high-sensitivity sensors (Hall sensors, inductive coils) [5].

1.2. Specifics of Cylindrical Structures and Current Scientific Challenges

Despite the wide practical application of the MFL method, The diagnosis of steel ropes is characterized by specific fundamental complexities, which distinguishes it from the inspection of homogeneous components such as main pipelines or metal sheets [6]. A steel wire rope is a discrete multi-strand system, composed of wires with different geometric profiles and lay lengths. This discretization causes constant structural inhomogeneity and creates high-intensity electromagnetic 'noise' (Background Structural Noise) [7]. An analysis of the scientific literature shows that modern flaw detectors accurately detect superficial defects on the rope's outer layers (Localized Flaws - LF) and global loss of metallic mass (Loss of Metallic Area - LMA) [8]. However, the reliable identification of hidden breaks in the inner, deep layers of the rope remains an unsolved scientific and technical challenge to this day. The scattered magnetic field generated by an internal wire break decays exponentially with increasing distance and is subject to a form of magnetic shielding by the cable's outer layers (Magnetic Shielding) [9]. As a result, the amplitude of the useful signal emerging at the surface of the component is often below the level of structural noise, which significantly reduces the reliability of the diagnosis.

1.3. Magnetic field of permanent magnets and the mathematical formulation for numerical modelling

The application of analytical methods to study the physical principles of MFL signal formation and to optimize sensor systems is limited by the complex three-dimensional geometry of the cable and the non-linear magnetic properties of steel. The properties (B–H curve) [10]. In this context, numerical modelling based on the Finite Element Method (FEM) plays a leading role. For magnetostatic systems excited by permanent magnets, where the free current density is zero (J=0), the material continuity equation for the ferromagnetic medium takes the form:

$$B = \mu_0 \mu_r H + B_r \qquad (1)$$

Accordingly, the solution of the computational problem in the Multiphysics software environment is based on Maxwell's differential equation for the magnetic vector potential (A), where the source for the initial excitation of the field is the vector of residual magnetic induction of permanent magnets ($\boldsymbol{B_r}$):

$$\nabla \times \left(\frac{1}{\mu_0 \mu_r} \nabla \times A\right) = \nabla \times \left(\frac{1}{\mu_0 \mu_r} \times B_r\right) \qquad (2)$$

The physical quantities, constants, and vector operators featured in this mathematical model are defined as follows:

A — magnetic vector potential (Weber's per meter, Wb/m);

B — the vector of magnetic induction (tesla, T), which is related to the vector potential by the mathematical relationship: $B=\nabla \times A$;

H — the vector potential (amperes per meter, A/m);

B_r — the vector of residual magnetic induction of the permanent magnet material (tesla, T);

μ_0— the magnetic constant that defines the permeability of free space and is equal to $\mu_0 = 4\pi \times 10^{-7}$ H/m (Henries per meter);

μ_r— the dimensionless relative magnetic permeability of the medium. For steel elements in the computational domain, it is a non-linear function of the local magnetic field intensity and, in numerical calculations, depends on the magnitude of the rotor of the vector potential: $\mu_r = f(|\nabla \times A|)$;

$\nabla \times$ is the curl operator, which characterizes the rotational nature of a vector field in space.

In recent studies [11, 12], FEM models have mainly been used to simulate simplified, solid cylindrical rods, thereby bypassing the internal structural influence of a real rope on the scattering field.

Research Gap: The interaction of internal defects in neighbouring, multi-layered discrete structures is poorly studied in the scientific literature, undamaged ferromagnetic elements and the reflection of this interaction in the atmospheric environment where the measuring sensor is located.

1.4. Aim and Scientific Novelty of the Study

The aim of the present work is to investigate, using numerical simulation, the magnetic field scattering caused by internal defects in a simplified two-layer ferromagnetic rod structure, Using numerical simulation, to investigate the spatial distribution characteristics of the leakage magnetic field caused by internal defects. This paper analyses the influence of the defect's geometric parameters (depth, width) on the topography of the MFL signal in both the ferromagnetic body and the air gap. This provides the theoretical basis for the design of new-generation magnetic sensor arrays and the development of signal filtering algorithms.

