HOCHSCHULE HEILBRONN

Campus Künzelsau
Reinhold-Würth-Hochschule

TECHNIK WIRTSCHAFT INFORMATIK

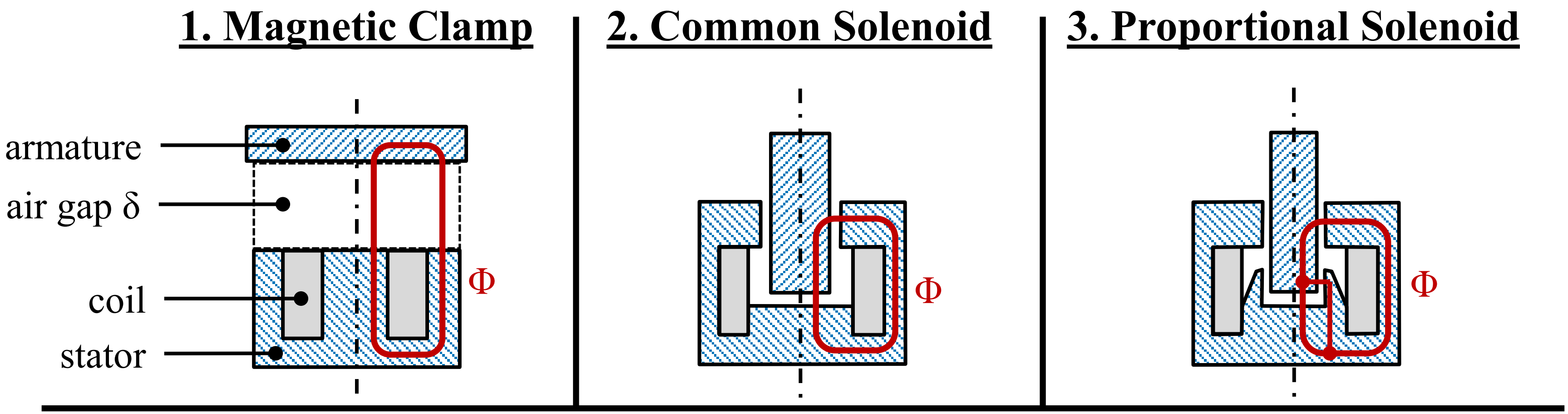
Theory of Proportional Solenoids and Magnetic Force Calculation

Presented at the COMSOL User Conference 2011 Ludwigsburg, Germany

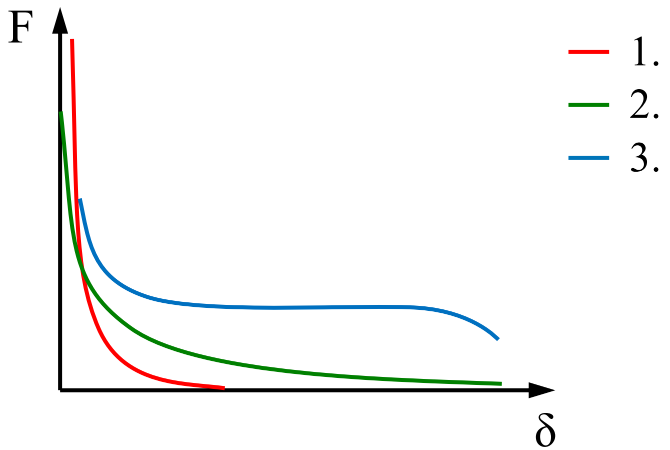
Agenda

1. Common Electro-magnetic Actuator Types
2. Functional Principle of Proportional Solenoids
3. Analytic Approach
4. Finite Element Approach
5. Summary

