3
CHAPTER
Motors

There is one basic idea that is the key to understanding the electrical behavior of motors:

When a motor is operating as a motor, it is also acting a bit like a generator.

Just what does this mean? When a motor is running, there will be an **internally generated** voltage E_A in the armature that is caused by the coils of the armature moving within the motor's magnetic field. This internally generated voltage should not be confused with the external voltage that is applied to the armature. (See Fig. 3-1.) The voltage E_A is a function of the magnetic flux ϕ in the motor and the speed ω of the rotor:

$$E_A = k\phi\omega \tag{3-1}$$

where k is a constant based on details of the motor's construction. In a motor, the polarity of E_A will always oppose the externally applied voltage so the KVL equation for the armature circuit is written as:

$$V_T = E_A + I_A R_A \tag{3-2}$$

where

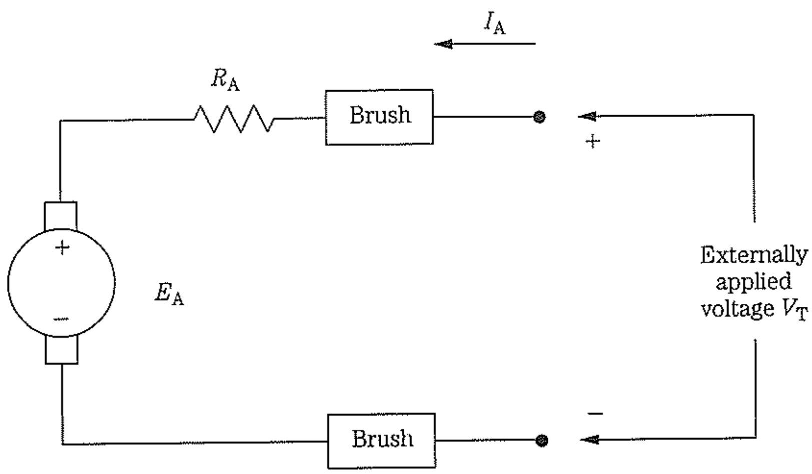
V_T = voltage applied to external terminals
I_A = armature current
R_A = armature resistance

Contrast this with the case of dc generators in which the polarity of E_A will agree with the externally applied voltage and for which the KVL equation for the armature circuit is written as:

$$V_T = I_A R_A - E_A$$

The armature current determines the amount of torque τ_{ind} induced upon the rotor:

$$\tau_{\text{ind}} = k\phi I_A \tag{3-3}$$

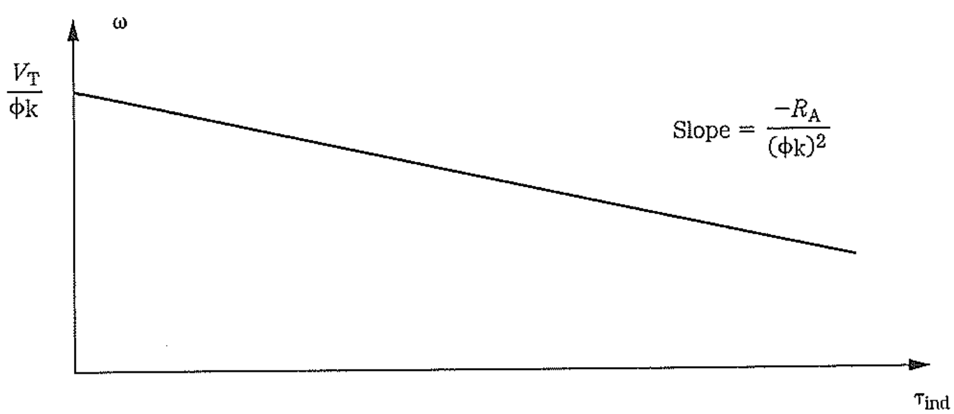


3-1 Equivalent circuit for KVL analysis of a motor's armature circuit.

