Motion in The Electromagnetic Field: Forces, Motors and Actuators



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Schedule

- 1. Electromagnetic Force Calculation
- 2. Moving Mesh & Deformed Geometry
- 3. Actuators
- 4. Rotating Machinery





Electromagnetic Force Calculation

Means To Calculate The Electromagnetic Force

Force Calculation

- From surface integration of Maxwell tensor
 - Requires fine surface mesh and mesh verification study
- Both magnetic and electric interfaces
- Lorentz Force
 - Requires electric current in conductive material
 - Automatically calculated where possible
- Virtual work
 - $-W = F \cdot s$
- Electromechanics
- Magnetomechanics



Tips for Accurate Force Calculation

- Do not apply the force calculation node to permanent magnet
- Avoid field singularities by filleting away sharp edges
- Focus on surface mesh quality of the target object
 - Improve the quality for surface integration of Maxwell tensor
- Create a circular domain around the target object
 - Avoid sharp edges
 - Can be applied to calculate forces acting on:
 - Permanent magnets
 - Magnetically soft materials
 - Reduce mesh dependency



Electromechanics & Magnetomechanics

- Universal multiphysics interfaces coupling various force sources with arbitrary structural mechanics interface
 - Solid, Shell and Membrane
- Improved resolution of electrostatic singularities
- Unified into two multiphysics nodes in v6.2
- Accompanied by couplings for rotating machinery



DEMO: Force Calculation

- Comparison of different approaches to calculate electromagnetic force
 - Magnetic Fields (No Currents)
- Improving accuracy by following the recommended steps
 - Filleting corners
 - Creating an extra force calculation domain







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Moving Mesh & Deforming Domain

Moving Mesh

- Deforms Spatial frame relative to the Material frame
- Deforming Domain feature captures deformation of medium
 - E.g. air in a cavity filter
- Deformation comes from Solid Mechanics interface or is explicitly prescribed
 - FSI simulations
 - PZT cavity filter tuning
 - Rotating machinery



DEMO: Moving Mesh

- Coupling Magnetic Fields, No Currents with Solid Mechanics using the Magnetomechanics multiphysics interface
- Setting up *Moving Mesh* interface
- Preparing geometry and mesh for domain deformation



DEMO: Moving Mesh

- Setting up *Moving Mesh* interface
- Preparing geometry and mesh for domain deformation

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Deformed Geometry

- Deforms *Material* frame relative to the *Geometry* frame
- Deforming Domain feature captures addition or removal of material
 - Copper electrodeposition
 - Laser welding (and evaporation)



Rotating Domain

- Prescribing rotational movement
 - User defined relationship for rotation angle
 - Through rotational velocity
 - Treated as rigid body with applied moment and given moment of inertia
- Requires Form Assembly geometry closure
- Automatically added with certain physics



Actuators

Electric Actuators

- Electrostatics combined with:
 - Structural mechanics
 - Piezoacoustics
 - Heat transfer
- Common use cases:
 - Small sensors or actuators, also referred to as microelectromechanical systems (MEMS) and consumer electronics, such as touchscreens

Electromagnetic Actuators

- Magnetic fields combined with
 - Structural mechanics
 - Piezomagnetics/Magnetostriction
- Quasistatic approach
 - Parametric sweep
- Dynamic approach
 - Time domain
 - Eddy currents handling
 - Linear discretization
 - Solver tuning

Rotating Machinery

Radial Flux Machines

- 2D & 2.5D modeling
 - Suitable approximation for efficient prototyping, sweeping and optimization

3D modeling

 Enables calibration of 2D models and investigation of the end effects, flux leakage in skewed rotors and stators, and circulating currents in the magnets

(Not Only) Rotating Machinery

- Axial flux motors
 - More inherently 3D (although 2D approximations are possible)
- Linear motors
 - Can be modeled in 2D, 2D axisymmetry (for tubular machines), or 3D
 - Sometimes approximated using periodic conditions, ignoring the end effects

Multiphysics Behind Electric Motors

Time-Periodic Electromagnetics

Traditional transient
approach:
$$\sigma \frac{\partial \mathbf{A}}{\partial t} + \nabla \times \mathbf{H} = 0$$
Time-periodic approach: $\sigma \frac{\mathbf{A}_{i+1} - \mathbf{A}_{i-1}}{2dt} + \nabla \times \mathbf{H}_i = 0$

Time-Periodic Electromagnetics

- For nonlinear time-periodic problems:
 - Solves for the steady-state conditions directly
 - Imposes periodicity in the time dimension
 - Solves for all time frames at once
- Supports the exact modeling of rotations, nonlinear magnetic materials, induced currents, and general periodic excitations
- Particularly well suited for:
 - Parametric studies efficiency maps and temperature maps
 - Multiphysics heat transfer, deformations, and vibrations
 - Optimization topology optimization and objectives based on the fast Fourier transform (FFT)
 - Models that require many cycles to reach a steady state

Parametric Sweeps and Efficiency Maps

- Electromagnetics and heat transfer are solved together using a stationary solver
- Stationary, transient, and frequencydomain phenomena are all processed using the same solver
- No need to iterate between study types; this is true multiphysics
- When sweeping, previously obtained results can be reused to accelerate the solver
- Collecting 64 data points in one hour is achievable on an average laptop

Going Beyond Thermal Efficiency

- Time-periodic electromagnetics can be one-way coupled to solid mechanics and acoustics — for a vibroacoustic analysis
- The harmonics of the local electromagnetic force density can be extracted on the fly and directly coupled to a frequency-domain structural mechanics and acoustics analysis

Horizontal: Mechanical EigenFreq, Diagonal: Sound Pressure Level Harmonics

7000rpm, 4th harmonic

9000rpm, 6th harmonic

dB

DEMO: Electric Motor Optimization

Parametrized geometry

DEMO: Electric Motor Optimization

- Parametrized geometry
- Physics setup

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DEMO: Electric Motor Optimization

- Parametrized geometry
- Physics setup
- Optimization study

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DEMO: Electric Motor Surrogate Model

- Parametrized geometry
- Physics setup
- Optimization study
- Surrogate model

DEMO: Electric Motor Surrogate Model

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- Parametrized geometry
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- Surrogate model
 - Generating training data

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DEMO: Electric Motor Surrogate Model

- Parametrized geometry
- Physics setup
- Optimization study
- Surrogate model
 - Generating training data
 - Training DNN's
 - Time period averaged torque
 - Spatial distribution of B-field

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DEMO: Electric Motor Surrogate Model

- Parametrized geometry
- Physics setup
- Optimization study
- Surrogate model
 - Generating training data
 - Training DNN's
 - Time period averaged torque
 - Spatial distribution of B-field
 - Improve
 - Create more DNN's representing different geometry domainds

