Electro-Mechanical FEM Simulations with "General Motion"

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Maxwell's equations

$$\nabla \cdot \mathbf{B} = 0 \qquad \text{Magnetic Gauss's law}$$

$$\nabla \times \mathbf{E} = -\frac{\partial}{\partial t}\mathbf{B} \qquad \text{Faraday's law}$$

$$\nabla \cdot \mathbf{D} = \rho \qquad \text{Gauss's law}$$

$$\nabla \times \mathbf{H} = \frac{\partial}{\partial t}\mathbf{D} + \mathbf{J} \qquad \text{Ampere's law}$$

Newtons Laws of Motion

$$\mathbf{F} = \mathrm{m}\,\ddot{\mathbf{x}} \qquad \text{Newtons Second law}$$

- With **E** and **H** being the **electric** and **magnetic fields**; **D** and **B** being the **displacement field** and **magnetic flux density**
- And **F**, m and $\ddot{\mathbf{x}}$ being **force**, **mass**, and **acceleration**

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Material Laws

- Assume a constant permittivity, i.e. $\mathbf{D} = \epsilon\,\mathbf{E}$; and
- A non-linear permeability, $\mathbf{B} = \mu(t)\,\mathbf{H}$, i.e. by a given non-linear B-H Curve

Gauge Fields

- Re-write Maxwell's equations in terms of gauge fields

$$\mathbf{E} = -\frac{\partial}{\partial t}\mathbf{A} - \nabla\phi,$$
$$\mathbf{B} = \nabla \times \mathbf{A},$$

- Where $\mathbf{A}$ is the Vector potential and ϕ is the scalar potential
- Fix gauge degrees of freedom, thus apply, e.g. Coulomb's gauge $\nabla\mathbf{A} = 0$ or temporal gauge $\phi = 0$

Magnetodynamic Approximation

- Assume slowly varying electric Fields, i.e. $\frac{\partial}{\partial t}\mathbf{E} = 0$
- Split Ohms Law, i.e. $\mathbf{J} = \sigma\mathbf{E} + \mathbf{J}_s$ where $\mathbf{J}_s$ is on Inductors

$$\nabla \times \frac{1}{\mu}\nabla \times \mathbf{A} + \sigma(\frac{\partial}{\partial t}\mathbf{A} + \nabla\phi) = \mathbf{J}_s$$

Approximation

- Approximate the Vector potential and the Scalar potential

$$\mathbf{A} \approx \sum_{p=0}^{P} \mathbf{a}^p \quad \text{and} \quad \phi \approx \sum_{p=0}^{P} \mathrm{v}^p$$

Testing

- Perform a Galerkin testing with continuous test functions $(\mathbf{a}', \mathrm{v}') = \sum_{q=0}^{P}(\mathbf{a}^q, \mathrm{v}^q)$

- For the sake of brevety we ommit the sums and write $(\mathbf{a}, \mathrm{v}; \mathbf{a}', \mathrm{v}')$ for the whole approximation and testing sets
- With this the formulation reads

$$(\nabla \times \frac{1}{\mu}\nabla \times \mathbf{a} + \sigma \frac{\partial}{\partial t}\mathbf{a}) \cdot \mathbf{a}' + (\sigma \nabla \mathrm{v}) \cdot \nabla \mathrm{v}' = \mathbf{J}_s \cdot \mathbf{a}'$$

- Here, we employed that $\mathbf{a}' = \nabla \mathrm{v}'$
- In the next step we integrate the above equation cell-wise and perform Stokes Theorem (assume cell wise continuous functions)

$$\left(\frac{1}{\mu}\nabla \times \mathbf{a}, \nabla \times \mathbf{a}\right)_{\Omega} + \left(\sigma \frac{\partial}{\partial t}\mathbf{a}, \mathbf{a}'\right)_{\Omega} + \left(\sigma \nabla \mathrm{v}, \nabla \mathrm{v}'\right)_{\Omega_s} = \left(\mathbf{J}_s, \mathbf{a}'\right)_{\Omega_s}$$

- This formulation is the basis for a GetDP simulation

- The **General Motion** solver of MAGNETICS allows to couple translatory or rotational rigid body motions with an EM FEM simulation
- Coupling is done via Newtons Law, with Forces steaming from the **Lorentz Force** or the **Reluctance Force**

Enforced Motion

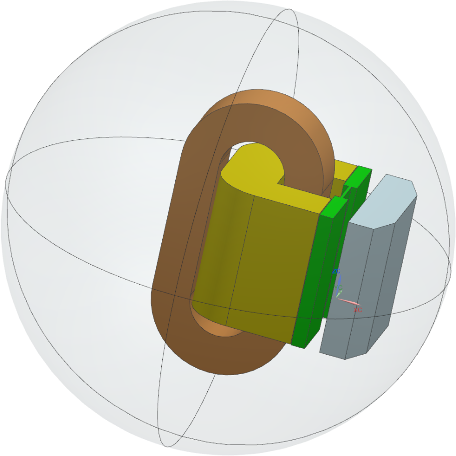
- In Enforced Motion simulations the moving part / object is externaly driven (Generator Mode)
- Then, the resulting fields are calculated

