

Chapter 4:

ElectroMagnetic Actuator Basics

Objectives

The objectives for this chapter are as follows:

- Discover what the components of an electromagnetic actuator are, how they are constructed and how the components interact.
- Learn about the pancake and tubular shaped armatures as well as the three variations on the tubular shape.
- Understand the concept of Force vs Air Gap and when to use the flat face, conical and proportional style actuators.
- Learn what parameters affect Solenoid force and how the process of solenoid design must juggle these parameters depending on the application.

Introduction

In the previous chapters we learned about the basics of magnetics and electronics. In this chapter we will use these basics to describe the construction and operation of an electro-magnetic actuator. Various designs of actuators will be compared, as well as a description of how the performance of each varies.

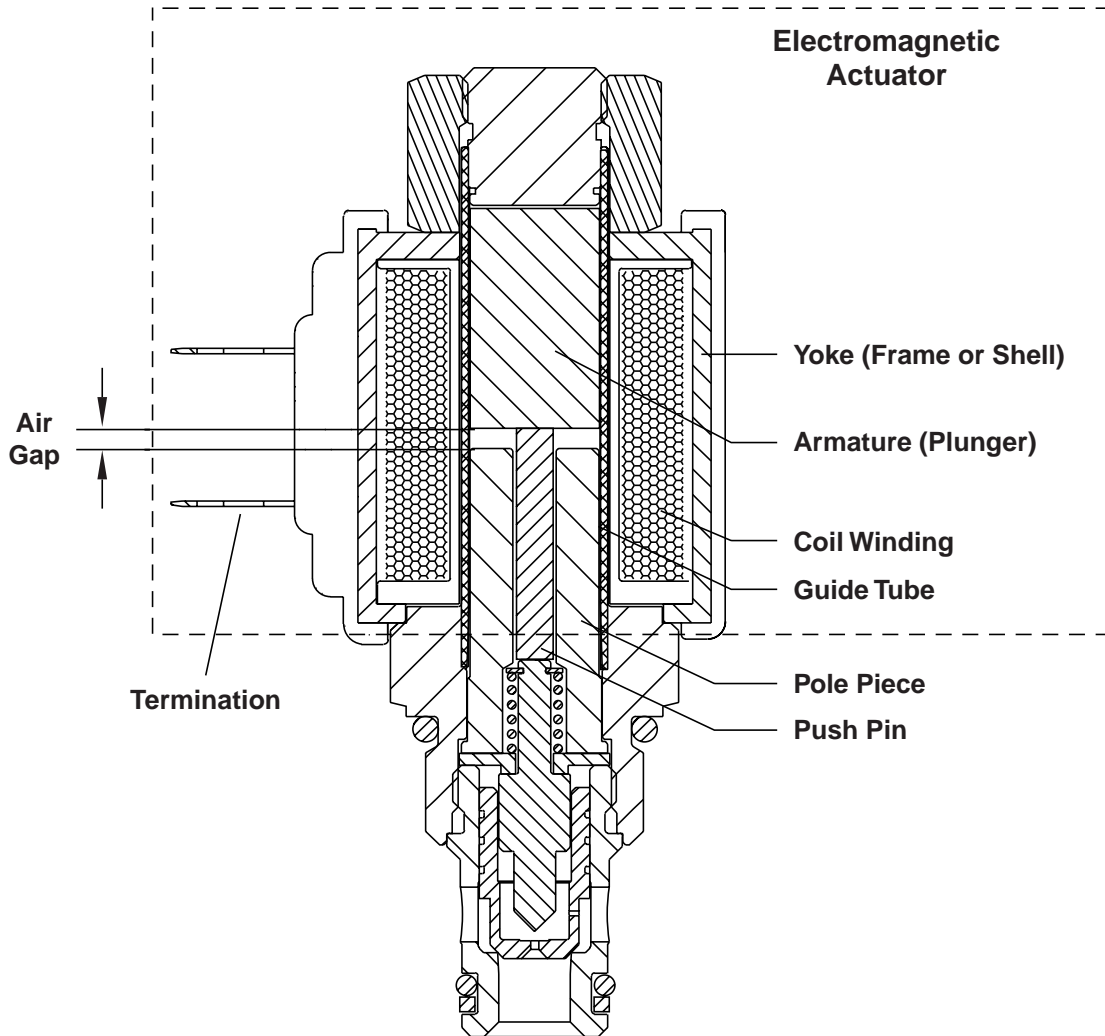
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Electromagnetic Actuator

Recall the definition of an electromagnetic actuator from Chapter 1. A solenoid valve is one which uses an electromagnetic actuator to move a hydraulic control element such as a poppet or spool.