1. Common Electro-magnetic Actuator Types

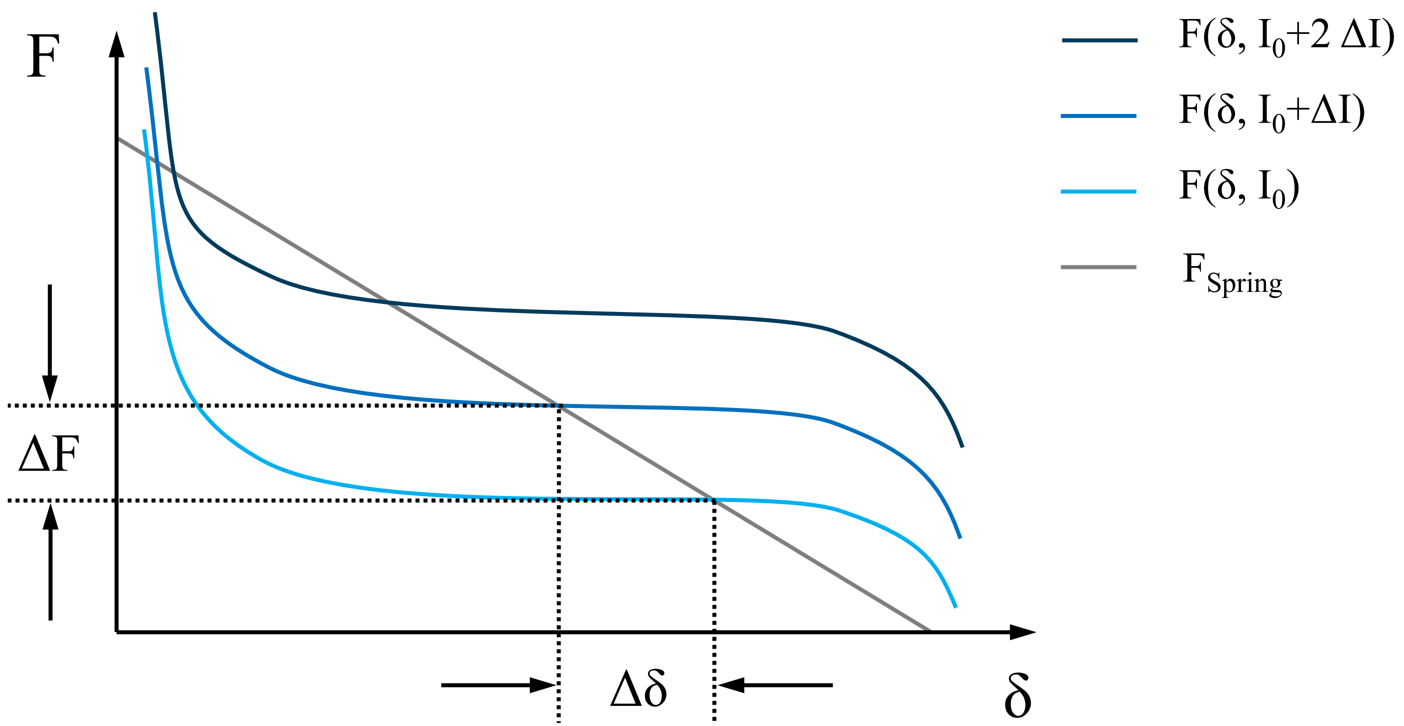


Characteristic force-stroke-curves:



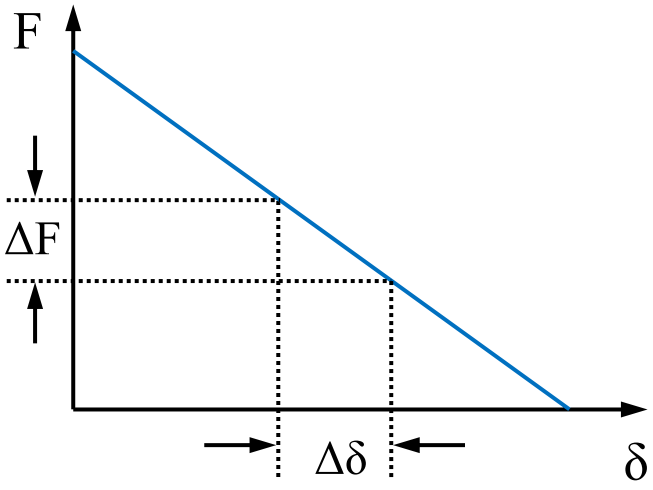
2. Functional Principle of Proportional Solenoids

Interaction of a Proportional Solenoid and a Spring



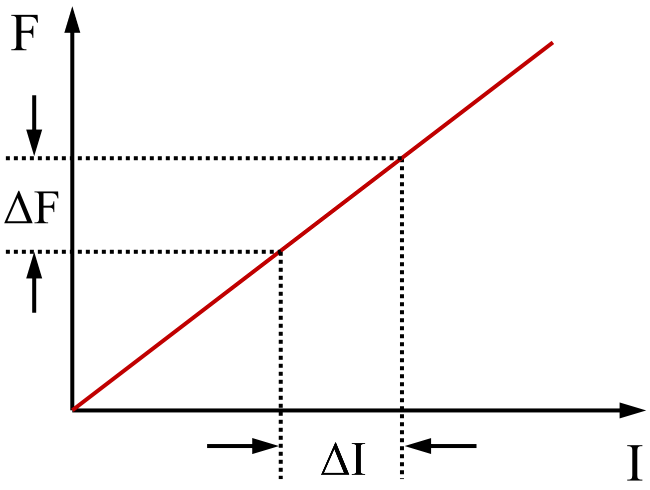
2. Functional Principle of Proportional Solenoids

