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Multiscale Modelling of Nonlinear Eddy Current Problems Using the h -conforming Formulation

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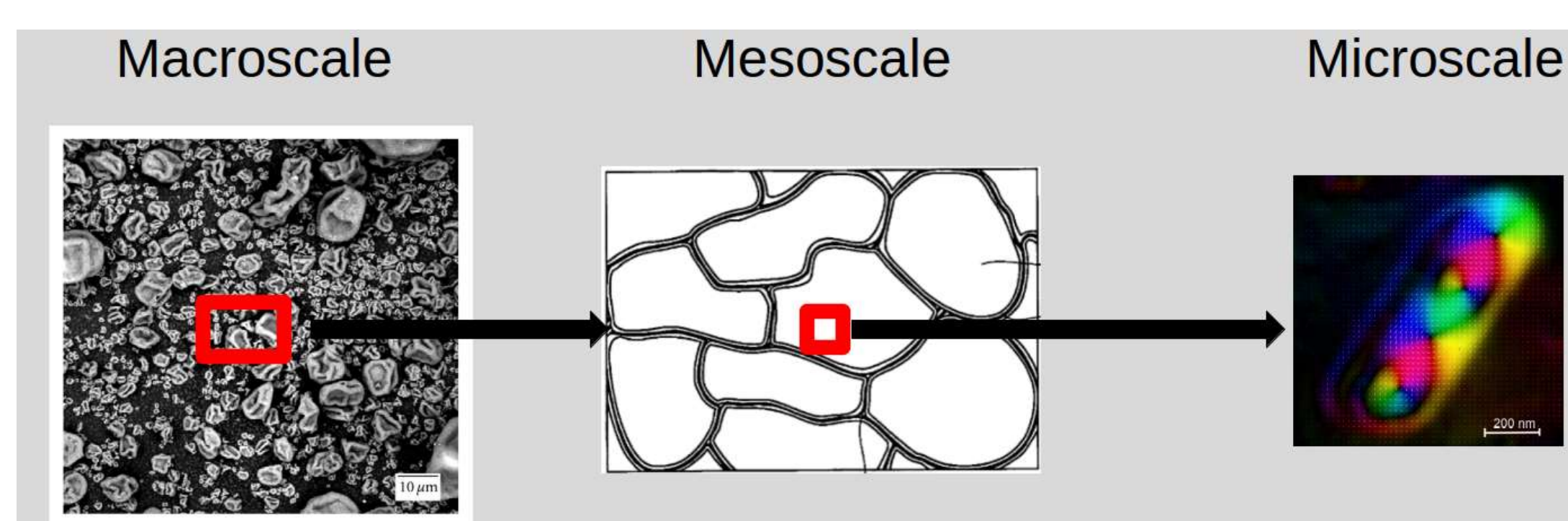
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Abstract

This paper deals with an h -conforming multiscale formulation for nonlinear eddy current problems in idealized soft magnetic composites using the heterogeneous multiscale method. The classical h - ϕ formulation is recalled before presenting the different components of the h - ϕ multiscale formulation including the governing weak forms, the upscaling of quantities of interest and details some on the numerical implementation. Validation results are then presented before a conclusion.