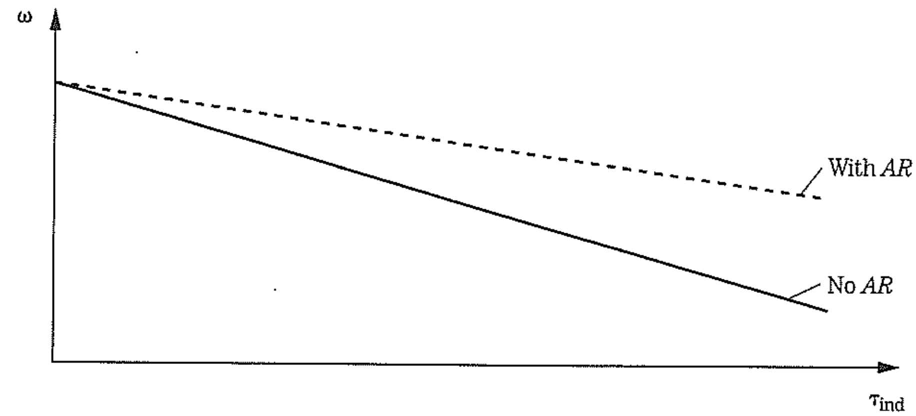
We can combine Eqs. 3-1, 3-2, and 3-3 to obtain:

$$\omega = \frac{V_T}{\phi k} - \frac{R_A}{(\phi k)^2}\,\tau_{ind} \tag{3-4}$$

Based on Eq. 3-4, the speed versus torque characteristic is a straight line (as shown in Fig. 3-2) having a vertical intercept of $V_T/(\phi k)$ and a slope of $-R_A/(\phi k)^2$. Equation 3-4 is somewhat of an idealization. In the real world, many motors will exhibit a phenomenon called *armature reaction* that tends to weaken the motor flux as the load increases. This armature reaction will cause the speed versus torque characteristic to curve upward as shown in Fig. 3-3. This effect is less pronounced in permanent magnet motors than it is in wound-field motors.

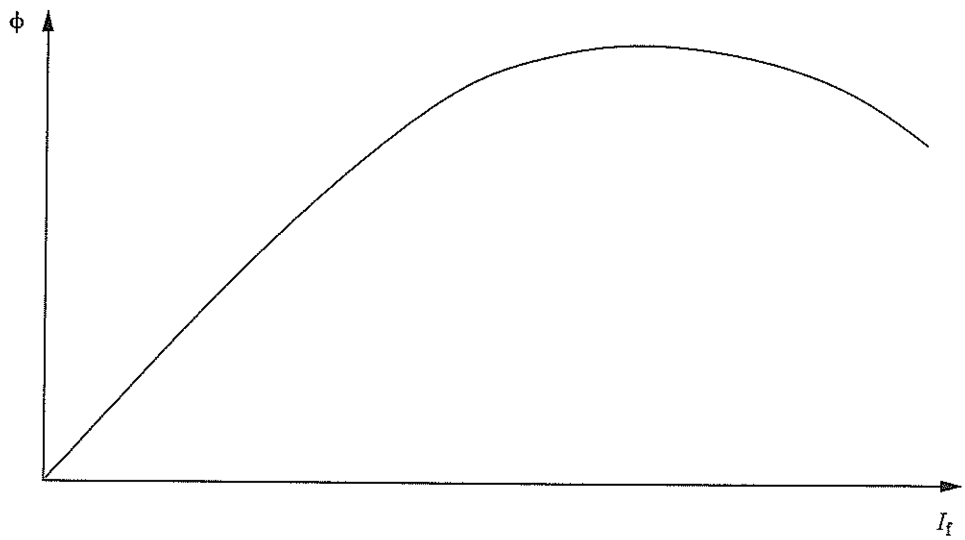


3-2 Idealized speed-versus-torque characteristic for a dc motor.



3-3 Speed-versus-torque characteristic for a dc motor.