Force-δ-Curve



$$F \sim \frac{1}{\delta}$$

Force-Current-Curve



$$F \sim I$$

$$\rightarrow \delta \sim \frac{1}{I}$$

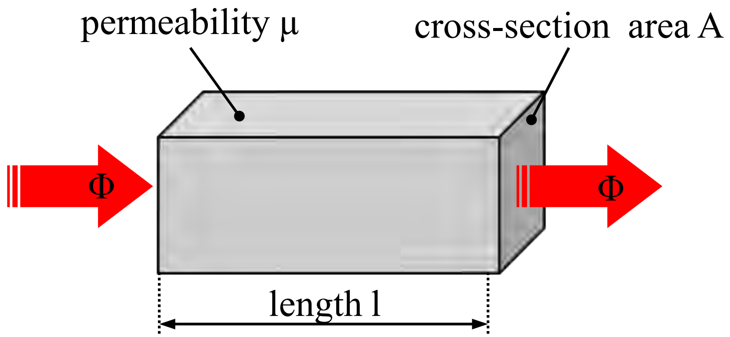
3. Analytic Approach

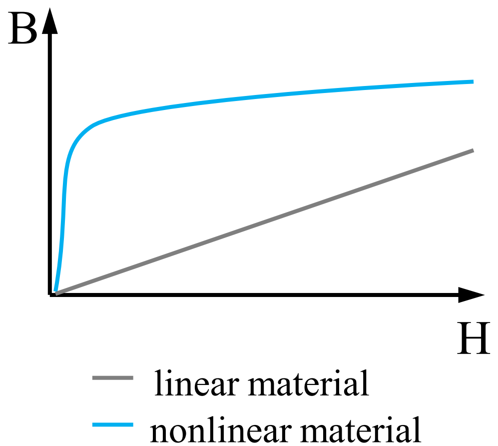
Introduction of Reluctances

(Reluctances = magnetic resistors)

$$R_{linear} = \frac{l}{\mu_0 A}$$

$$R_{nonlinear} = \frac{H\, l}{B\, A}$$





3. Analytic Approach

Magnetic clamp or common solenoid

Total reluctance:

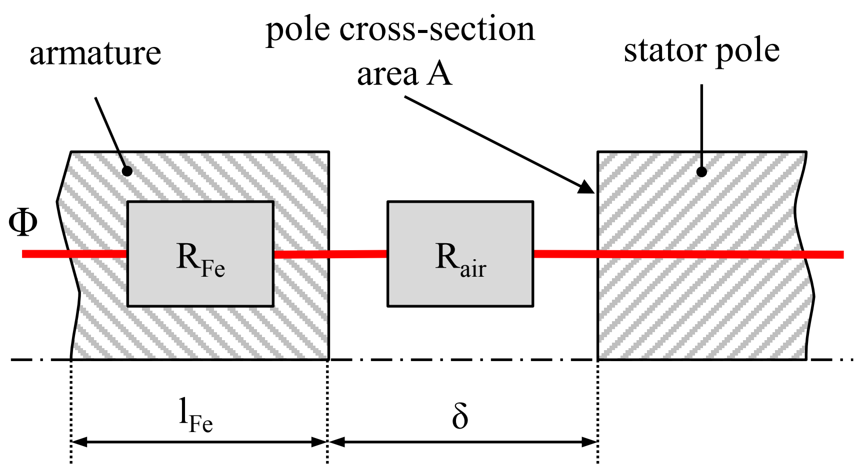
$$R_{tot} \approx R_{air} = \frac{\delta}{\mu_0 A}$$

Magnetic flux:

$$\Phi = \frac{\Theta}{R_{tot}} = \frac{\Theta \mu_0 A}{\delta}$$

Magnetic force (Maxwell Tensile Force):

$$F = \frac{\Phi^2}{2 \mu_0 A} = \frac{\Theta^2 \mu_0 A}{2 \delta^2}$$



3. Analytic Approach

Proportional Solenoid at Maximum Man Air Gap

Reluctance of main air gap and bypass at δ_{max}:

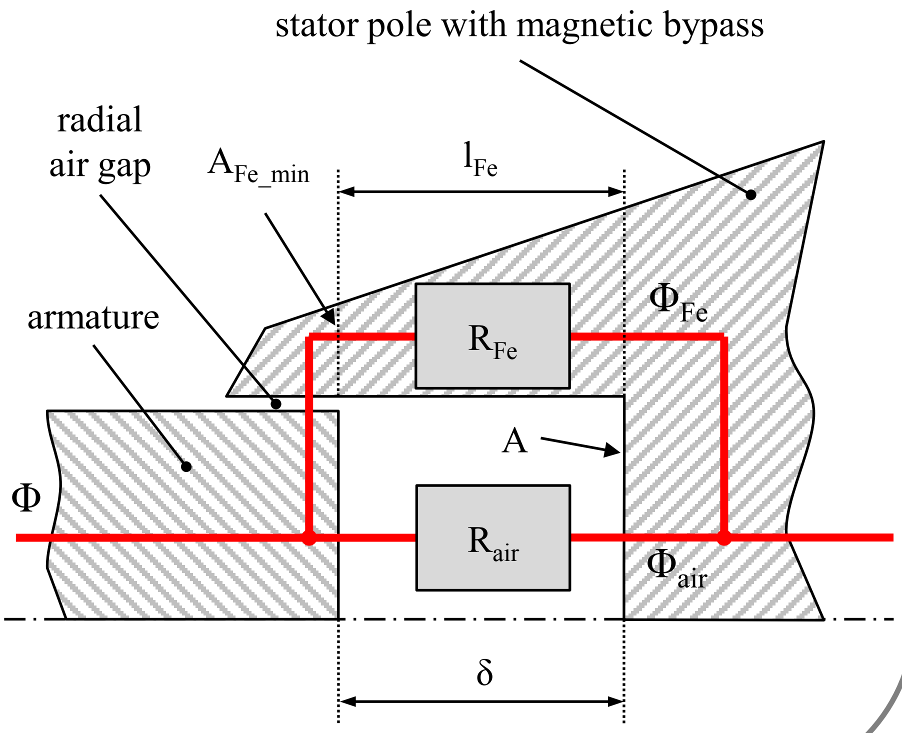
$$R_{air} = \frac{\delta_{max}}{\mu_0 A}$$

