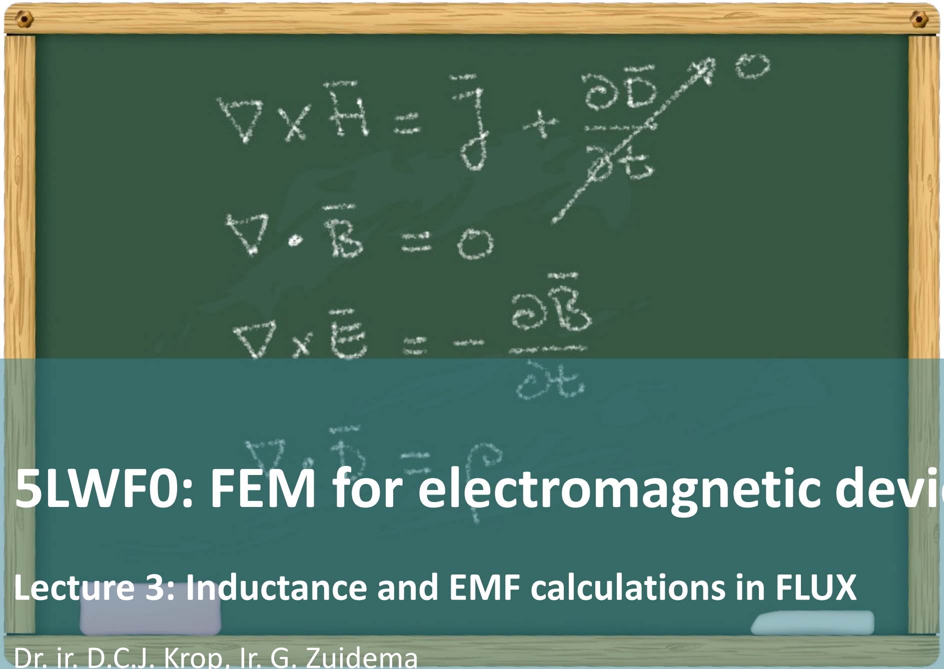

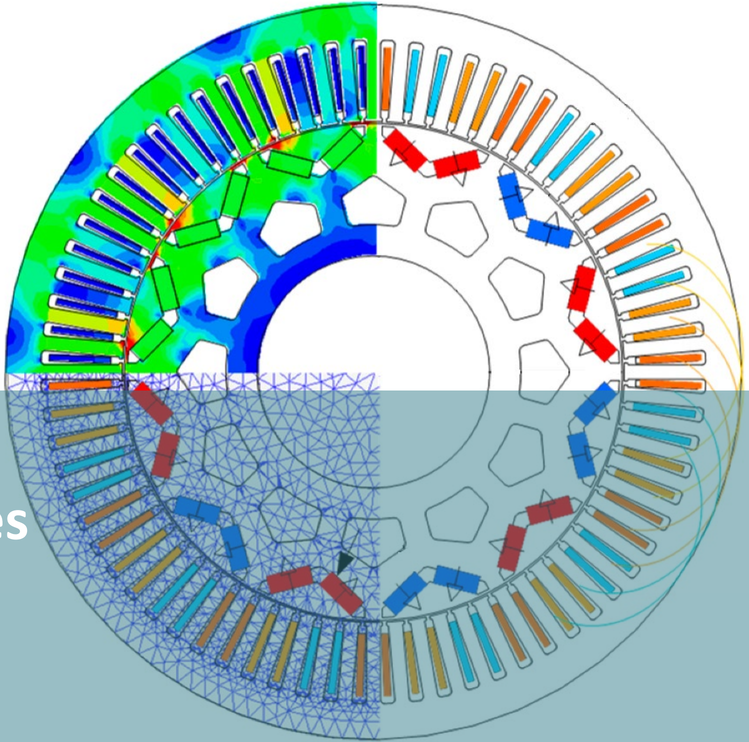

5LWF0: FEM for electromagnetic devices

Lecture 3: Inductance and EMF calculations in FLUX

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Outline and topics of the previous lecture

Recognizing and exploiting boundary conditions

- Truncation of problem space through boundary conditions
- Model reduction by exploiting geometric and physical symmetries and/or periodicities

EMF: Electromotive force

- Transformer EMF (induced by time-variation of *stationary* time-varying sources)
- Movement EMF (induced by *movement* of time-(in)variant sources)

Inductances and materials

- Self- and mutual inductance calculations for non-linear magnetic materials
- Different interpretation/results for different solver types

Interpreting results from different formulations of the PDE (solver types)

