Motor Design Optimization
Including electromagnetic performance and mechanical stress

Christian Kremers – Dassault Systèmes
Electric Drive Engineering

**Electric Machine**
- High energy density
- High speed (20k+ rpm)
- High efficiency
- Acoustic comfort
- Thermal management

**Gearbox**
- Lightweight structure
- Compact design
- Well lubricated
- Efficient
- Durable

**Structural housing**
- Protection
- Lightweight structure
- Heat dissipation
- Noise mitigation
- Chassis integration
Electric Drive Engineering

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Electric Drive Engineering

- Electromagnetic Performance
- Noise & Vibration
- Electric Drive System Design
- Electric Drive Control System Design & Verification & Validation
- Battery Engineering
- Related Processes
- Thermal Management
- Lubrication
- Strength & Stiffness
- Durability
- Detailed Design
- Conceptual Design
- Power Electronics Engineering
Long-term Commitment to Simulation

- Design 2000
- Simulation 2000
- CATIA Analysis
- Abaqus
- Geensoft
- Isight
- Dymola
- Simpoe
- Tosca
- SFE
- fe-safe
- Simpack
- CST
- Opera
- Wave6
- EXA
- XFlow
Long-term Commitment to Simulation

- Design 2000
- System Level Simulation
- Structural Analysis
- Process Automation
- Simulation 2005
- 2010
- CATIA Analysis
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- XFlow
- EXA
- Electromagnetic Analysis

3D Experience
Outline

» Optimization phases
» Electromagnetic performance analysis
» Mechanical stress analysis
» Optimization / design space exploration
» Outlook & conclusion
Electrical Machine Optimization

- Optimization Goals
  - Maximize Power-to-weight ratio
  - Maximize Efficiency
  - Minimize costs
  - Design torque-speed characteristic

- Constraints
  - Mechanical stiffness
  - Thermal limits
  - Noise and vibration limits
Electrical Machine Optimization

- **Optimization Goals**
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- **Constraints**
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IPMSM, 48 slots, 8 poles, distributed winding with 8 turns
**Multiphase Optimization**

**Phase 1:**
- Electromagnetic performance
- Simplified loss calculation
- Mechanical stress

**Phase 2.1:**
- System level simulation including controller, inverter

**Phase 2.2:**
- Detailed loss/force calculation
- Thermal/CFD calculation
- Noise and vibration analysis

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**Start**

Current waveforms

Dymola
Optimization in Phase 1

- **Goal:** Obtaining “good” design candidate(s)
- **Desired:** Short simulation time per design point (huge design space)

Parametrized CATIA model on 3DEXPERIENCE

CST

Abaqus

DOE / Optimization
Electromagnetic Performance

★ Goals:
  ▶ Maximize torque and power
  ▶ Minimize torque ripple
  ▶ Maximize efficiency at selected operating points

★ Constraint:
  ▶ Demagnetization under fault condition

IPMSM, 48 slots, 8 poles, distributed winding with 8 turns
Electromagnetic Performance

- Simplified geometry, 2D mesh, Subvolume
  1. Uniform current distribution, loss less materials, linear magnets
  2. Individual conductors, conductive linear magnets
  3. Nonlinear magnets

DQ-Model

Efficiency at Operating Points

Demagnetization

Increasing current

1+3

1

2

3
Electromagnetic Performance: DQ Model

Main motor parameters are calculated for dq-current range

![Graph showing average torque versus peak current and load angle degrees.](image-url)
Electromagnetic Performance: DQ Model

Main motor parameters are calculated for dq-current range
Electromagnetic Performance: DQ Model

Main motor parameters are calculated for dq-current range

- Based on the DQ-Model the torque-speed characteristic is obtained
Electromagnetic Performance: DQ Model

Dynamic characteristic: Torque vs. speed & Operating Points

Average torque versus Speed

OP 1

OP 2

Voltage / V
Peak Current / A

I vs n
V vs n

Mechanical power / W

OP 1

OP 2
Electromagnetic Performance: DQ Model

Dynamic characteristic: Torque vs. speed & Operating Points

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Efficiency @ Operating Points

- Individual conductors → Eddy current losses
- Eddy currents in magnets
- Iron losses based on fitted loss density curves
Demagnetization

- **Fault condition**: 1.5x short circuit current calculated based on DQ-model (rated torque, no-load flux) applied to negative d-axis → Maximal demagnetization
- Magnets at 120°C
Mechanical Stress Analysis

- Stress due to
  - Press fit mounting of the shaft in the rotor core → initial stress
  - Centrifugal force at 20000 rpm
- End effects are ignored → 2D simulation
- Maximum von Mises stress of 400 MPa is accepted
Optimization in Phase 1

Goals:
- Maximize torque and power
- Minimize torque ripple
- Maximize efficiency
- Minimize costs, i.e. minimize magnet mass

Constraints:
- Stress < 400 MPa
- Demagnetization voltage reduction ratio > -5%
Optimization in Phase 1

- Latin Hypercube DOE with 2000 iterations has been performed (16 input parameters)
- Single thread run time ≈ 20 min per design point
- Workload can be distributed (cores & machines)
Design Space Exploration: Scatter Plots

- **Design Limit (Pareto Front)***

![Scatter Plot](Image)

**Axes:**
- Maximum Torque / Nm
- Torque Ripple (6th) / %
- Magnet Mass / kg

**Graph Description:**
- The scatter plots show the relationship between Maximum Torque and Torque Ripple, as well as Maximum Torque and Magnet Mass.
- The red dashed line represents the Design Limit (Pareto Front).

[Image: Scatter Plots showing Maximum Torque vs. Torque Ripple and Magnet Mass]
Design Space Exploration: Self-Organizing Map
## Design Space Exploration: Compare

### Compare “Good” candidates

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<th>Alternative 1456</th>
<th>Alternative 67</th>
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| Metric                  | | | |
|-------------------------| | | |
| Efficiency              | | | |
| Power & Torque          | | | |
| Torque ripple           | | | |
| Cost ≡ Magnet mass      | | | |
Design Space Exploration: Compare

- Compare “Good” candidates

- Alternative 566
- Alternative 1456
- Alternative 67

- Cogging Torque
- Torque Max
- Torque Ripple 6th
- Torque Ripple 12th
- Power Max
- Eff. OP1
- Eff. OP2
- Magnet Mass
Multiphase Optimization

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MQS –FD (linear)

MQS –TD (non-linear, 2d)
Summary

- Fast initial optimization using 2D FEM
- KPI’s from mechanical and electromagnetic domain are considered
- 3DEXPERIENCE platform manages geometry, simulation data and results
**3DEXPERIENCE Conference for Design, Modeling & Simulation 2020**

<table>
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<th>WHEN</th>
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WE ARE LOOKING FORWARD TO SEEING YOU AGAIN!