2. An analytical model for the homogenized boundary layer of a multilayer ferromagnetic structure

A two-dimensional model of a five-layer ferromagnetic rod structure is considered for the analytical estimation of the magnetic field propagation caused by scattering from internal defects in a ferromagnetic medium. The total length of the model is L=100 mm, and the total thickness is T=25 mm. The layer thicknesses are t1= 6 mm, t2= 5 mm, t3= 3 mm, t4= 5 mm, and t5= 6 mm, respectively.

A rectangular defect filled with air, with dimensions 2a×2b = 1×1 mm, is placed in the central layer of the structure. The defect is symmetrical with respect to the vertical axis of the model. The layer material is assumed to be an isotropic ferromagnet with relative magnetic permeability μ_r= 500. The structure is subjected to uniform longitudinal magnetization

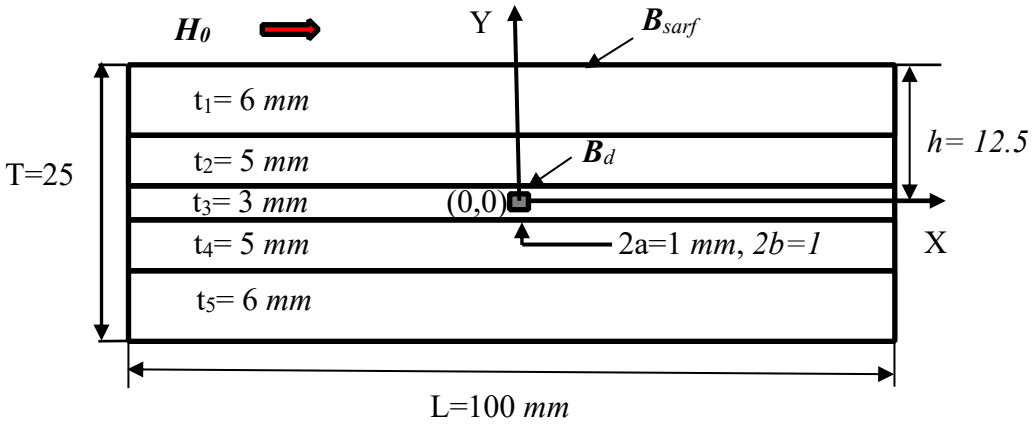
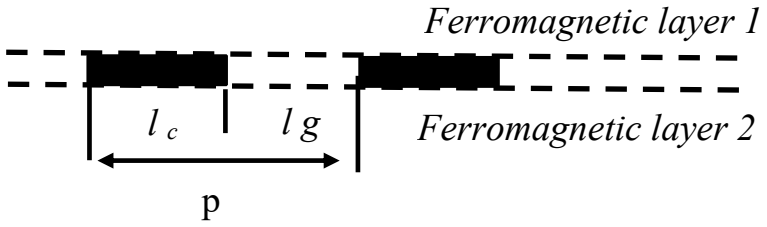


Fig. 2. 2D model of the layered structure of a steel cable with an internal defect

$$H_0 = H_0 e_x$$

2.1 Interlayer Contact Zone Model Interlayer Contact Zone (ICZ)

As in real multiferroic ferromagnetic systems, the metallic contact between the layers is not continuous. The Interlayer Contact Zone (ICZ) between neighboring layers is characterized by periodically alternating contact and non-contact regions.



$$p = l_c + lg\,, \qquad \lambda = l_c / p$$

Fig. 3. Visualization of homogeneous contact between ferromagnetic layers .

The geometry of the contact zone is determined by the Contact Fraction parameter λ

$$\lambda = \frac{l_c}{l_c + l_g} \qquad (3)$$

where: lc is the length of the metallic contact; lg is the length of the air contact gap.

The period of the ICZ in the contact zone between the layers is equal to

$$p = l_c + l_g \qquad (4)$$

Homogenization condition

Replacing microstructural details with their average effect is permissible when the contact zone period is significantly less than the characteristic transverse size of the defect:

$$p \ll 2a \qquad (5)$$

In this case, the actual discontinuous interlayer contact zone, the Interlayer Contact Zone, can be replaced by an equivalent interlayer contact zone model, the Equivalent Interlayer Contact Zone, which is characterized by an effective magnetic permeability.

