Multiscale modelling of magnetic sensors

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The conventional methods for the numerical evaluation of the behavior of magnetic materials are only valid within specific size ranges, using either micromagnetic or macroscopic models. In this work, we propose a multiscale modeling approach that bridges the gap between micromagnetism and the electromagnetic response of magnetic materials. The goal is to describe the effective behavior of magnetic sensors based on the magnetization effects emerging at the micromagnetic scale. As an example, we describe a novel methodology to model the magnetoimpedance (MI)-based sensors. Additionally, we apply this methodology to predict the MI effect in a permalloy multilayer structure and compare the results with experimental measurements.

Keywords: multiscale modelling; micromagnetic simulations; magnetic sensors

1. Introduction

In recent years, there has been a significant increase in the use of numerical methods to evaluate phenomena occurring in magnetic materials, as well as to validate experimental results. However, these well-established methods are only valid within specific size scales. In this context, multiscale modeling emerges as a key tool to accurately describe the behavior of magnetic materials across different scales [1, 2].

Since magnetic sensors depend on the interaction between magnetization and the electromagnetic field, multiscale modeling is a crucial tool for their analysis. In this work, a numerical framework integrating both micromagnetic and macroscopic models is developed to study magnetic sensors. The workflow involves computing the intrinsic material parameters using micromagnetic simulations. These results are then transferred to a Finite Element Method (FEM) modeling program, which self-consistently solves the equations governing macroscopic phenomena in the material, providing the sensor response. This methodology has been successfully applied to sensors based on anisotropic magnetoresistance (AMR) [2], and can be extended to other phenomena such as magnetoimpedance (MI). To illustrate the methodology, we detail the modeling procedure for the MI effect, compare the numerical results with experimental measurements on a permalloy multilayer structure, and discuss potential future research directions.

2. Results and Discussion

MI refers to the change of the electrical impedance as a function of the external magnetic field when an alternating electrical current flows through a ferromagnetic material. These changes are related to the skin effect, which strongly depends on magnetic permeability. The permeability μ is influenced by the variations of the magnetization m with respect to the total magnetic field (sum of the field generated by the alternating current h_{ac} and the dc external magnetic field H_{bias}). Mathematically, this relationship can be expressed as:

$$\mu = 1 + \chi = 1 + dm/dH,$$

where χ is the magnetic susceptibility and H is the sum of the dc and ac magnetic fields. The magnetic permeability establishes the connection between the micromagnetic model through m, and the macroscopic model via h_{ac}. Determining the correct value of h_{ac} is not trivial, as it depends on various factors, including the amplitude of the total electric current I_{ac} applied to the specimen, the distribution of the current density governed by Ampere's Law, and the skin effect. Therefore, a circular dependency arises between h_{ac} and the skin effect, since the latter strongly depends on permeability.

To resolve this dependency, we employ a systematic approach: using a FEM program to compute the distribution of h_{ac} for different values of I_{ac} and μ. Then, this distribution is used as an input for micromagnetic simulations to determine the corresponding distribution of magnetic permeability as a function of h_{ac}. Finally, this function is incorporated into Maxwell's equations, which are solved self-consistently at each point in the material, ultimately resolving the circular dependency and yielding the macroscopic sensor response.

This multiscale approach allows us to reproduce experimental MI results directly from fundamental properties of the magnetic material (Fig. 1). It becomes a useful tool to analyze different phenomena of interest, such as the influence of current on permeability or the emergence of ferromagnetic resonance (FMR) effects at low fields. The agreement between numerical and experimental results confirms the robustness of the proposed methodology.

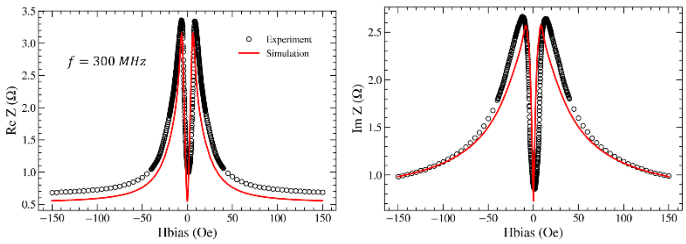

Figure 1: Experimental results (red line) and numerical calculation (black dots) of the Z components as a function of the external magnetic field at 300 MHz., for a permalloy multilayer structure.

3. Conclusions

In conclusion, we present a new approach to numerically model different types of magnetic sensors, along with their experimental validation. This methodology can be extended to other sensors or to study macroscopic effects at the microscopic scale. Furthermore, this framework opens up the door to designing more complex devices, due to the integration within a multiphysics software environment.

References

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