Spectral Element Method Modeling of eddy current losses in conductive materials

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Spectral Element Method Modeling of Eddy Current Losses in Conductive Materials

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Introduction

• High-frequency wireless power transfer systems impose challenges in the electromagnetic modeling.
• The skin depth is several orders of magnitude smaller in comparison to the object dimensions.
• Meshing problems arise in the widely applied Finite Element Method (FEM).
• As an alternative, higher order methods, such as the Spectral Element Method (SEM) can be applied.
• In this work, the advantages of the SEM in terms of computational effort and accuracy w.r.t. the FEM are shown.

Benchmark System & Modeling

• The benchmark system consists of a C-shaped transformer operated at 1 MHz, and a conductive plate positioned in the fringing-flux path parallel to the air gap, as shown in Fig. 1.
• The meshing requirements are reduced by only considering a plate width equal to three times the skin depth, which introduces a discrepancy of less than 0.1%, as shown in Fig. 2.
• The SEM discretizes the domain into rectangular elements and uses Legendre polynomials to approximate the solution.
• In the FEM model, rectangular and triangular mesh elements are used in the conductive and non-conductive regions, respectively.
• The FEM requires at least two mesh layers per skin depth.

Table I

<table>
<thead>
<tr>
<th>Physical quantities and material properties.</th>
<th>Frequency</th>
<th>Conductivity</th>
<th>Relative permeability</th>
<th>Skin depth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Symbol</td>
<td>Value</td>
<td>Value</td>
<td>Value</td>
<td>Value</td>
</tr>
<tr>
<td>Frequency</td>
<td>1.0 MHz</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Conductivity</td>
<td>8.41·10^{4} S/m</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Relative permeability</td>
<td>100</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Skin depth</td>
<td>17.4 μm</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 1a: Overview of the investigated domain.

Convergence Analysis & Results

• The results indicate that a higher accuracy per degree of freedom (d.o.f.) is obtained by applying the SEM, as shown in Fig. 2.
• At the converged solution, the SEM reduces the number of d.o.f. and computation time by 84.7% and 94.8%, respectively.
• The Pareto optimum is evaluated, defined as the weighted sum of the normalized number of d.o.f. ($f_{n}$) and discrepancy ($f_{d}$)

$$
\text{minimize} \quad F(x) = w_1 f_n(x) + w_2 f_d(x) \\
\text{subject to} \quad w_1 + w_2 = 1
$$

where: \{w_1, w_2\} \in (0, 1)

Conclusions

• The SEM provides a highly accurate estimation of the eddy current losses, while significantly reducing the number of d.o.f. and computation time w.r.t. the FEM.
• The SEM has proven to be particularly useful in problems where the skin depth is several orders of magnitude smaller in comparison to the object dimensions.