An electromagnetic actuator takes electricity and converts it into magnetic force. Magnetic force is used to move the spool or poppet which in turn controls the direction of flow.

The actuator portion of the solenoid valve is highlighted in the following diagram.



Actuator Components

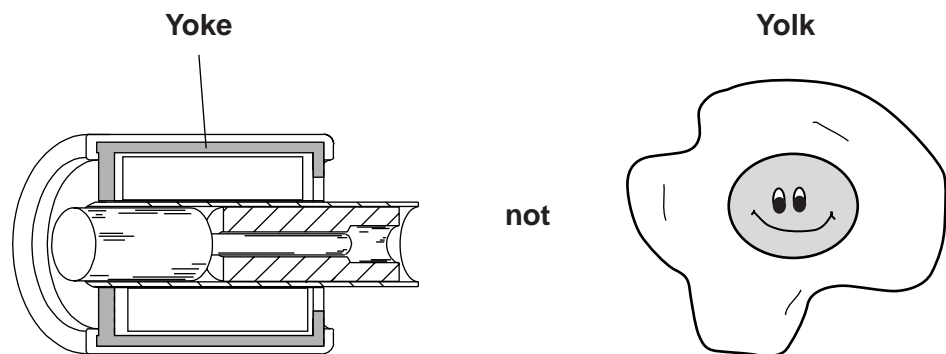
Coil winding

The coil winding is the solenoid that we learned about in the previous chapter. As we learned, it creates an electromagnetic field when the current is applied across the terminals. It is typically made from copper which is the most cost effective and efficient conductor of electricity.

Yoke

The yoke, also referred to as the shell or frame, concentrates the magnetic field. It surrounds the outside of the solenoid coil and is typically made from low carbon steel. Recall from chapter three that steel or iron is a Ferromagnetic material. The flux created by the solenoid can flow easily through this Ferromagnetic material. A Ferromagnetic material can also intensify the magnetic field. If the yoke did not exist, the flux lines or magnetic field would be loosely spaced, and the actuator would be inefficient.

Low carbon steel is used for most electromagnetic actuators. It has a high permeability (good conductor of magnetics), and a relatively low cost. There are better magnetic materials, but the increase in efficiency does not justify the increase in cost. The components of the actuator which are made from iron are, the yoke, pole piece and the armature.



Guide Tube

The guide tube acts as a guide for the armature. It is typically made from a nonmagnetic material such as stainless steel. The material needs to be nonmagnetic to avoid the armature being attracted to it.

Pole Piece

The pole piece acts as a magnet when the current is applied to the winding. It is a fixed Ferromagnetic part of the armature. Refer back to the summary diagram in Chapter 3, in which two pieces of iron are shown. When the coil is energized, a magnetic field forms a north and south pole in these pieces of iron. The pieces are attracted and move towards one another. Similarly, in the pole piece, as the coil is energized, the pole piece and corresponding armature are attracted to one another. The pole piece however, is fixed into place and draws the armature toward it.

Armature (Plunger)

As mentioned in the pole piece description, the armature is the piece of iron which the pole piece attracts. This part is allowed to move freely, constrained only by the guide tube. If nothing opposes the movement of the armature, it will be attracted to, and move towards the pole piece. However, if something does oppose the movement of the armature, it will exert a force on that object.

Air Gap

The air gap is the distance between the pole piece and the armature. The size of the air gap depends on the product which the electromagnetic actuator is coupled (hooked up) to, such as the stroke of the spool or pilot pin.

If the actuator was not connected to anything, the air gap would not exist, because the parts would remain attracted to each other once the current was applied. There would be no force to break the magnetic attraction between the pole piece and the armature.

Push Pin (Connecting Element)

The push pin is the element that transfers the magnetic force to the part outside of the actuator. In addition, any forces which oppose the magnetic force will be transferred to the armature through the push pin.

The push pin is typically made of a nonmagnetic material such as stainless steel so that it is not attracted to the pole piece.

