# L2c: Magnetic Actuators Operated by DC (Ch 7)

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# Why

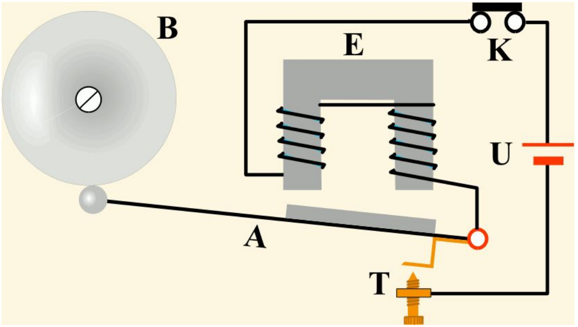
As we have seen from many of the examples, there are many applications where motion or force is needed in a linear direction.

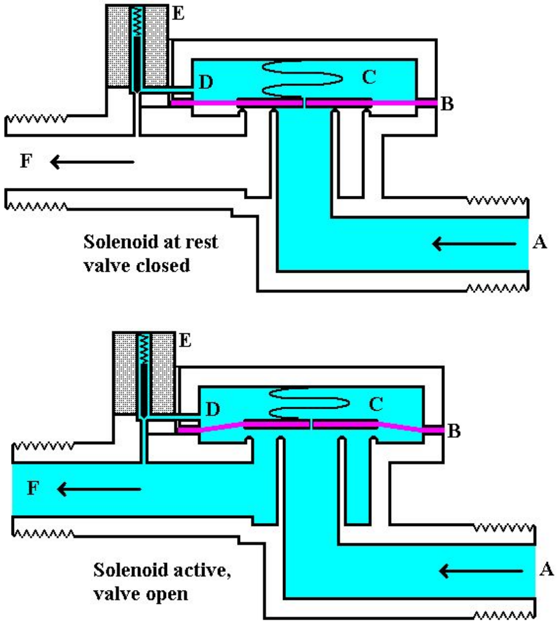
This linear motion is achieved by a “Magnetic actuator”

Different actuators are available depending on how the force is required to change with displacement.

# Solenoid Actuator Introduction

- Creating movement (bell)
- Switching fluid flow (valve)
- Switching current flow (contactor)

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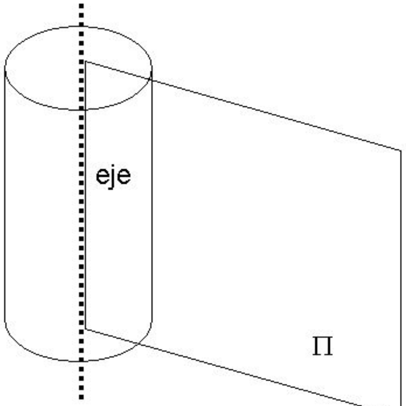
# Axisymmetric vs 2D Planar

Axisymmetric

- 2d shape rotated around an axis

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2D Planar

- 2d shape extruded into the page

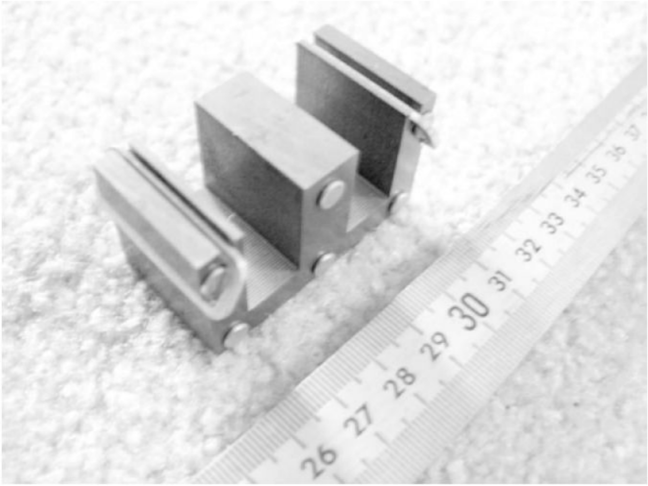
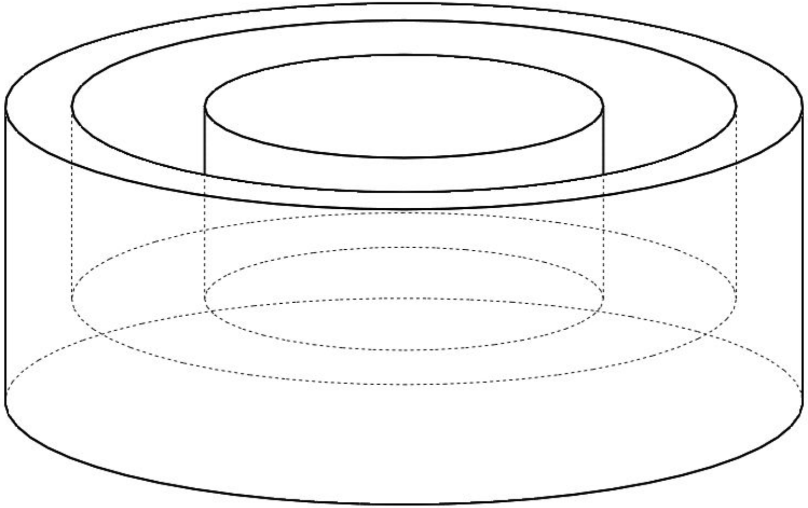