(low permeabiltiy) $R_{Fe} \approx \frac{l_{Fe}}{\mu_0 A_{Fe}} = \frac{\delta_{max}}{\mu_0 A_{Fe\_min}}$

Reluctance ratio at δ_{max}:

$$\frac{\Phi_{air}}{\Phi_{Fe}} = \frac{R_{Fe}}{R_{air}} = \frac{A}{A_{Fe\_min}}$$

$A >> A_{Fe\_min} \rightarrow \Phi_{air} >> \Phi_{Fe}$



3. Analytic Approach

Proportional Solenoid at Minimum Main Air Gap

Reluctance of main air gap and bypass at δ_{min}:

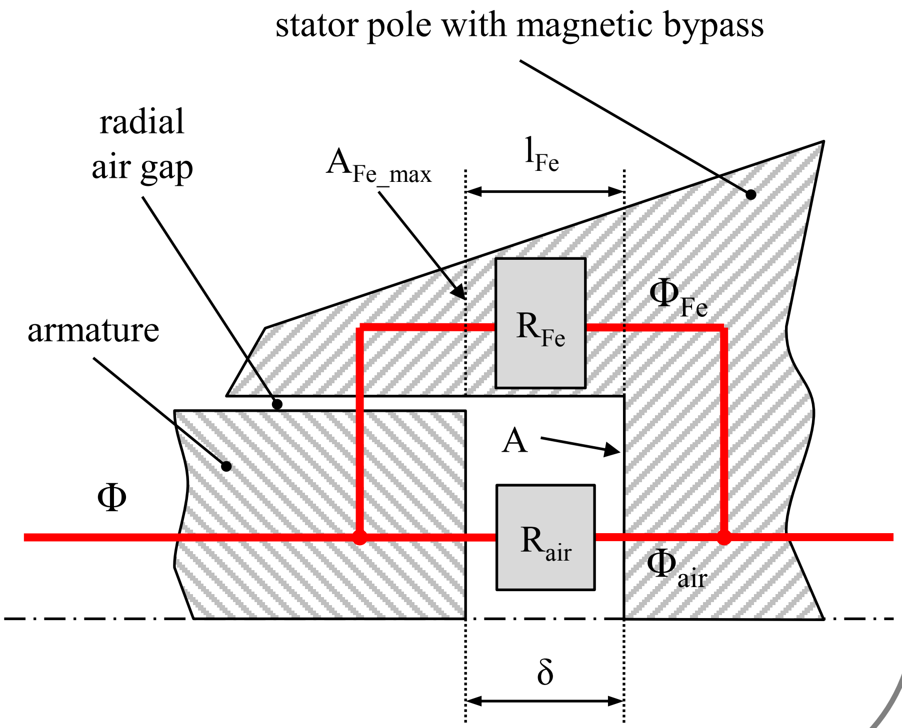
$$R_{air} = \frac{\delta_{min}}{\mu_0 A}$$

(high permeability) $$R_{Fe} \approx \frac{\delta_{min}}{100\ \mu_0\ A_{Fe\_max}}$$

Reluctance ratio at δ_{min}:

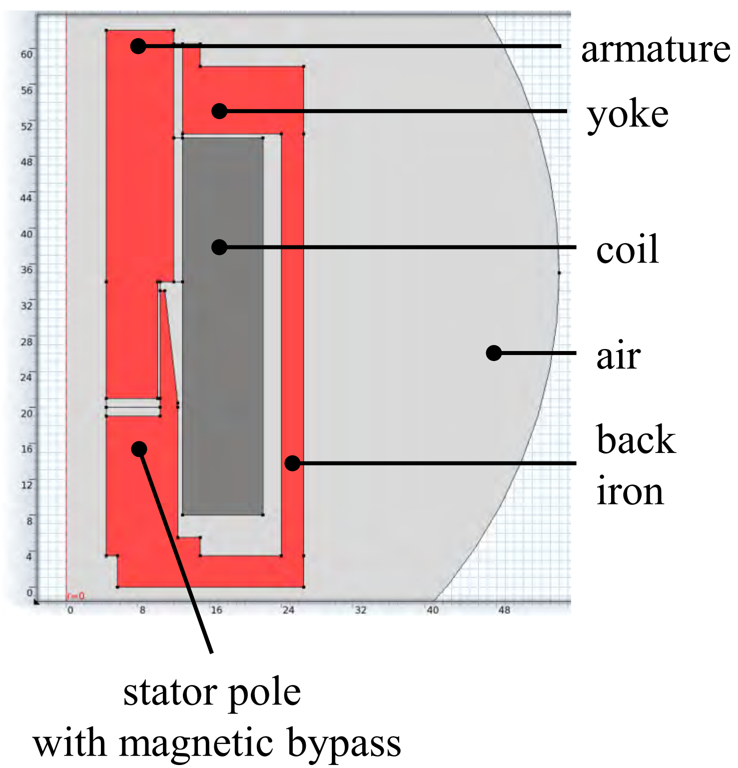
$$\frac{\Phi_{air}}{\Phi_{Fe}} = \frac{R_{Fe}}{R_{air}} = \frac{A}{100\ A_{Fe\_max}}$$