As a result of the homogenization, the equivalent magnetic permeability of the contact zone is obtained as the Equivalent Permeability of the Contact Zone

$$\mu_{eq} = \mu_0[\lambda\mu_r + (1-\lambda)] \qquad (6)$$

Magnetic Transmission Coefficient

The influence of the Equivalent Interlayer Contact Zone is described by the Magnetic Transmission Coefficient τ.

$$\tau = \frac{1+(\mu_r - 1)\lambda}{\mu_r} \qquad (7)$$

which determines the efficiency of the transmission of the scattered field between the layers.

In the special case when

$$\lambda = 0.5, \mu_r = 100, \qquad \tau \approx 0.505$$

Leakage Field Transmission Factor (LFTF)

The magnetic field of the defect-generated scattering, when propagating through the layers, simultaneously undergoes:

spatial attenuation;

inter-layer transmission losses.

If the defect is located at a depth h from the ferromagnetic outer surface, then the amplitude of the scattered magnetic field at the surface can be estimated by the formula

$$B_{surf} = B_d \tau^N e^{-k1h} \quad (8)$$

where, $k_1 = \frac{\pi}{L}$, N is the number of Interlayer Contact Zones in the distance h between the defect and the external surface.

A Leakage Field Transmission Factor (LFTF) formula is introduced to quantitatively assess the detectability of an internal defect.

$$LFTF = \frac{B_{surf}}{B_d} \quad (9)$$

which is the final analytical expression for

$$LFTF = \tau^N e^{-k_1 h} \quad (10)$$

The presented image shows the result based on the main homogenized semi-analytical model of the study and is used for the validation and comparative analysis of the FEM results obtained in the EMCoS Studio 2025 environment.

3. 2D numerical analysis of a two-layered ferromagnetic structure with a homogenized , using EMCoS Studio 2025

The rapid growth of modern electronic and computational resources makes it possible to model commercial and/In the EMCos study environment, adequate models of with various complexities and geometries can be modelled to closely approximate real ferromagnetic systems.

Below, a two-layered composite ferromagnetic body is constructed within an electromagnetic simulation environment with a homogenized boundary condition, where the scattering problem of a magnetic field excited by an internal defect in a layered structure is investigated in a ferromagnetic medium, as well as in the homogenized boundary layer and in the space near the composite body.

Numerical analysis is performed in a laminated ferromagnetic body of laminated composite steel under an applied external static magnetic field of H = 1.9 Tesla.