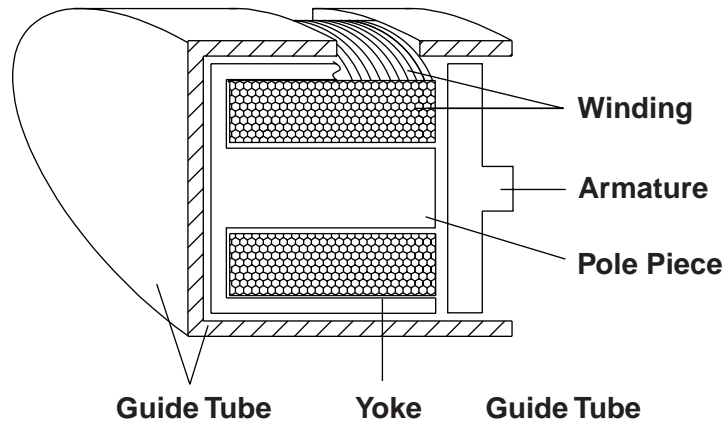
Armature Shapes

There are two basic shapes of armatures; pancake and tubular. The tubular style has three variations; flat, conical and proportional. The following sections describe each.

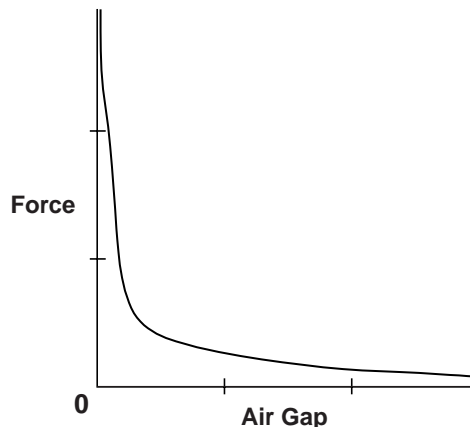
Pancake

The pancake style armature is used in applications where a high holding force is required but the air gap initially separating the plunger and pole piece is small. The name *pancake* comes from the shape of the flat armature which is the same diameter as the outside of the yoke. *Holding force* refers to the magnetic force between the pole piece and armature, when the air gap is zero.

The following diagram shows a cross section of a pancake style actuator.



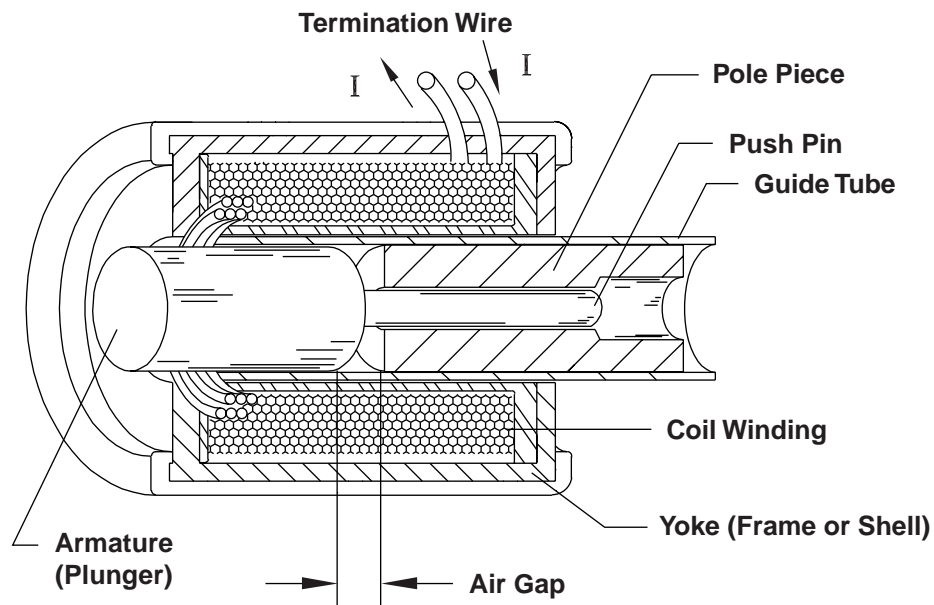
The graph below shows force vs. the air gap. This represents the magnetic attractive force between the pole piece and the armature when a constant current is applied and the position of the armature changes. Notice that the force is high when the air gap is zero (pole piece and armature are in contact), but decreases sharply as the air gap is increased.



Tubular

The tubular shape armature is used in hydraulic valves and pneumatic valves. There are three variations on the tubular shape, based on the shape of the pole piece and armature; flat, conical, and proportional.