- Comparison of results for the same problem solved with different formulations of the PDE

Outline for the lecture of week 3

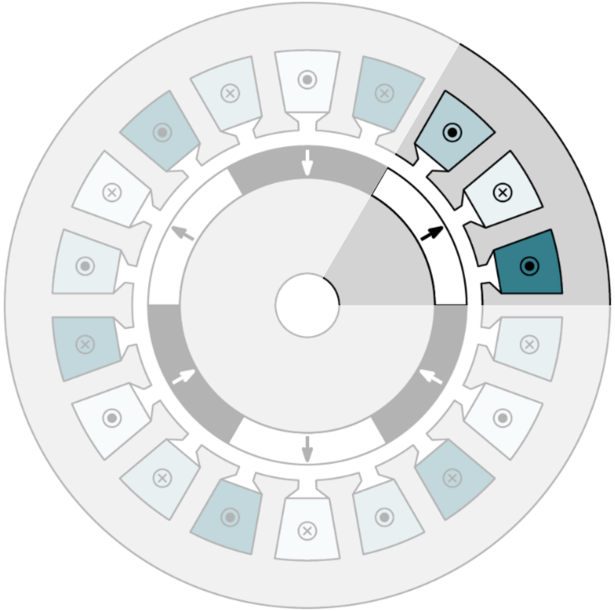
Interactive demonstration on performing calculations in FLUX2D

- Model reduction by exploiting geometric and physical symmetries and/or periodicities

EMF and inductance calculations

- Flux linkage calculations in FLUX2D
- Inductance and EMF calculations from a magnetostatic model
  - Exporting flux linkage data to Matlab and perform postprocessing
- Inductance and EMF calculations from a transient model
  - Direct EMF-calculation

Model reduction by exploiting boundary conditions



1. Reducing the gapless model of instruction 2

Model reduction of the nonlinear gapless toroid

a) Open the nonlinear gapless model of problem 3 of week 2 (INS2Q3.FLU) and save it under a different name (e.g. LEC3Q1.FLU)

b) Which type of BC can be assigned to any **two** lines of symmetry to reduce the model?

- All straight lines through the origin are lines of symmetry. The surface between the lines (a wedge) forms a domain that needs to be meshed. On these lines only the **normal** field component is nonzero

c) Is it possible to reduce the model exploiting periodicity and/or anti-periodicity instead?

- Yes, the model can be reduced to a **periodic** model with $\tau = 0°$. However, since the FLUX2D model can only handle 2D problems a wedge with $\tau > 0°$ needs to be created. The actual angle needs to be such to allow a good quality mesh, i.e. no elongated ('thin') triangles. Observe that choosing the periodicity BC is more convenient as it does not present you with the choice of setting either the tangential or normal field component to zero.

1. Reducing the gapless model of instruction 2

Model reduction of the nonlinear gapless toroid

d) Which type of domain truncation results in the smallest model?

- Due to the toroidal symmetry of the gapless model ($B_\theta \neq 0, B_r = 0$) all flux lines are concentric circles with the center located at the origin. Hence, a constant value of the MVP at the outer radius of the outer radius of the outer coil-side can be imposed. Note, assigning only Neumann-type BCs is not sufficient!

e) Reduce the FEM model in accordance with the answers above. Make sure the proper MMF is imposed in the coil conductor region.

f) Create a new nonlinear material of the type **Isotropic analytic saturation + knee adjustment** with parameters as defined below and assign it to the core and airgap. Solve the model and compare the results to the full models of week 2

$$J_\mathrm{s} = 1.9\ \mathrm{T}; \qquad \mu_\mathrm{r} = 3000; \qquad a_\mathrm{knee} = 0.1$$

2. Reducing the gapped model of instruction 2

Model reduction of the nonlinear gapped toroid

a) Open the nonlinear gapped model of problem 3 of week 2 (INS2Q3.FLU) and save it under a different name (e.g. LEC3Q2.FLU)

b) Which type of BC can be assigned to any **two** lines of symmetry to reduce the model?

- Only a horizontal straight line passing through the origin and the center of the airgap is a line of symmetry. On this line only the **normal** field component is nonzero

c) Is it possible to reduce the model exploiting periodicity and/or anti-periodicity instead?

- No, the **periodicity** of the model is $\tau = 360°$. Model reduction via any form of periodicity is not possible.

2. Reducing the gapped model of instruction 2

Model reduction of the nonlinear gapped toroid

d) Which type of domain truncation results in the smallest model?