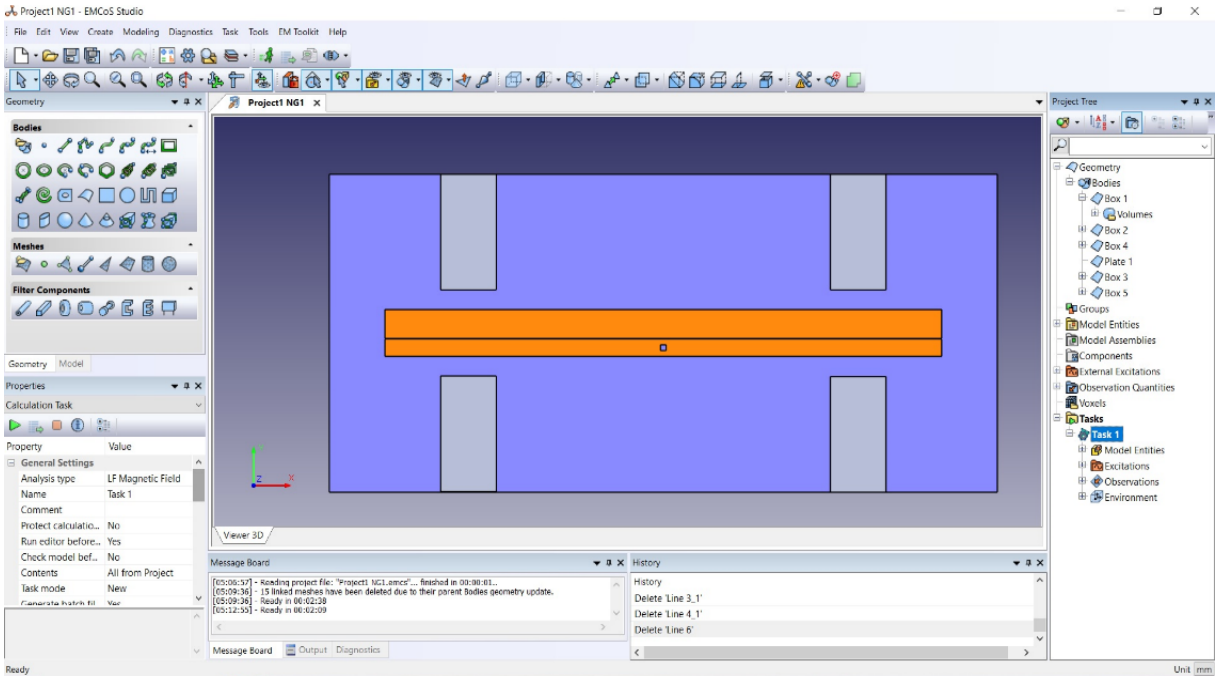


Fig. 4 Dispersion field modelling problem in a two-layer ferromagnetic medium EMCos studio

The scatter B-field image is shown for the 9 zones selected in the region adjacent to the internal defect, which are arranged parallel to the longitudinal layers. The problem setup interface in the software environment is shown below.

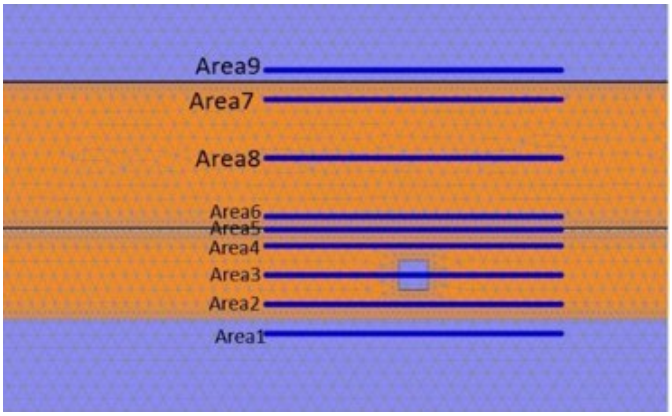


Fig. 5 Scanning area of the scattered field in the defect vicinity in the -5 mm +5 mm zone.

Region 1-4 line shows the region of the B magnetic field distribution in the first (3mm x 100 mm) ferromagnetic body and its adjacent external region. The distribution of the scattered magnetic field is presented in the graphs Fig. 6 – 9.