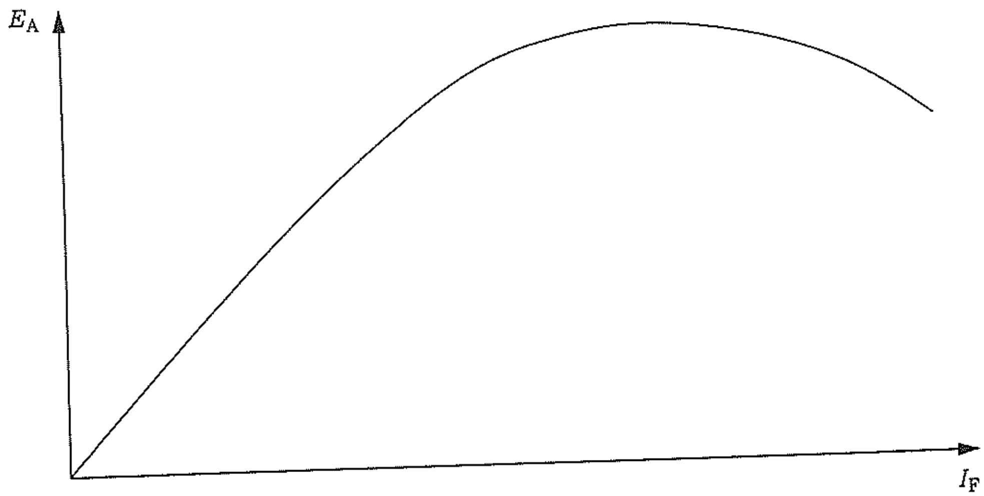
Magnetic flux is one of the parameters used to characterize a motor's behavior. In a wound-field motor, the flux is a function of the field current I_F as shown in Fig. 3-4. As stated in Eq. 3-1, the internally generated armature voltage E_A is a function of the magnetic flux ϕ and speed ω. Instead of the plot of ϕ versus I_F shown in Fig. 3-4, it is customary to present the magnetization curve as shown in Fig. 3-5 that plots E_A versus I_F for some specified constant speed ω_0.



3-4 Flux as a function of field current for a typical motor.

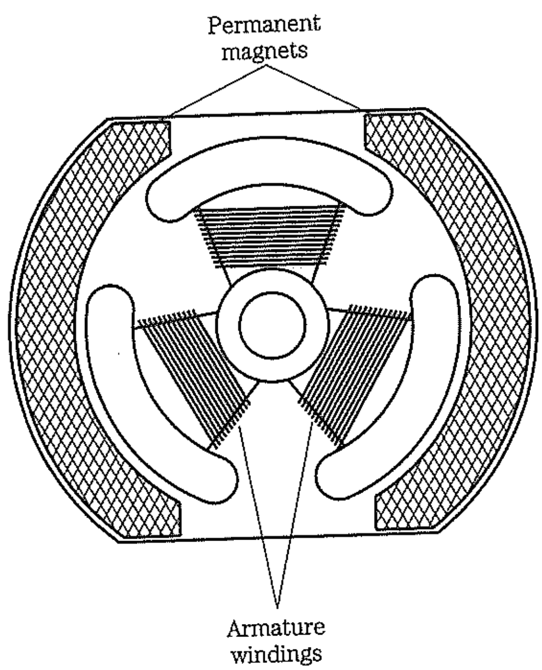
Permanent-magnet dc motors

Permanent-magnet motors are so named because they use permanent magnets instead of field windings to create the field flux for the motor. Toys and other inexpensive items often contain permanent-magnet dc motors. Therefore, this type of



3-5 Magnetization curve for a typical motor.

motor is one of the easiest for experimenters to obtain. An end-on view of a typical permanent-magnet motor is shown in Fig. 3-6. The *stator* consists of permanent magnets that provide a constant magnetic field. Current is passed to the *armature windings* via *brushes* and *commutator segments*. Connections between the windings and the commutator segments are arranged so as to change the polarity of the armature at the appropriate times for continuous rotation of the armature.



3-6
Internal end-on view of a permanent-magnet dc motor.

Electrical properties

The equivalent circuit of a permanent-magnet dc motor is shown in Fig. 3-1. As discussed earlier in this chapter, if the voltage drop across the brushes is neglected, the equations that govern the motor's behavior are:

$$E_A = k\phi\omega \tag{3-5}$$

$$V_T = E_A + I_A R_A \tag{3-6}$$

$$\tau_{\text{ind}} = k\phi I_A \tag{3-7}$$

where

E_A = internally generated armature voltage
k = a constant based on details of the motor's construction
ϕ = magnetic flux
ω = rotational speed of the motor
V_T = voltage applied to the motor's external terminals
I_A = armature current
R_A = armature resistance
τ_{ind} = induced torque

Equations 3-5, 3-6, and 3-7 can be combined to yield the speed versus torque relationship:

$$\omega = \frac{V_T}{\phi_k} - \frac{R_A}{(\phi k)^2}\,\tau_{\text{ind}} \tag{3-8}$$

As shown in Fig. 3-2, Eq. 3-8 is the equation of a straight line having a vertical intercept of $V_T/(\phi k)$ and a slope of $-R_A/(\phi k)^2$.

