Tutorial Two: Force on Plunger due to Magnetic Field in a Nonlinear Solenoid

Description:
A solenoid actuator consists of a coil enclosed in a ferromagnetic core with a plunger.

![Image of solenoid actuator]

Given:

<table>
<thead>
<tr>
<th>Relative permeability of air and coil</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current density in coil</td>
<td>1e6 Amp/m²</td>
</tr>
</tbody>
</table>

The B-H curve for the core and plunger

<table>
<thead>
<tr>
<th>H (A/m)</th>
<th>460</th>
<th>640</th>
<th>720</th>
<th>890</th>
<th>1280</th>
<th>1900</th>
<th>3400</th>
<th>6000</th>
</tr>
</thead>
<tbody>
<tr>
<td>B (T)</td>
<td>0.8</td>
<td>0.95</td>
<td>1</td>
<td>1.10</td>
<td>1.25</td>
<td>1.40</td>
<td>1.55</td>
<td>1.65</td>
</tr>
</tbody>
</table>

1. Draw the given electromagnet-plunger diagram as described above using preprocessor menu. The problem is solved in axisymmetric system. Since the problem is symmetric about the central vertical axis, only half of the geometry needs to be modeled. This symmetric half problem domain needs to be enclosed by a fictitious outer boundary on which boundary conditions can be imposed.
2. Use appropriate finite element type from the menu.
3. Define material properties. It should be remembered that relative permeability of coil and air zones is 1. Core and plunger should be assigned B-H characteristics as defined in the table given above.
4. Choose small enough mesh size to get accurate results.
5. Define sources: enter current or current density for the coil.
6. Define flux-parallel boundary condition (magnetic vector potential = 0) on the outermost boundaries.
7. Solve the problem as a nonlinear magnetostatic one.
8. Plot the equipotential lines (magnetic flux lines in this case).

Analytical solution:-

The core is assumed to have infinite permeability requiring no magnetizing mmf.

Cross sectional area of coil = Height × Width

\[ = 0.16 \text{ meter} \times (0.078 \ - \ 0.04) \text{ meter} \]

\[ = 6.08 \times 10^{-3} \text{ m}^2 \]

Let,

Ampere turn density (ATD) = Current density (J)

\[ \text{Current density} = 1e6 \text{ A/m}^2 \]

\[ \text{Ampere turn (AT)} = \text{Ampere turn density } \times \text{Area of coil} \]

\[ = 1e6 \times 6.08 \times 10^{-3} \]

\[ = 6080 \]

\[ H_g = \frac{\text{AT}}{g} = 6080/0.02 = 304000 \text{ Ampere/meter} \]

where, g is air gap distance

\[ B_g = \mu_0 H_g = 4\pi \times 10^{-7} \times 304000 \]

\[ = 0.382 \text{ Tesla} \]

Force exerted on plunger \( f_c = \frac{1}{2} \frac{B_g}{\mu_0} \times A \)
where, cross sectional area(A) coil = \((\pi/4) \times (d)^2\)
\[
= (\pi/4) \times (0.08)^2
\]
\[
= 5.02e^{-3}\ m^2
\]

Hence, force \(f_c = 291.467\ N\)

The difference in numerical and analytical solution is due to fringing.