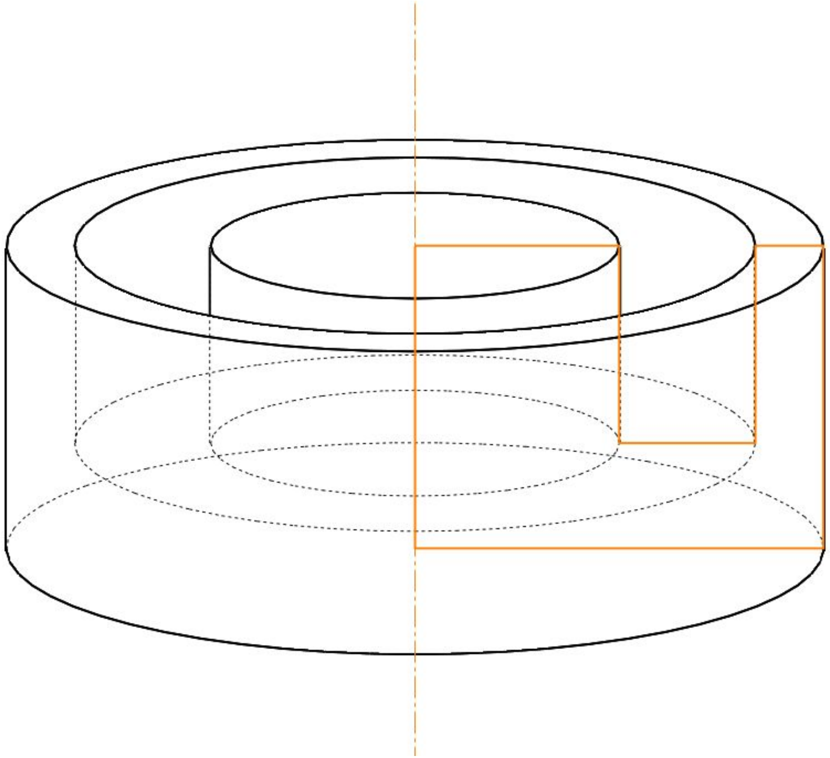

**FIGURE 8.4** Photo of stator core with two shading rings in Eaton AC actuator of Chapter 4.

# Test for understanding

Draw the 3D axisymmetric shape for the 3D shape below



# Test for understanding - discussion



# Clapper Armature

# Why - Clapper Armature

Clapper armatures have a high force when closed

Their force rapidly drops off as the air gap increases

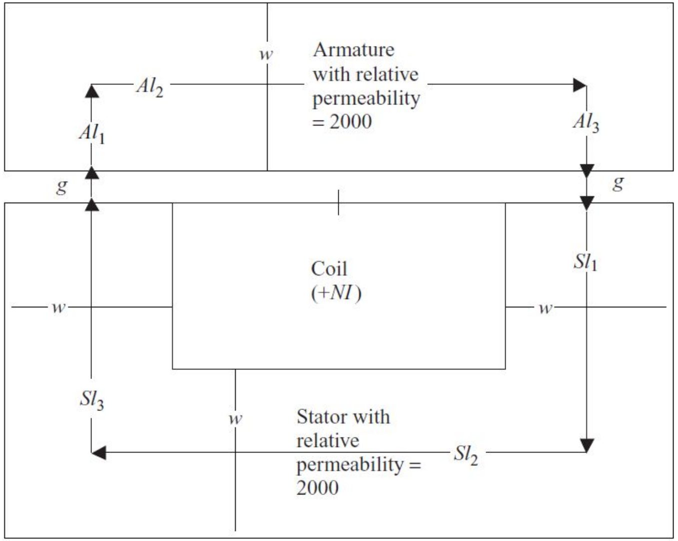



**FIGURE E7.1.1** Example 7.1 clapper solenoid actuator of planar geometry.

# Pull curves for Clapper Armature

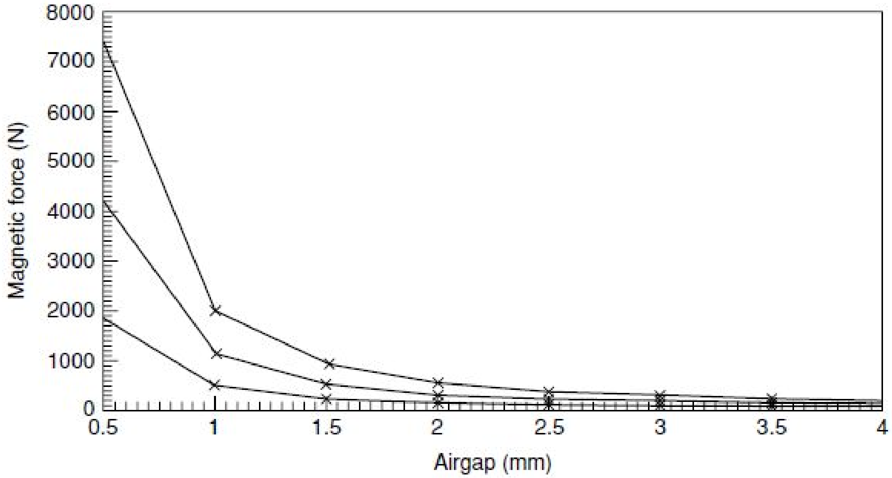



**FIGURE E7.1.2** Pull curves computed for Example 7.1. The curves are for currents of 2, 3, and 4 A in order from the lowest curve to the highest curve. The force (N) on the vertical axis is plotted against the airgap (mm) on the horizontal axis.

