Electric Machine Design: Current Status and Alternatives for Improved Performance

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Motivation

• “Electrification” of transportation fleets
• All-electric battleship
• New design tools needed for innovative machines
• Classic methods from, e.g. Veinott (1959) and Alger (1970) and more recent books by Hamdi (1994) and Lipo (2004) won’t necessarily apply
Design-By-Iterative-Analysis

Problems:
• Bottleneck
• Irreversibility

Large-scale numerical analysis method
System Simulation Considerations

- Small enough time steps to capture highest frequencies
- Must reach steady state, or do harmonic analysis

\[ \gamma \equiv \frac{(\text{real time})}{(\text{time simulated})} \]

- Ideally, \( \gamma \leq 1 \)
- Startup of nonlinear machine with 60 Hz ramp, using “moderate” 3D FEM gives \( \gamma \approx 216,000 \) (2.5 days)
Reducing the Ratio

Moore’s Law

Current tools → Better tools → Ideal design tool

Active design tool improvement
Moore’s Law Path

• Computer processing power doubles roughly every 18-24 months
• Wait for computers to “catch up”
• “Catch up” time horizon to reach $\gamma \leq 1$:

\[
\tau = \alpha \log_2 (\gamma) \\
1.5 \leq \alpha \leq 2
\]
Moore’s Law Path

- Example:
  - Linear ramp startup, 0-50 Hz
  - 4 poles, 120 V, 500 W, 1500 rpm, induction machine
  - 3D FEM using Ansoft’s *Maxwell* using a Pentium 4, 2 GHz processor with 2 GB RAM
  - Direct solver, pre-loaded nonlinear $B$-$H$ curve

<table>
<thead>
<tr>
<th>Run</th>
<th>Tetrahedra</th>
<th>Time sim.</th>
<th>Steps</th>
<th>Real time</th>
<th>Time per step</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>204,262</td>
<td>0.01 s</td>
<td>40</td>
<td>74 hrs.</td>
<td>111 mins.</td>
</tr>
<tr>
<td>2</td>
<td>204,262</td>
<td>0.04 s</td>
<td>16</td>
<td>36 hrs.</td>
<td>135 mins.</td>
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<tr>
<td>3</td>
<td>204,262</td>
<td>0.20 s</td>
<td>80</td>
<td>226 hrs.</td>
<td>170 mins.</td>
</tr>
<tr>
<td>4</td>
<td>211,603</td>
<td>0.08 s</td>
<td>20</td>
<td>33 hrs.</td>
<td>99 mins.</td>
</tr>
</tbody>
</table>
Moore’s Law Path
Moore’s Law Path

<table>
<thead>
<tr>
<th>Run</th>
<th>$\gamma$</th>
<th>$\tau$</th>
<th>$\gamma_{pwm}$</th>
<th>$\tau_{pwm}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$333 \times 10^3$</td>
<td>36.7 yrs.</td>
<td>$400 \times 10^6$</td>
<td>57.2 yrs.</td>
</tr>
<tr>
<td>2</td>
<td>$355 \times 10^3$</td>
<td>36.9 yrs.</td>
<td>$486 \times 10^6$</td>
<td>57.7 yrs.</td>
</tr>
<tr>
<td>3</td>
<td>$510 \times 10^3$</td>
<td>37.9 yrs.</td>
<td>$612 \times 10^6$</td>
<td>58.4 yrs.</td>
</tr>
<tr>
<td>4</td>
<td>$297 \times 10^3$</td>
<td>36.4 yrs.</td>
<td>$356 \times 10^6$</td>
<td>56.8 yrs.</td>
</tr>
</tbody>
</table>

Test case

General trend
Ideal Design Tool Properties

- 3D capability
- Handle nonlinear materials
- Accurate (torque and losses)
- Fast
- Efficient
- Scalable
- Parameterizable
- Reversible
- Easy to use
Survey of Methods

- Schwarz-Christoffel method (S-C)
- Finite element method (FEM)
- Boundary element method (BEM)
- Magnetic equivalent circuits (MEC)
Schwarz-Christoffel (S-C) method

• Small system of nonlinear equations (O(N))
• Boundary-based
• Domain-mapping only
  – Fields computed using any other method
S-C method

• Negatives
  – 2D only
  – Only maps interior or exterior regions, not both simultaneously
  – Mapping speed depends on “narrowsness” of elongated regions

