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

1. Magnetic Clamp
- Armature
- Air gap $\delta$
- Coil
- Stator

2. Common Solenoid

3. Proportional Solenoid

Characteristic force-stroke-curves:

F
\delta

1.  
2.  
3.
2. Functional Principle of Proportional Solenoids

Interaction of a Proportional Solenoid and a Spring

\[ F(\delta, I_0 + 2\Delta I) \]
\[ F(\delta, I_0 + \Delta I) \]
\[ F(\delta, I_0) \]
\[ F_{Spring} \]
2. Functional Principle of Proportional Solenoids

**Force-δ-Curve**

\[
F \sim \frac{1}{\delta}
\]

\[\rightarrow \delta \sim \frac{1}{I}\]

**Force-Current-Curve**

\[F \sim I\]
3. Analytic Approach

**Introduction of Reluctances**

(Reluctances = magnetic resistors)

\[ R_{\text{linear}} = \frac{l}{\mu_0 A} \]

\[ R_{\text{nonlinear}} = \frac{H l}{B A} \]
3. Analytic Approach

Magnetic clamp or common solenoid

Total reluctance:

\[ R_{\text{tot}} \approx R_{\text{air}} = \frac{\delta}{\mu_0 A} \]

Magnetic flux:

\[ \Phi = \frac{\Theta}{R_{\text{tot}}} = \frac{\Theta}{\mu_0 A} \frac{A}{\delta} \]

Magnetic force (Maxwell Tensile Force):

\[ F = \frac{\Phi^2}{2 \mu_0 A} = \frac{\Theta^2}{2 \mu_0 A} \frac{A}{\delta^2} \]
3. Analytic Approach

Proportional Solenoid at Maximum Man Air Gap

Reluctance of main air gap and bypass at $\delta_{\text{max}}$:

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

(low permeability) $R_{\text{Fe}} \approx \frac{l_{\text{Fe}}}{\mu_0 A_{\text{Fe}}} = \frac{\delta_{\text{max}}}{\mu_0 A_{\text{Fe}_{\text{min}}}}$

Reluctance ratio at $\delta_{\text{max}}$:

$$\frac{\Phi_{\text{air}}}{\Phi_{\text{Fe}}} = \frac{R_{\text{Fe}}}{R_{\text{air}}} = \frac{A}{A_{\text{Fe}_{\text{min}}}}$$

$A \gg A_{\text{Fe}_{\text{min}}} \Rightarrow \Phi_{\text{air}} \gg \Phi_{\text{Fe}}$
3. Analytic Approach

Proportional Solenoid at Minimum Main Air Gap

Reluctance of main air gap and bypass at $\delta_{\text{min}}$:

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

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

Reluctance ratio at $\delta_{\text{min}}$:

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

$A < 100 A_{\text{Fe min}} \rightarrow \Phi_{\text{air}} < \Phi_{\text{Fe}}$
4. Finite Element Approach

**Geometry**
- armature
- yoke
- coil
- air
- back
- iron
- stator pole with magnetic bypass

**Mesh**
- rectangular elements
- triangular elements
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 $2 \text{ mm} < s < 11 \text{ mm}$.

- Nonlinear ascent of force near minimum main air gap.

- Nonlinear ascent of force for high currents.

![Force-Current-Curves](image)
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).

\[ F = -\frac{dE_{\text{mag}, co}}{ds} \]

- Constant growth of energy/co-energy \(\rightarrow\) constant force.
5. Summary

Analytic model

- Analytic approach works fine for quite simple geometries. Influence of geometric parameters can easily be identified.
- Geometries becoming more complex and materials having nonlinear characteristics analytic approach rapidly gets complicated. Simplifications 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.

Simultaneous application of both approaches lead to a better and deeper understanding!
Thank you very much for your kind attention!