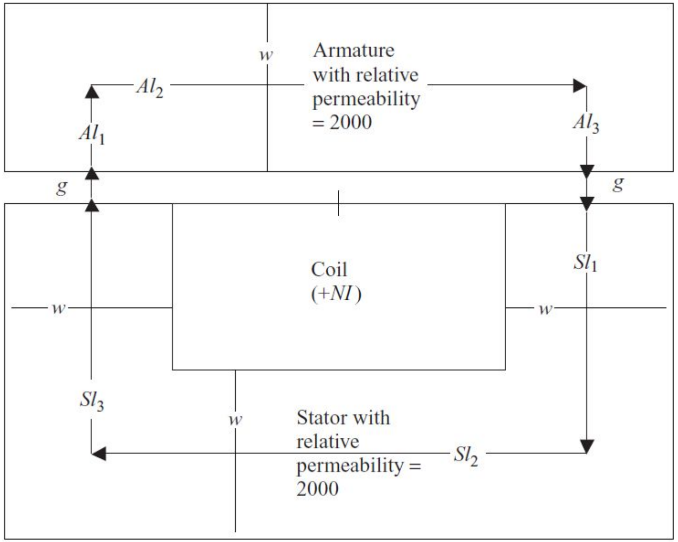



**FIGURE E7.1.1** Example 7.1 clapper solenoid actuator of planar geometry.

# How - Clapper Armature

1. Analytical
   a. Use the reluctance method to find the flux in the air gap
   b. Use virtual work or Maxwell stress tensor to find the force
2. FEA

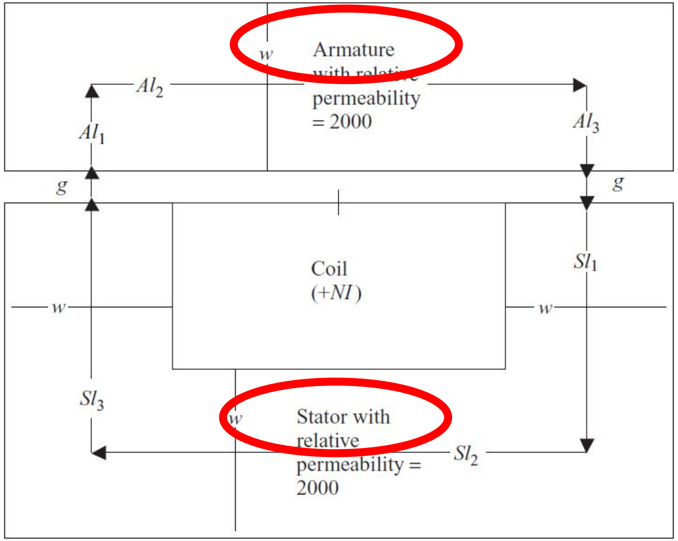



**FIGURE E7.1.1** Example 7.1 clapper solenoid actuator of planar geometry.

# Example 7.1

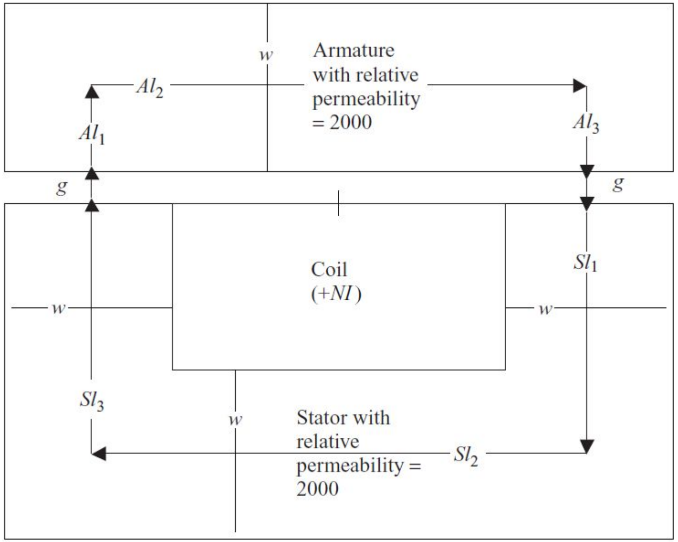



**FIGURE E7.1.1** Example 7.1 clapper solenoid actuator of planar geometry.

Find the flux in the air gap using the "Reluctance method" (Ch 3) [eq 3.9 - 3.11]

$$\mathcal{R} = l/(\mu S)$$

$$\varphi = (NI)/\left(\sum_k \mathcal{R}_k\right)$$

$$B_k = \varphi_k / S_k$$

Find the force using from the flux using the normal component of the "Maxwell Stress Tensor" (Ch 5) [eq 5.11]

$$F_{\text{mag}} = SB^2/(2\mu_o)$$

# Plunger Armature

# Why - Plunger Armature

More controllable force over the displacement

Little or no useful force produced on the sides of the plunger - only then end

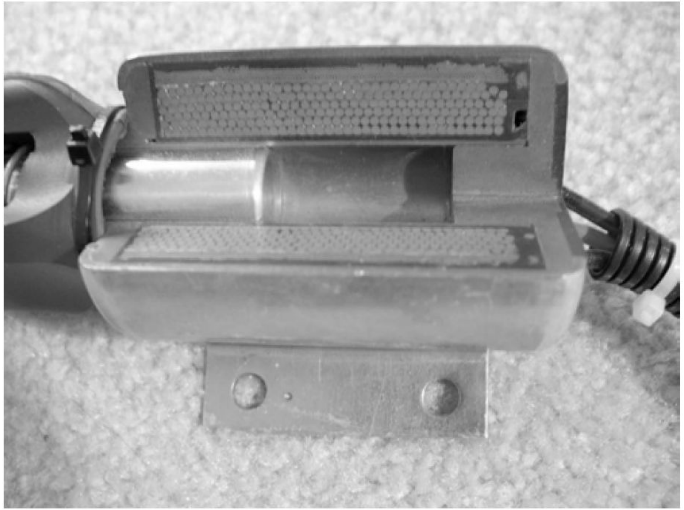


**FIGURE 7.2** Photo of typical plunger-type axisymmetric solenoid actuator. A sector of the stator has been sawed away to show the coil cross section.