• Positives
  – Any 2D soln. method can be coupled to it (preconditioner)
  – Highly accurate map near corners might improve accuracy of overall solution when combined
    • Field accuracy depends on method chosen
  – Can be used to quickly narrow a design parameter space
Finite Element Method (FEM)

- Large, sparse, symmetric and banded matrix
  - Can be several 100,000 or 1,000,000 elements
- Domain-based
- Handles nonlinear and non-homogeneous materials
- 2D or 3D, 3D more intensive
FEM

• Negatives
  – 3D problems are very large
  – Not reversible
  – Stress tensor path dependence
  – Air-gap requires re-meshing with motion
  – Balloon boundary

• Positives
  – Nonlinearity/non-homogeneity
  – Time-domain or harmonic
  – Sparse methods available
  – Widely available
Boundary Element Method (BEM)

- Boundary-based, using boundary integral equations, Green’s functions
- Dense system matrix (smaller than FEM)
BEM

• Solver methods differ from FEM due to dense matrix
  – Fast multipole method $O(N \log N)$
  – FFT $O(N \log N)$ when using multilevel

• Linear, homogeneous regions easiest (traditionally used for scattering problems)

http://www.aerospaceweb.org/aircraft/fighter/f16/
BEM

• Negatives
  – Linear material requirement is limiting, but volume integrals can be used
  – Not obviously reversible
  – Double surface integrals required in 3D problems
  – Time-stepped BEM can be unstable
    • Harmonic analysis more appropriate

• Positives
  – 2nd-order accuracy due to Green’s fcn./integral eqn. method
  – No air gap mesh
  – No balloon boundary
  – Force fields focused near boundaries, and solution can be selective of those pts.
  – Eddy currents automatic in Green’s function.
Magnetic equivalent circuits (MEC)

- Medium-sized matrix
- Flux-path based (domain based)
- 2D or 3D
MEC

• Negatives
  – Impossible to use for vector fields
  – Eddy currents/skin effect require more complex model
  – Flux paths must be known \textit{a priori}
  – Rotor motion complicates connectivity mesh

• Positives
  – Fast and intuitive
  – Can be used for fast iterative design
  – Reversibility may be possible
  – Expansion to 3D straightforward and scales well
  – Nonlinear materials directly handled
**Alternatives for Design**

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>FEM</th>
<th>MEC</th>
<th>BEM</th>
<th>S-C</th>
</tr>
</thead>
<tbody>
<tr>
<td>3D capability</td>
<td>0</td>
<td>+</td>
<td>0(+)</td>
<td>-</td>
</tr>
<tr>
<td>Nonlin. mater.</td>
<td>+</td>
<td>+</td>
<td>-</td>
<td>*</td>
</tr>
<tr>
<td>Accuracy</td>
<td>+</td>
<td>0</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Speed</td>
<td>-</td>
<td>0</td>
<td>-</td>
<td>*</td>
</tr>
<tr>
<td>Efficiency</td>
<td>-</td>
<td>0</td>
<td>+</td>
<td>*</td>
</tr>
<tr>
<td>Scalability</td>
<td>-</td>
<td>+</td>
<td>+</td>
<td>*</td>
</tr>
<tr>
<td>Parameterization</td>
<td>0</td>
<td>+</td>
<td>0</td>
<td>*</td>
</tr>
<tr>
<td>Reversibility</td>
<td>-</td>
<td>0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Ease of use</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
Alternatives for Design

• Hybrid methods
  – Capture benefits of domain and boundary methods
  – FEM-BEM combo is common in EM scattering literature, some machine literature (Pichon and Razek, 1996), (Nysveen, 1997), (Onuki et al 1997)

• Parallel computing
  – Calculate matrix elements independently
  – Graphics processor units (GPUs)
    • Orders of magnitude speed increases shown
    • Faster generational rate
    • Improved programming tools (CUDA, etc.)
Proposed Design Scheme

3D machine design parameter space

S-C method for rapid 2D evaluation

Reduced parameter space

3D analysis (MEC or BEM)

Choose parameters

Design-by-iterative-analysis loop

3D FEM Verification
Conclusion

• Improved tools are needed to design state-of-the-art powertrain systems
• Moore’s Law will help, but not soon enough
• Promising areas
  – Alternative algorithms from EM scattering
  – Parallel processing
  – Hybrid schemes