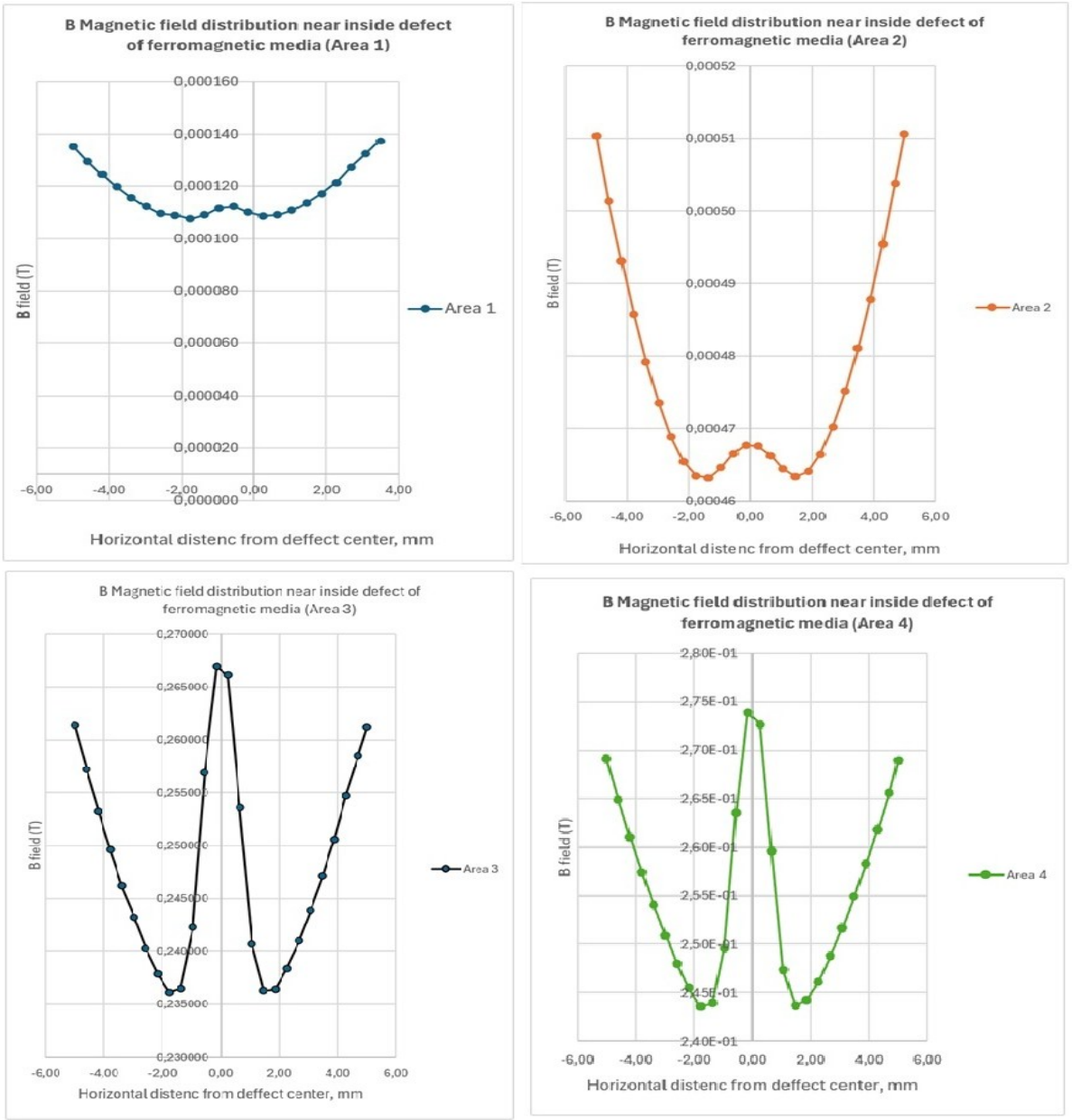


Fig. 6-9. Scattered magnetic field 2 D in the ferromagnetic medium (3 mm x 100 mm)

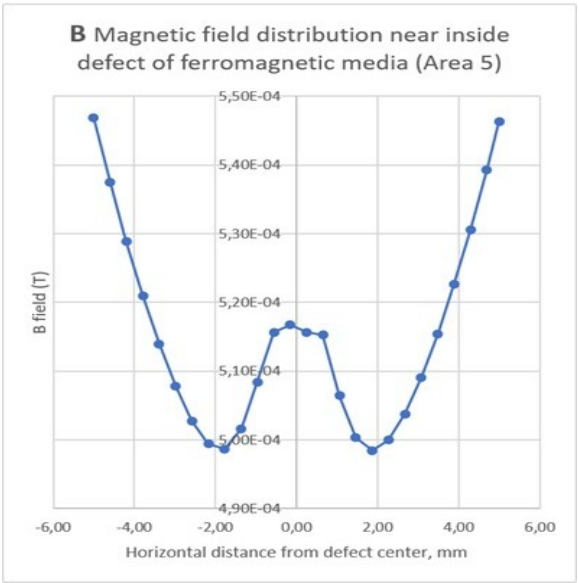


Fig. 10. Scattering magnetic field 2 in the homogenized boundary layer separating the ferromagnetic medium (0.1 mm x 100 mm)