$A < 100\ A_{Fe\_min} \rightarrow \Phi_{air} < \Phi_{Fe}$

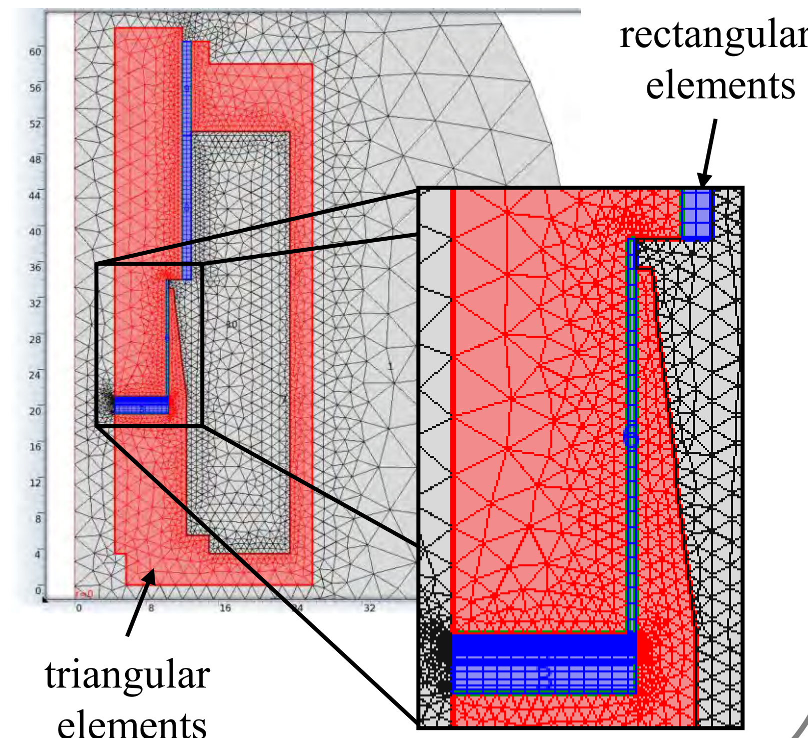


4. Finite Element Approach

Geometry



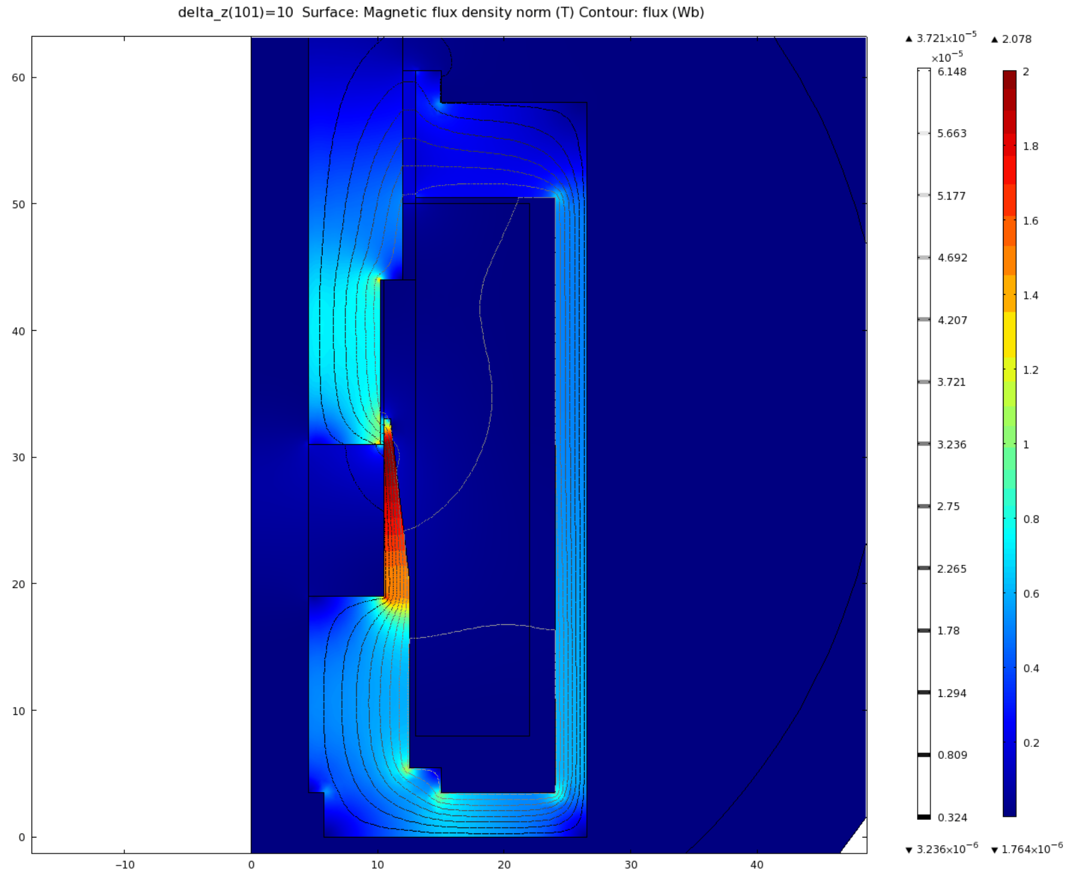
Mesh



4. Finite Element Approach