A diagram of a tubular shaped actuator is shown below.



As with the pancake shape actuator we can plot a force vs air gap graph (see the following graph). The tubular shaped armature gives flexibility in controlling the shape of this graph. Three basic types of armature and pole piece designs are outlined and described in the following sections. Refer to the following comparison graph while reading through the descriptions of each shape.

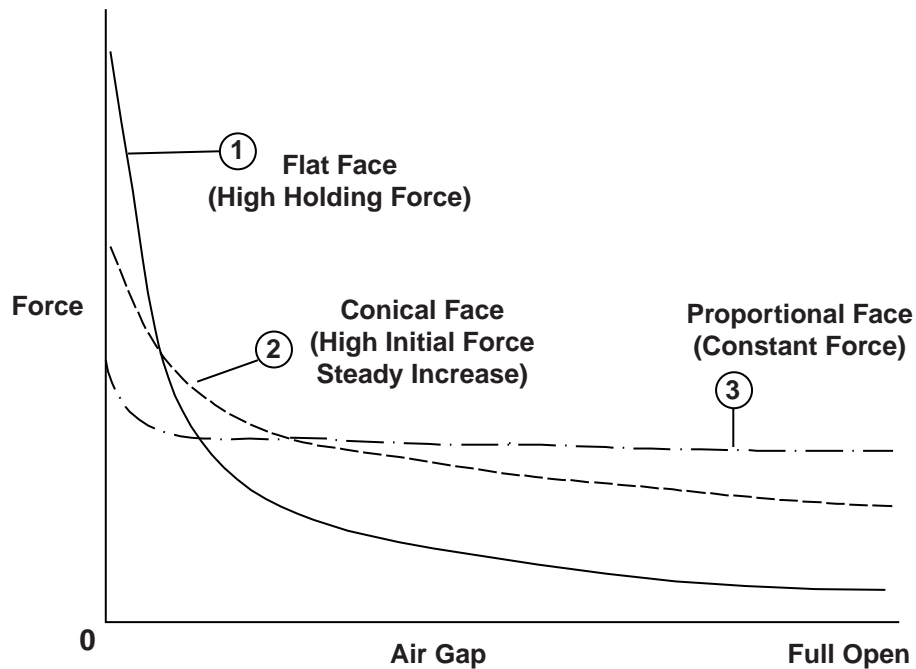
The *flat face* armature (number one on the graph) has a high holding force (magnetic force between the pole piece and armature, when the air gap is zero). This style of actuator is characterized by a low force at the full open point and a high force when the air gap is zero.

The *full open* point is the initial position of the product which the armature is connected to. This point varies depending on the application of the solenoid. It is defined by the distance the armature will be required to move

The *conical face* armature (number two on the graph) has a high initial force with a steady increase. The curve for this actuator shows that the initial force at full open is higher than the flat face, but the holding force is lower.

The *proportional face* armature (number three on the graph) has a constant force. The graph shows a constant or level force for the majority of movement (change in the air gap) of the armature.

The application (what the solenoid will be hooked up to) usually dictates which force versus air gap curve will be used. Not only is the performance of the solenoid or actuator force considered, the cost is as well. Each style discussed requires a better manufacturing process with the flat face being the least costly and the proportional being most costly.



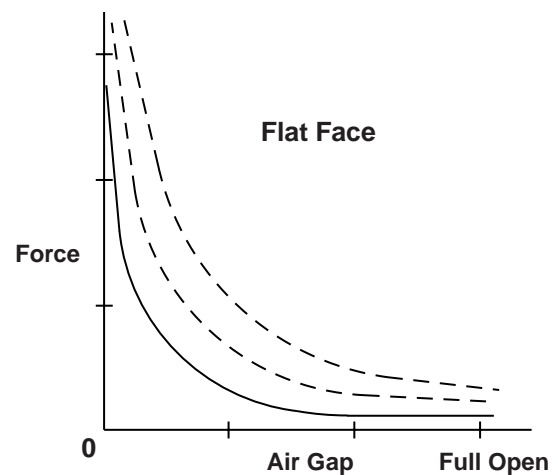
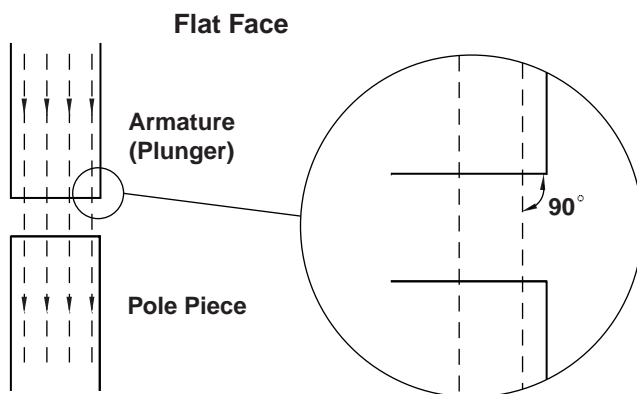
Flat Face