# How - Plunger Armature

1. Analytical
   a. Use the reluctance method to find the flux in the air gap
   b. Use virtual work or Maxwell stress tensor to find the force
2. FEA

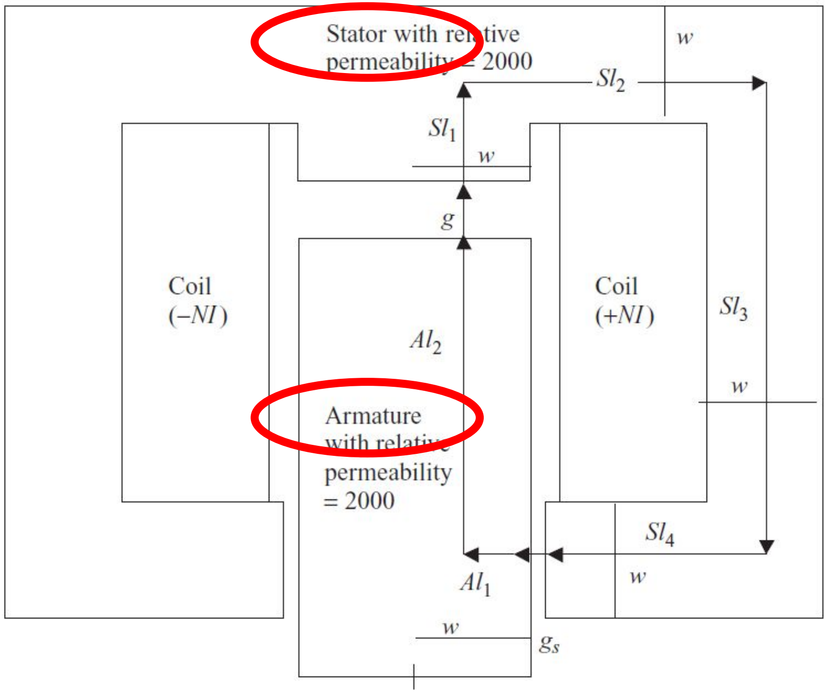



**FIGURE E7.3.1** Example 7.3 plunger solenoid actuator of planar geometry.

# Example 7.3 - Planar Plunger (Class task)

1. Use the reluctance method, $\mu_r = 2000$, to find **B** and **F** (assume no leakage or fringing flux)
2. Use FEMM to find **B** and **F** (use the points shown in the figure on the right and use mirror)

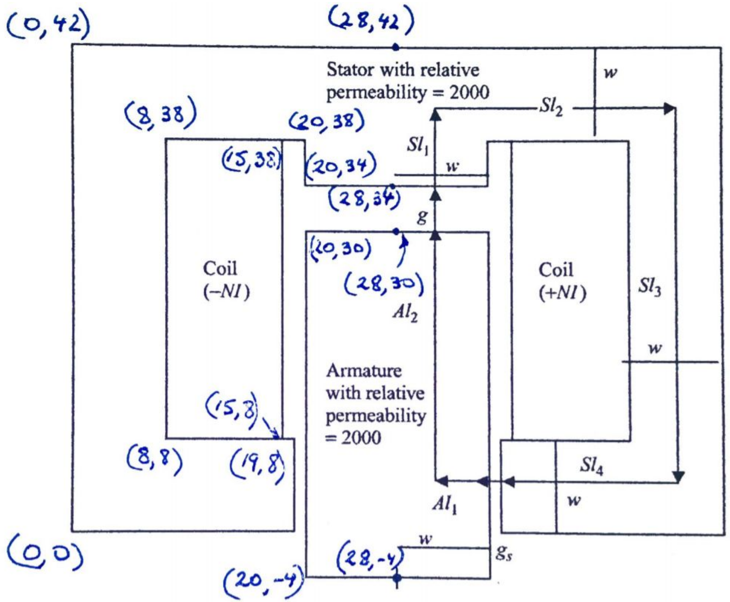
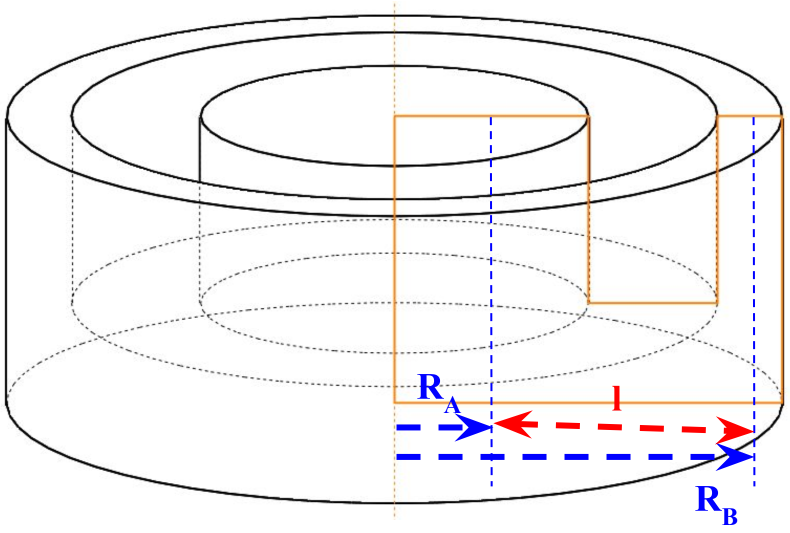



**FIGURE E7.3.1** Example 7.3 plunger solenoid actuator of planar geometry.

**Example 7.3 Fluxes and Forces on Planar Plunger Armature Solenoid** Figure E7.3.1 shows a planar solenoid with a plunger armature. The number of turns $N = 1000$ and the current $I = 2$ A. The dimensions are $w = 8$ mm, $g = 4$ mm, $g_s = 1$ mm, $Al_1 = 4$ mm, $Al_2 = 22$ mm, $Sl_1 = 8$ mm, $Sl_2 = 20$ mm, $Sl_3 = 34$ mm, and $Sl_4 = 15$ mm.