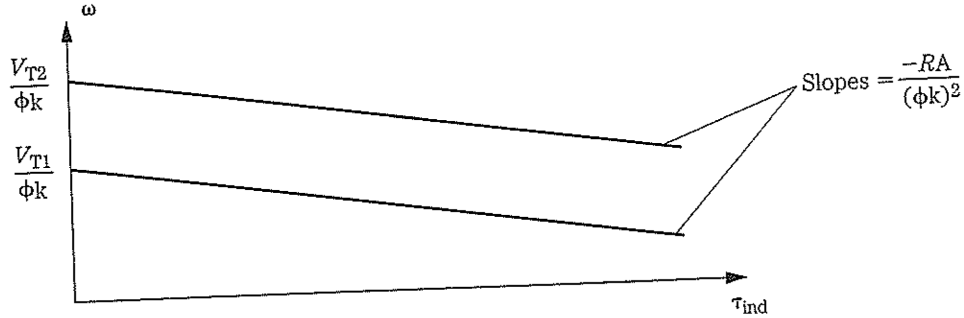
Of all the parameters listed above, the applied voltage V_T is the only one over which we can exercise direct control. What can we say about the motor's reaction to a change in armature voltage? If V_T is **increased**, the following behavior will be observed:

- Based on Eq. 3-6, an increase in V_T will cause I_A to increase.
- Based on Eq. 3-7, an increase in I_A will cause an increase in the induced torque τ_{ind}.
- When τ_{ind} increases above τ_{load}, the motor will increase its speed ω.
- Based on Eq. 3-5, an increase in ω will cause the internally generated voltage E_A to increase.
- Based on Eq. 3-6, increasing E_A causes the armature current I_A to decrease.
- The current I_A will continue decreasing, causing τ_{ind} to decrease until $\tau_{\text{ind}} = \tau_{\text{load}}$, thus causing the speed to stop increasing.

Another way to look at the impact of increasing V_T involves the speed versus torque relationship given by Eq. 3-8. As shown in Fig. 3-7, an increase in V_T causes the vertical intercept (no-load speed) to increase, while keeping the slope constant.

Reaction to changes in load

How will a permanent-magnet motor react to changes in mechanical load? If the applied load increases while the terminal voltage V_T is held constant, the following behavior will be observed:



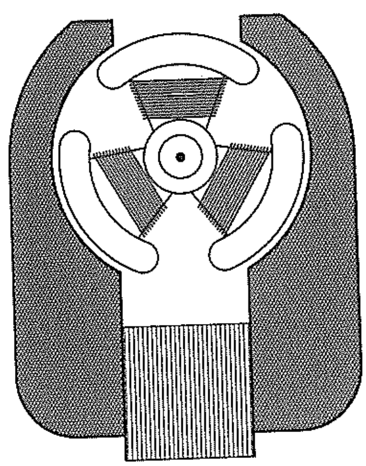
3-7 Speed-versus-torque characteristics of a permanent-magnet motor for two different loads.

- Because $\tau_{load} > \tau_{ind}$, the motor will begin to slow down. Based on Eq. 3-5, a decrease in speed ω will cause a decrease in the internally generated voltage E_A.
- Based on Eq. 3-5, a decrease in E_A will cause an increase in the armature current I_A.
- Based on Eq. 3-7, this increase in I_A will cause an increase in the induced torque τ_{ind}. The increase in τ_{ind} will exactly balance the increase in load, but the motor will be operating at a lower speed and drawing increased current.

This behavior is consistent with Eq. 3-8, and the speed versus torque characteristics shown in Figs. 3-2 and 3-7. If they are used in applications requiring anything beyond simple relative speed control, permanent-magnet motors will need fairly sophisticated control circuitry to maintain constant or fixed speeds over a range of load torque.