Dynamic Motion

- In General Motion the moving part / object is driven by calculated fields (Motor Mode)

Setup of the Actuator I: Overview

- For the CAD geometry creation and for the meshing we used Siemens SC / NX
- For the electromagnetic simulation we use MAGNETICS for SC
- For the electro- mechanical coupling we use GM
- Both MAGNETICS and GM are fully integrated in the Siemens framework



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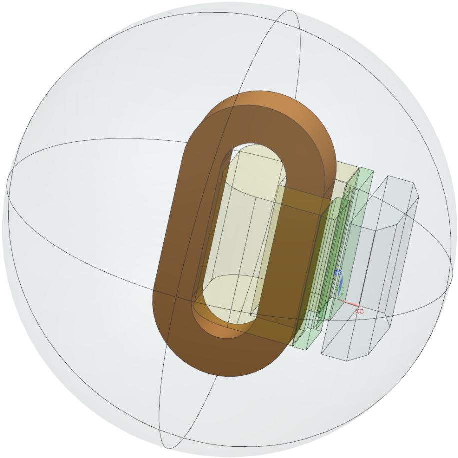
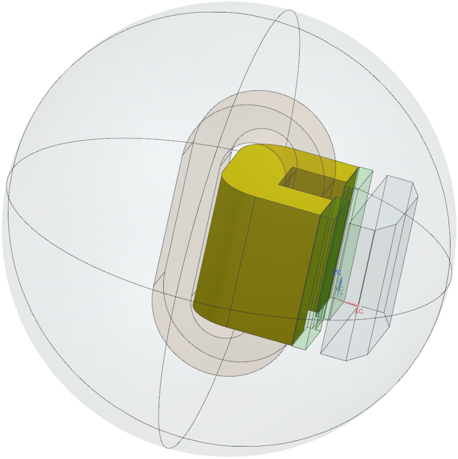
- We use a stranded coil, i.e. the EM fields from the coil are precomputed
- Here, the stranded coil is simulated with 185 turns and a fillfactor of 1
- As employed material we choose copper
- The turn direction is clockwise
- We apply a constant current of 3A

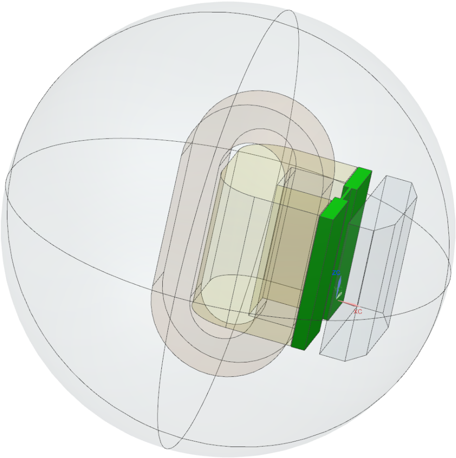


- As core material we use a special pre-glowed magnet material (with certain similarities to steel) that serves as a flux amplifyer
- Said magnet material exhibits a complicated non-linear B-H curve
- Moreover, it is temperature dependent in general; but we assume a pre-glowed state here

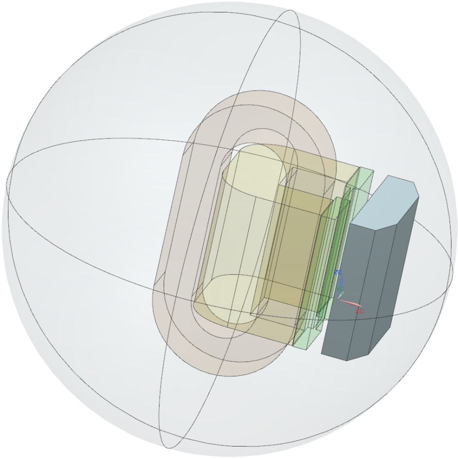


Setup of the Actuator IV: Stopper

- In addition we simulate an additional Stopper that is between the magnet and the moving anchor
- The stopper is also made of the same non-linear magnet material in order to guide the magnetic flux
- As a result of the stoppers form the coil/magnet/-stopper assembly acts like a horseshoe magnet



- The anchor is the actual moving part
- It is also made of the same non-linear material as core and stopper
- The total weight is 37 grams
- We expect the anchor to be attracted until the stopper is reached
- We can approximate the time-scale in the ms region