Simulation Results

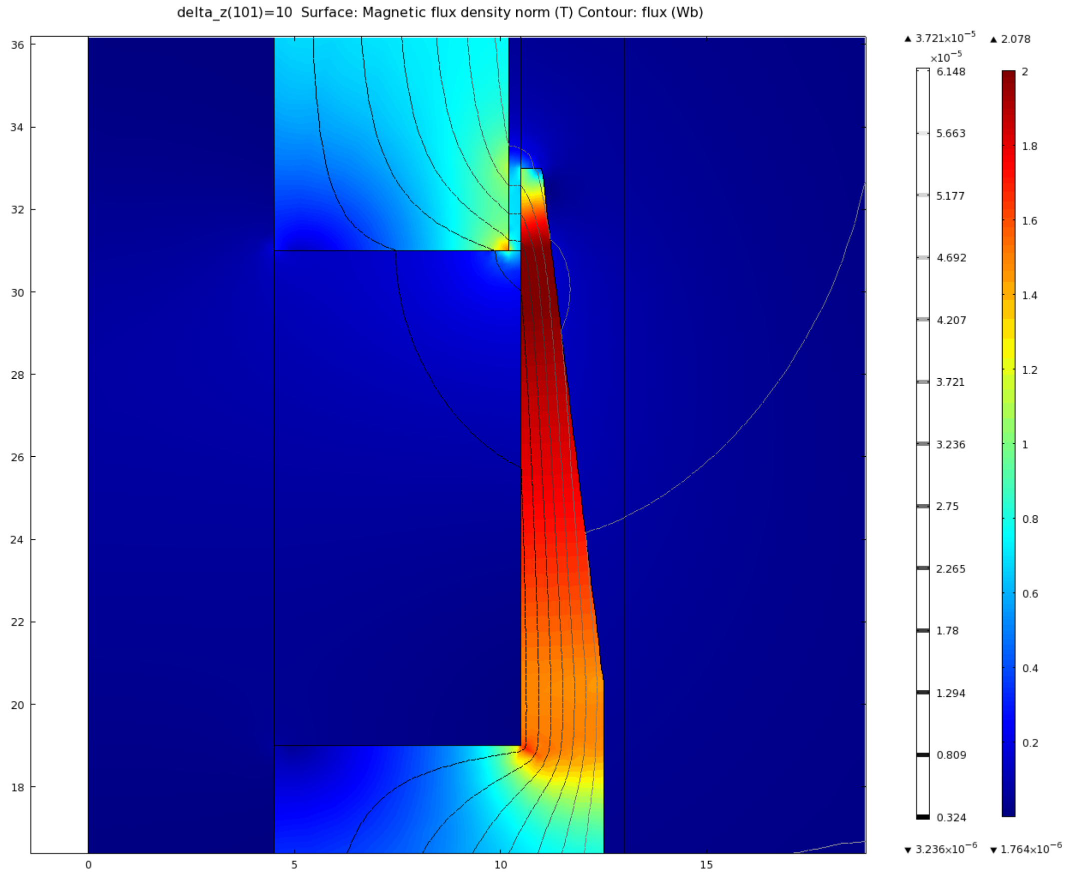
- Animated results of stationary study for different armature positions at constant coil current.
- Highly saturated regions in magnetic bypass due to radial flux component.