1. Introduction

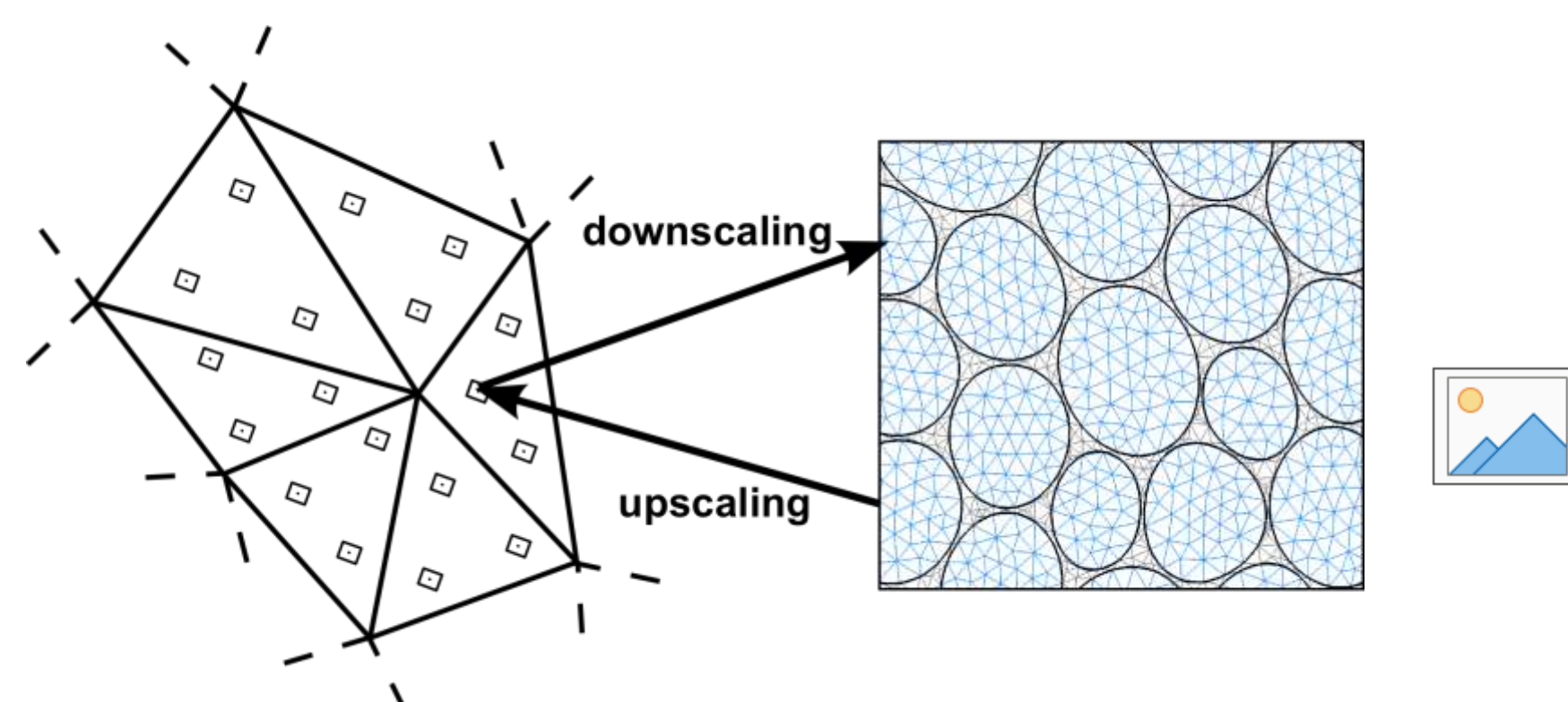
- Electrical devices with soft magnetic composites (SMC) can operate at higher frequencies with reduced eddy current losses.
- SMC exhibit isotropic nonlinear/hysteretic behaviour.
- Classical numerical methods such as FEM are too costly and multiscale methods are more convenient to characterize SMC. In this research work, we used the heterogeneous multiscale method (HMM).



3. Multiscale formulation

Scale separation :

Length of the microstructure \ll length of device / characteristic length of external loadings.



- At each iteration: 1 macroproblem and many microproblems (1 per Gauss point of the Macro mesh). Couple these problems (**upscaling-downscaling**).

Strong form :

• **Macro** : $\text{curl}_x \mathbf{h}_M = \mathbf{j}_M$, $\text{curl}_x \mathbf{e}_M = -\partial_t \mathbf{b}_M$,

$$\mathbf{b}_M = \mathcal{B}_M(\mathbf{h}_M), \mathbf{e}_M = \rho \mathbf{j}_M = \rho \text{curl}_x \mathbf{h}_M.$$

• **Meso** : $\text{curl}_y \mathbf{h}_c = \mathbf{j}_c$, $\text{curl}_y (\mathbf{e}_c - \kappa \partial_t \mathcal{B}_M \times \mathbf{y}) = -\partial_t \mathbf{b}_m$,

$$\mathbf{b}_m = \mathcal{B}(\mathbf{h}_M + \mathbf{h}_c), \mathbf{e}_c = \rho \mathbf{j}_c = \rho \text{curl}_y \mathbf{h}_c.$$

