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Neural-Network-based Homogenized Model for Ferromagnetic Laminated Cores

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Abstract

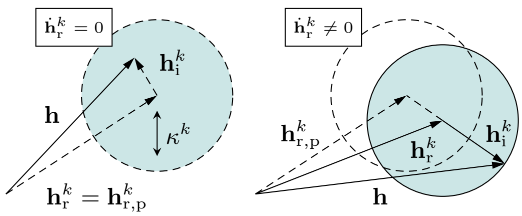
Accounting for hysteresis and eddy currents in finite element simulations of electrical machines is usually computationally expensive. These phenomena have however a significant impact on the machine performance. To account for **iron losses** with a **low computational cost**, we have trained a **Recurrent Neural Network** to serve as material law in **2D finite element simulations**.

Static Mesoscopic Model: EB Hysteresis

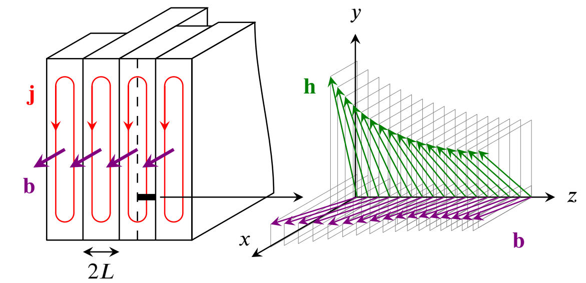
N cells subjected to the same input magnetic field $\mathbf{h} = \mathbf{h}^k,\ k = 1, ..., N$. For each cell, $\mathbf{h}$ is decomposed into a reversible part $\mathbf{h}_\mathrm{r}^k$ and an irreversible part $\mathbf{h}_\mathrm{i}^k$. If κ^k denotes the maximum norm of $\mathbf{h}_\mathrm{i}^k$ and $\mathbf{h}_{\mathrm{r,p}}^k$ the previous $\mathbf{h}_\mathrm{r}^k$, the model update law is:

$$\mathbf{h}_\mathrm{r}^k = \begin{cases} \mathbf{h}_{\mathrm{r,p}}^k & \text{if } |\mathbf{h} - \mathbf{h}_{\mathrm{r,p}}^k| \le \kappa^k \quad (\dot{\mathbf{h}}_\mathrm{r}^k = 0) \\ \mathbf{h} - \kappa^k \frac{\mathbf{h} - \mathbf{h}_{\mathrm{r,p}}^k}{|\mathbf{h} - \mathbf{h}_{\mathrm{r,p}}^k|} & \text{otherwise} \quad (\dot{\mathbf{h}}_\mathrm{r}^k \neq 0) \end{cases}$$

The output magnetic flux density $\mathbf{b}$ is given by $\mu_0 \mathbf{h} + \mathcal{L}(|\mathbf{h}_\mathrm{r}|) \frac{\mathbf{h}_\mathrm{r}}{|\mathbf{h}_\mathrm{r}|}$ with $\mathcal{L}$ the Langevin function and $\mathbf{h}_\mathrm{r} = \sum_{k=1}^N w^k \mathbf{h}_\mathrm{r}^k$ $(\sum_{k=1}^N w^k = 1)$. $\frac{\partial \mathbf{b}}{\partial \mathbf{h}}$ has an analytical expression.



Dynamic Mesoscopic Model: Laminations with Eddy Current and Hysteresis



One-dimensional magneto-quasistatic formulation in terms of the magnetic field: Find $\mathbf{h}(z,t) = (h_x(z,t), h_y(z,t))$ on a half lamination such that, for $z \in [0, L]\,, t > 0$:

$$\begin{cases} \partial_t \left(b_x(\mathbf{h}), h'_x\right)_{[0,L]} + \left(\sigma^{-1}\partial_z h_x, \partial_z h'_x\right)_{[0,L]} = 0 \\ \partial_t \left(b_y(\mathbf{h}), h'_y\right)_{[0,L]} + \left(\sigma^{-1}\partial_z h_y, \partial_z h'_y\right)_{[0,L]} = 0 \end{cases}$$

holds for all test functions h'_x, h'_y, with $\partial_z \mathbf{h}(t, 0) = 0$ and $\mathbf{h}(t, L) = \mathbf{H}_\mathrm{macro}$. $\mathbf{B} = \mathbf{B}_\mathrm{macro}$ is retrieved by averaging $\mathbf{b}$ over the half lamination thickness. $\frac{\partial \mathbf{B}}{\partial \mathbf{H}}$ is obtained by a perturbation method.