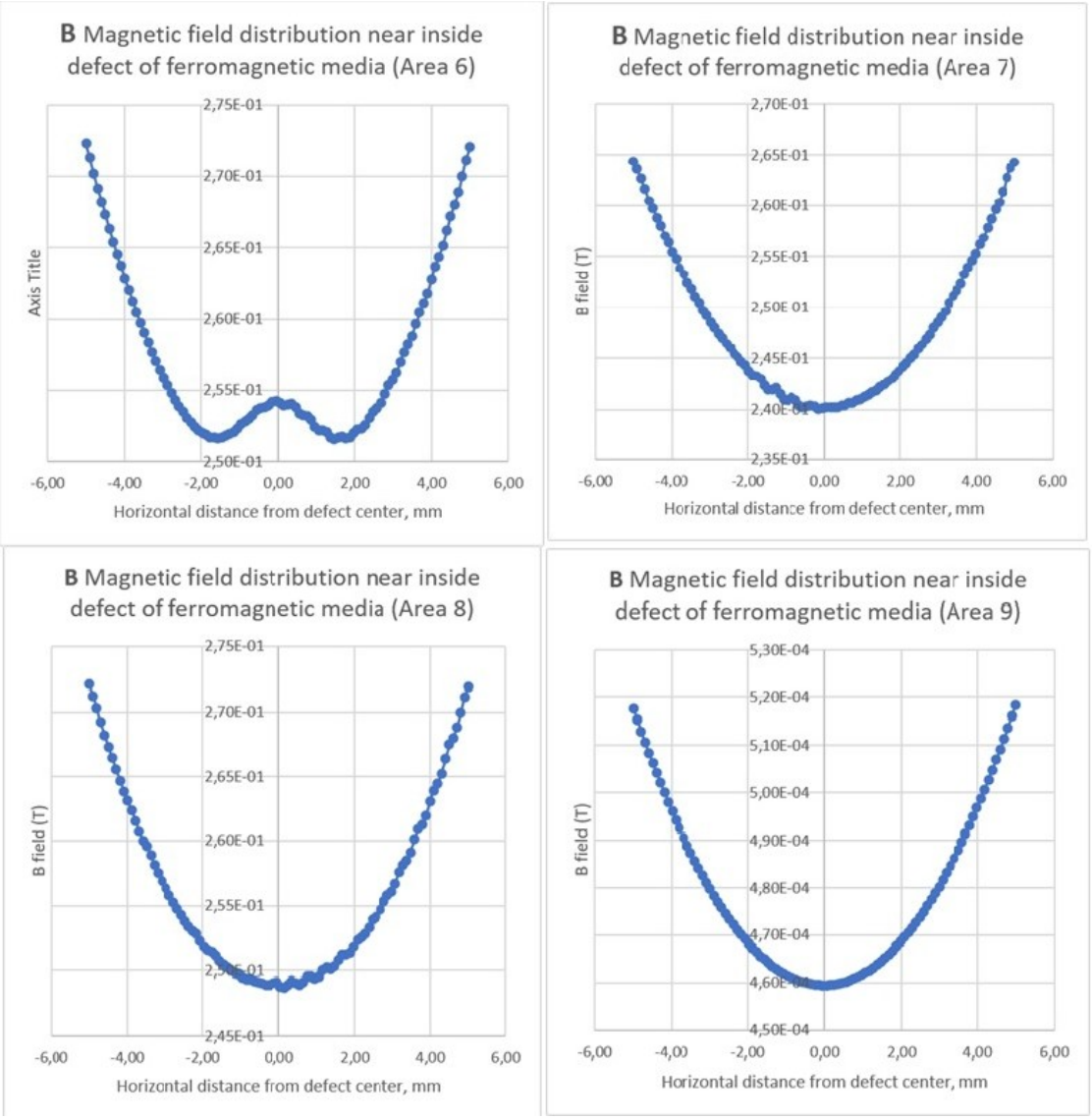


Fig. 11-14. Diffracted magnetic field in a 2D ferromagnetic medium (3 mm x 100 mm)

4. Results and Discussion of Numerical Modelling

Two-dimensional numerical simulations, performed in the EMcOS Studio 2025 environment, investigated the spatial distribution of the scattered magnetic field caused by an internal defect in a multilayer ferromagnetic structure. The model was based on the magnetization of the layered structure under the conditions of a 1.9 T saturating longitudinal magnetic field.