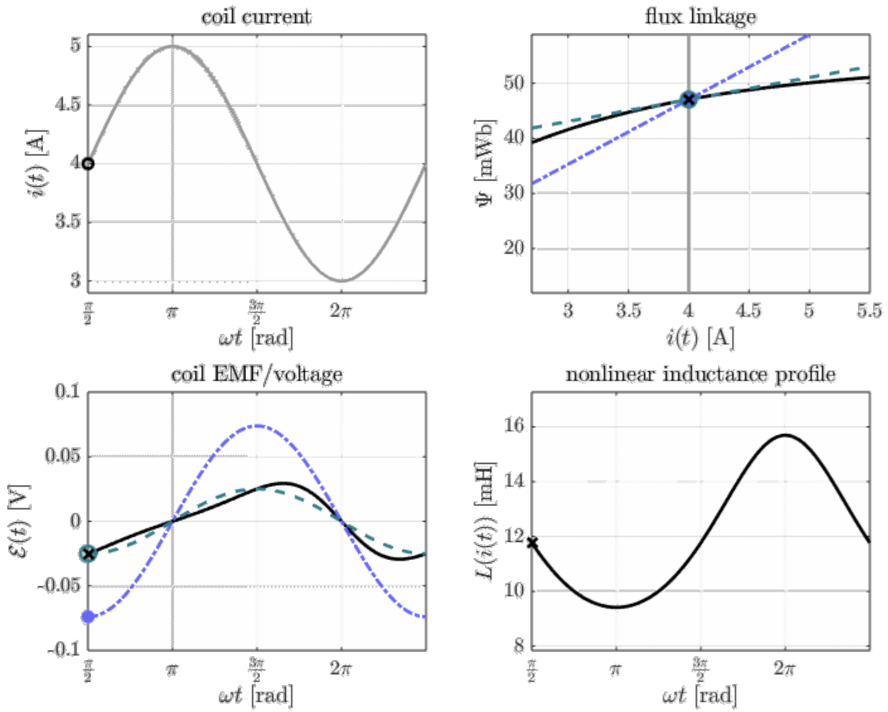
- No toroidal symmetry for the gapped model ($B_\theta \neq 0, B_r \neq 0$). Hence, an infinite box is required

e) Reduce the FEM model in accordance with the answers above. Make sure the proper MMF is imposed in the coil conductor region.

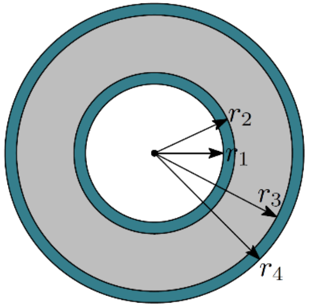
f) Create a new nonlinear material of the type **Isotropic analytic saturation + knee adjustment** with parameters as defined on slide 6 and assign it to the core. Solve the model and compare the results to the full models of week 2. Why is the discrepancy now less as compared to the full model

- Discrepancy between reduced and full model is less for the gapless case, because the airgap is the dominant reluctance. For the gapped model the permeability of the core is dominant (different material!)

3. Linearized inductance calculations



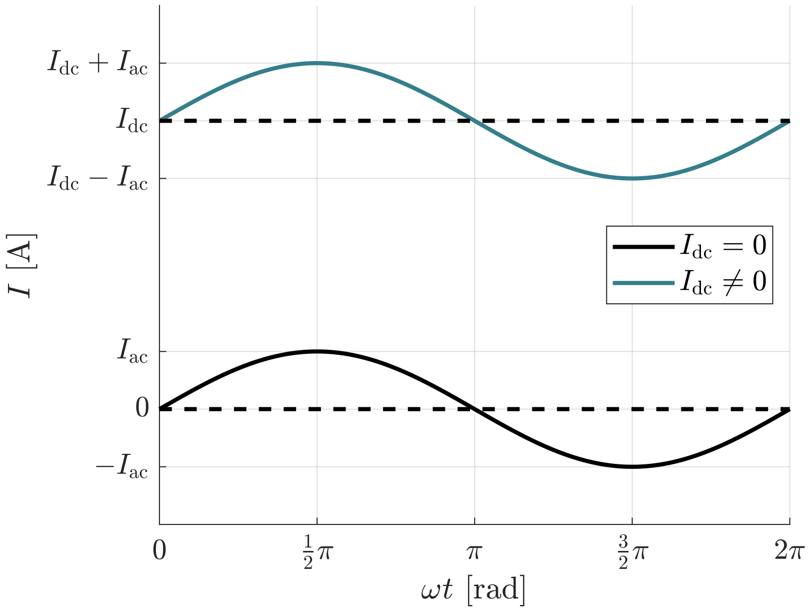
3. Problem description



Toroidal inductor excited by an AC current with a dc-offset:

$$i(t) = I_{\mathrm{dc}} + I_{\mathrm{ac}} \sin(\omega t)$$

- DC-current determines the working point (H_{wp})
- AC-current (amplitude) determines the variation in ΔH around H_{wp}