The illustration and graph below show a flat face plunger and pole piece. Magnetic field lines are overlaid on top of these parts. These indicate that magnetic field lines jump directly across from the plunger to the pole piece. The tendency of the field lines is to exit through the armature face and enter through the pole piece face at a right angle or perpendicular to the surface.

Recall from the previous chapter that the flux, or strength of the magnetic attraction between the parts is based on the magneto-motive force (nI), multiplied by the area through which the field flows (in this case the circular area of the armature and pole piece). The graph to the right represents the same actuator with various current levels applied. Each curve represents a different current value or a different value of ampere-turns (magneto-motive force). The lowest curve represents the lowest current level. The shape of the curve is based on the shape of the pole piece, armature (the area which the flux passes through), and the amount the domains within the material are aligned (the amount of nI).

When the armature is at the full open point, the force is low because the magnetic field has a greater distance to travel from the plunger to the pole piece. Recall that the permeability of air is low, so the magnetic field is reluctant to flow through the air. At this point very few domains are aligned in the pole piece and plunger. As the plunger and pole piece move closer together, the attraction increases as more domains align. While the parts are moving closer together, the magnetic field has a decreasingly smaller distance to travel. This results in an increase in force, because it can align more domains.

The cost of this shape actuator is relatively low due to the simplicity of the parts. There is very little machining time required to manufacture these parts and are therefore inexpensive to make.

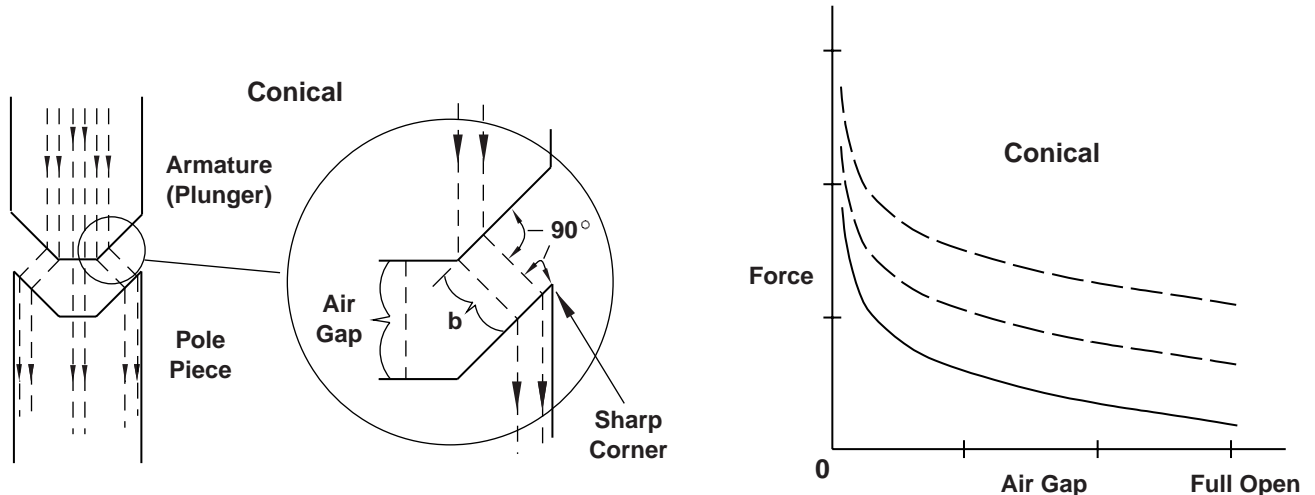


Conical

The following section describes the conical shape actuator. Refer to the diagram and graph below.