4. Finite Element Approach

Simulation Results

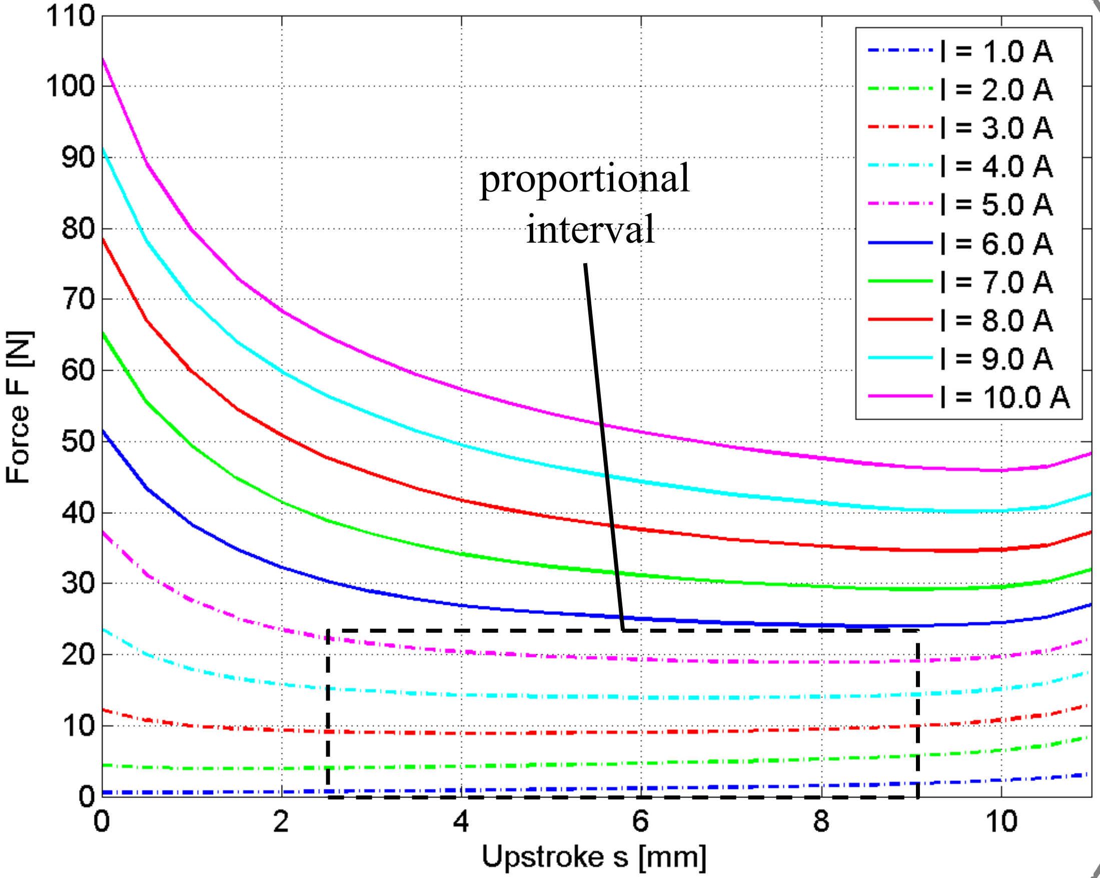
- Increasing bypass flux with decreasing main air gap.
- Highly saturated region (bottle neck) next to tip of armature.
- Dispersed flux passing by highly saturated region generating axial force.
- Direct flux between pole areas appears near minimum air gap.



4. Finite Element Approach

Force-Stroke-Curves:

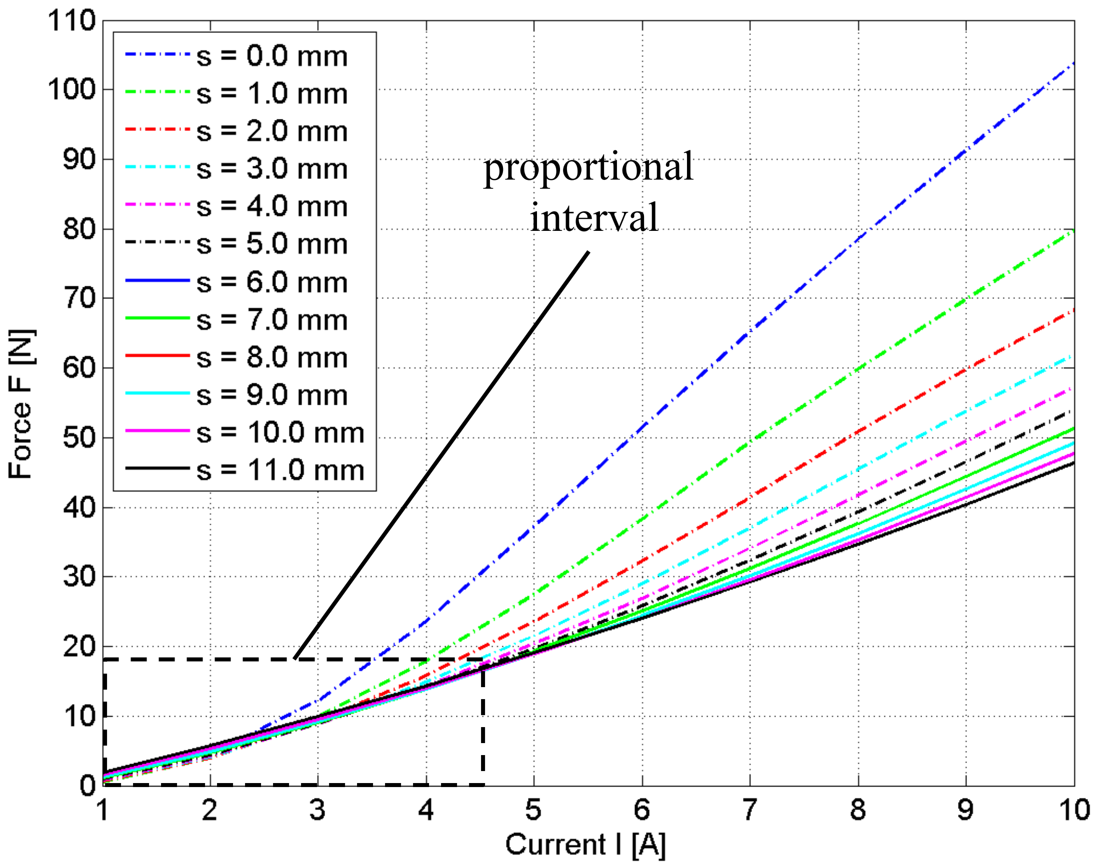
- Proper bypass dimensions provided force-stroke-curves show interval of approximately proportional interrelationship.
- Typical nonlinear ascent of force near minimum and maximum air gap.