Weak form :

• **Macro** : $\left(\frac{\partial}{\partial t} \mathcal{B}_M(\mathbf{h}_M), \mathbf{v}_M \right)_{\Omega} + \left(\rho \text{curl}_x \mathbf{h}_M, \text{curl}_x \mathbf{v}_M \right)_{\Omega_c} + \sum_{i \in \mathcal{C}} \mathcal{I}_i V_i = 0.$

• **Meso 1** : $\left(\frac{\partial}{\partial t} \mathcal{B}(\mathbf{h}_M + \mathbf{h}_c), \mathbf{v}_c \right)_{\Omega_m} + \left(\rho \text{curl}_y \mathbf{h}_c, \text{curl}_y \mathbf{v}_c \right)_{\Omega_{mc}} = \left(\kappa \sigma \partial_t \mathcal{B}_M \times \mathbf{y}, \text{curl}_y \mathbf{v}_c \right)_{\Omega_{mc}}$

• **Meso 2** : $\left(\mathcal{B}(\mathbf{h}_M + \text{grad}_y \phi_c), \text{grad}_y \phi_c' \right)_{\Omega_m} = 0$

Upscaling :

Upscaling of \mathcal{B}_M using Meso 1: $\mathcal{B}_M = \frac{1}{|\Omega_m|} \iiint_{\Omega_m} \mathcal{B}(\mathbf{h}_M + \mathbf{h}_c)$

Upscaling of $\frac{\partial \mathcal{B}_M}{\partial t}$ using problem Meso 2 and the finite difference method.

Implementation :

- Temporal discretization using the Backward Euler method
- Nonlinear problem solved using a relaxed Newton-Raphson scheme

Conclusions:

- HMM yields accurate local fields and global quantities (Joule losses, voltage, etc.) for nonlinear eddy current problems with idealized SMC.
- \mathcal{B}_M is upscaled using fields of the magnetodynamic problem whereas $\frac{\partial \mathcal{B}_M}{\partial t}$ is obtained using fields of the magnetostatic problem.
- Adaptive relaxation should be used for the convergence of the nonlinear meso-problems and of macro-problem (if there is too much saturation).
- The HMM algorithm scales very well on clusters.

2. Classical formulation

- Maxwell's equations and constitutive law:

$$\text{curl} \mathbf{h}^\varepsilon = \mathbf{j}^\varepsilon, \text{curl} \mathbf{e}^\varepsilon = -\partial_t \mathbf{b}^\varepsilon,$$

$$\mathbf{b}^\varepsilon = \mathcal{B}(\mathbf{h}^\varepsilon), \mathbf{e}^\varepsilon = \rho^\varepsilon \mathbf{j}^\varepsilon = \rho^\varepsilon \text{curl} \mathbf{h}^\varepsilon.$$

- Weak form: $\left(\frac{\partial}{\partial t} \mathcal{B}(\mathbf{h}^\varepsilon), \mathbf{v} \right)_{\Omega} + \left(\rho^\varepsilon \text{curl} \mathbf{h}^\varepsilon, \text{curl} \mathbf{v} \right)_{\Omega_c} + \sum_{i \in \mathcal{C}} \mathcal{I}_i V_i = 0.$