As in the flat face armature, the magnetic field in the conical armature still flows perpendicular from one face to another. The force when the armature is at the full open point is higher than in the flat face for two reasons:

1. The area of a conical surface is larger than that of the flat face even if the diameter of both is the same.
2. Although the air gap is equal on both the flat and conical, the distance the magnetic field must jump is less on the conical. Notice distance b shown in the diagram below is less than the air gap. This is simply a property of the conical surface which is triangular in shape.

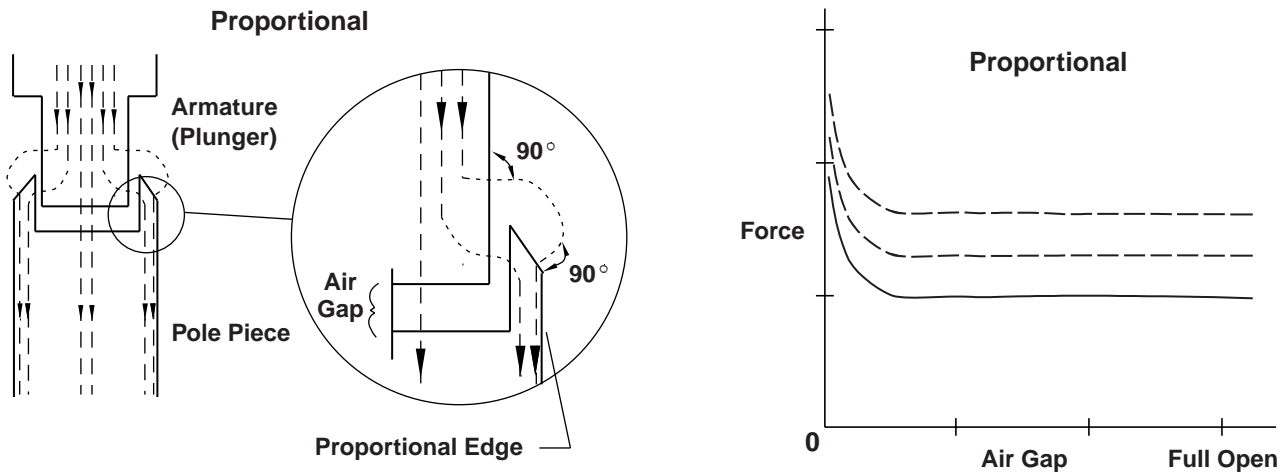


The graph above shows three curves for various current levels. The curves are similar to each other because the shape of the pole piece and plunger remain the same. The force is lowest at the largest air gap. As the distance between the pole piece and the armature decreases, the force increases and more domains become aligned. This happens because the magnetic field aligns almost all the domains at the sharp corners of the pole piece even before the air gap is zero. Since there is less material at the corners of the pole piece, a lower amount of flux at a larger air gap, can align these domains (saturate the material). As more and more domains become aligned, the change in magnetic force decreases. Therefore, since the domains at the corners align at larger air gaps, the change in force is less dramatic than with the flat face.

The conical shaped armature and pole piece are slightly more expensive than the flat parts because the shape is more complex and requires more machining.

Linear Proportional Face

The following section describes the linear proportional shape actuator. Refer to the diagram and Force vs Air Gap graph below.



As with the other two styles of armatures, the magnetic field lines leave and enter the surface of the steel or Ferromagnetic parts at a right angle. In this case, the magnetic field lines exit from the side of the plunger and enter the pole piece at a protrusion called the proportional edge (see diagram above).

The three curves shown in the graph above are a result of different current levels applied to the solenoid, and the area the magnetic field lines pass through. In the proportional armature, the force remains constant even after the air gap has changed, because the amount the domains are aligned in the proportional edge does not change. In addition, the distance the field lines jump from the plunger to the pole piece does not change.

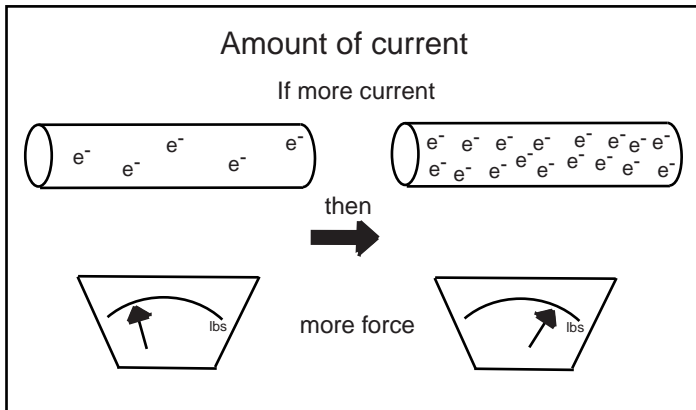
When the plunger is very close to the pole piece (near the zero point on the graph), the force begins to increase. This happens as the flat portion of the plunger approaches the flat face of the pole piece. At this point the graph of the flat face armature and the proportional armature are similar.

