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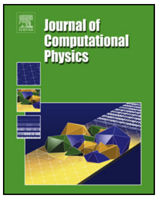

Comparison of multiscale models for eddy current computation in granular magnetic materials

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ABSTRACT

In this paper, two multiscale numerical techniques are applied to the study of eddy current phenomena in magnetic granular materials. In particular, the Multiscale Finite Element Method and the Variational Multiscale Method are compared in terms of accuracy and computational efficiency with respect to a standard Finite Element approach and to a homogenization technique with second-order correctors. The numerical analysis is carried on focusing on specific conditions arising in the simulation of actual granular materials, such as soft ferrites and composite materials. In particular, depending on the working frequency and domain size, the electromagnetic phenomena may have a mainly local or global behavior, resulting in a different numerical response of the considered techniques. The results show that the Variational Multiscale Method is more accurate than the Multiscale Finite Element Method, but less efficient from a computational point of view. Moreover, the Multiscale Finite Element Method is found to have a complementary behavior with respect to the homogenization approach with local correctors.

1. Introduction

Heterogeneous soft magnets are largely adopted in many industrial applications to reduce eddy current losses due to medium-high frequencies components in magnetic flux (see for example [1–8]). Soft ferrites (e.g. Mn–Zn) are widely employed in power electronics for transformers and inductor cores, while soft magnetic composites are very promising for high speed electrical machines. Soft ferrites and composites combine sufficiently good magnetic properties with a quite high macroscopic resistivity, limiting the eddy current circulation caused by electromagnetic induction phenomena.

Ferrites are produced by heating an intimate mixture of powdered precursors pressed into a mold, while soft composites are obtained by pressing and heating iron powders. In both cases, a granular structure arises, where magnetic grains are separated by high resistivity layers. Size and electromagnetic properties of grains and grain boundary layers are strongly different for ferrites and soft composites, but from a schematically viewpoint the two categories of materials can be modeled in a similar way. In both materials, eddy currents are expected to be mainly confined within conductive grains, but by increasing frequency and/or sample size macroscopic eddy current circulation appears, causing a loss increment. The quantification of eddy current phenomena and energy losses in these heterogeneous materials is therefore of great interest for a large variety of engineering applications.

Due to the granular nature of ferrites and soft composites, models based on the solution of the Maxwell equations should be able to consider the interaction between the macroscopic scale (that is the sample size) and the microscopic one (essentially determined by the grain size). In actual materials, size, shape and physical properties of grains and grain

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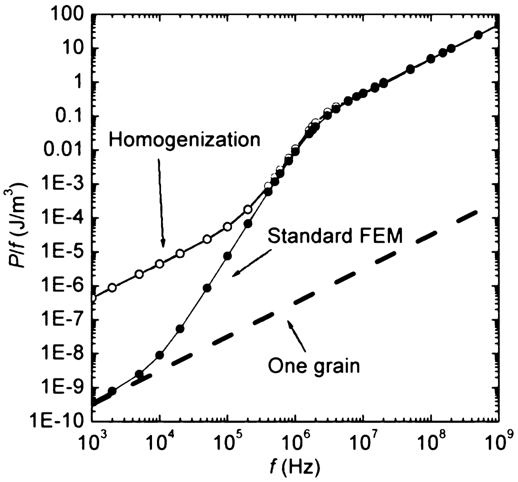

Fig. 1. Frequency behavior of eddy current specific energy losses in a Mn–Zn ferrite sample. The correct behavior, obtained with standard finite element solution, is compared with those computed by adopting equivalent properties determined by homogenization.

boundary layers are stochastically distributed, but deterministic models can be defined, modeling the microstructure as a finely periodic medium with a well defined separation between large and small spatial scales. Under this simplifying assumption, the microscopic structure of the material can be described by the multiple repetition of an elementary cell, composed of a magnetic grain surrounded by a grain boundary layer.

Homogenization techniques have been widely applied in various physical contexts to determine "averaged" properties of finely periodic structures in the case of problems described by various types of differential equations (elliptic, parabolic and hyperbolic) [9–16]. Homogenization approaches have been brought in electromagnetism for many years, with the aim of determining the electric and magnetic properties of materials having a periodic microstructure, starting from the solution of a local problem defined on an elementary cell or spatial period [17–19]. These techniques have been increasingly used for the analysis of soft magnetic composites and ferrites [20–23], metamaterials [24,25], laminated cores [26–29] and magnetic shielding [30,31]. Anyway, even if powerful and useful for a lot of cases, homogenization limits lie in the assumption of spatial periodicity and in the absence of upscaling to intermediate spatial scale phenomena. Attempts to remove these limits have been more recently proposed. For example, the use of high-order correctors to be superposed to the homogenized field solution provides good results [32], even if this approach is practically limited to second-order terms, due to the complexity in evaluating higher-order contributions, and the accuracy of local correction is weak in the presence of strongly localized phenomena. On the other hand, extensions towards stochastic homogenization [20,33] are based on the concept of representative elementary volume. In order to include all random events, a sufficiently large macro-element is defined with a consequent strong increase in the unknown number.

As a matter of fact, the analysis of eddy current losses in heterogeneous magnetic materials is particularly critical for homogenization. As an example, experimental evidence in soft ferrites proves that eddy current losses increase more than expected with frequency [34]. Similarly, in soft magnetic composites a dependence of eddy current losses versus the sample dimension is found, keeping fixed the grain size [35]. Both these behaviors demonstrate an evolution from a "local" to a "global" character of eddy current flow within the material, which cannot be properly taken into account by adopting the material equivalent properties obtained by homogenization. This effect is well evident from the analysis of Fig. 1, where eddy current energy losses in Mn–Zn ferrites are plotted versus frequency. Homogenization predicts quite well losses in the high frequency region, where almost global eddy current circulation is settled, while large discrepancies are found in the lower frequency limit where the homogenization prediction strongly differs from the physical limit of specific energy losses obtained in a single grain. In these situations, depending on the ratio of grain size to core dimensions, the results obtained with equivalent homogenized parameters can overestimate or underestimate the actual limit value obtained when induced currents totally flow within each single grain.

These results put is evidence the need of a modeling approach able to accurately predict the electromagnetic phenomena in a wide range of working conditions, considering the multiscale nature of the problem. Standard numerical techniques for the direct solution of Maxwell equations cannot be reasonably adopted for the analysis of actual problems, because the number of unknowns becomes too large, rapidly reaching the limits of computing resources. For these reasons, multiscale techniques can be conveniently applied with the aim of separating the different spatial scales, but keeping the influence of each scale on the other one.

Multiscale methods, capable of upscaling to intermediate spatial scales, have been applied in various scientific and engineering disciplines, such as material science, mechanics, fluidodynamics and electromagnetics. A theoretical concept provided by the coarse graining method to upscale the electric field in the eddy current approximation of the Maxwell equations has been proposed in [36]. In this work, an upscaled equation for the electric field by the coarse graining method