# Calculating *l* and *S* in Axisymmetric Problems

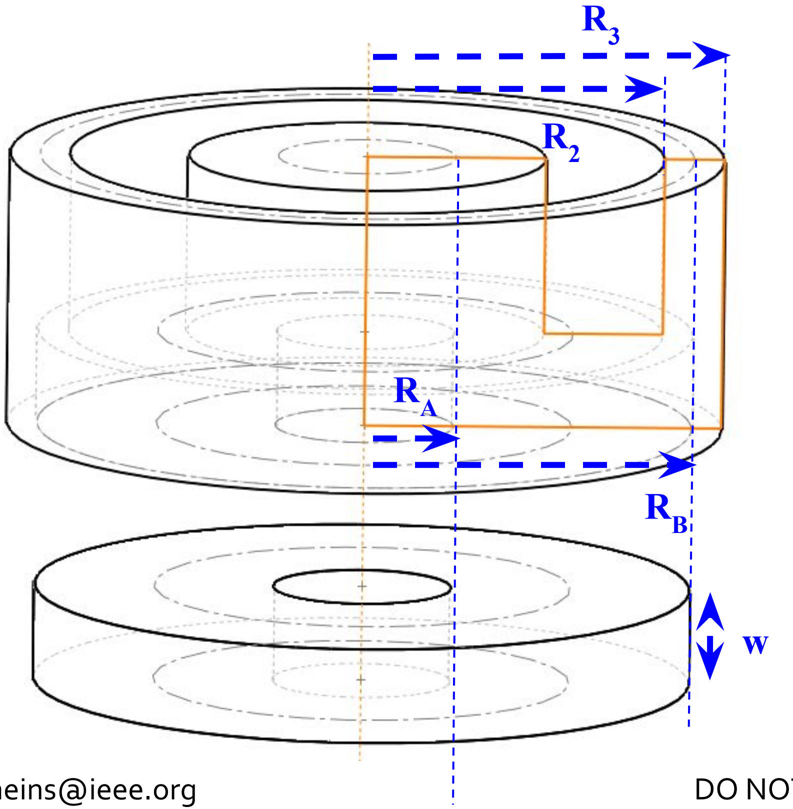



Length in the z direction is relatively straightforward

Length in the r direction is the difference between the two average radii

$$l = R_A - R_B$$

# Calculating *l* and *S* in Axisymmetric Problems




The cross sectional area of cylinders is the difference in areas of circles

$$S = \pi(R_3^{\,2}-R_2^{\,2})$$

The cross sectional area when the flux is travelling in the r direction is the average radius multiplied by the width in the z direction

$$S_{average} = \pi(R_A+R_B)w$$

# Example 7.2 - Axisymmetric Clapper

**Example 7.2 Fluxes and Forces on Clapper Armature Solenoid of Axisymmetric Geometry** Figure E7.2.1 shows an axisymmetric solenoid with a clapper armature. The number of turns $N = 2000$ and the current $I = 1$ A. The dimensions are $g = 2$ mm, $w_a = 8$ mm, $R_1 = 15$ mm, $R_2 = 25$ mm, $R_3 = 30$ mm, $Z_1 = 8$ mm, and $Z_2 = 23$ mm.

Use the reluctance method with steel relative permeability = 2000, assuming no leakage or fringing fluxes, to find the approximate values of the following.

(a) **B** and **F** on inside of clapper,

(b) **B** and **F** on outside of clapper.

(c) Obtain the above answers with finite-element software.

(d) Obtain the answers for the above with finite-element software with steel relative permeability = 10,000, and comment on why the results differ.

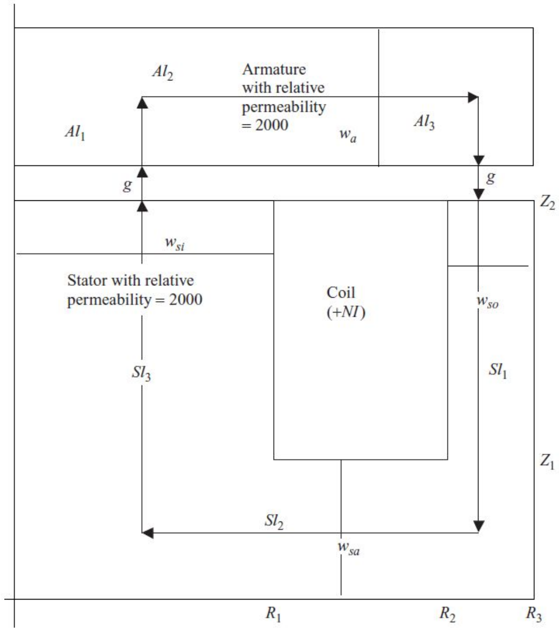



**FIGURE E7.2.1** Example 7.2 clapper solenoid actuator of axisymmetric geometry. As customary, the axis of symmetry is the vertical line on the left border.

# Example 7.4 - Axisymmetric Plunger (Class Task)

1. Use the reluctance method, $\boldsymbol{\mu_r = 2000}$, to find $\mathbf{B}$ and $\mathbf{F}$ (assume no leakage or fringing flux)
2. Use FEMM to find $\mathbf{B}$ and $\mathbf{F}$ (use the points shown in the figure on the right and use mirror)