4. Finite Element Approach

Force-Current-Curves:

- Very good proportional interrelationship between force F and coil current I for 2 mm < s < 11 mm.
- Nonlinear ascent of force near minimum main air gap.
- Nonlinear ascent of force for high currents.



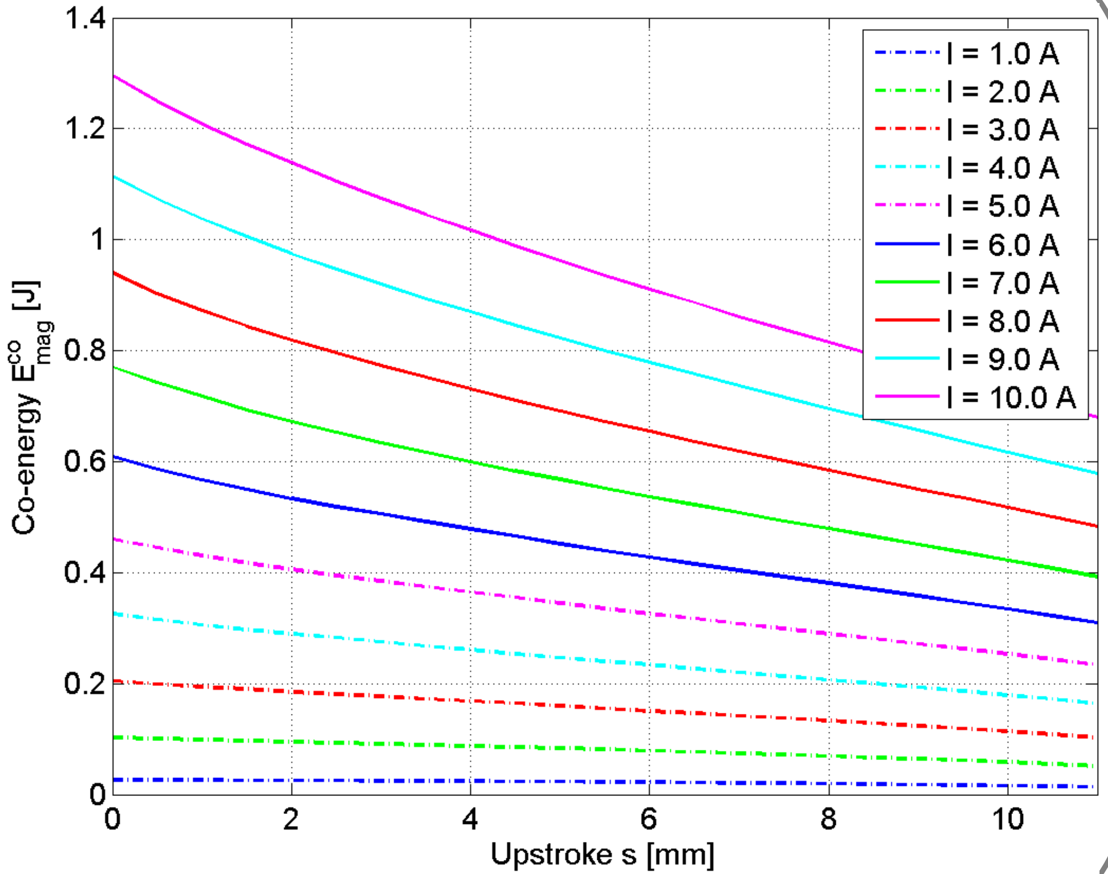
4. Finite Element Approach

Force-Co-Energy-Curves:

- Magnetic energy/co-energy can be used for force calculation via method of virtual displacement (see paper for more details).

$$F = -\frac{dE_{mag\_co}}{ds}$$

- Constant growth of energy/ co-energy → constant force.



5. Summary

Analytic model

- Analytic approach works fine for quite simple geometries. Influence of geometric parameters can easily be identified.
- Geometries becomming more complex and materials having nonlinear characteristics analytic approach rapidly gets complicated. Simplyfications help to reduce efforts but also reduce accuracy of the model.

FEM model

- Almost no limits to complexity of geometry and material properties exist. Accuracy of results in regions of special interest can be increased on demand by refining and improving mesh quality.
- Immense postprocessing capabilities.
- Influence of geometric parameters can not be seen directly. Therefore systematic Parameter studies have to be performed.

Simulatneous application of both approaches lead to a better and deeper understanding!

Thank you very much for your kind attention!