3. Magnetostatic sweep for a time-dependent problem

In principle the problem is time-dependent

$$\left(\nabla \cdot (\nu(x,y)\nabla) - \sigma \frac{d}{dt}\right) A_z(x,y,t) = -J_z(x,y,t) - \nabla \times \left(\nu_r(x,y)\vec{M}_0(x,y)\right)$$

- No permanent magnets: $M = 0$ for all domains/regions
- Non-conductive core: $\sigma_{core} = 0$
  - J is **imposed** in coil-sides, regardless of the coil-material!
- No time delay (phase-shift) ➔ proportionality between between J_z and A_z

Magnetostatic sweep allowed to mimic time-dependency

- Speed with which quantities change do not affect the solution, just a proportionality constant

3. Inductance of the pre-biased nonlinear toroids

For the inductance calculations half of the present students will make the adjustments that follow on the next slides to the full models of week 2, the remaining half will continue with the reduced models of the previous slides

3. Inductance of the pre-biased nonlinear toroids

Model adjustment for the nonlinear toroids of week 2

Geometrical parameters	
Name	**Value**
HII	5
HIO	6
G	2
HOI	15
HOO	2

New physical parameters		
Description	**Name**	**Value**
DC-current	I_DC	4
Incremental current	DI	{-0.05, 0, 0,05}
Number of turns (gapless)	N_TRNS	20
Number of turns (gapped)	N_TRNS	360

3. Apparent inductance of the pre-biased nonlinear toroids

Apparent inductance approximation from a magnetostatic simulation:

1. Improve the mesh
2. Solve the FLUX2D model with the values of slide 13 with the coil current in the coil conductor set to **I = I_DC+DI**
3. Record the value of the flux linkage (sensor) for **DI = 0**
4. Perform the division below to find the apparent inductance:

$$L_{\mathrm{app}} = \frac{\Psi_{\mathrm{wp}}}{I_{\mathrm{dc}}}$$

3. Incremental inductance of the pre-biased nonlinear toroids

Incremental inductance approximation from a magnetostatic simulation:

1. Solve the FLUX2D model with the values of slide 14 with the coil current in the coil conductor set to **I = I_DC+DI**

2. Record the value of the flux linkage (sensor) for **DI = -0.05** and **DI = 0.05**

3. Perform the division below to find the incremental inductance

$$L_{\mathrm{inc}} = \frac{\mathrm{d}\Psi_{\mathrm{wp}}}{\mathrm{d}I_{\mathrm{dc}}} \approx \frac{\Delta\Psi_{\mathrm{wp}}}{\Delta I_{\mathrm{dc}}} = \frac{\Psi_{I_{\mathrm{dc}+\Delta I}} - \Psi_{I_{\mathrm{dc}-\Delta I}}}{2\Delta I}$$

3. Result for the gapless and gapped toroid

		Gapless (animation)	Gapped
Flux linkage	DI = -0.05	$46.873 \cdot 10^{-3}$	$828.089 \cdot 10^{-3}$
	DI = 0	$47.075 \cdot 10^{-3}$	$837.602 \cdot 10^{-3}$
	DI = 0.05	$47.272 \cdot 10^{-3}$	$846.987 \cdot 10^{-3}$
Inductance	Apparent	$\frac{\psi}{I_{\mathrm{dc}}} = \frac{47.075}{4} = 11.77\ \mathrm{mH}$	$\frac{\psi}{I_{\mathrm{dc}}} = \frac{837.602}{4} = 209.40\ \mathrm{mH}$
	Incremental	$\frac{\Delta\psi}{\Delta I} = \frac{47.272 - 46.873}{0.05 - (-0.05)} = 3.99\ \mathrm{mH}$	$\frac{\Delta\psi}{\Delta I} = \frac{846.99 - 828.09}{0.05 - (-0.05)} = 188.98\ \mathrm{mH}$

When to use which inductance for nonlinear problems?

Apparent inductance:

- No bias field: $H_{wp} = B_{wp} = 0$
- Sweep around the working point 'small'

Incremental inductance:

- Any bias field (including $H_{wp} = B_{wp} = 0$)
- Sweep around the working point 'small'