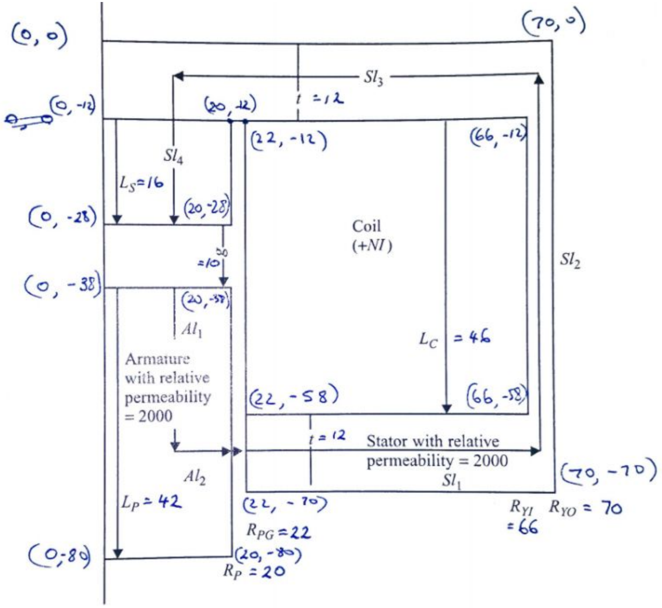



**FIGURE E7.4.1** Example 7.4 plunger solenoid actuator of axisymmetric geometry.

**Example 7.4 Fluxes and Forces on Axisymmetric Plunger Armature Solenoid**
Figure E7.4.1 shows an axisymmetric solenoid with a plunger armature. The number of turns $N = 400$ and the current $I = 4$ A. The dimensions are plunger and pole outer radius $R_P = 20$ mm, side airgap outer radius $R_{PG} = 22$ mm, stator yoke outer radius $R_{YO} = 70$ mm, stator yoke inner radius $R_{YI} = 66$ mm, working airgap $g = 10$ mm, plunger length $L_P = 42$ mm, stator stopper length $L_S = 16$ mm, coil axial length $L_C = 46$ mm, and stator yoke axial thickness $t = 12$ mm (on top; same on bottom).

# Voice Coil Actuators

# Why - Voice Coil Actuator

Commonly used in loudspeakers

Force can be in two directions

Force is less dependant on location and proportional to current

High force vs inertia (high frequency response)

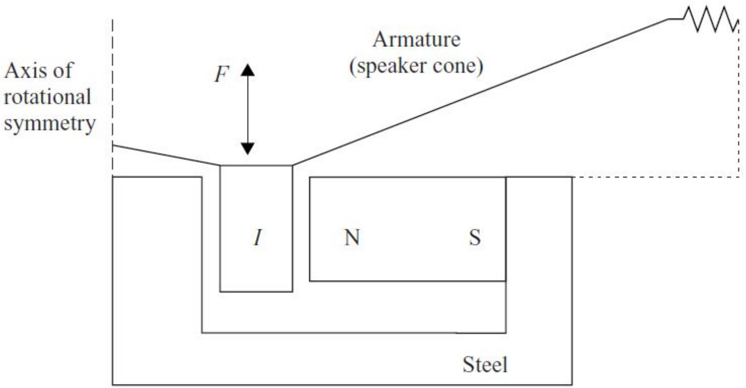



**FIGURE 7.3** Typical voice coil actuator, shown driving a loudspeaker. The movable voice coil carries the current *I* and is subjected to the magnetic field from a permanent magnet with north (N) and south (S) poles.

# How - Voice Coil Actuators

Lorentz force

$$F = NBIl \ (7.4)$$

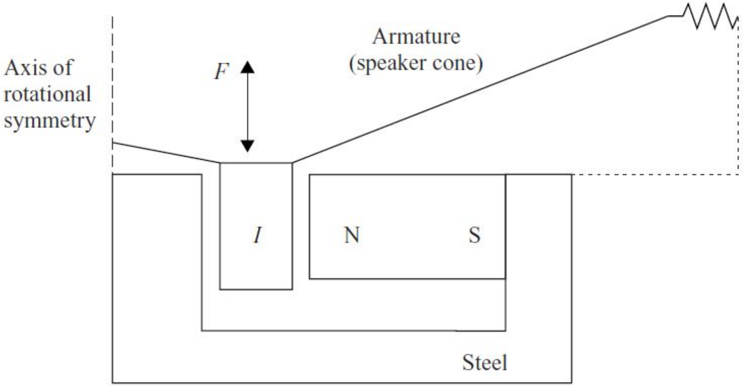



**FIGURE 7.3** Typical voice coil actuator, shown driving a loudspeaker. The movable voice coil carries the current *I* and is subjected to the magnetic field from a permanent magnet with north (N) and south (S) poles.

# Example 7.5

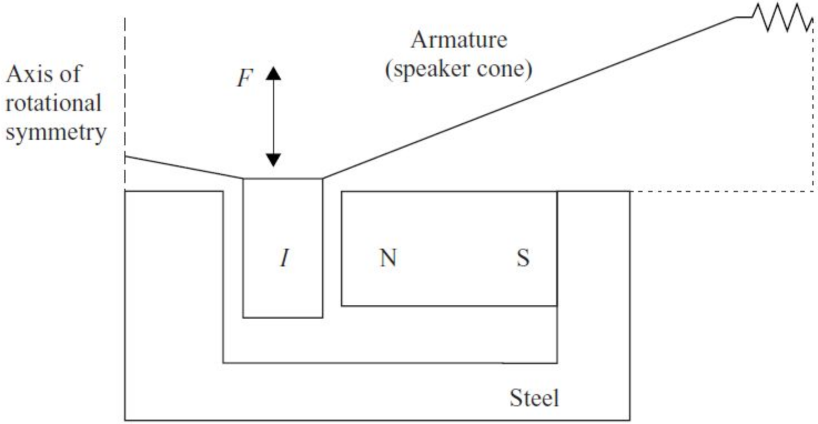



**FIGURE 7.3** Typical voice coil actuator, shown driving a loudspeaker. The movable voice coil carries the current *I* and is subjected to the magnetic field from a permanent magnet with north (N) and south (S) poles.

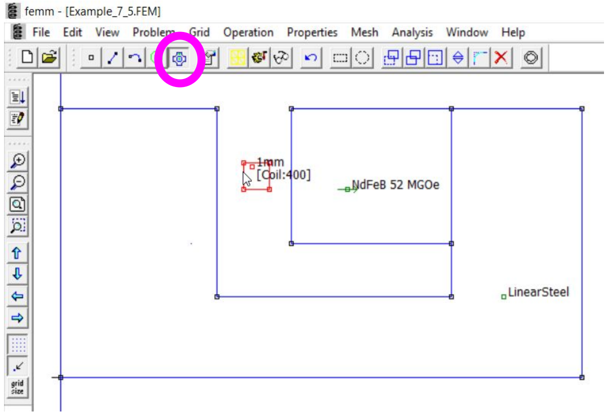
**Example 7.5 Force of Voice Coil Actuator** A voice coil has a resistance of 20 Ω and 400 turns. A permanent magnet provides a DC magnetic flux density of 0.8 T in the radial *r* direction. The average radius *r* of the voice coil is 15 mm. Given 12 V DC applied to the voice coil, find the steady-state force produced.