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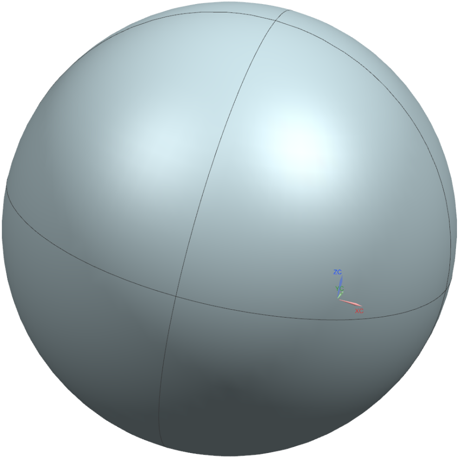
- In addition an a surrounding air volume is simulated
- At the boundaries we employ flux tangent conditions, i.e. $\mathbf{A} = 0$
- Since we use an Electrical-Mechanical coupled simulation the air is remeshed after each timestep
- To this end an solid from shell mesh is used



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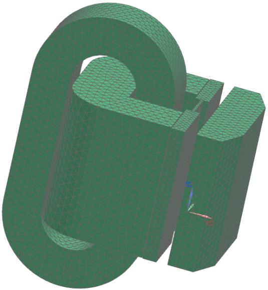
- The meshing is completely done in SC / NX
- 3D tetrahedral meshes are used on the inner bodies
- Triangular surface coat meshes are added on all surfaces of said bodies
- A 2D triangular mesh is used on the air boundary
- The air is then meshed with a 3D tetrahedral solid from shell mesh



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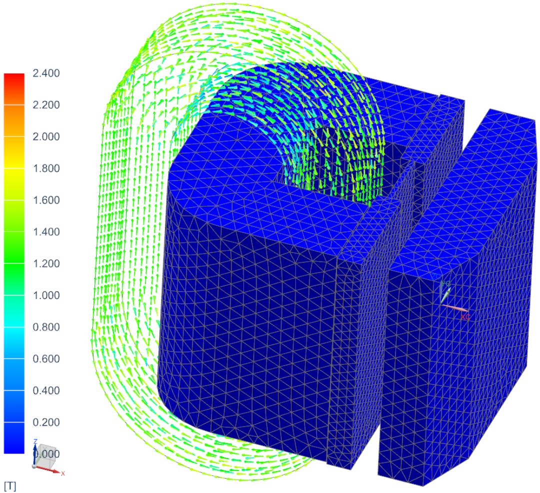
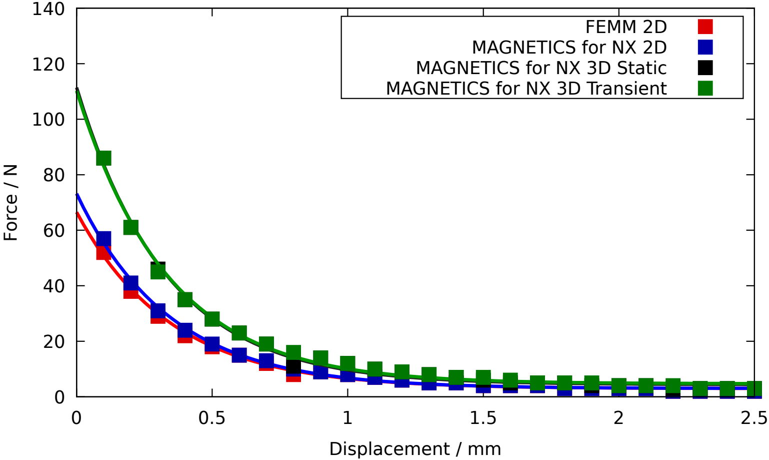
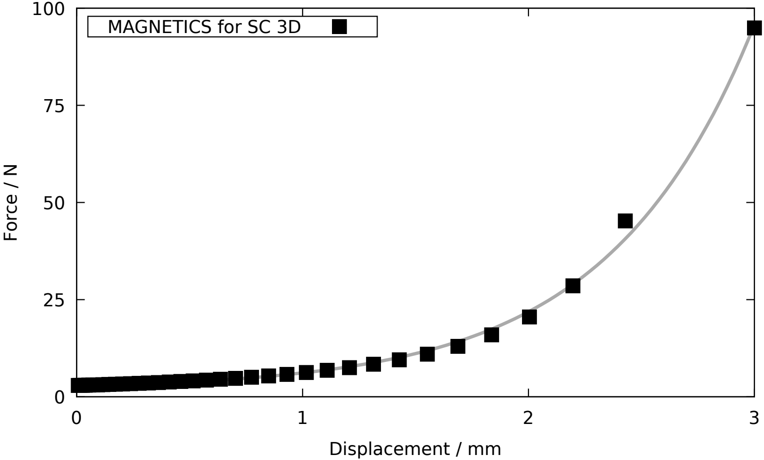


- We obtain a huge difference between 2D and 3D FEM



- Simulations agree with measurements



Thank You!

Our special thank goes to:

Daimler AG: For allowing us to use and show this model
GetDP Team: For providing the underlying Solver
Siemens AG: For letting us implement MAGNETICS into the SC / NX system