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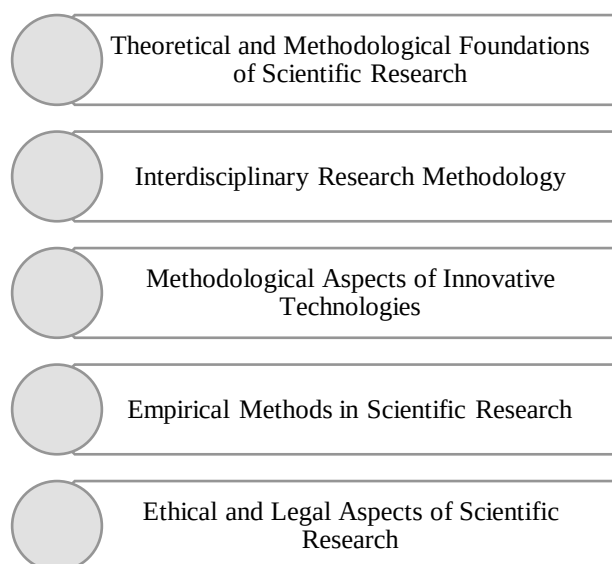


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DETERMINING EFFECTIVENESS BASED ON THE ACCURACY CRITERION OF THE OPTIMIZATION METHOD FOR RECONSTRUCTING PROFILES IN THE PCA SPACE

Abstract. This study presents a method for simultaneously reconstructing the electrical conductivity and magnetic permeability profiles of planar conductive objects using surface eddy current probes, leveraging surrogate optimization with deep neural network metamodels in reduced PCA-dimensional spaces. The approach addresses the computational complexity of inverse problems by incorporating apriori information and applying dimensionality reduction, achieving high accuracy in profile reconstruction as demonstrated in comprehensive numerical experiments. The results confirm the effectiveness and potential of this method for nondestructive testing and material characterization in various industrial applications.

Key words: electrical conductivity, magnetic permeability, profile reconstruction, inverse problem, surrogate model, PCA space, surface eddy current probes

Introduction. The electrical conductivity and magnetic permeability of materials are fundamental electrophysical properties that inform us about their structural and functional characteristics. Accurate reconstruction of these profiles is crucial in nondestructive testing and material diagnostics, particularly using surface eddy current probes. The inverse problem of determining such profiles from measurement data is computationally challenging due to high dimensionality and complex interactions affecting probe signals. This study employs surrogate modeling and dimensionality reduction techniques to enhance reconstruction accuracy and computational efficiency.

The primary **aim** of this work is to develop a computationally efficient method for reconstructing electrical conductivity and magnetic permeability profiles of planar metal objects using surrogate optimization techniques. The study focuses on reducing the dimensionality of the optimization problem by applying advanced dimensionality reduction methods such as PCA, thereby enhancing the accuracy and efficiency of the reconstruction process. Additionally, the method aims to incorporate apriori information into neural network-based surrogate models to improve predictive accuracy in diverse operational conditions. This approach addresses the challenges of high computational cost and complexity inherent in inverse problems related to electromagnetic property profiling.

Methods and Materials. The study focuses on reconstructing the electrical conductivity (EC) and magnetic permeability (MP) profiles of planar metal objects using surface eddy current probes (ECPs). The method employs surrogate optimization techniques with reduced-dimensional metamodels built by deep neural networks. The original high-dimensional design space is reduced using principal component analysis (PCA), which preserves the majority of the variance while minimizing computational complexity. Data for metamodel training were generated through a design of experiments based on Sobol's quasi-random sequences to uniformly fill the factor space.

The electrodynamic model follows the Uzal-Cheng-Dodd-Deeds analytical formulation, modified to consider multilayer subsurface zones representing varying material properties. The model accounts for excitation coil geometry, uniform current density, and the layered nature of the test

object. Output signals of the ECP are computed by summing the coil field in air and the perturbations caused by conductive layers. Computational experiments include variations in EC, MP, frequency, and probe lift-off distance to comprehensively capture their effects on output signals.

Neural network metamodels are separately trained for real and imaginary components of the ECP signal, using architectures with multiple hidden layers and activation functions such as hyperbolic tangent. Training is performed using advanced algorithms like Levenberg-Marquardt with normalization of input feature scales for stability. Model accuracy is validated via root mean square error (RMSE), mean absolute error (MAE), and relative mean absolute error (RMAE) across training, cross-validation, and test datasets.

Experimental profiles cover a wide range of EC and MP values, scaled to represent realistic surface and subsurface variations. The PCA-space dimensionality was tested for multiple values, ultimately selecting dimensions that balanced metamodel accuracy and computational efficiency. The inverse problem is formulated as an optimization to minimize the discrepancy between measured and surrogate-predicted ECP signals. Final reconstructed profiles demonstrate high accuracy with errors below 5%, validating the effectiveness of the surrogate-based inverse solution.

This approach reduces the “curse of dimensionality” typical of direct optimization in the full design space, enabling practical and efficient material characterization. The developed framework integrates physical modeling, statistical design, neural network learning, and global optimization for robust profile reconstruction. Future work may extend this methodology to multifrequency sensing and more complex geometries.

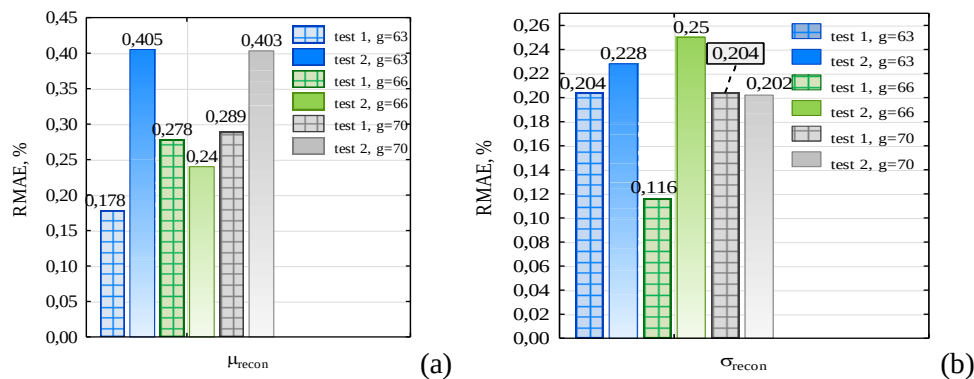


Fig. 1. Errors in determining the RMAE profiles (expressed as percentages) are presented for two separate test measurements conducted at different PCA space dimensions: (a) for magnetic permeability profiles and (b) for electrical conductivity profiles

Conclusions. To enhance the accuracy of profile reconstruction, it is essential to consider information from all significant factors influencing the formation of the combined VSP signal, all of which were accounted for in this study. The precision of solving the inverse problem for reconstructing magnetic permeability and electrical conductivity profiles is also affected by the accuracy of the developed metamodels. This work demonstrates that excessively reducing the PCA space dimension by discarding basis vectors linked to important eigenvalues leads to difficulties in creating metamodels with satisfactory mean squared error performance. Conversely, incorporating more information by increasing the PCA space dimension allows obtaining highly accurate metamodels. Minor changes in PCA space dimensions caused by eigenvalues below the 10^{-3} order did not significantly improve reconstruction accuracy, while expanding the search space dimension complicates finding the extremum due to the "curse of dimensionality", ultimately decreasing profile search accuracy. Therefore, selecting the smallest possible PCA dimension that ensures compact, accurate surrogate models and facilitates effective optimization is advisable.

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