# Test for understanding

Download the FEMM file for the voice coil actuator and find the force on the wire using:

1. The in-built integral for Lorentz force
2. The in-built integral for Weighted stress tensor
3. Calculating Lorentz force by extracting $\mathbf{B_n}$ in FEMM at the wire
4. Using a virtual work method
   a. Use the in-built integral for total co-energy (select everything)
   b. Use the group selection tool, select the wire (right click) and move it vertically by 1mm
   c. Use the in-built integral for total co-energy (select everything)
   d. Calculate the force using virtual work

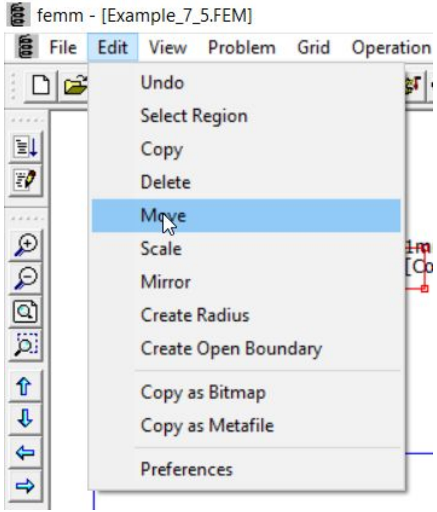
# Moving the wire for co-energy calculations

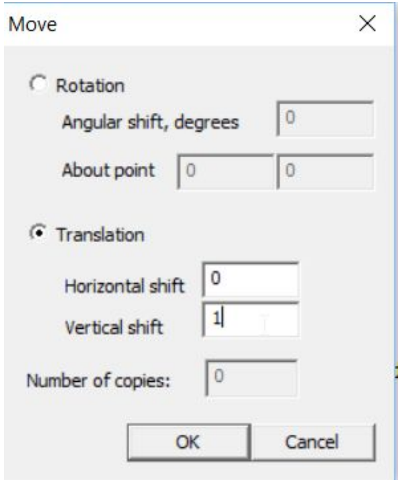



Use the group select tool to select the wire

Use Edit > Move

Choose a vertical shift of 1mm



# Proportional Actuators

# Why

Sometimes position control means it is desirable to have the displacement proportional to the current

$$x = kI \quad (7.5)$$

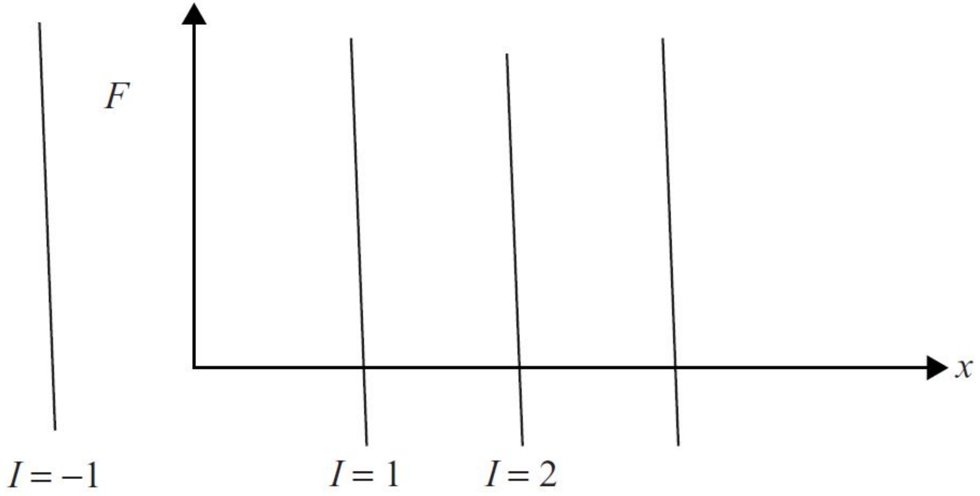



**FIGURE 7.6** Ideal proportional actuator force.

# How

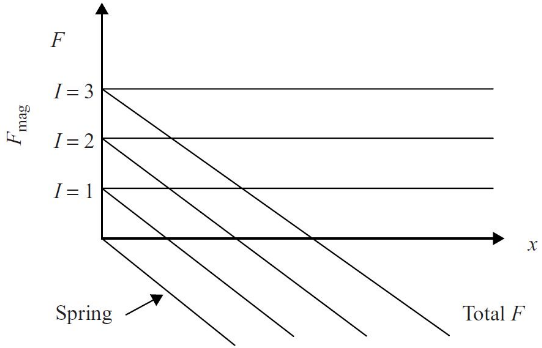



**FIGURE 7.7** Nonideal proportional actuator produced by constant magnetic force and opposing spring force.

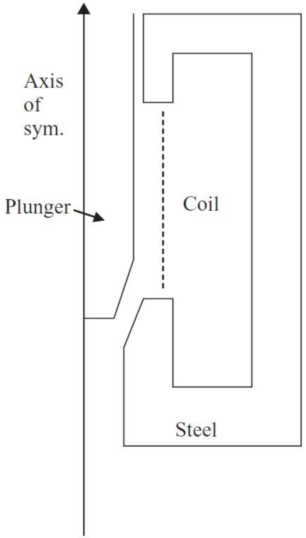



**FIGURE 7.8** Plunger solenoid shaped for approximately constant force.

# Rotary Actuators

# Why

Sometimes we want rotary motion rather than linear motion

For example if we want to turn on a valve that has a rotary mechanism (tap) then we need (non-continuous) rotary motion