The dynamic model accounts for eddy currents, and incorporate the effect of hysteresis if $b_x(\mathbf{h})$ and $b_y(\mathbf{h})$ make use of the static hysteresis model.

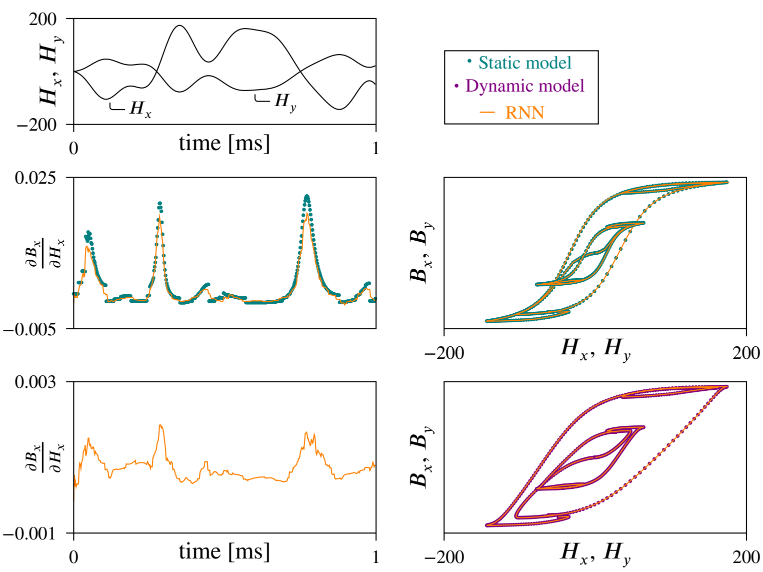
Recurrent Neural Network (RNN)

Architecture: Single-layer gated recurrent unit with a hidden size of 256. Embedding and decoding both use two feed-forward layers with respectively `ReLU` and `Linear` activation functions.

Dataset: $5\ 10^5$ $\mathbf{H}$ sequences of 10^3 time steps that mimic fields encountered in electrical machines are generated artificially. The corresponding $\mathbf{B}$ sequences are obtained by solving respectively the static model (50 minutes) and the dynamic model (3 hours) on an `AMD EPYC 7763 CPU`.

Training: Static and dynamic RNN models are both trained to minimize a mean square error over 10^6 iterations (about 6 hours) on a GPU node (`NVIDIA A100 40GB`) of the Lucia cluster. Both trainings reach a test error of about $2\ 10^{-6}$.

Inference: The material law $\mathbf{B}(\mathbf{H})$ is evaluated in a forward pass, $\frac{\partial \mathbf{B}}{\partial \mathbf{H}}$ is obtained by **automatic differentiation**.



Macroscopic Finite Element Simulations

Magnetostatic ϕ formulation: $\mathbf{H} = \mathbf{H}_\mathrm{s} - \nabla\phi$.

Weak formulation of the magnetic Gauss law $\nabla \cdot \mathbf{B} = 0$ with vanishing Newman boundary condition:

$$\Big(\mathbf{B}(\mathbf{H}), -\nabla\phi'\Big)_\Omega = 0, \quad \forall\, \phi'.$$

$\Rightarrow$ Linearize the non-linear $\mathbf{B}(\mathbf{H})$ material law, and solve for $\mathbf{H}_i$ with the Newton-Raphson scheme:

$$\left(\mathbf{B}(\mathbf{H}_{i-1}) + \frac{\partial \mathbf{B}}{\partial \mathbf{H}}(\mathbf{H}_{i-1})(\mathbf{H}_i - \mathbf{H}_{i-1}), -\nabla\phi'\right)_\Omega = 0,\ \forall\, \phi'$$