Relative to the two other styles, the proportional armature is much more costly to make. The shape of this armature is more detailed and the tolerances must be kept very tight to ensure that the performance does not vary.

Parameters which affect Solenoid Force

There are several factors which affect the force developed by the solenoid. These factors include:

- Current applied to the coil
- Coil resistance
- Ambient (room) temperature
- Number of turns on the solenoid coil
- Magnetic field density and construction (amount of iron used)

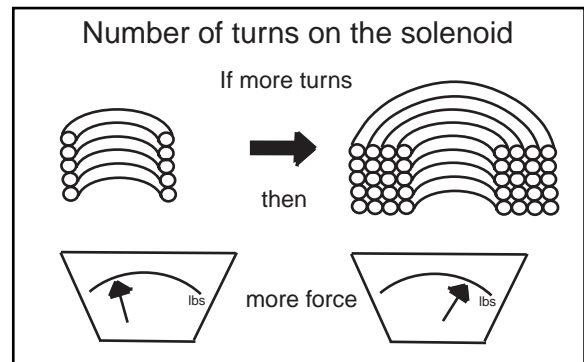


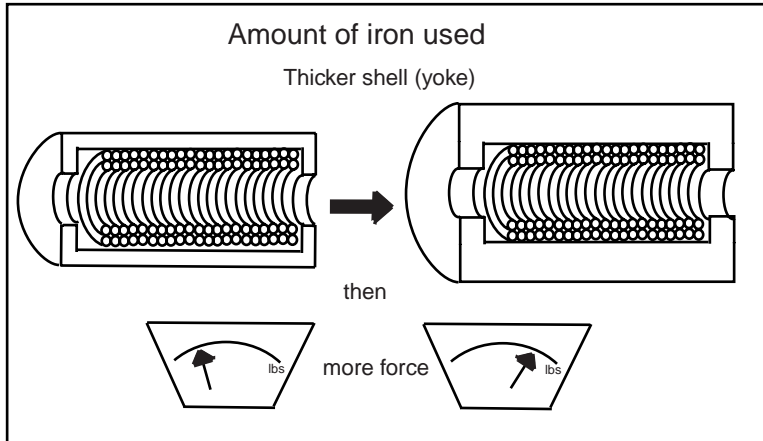
Amount of Current

Recall from the previous chapter that the magnetic field strength is dependant on the magneto-motive force (ampere-turns). Therefore, increasing the current, also increases the magneto-motive force. This in turn increases the magnetic field strength or the attraction between the armature and the pole piece.

Number of Turns

Again, as with the increase in current, increasing the number of turns increases the magneto-motive force.





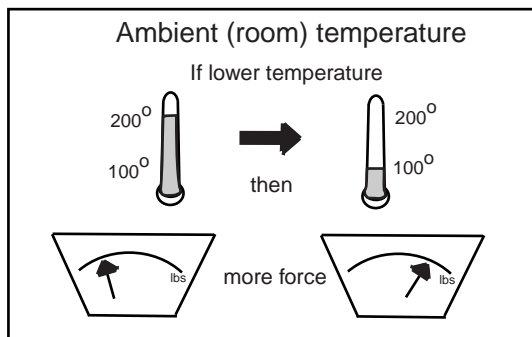
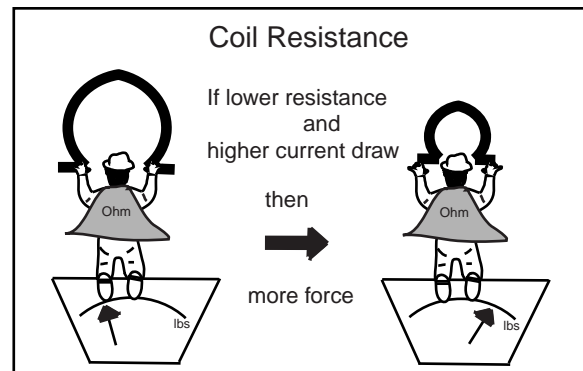
Amount of Iron

The amount of iron in the yoke affects the strength of the magnetic field. The frame is in the coil to concentrate the magnetic field. If it is too thin, the iron becomes saturated (all domains aligned) at a current level which is too low.