The results of the numerical analysis showed that the presence of an internal defect causes a local redistribution of the magnetic flux, resulting in a high-gradient leakage field being generated at the defect edges. The maximum field values are concentrated in the regions adjacent to the geometric boundaries of the defect, while their intensity decreases rapidly with increasing distance from the defect.

The resulting distributions confirm that the scattering field undergoes both spatial attenuation and inter-layer transmission losses as it propagates through the layers. This effect is particularly pronounced in homogenized boundary layers, where the quality of the inter-layer contact determines the efficiency of the field transmission.

The results obtained in the free-space region indicate that the amplitude of the signal generated by the defect is significantly smaller compared to the values in the ferromagnetic body, which is consistent with the physical mechanism of magnetic shielding. Nevertheless, the simulation showed that the local extrema of the scattered field maintain a clear spatial correlation with the defect's location, which ensures their detectability by high-sensitivity MFL sensors.

The results of the numerical model qualitatively agree with the regularities predicted by the homogenized analytical model. Specifically, a reduction in the Leakage Field Transmission Factor (LFTF) leads to a decrease in the amplitude of the scattered field registered at the surface, which confirms the physical adequacy of the developed model.

5. Conclusion

In this paper, a two-dimensional model of a multi-layered ferromagnetic structure was developed and analyzed, describing the formation and propagation of a leakage magnetic field caused by internal defects.

Based on the FEM simulations and the homogenized theoretical model, the following main results have been obtained:

1. It has been confirmed that an internal air defect causes a significant local distribution of the magnetic flux in the ferromagnetic structure, resulting in a characteristic spatial anomaly of the stray magnetic field. Local field maxima are formed near the defect edges, while a magnetic flux deficit occurs in the central part of the defect.

2. The results of the numerical analysis revealed that in regions distant from the defect, the field distribution maintains a smooth U-shape profile, whereas in the immediate vicinity of the defect, a double-peaked profile is formed. structure, which serves as a reliable magnetic indicator of the internal defect.
3. It has been shown that a layered ferromagnetic medium acts as a natural magnetic filter, which reduces the amplitude of the scattered field emerging from an internal defect to the surface. The results obtained confirm that the detectability of a defect is determined not only by its geometry but also by the efficiency of the magnetic coupling between the layers.
4. Within the scope of the study, the Interlayer Contact Zone (ICZ) was proposed for the first time. a homogenized description, which allows the complex discrete structure of a multilayer ferromagnetic system to be replaced by equivalent effective magnetic parameters.
5. The Magnetic Transmission Coefficient and the Leakage Field Transmission Factor (LFTF) were introduced, which quantitatively characterize the transmission efficiency of the leakage field generated by an internal defect in a multilayer ferromagnetic medium. These parameters establish a link between the microstructural characteristics of the interlayer contact and the MFL signal registered at the surface.
6. A unified analytical and numerical modelling framework was developed, which allows for the assessment of the detectability of an internal defect without full three-dimensional modelling. This significantly reduces computational resources while maintaining the ability to describe the key physical laws.
7. The scientific novelty of the work lies in the fact that, for the first time, a homogenized description of the propagation of the scattering magnetic field caused by internal defects is presented in multilayer ferromagnetic structures, where the process of defect information transfer is considered as an inter-layer magnetic transmission problem. The proposed approach represents an alternative to traditional full 3D FEM modelling and can be used for steel ropes, multi-layered ferromagnetic composites and other complex magnetic structures for the optimization of their non-destructive testing systems.
8. Further research is advisable to be extended to three-dimensional models of real spiral-wound steel cables, taking into account non-linear B–H characteristics, as well as conducting experimental validation.

Acknowledgments

This research was supported by the Shota Rustaveli National Science Foundation of Georgia [Grant Project No. AR 25-459], under the project title: 'Development and Laboratory Testing of a High-Precision Magnetic Sensor Device for Non-Destructive Testing of Longitudinal Ferromagnetic Structures'."

We are also grateful to the administration of EMCoS LLC, who granted us a scientific license to use the company's software product, EMCoS Studio 2025, in our research.

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