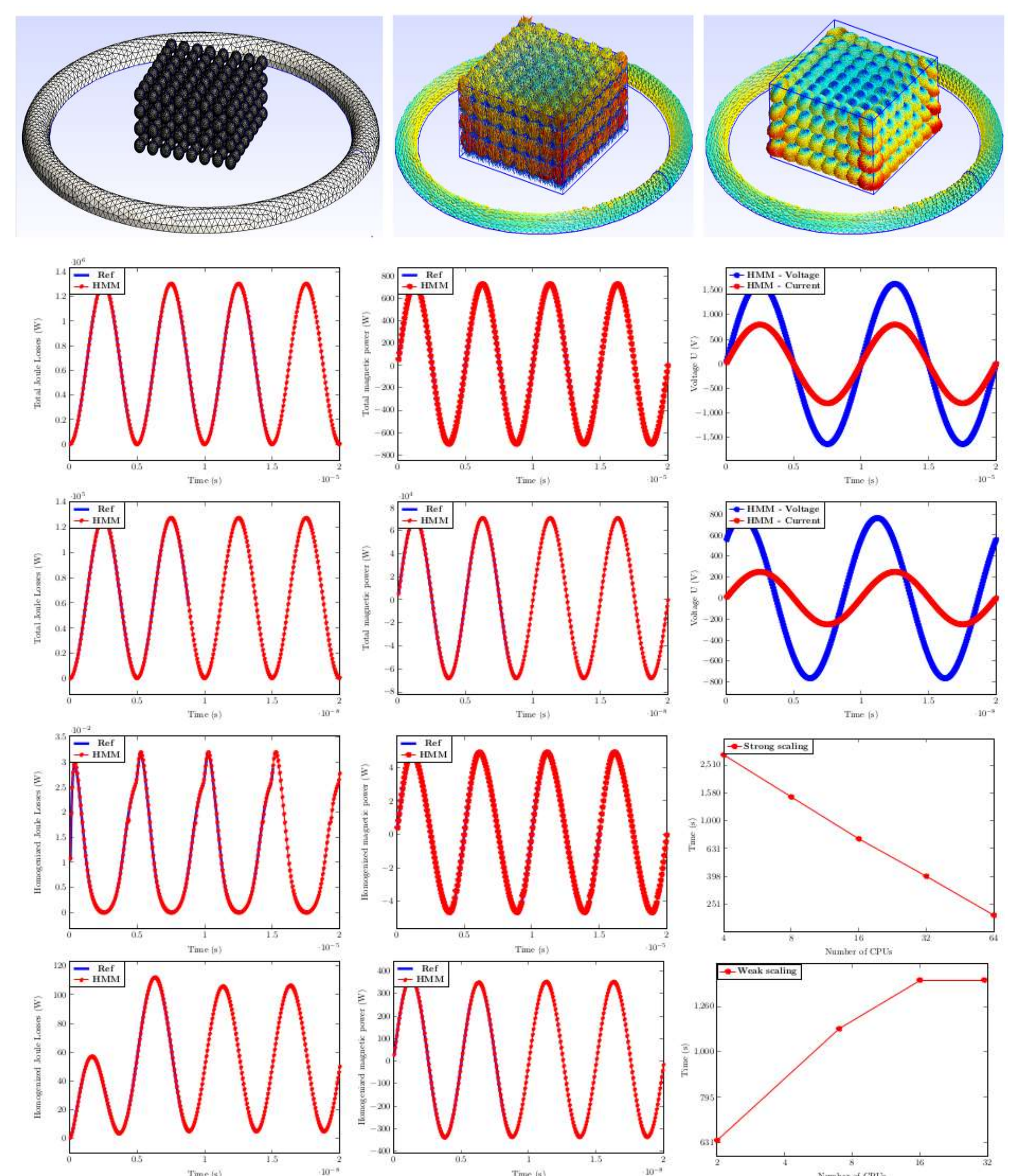
- Discretization of the magnetic field:

$$\mathbf{h}^\varepsilon(\mathbf{x}) = \sum_{e \in \Omega_c} h_e \mathbf{S}_e(\mathbf{x}) + \sum_{n \in \Omega_c^c} \phi_n \text{grad} S_n(\mathbf{x}) + \sum_{i \in \mathcal{C}} \mathcal{I}_i \mathbf{c}_i(\mathbf{x})$$

4. Numerical Results

Geometry : 8 x 8 x 8 conductive spheres (radius $r = 40\mu\text{m}$) surrounded by a massive inductor.

Material laws : conductivity $\sigma = 10^7 \text{Sm}$, nonlinear Fröhlich-Kennely law.



Perspectives :

- Use of the HMM method to model closed magnetic circuits such as the transformers.
- Extension of the formulation to account for macroscale currents (e.g., problems with macroscale displacement currents).
- Use of the model order reduction (MOR) for further reduction of the computational cost.