Resistance

Recall Ohms law $V = IR$. If resistance decreases while the voltage remains constant, the current will increase.

An increase in current results in an increase in nI (ampturns), which increases field strength.



Temperature

As the ambient (room) temperature increases so does the resistance of the coil.

The change in the resistance of copper due to the change in temperature can be determined by using the following equation:

$$R_F = R_{20} (1 + 0.00393 (T_F - 20))$$

R_{20} = the resistance of the coil winding at 20° C

20 = 20° C

0.00393 = a physical constant of copper representing the change in resistance due to change in temperature

T_F = the operating (ambient) temperature

R_F = the resistance at the operating (ambient) temperature

Example

What is the resistance of a coil that is 9.8Ω at 20°C , if it is used outside when the temperature is 95°F ?

The conversion for $^\circ \text{F}$ to $^\circ \text{C}$ is:

$$\begin{aligned} ^\circ \text{F} - 32 / 1.8 &= ^\circ \text{C} \\ 95 - 32 / 1.8 &= 35 ^\circ \text{C} \end{aligned}$$

Calculate the new resistance:

$$\begin{aligned} R_F &= R_{20} (1 + 0.00393 (T_F - 20)) \\ R_F &= 9.8 (1 + 0.00393 (35 - 20)) \\ R_F &= 10.4 \Omega \end{aligned}$$

Each of the parameters listed can increase the magnetic force. Therefore, it appears that it is easy to develop any level of force desired for an application. This however is not the case.

If, for example, we wanted to increase the force, but were restricted by the size of the coil, would the solution be to increase the number of turns? Recall that the magnetic force is proportional to the number of turns times the current. At the same time, increasing the number of turns increases the resistance. If the voltage remains constant, by Ohm's Law, the current drops. Therefore, increasing the turns does not necessarily increase the force.

The next parameter involves the thickness of the frame. Does increasing its thickness increase the magnetic force? The answer is, not necessarily. If there is not enough magnetic field created by the solenoid, then the domains will not align, regardless of the thickness of the frame. The added material and cost are therefore wasted.

Lowering the resistance to increase the magnetic force also has problems. If the resistance is lowered by removing turns of wire, then although there is more current, the magnetic force may not increase. This is because the magnetic field strength is a product of both turns and current. It is possible to maintain the number of turns and lower the resistance by using thicker wire. However, this solution may have a problem. The increase in current results in an increase in power or energy (recall $P = IV$). The energy is dissipated in the form of heat. As the current flows through the wire, it heats up. When the coil gets hot, the resistance increases. Increasing the resistance decreases the current, as does the magnetic force.

Each of the scenarios described indicates that there are many solutions and many right and wrong answers. Good solenoid design requires a balance between these factors.

Summary

In this chapter the following concepts were presented:

- The parts of the Electromagnetic Actuator were listed and discussed.
- We learned about the two styles of armatures, the pancake and tubular.
- The three variations on the tubular shape were presented; flat, conical and proportional.
- A discussion on force versus the air gap showed when to use the flat, conical and proportional shapes.
- The various parameters which affect solenoid force were presented along with what happens when the parameters are varied.
- The method to calculate the resistance of a coil when there is a change in temperature was displayed.

Review Questions

Use the following review questions as a measure of your understanding of the chapter material. Answers are provided in the appendix.

1. Name the parts of a solenoid electromagnetic actuator. _____
2. Why would a flat face armature be used? _____
3. What factors determine the shape or level of force for Force vs Air gap curve? _____
4. If the domains in the shell are all aligned (material is magnetically saturated) and there is excess magneto-motive force, will increasing the shell thickness increase the force? _____
5. What does increasing the current do for the magneto-motive force? _____
6. If it is 20° F outside, what is the current draw for a coil that is 7.2 Ω at 20° C? _____
7. How can lower resistance increase the magnetic force? _____
8. If the force applied to the push pin opposing the movement of the armature was constant, what type of armature could be used against this force. _____
9. Which style of tubular actuator is the most expensive? Why? _____ / _____
10. Which style of tubular actuator is the least expensive? Why? _____ / _____
11. What would happen if the force applied to the push pin holding the armature in place were suddenly removed? Why? _____ / _____

Notes