# How

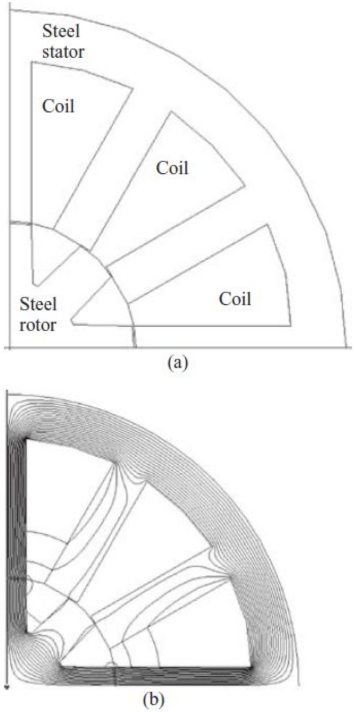



**FIGURE 7.10** Typical step motor. (a) geometry of one quadrant, (b) Computer display of calculated flux lines.

# Example

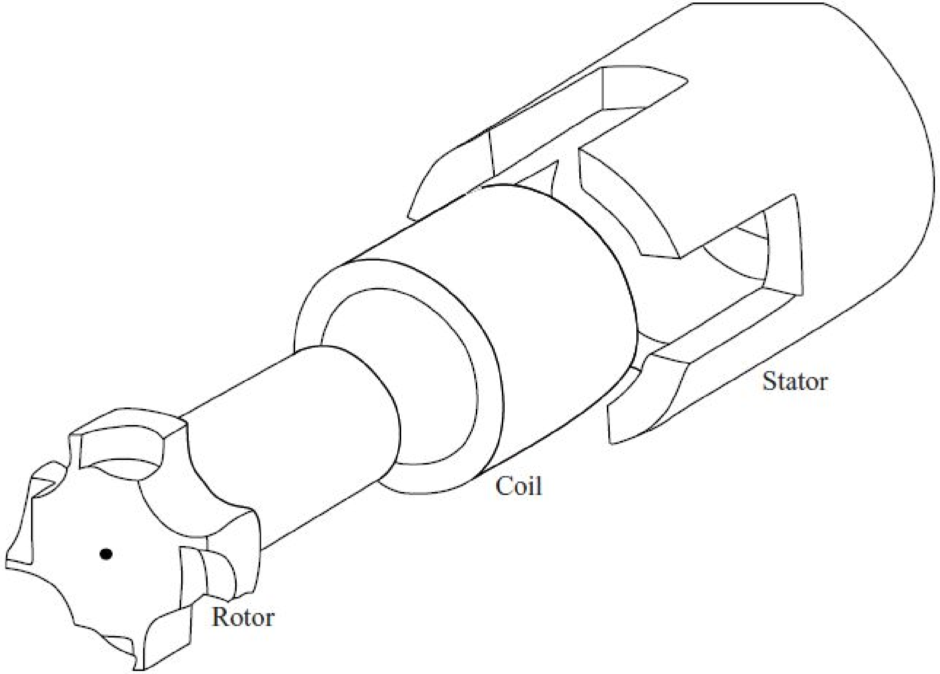



**FIGURE 7.11** Rotary actuator with solenoidal winding and three-dimensional flux paths.

# Magnetic Bearings

# Why - Magnetic Bearings

High speed rotation often requires magnetic bearings

Passive bearings are possible (imagine two opposing permanent magnets)

Active bearings are usually required on at least one axis (more depending on the level of control)

# How - Magnetic Bearings

For active magnetic bearings, position feedback is required

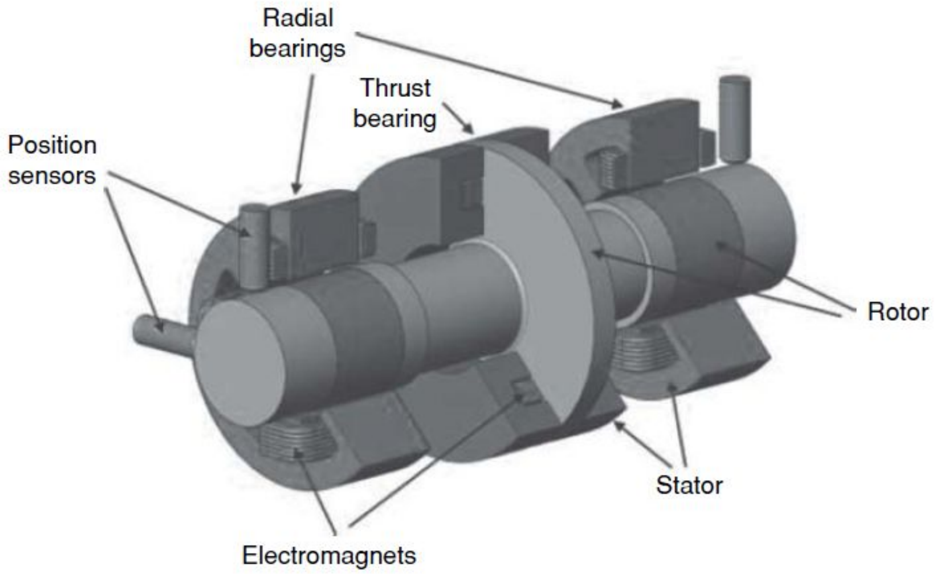



**FIGURE 7.12** Magnetic bearing basic layout. Used by permission of Synchrony [12].

# Example - Example

Commercially available bearing

Onboard position sensors and control


**FIGURE 7.13** Fusion® magnetic radial and thrust bearings with integrated control electronics. The radial bearing has a load capacity of 1330 N, and the thrust bearing has a load capacity of 4448 N. Used by permission of Synchrony [12].

# Summary

- Actuators provide force or movement for a finite distance (either linear or rotary)
- Depending on the force/ displacement goal different designs are available
- We analysed:
  - Clapper Armature
  - Plunger Armature
  - Voice coil
- Other actuators you need to be aware of are:
  - Rotary actuators
  - Magnetic bearings