Separately excited dc motors

A separately excited dc motor can be thought of as a generalized permanent-magnet motor in which a *stator* and *field coil* are used instead of permanent magnets for providing the field flux. An end-on view of a typical wound-field motor is shown in Fig. 3-8.



3-8
Internal end-on view of wound-field motor.

Electrical properties

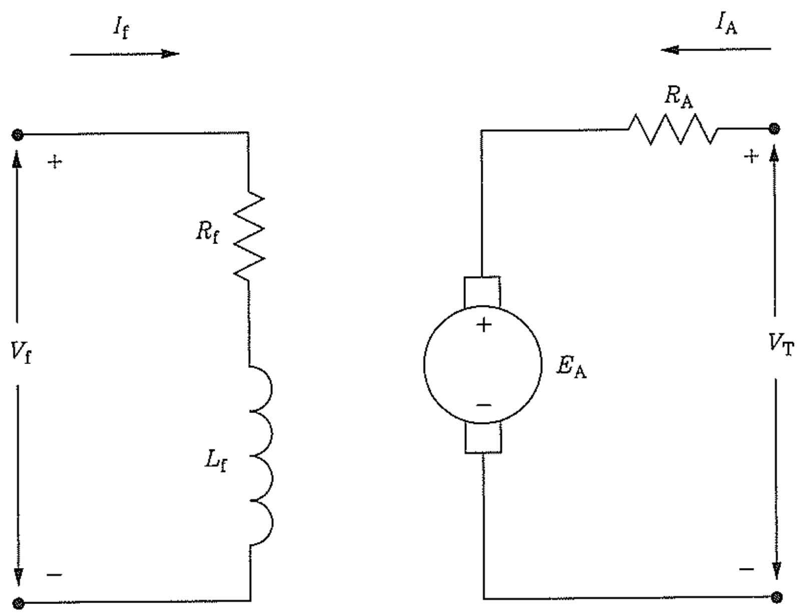
The equivalent circuit of a separately excited dc motor is shown in Fig. 3-9. The equations governing the motor's behavior are similar to the equations for a permanent-magnet motor.

$$E_A = k\phi\omega \tag{3-9}$$

$$V_T = E_A + I_A R_A \tag{3-10}$$

$$\tau_{ind} = k\phi I_A \tag{3-11}$$

$$\omega = \frac{V_T}{\phi_k} - \frac{R_A}{(\phi k)^2}\tau_{ind} \tag{3-12}$$



3-9 Equivalent circuit for a separately-excited dc motor.

The major difference is that instead of being constant as it is in permanent-magnet motors, the field flux ϕ is given by:

$$\phi = \frac{\mu NA}{L_C} I_F \tag{3-13}$$

where

μ = permeability of the core material
N = number of turns in the field winding
A = cross sectional area of the core
L_C = mean path length of the magnetic field
I_F = current through the field windings

Actually, for our purposes, μ, N, A, and L_C can be lumped into a single constant to yield:

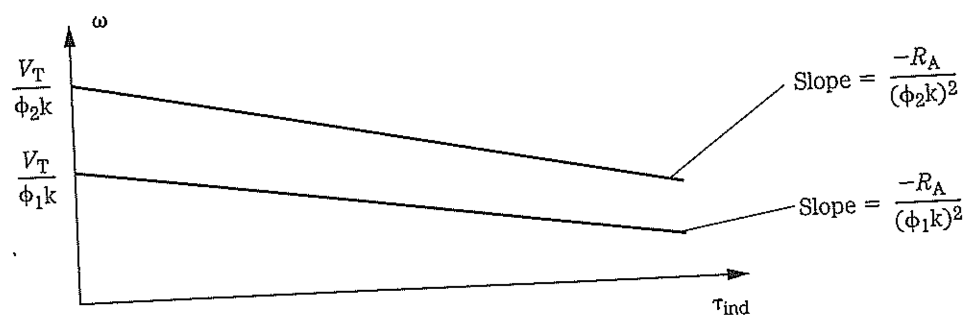
$$\phi = K_F I_F \tag{3-14}$$

This equation indicates that the flux within a wound-field motor is proportional to the field current. A decrease in I_F causes a proportional decrease in ϕ.

For an increase in V_T, the behavior of a separately excited motor will be the same as the corresponding behavior of a permanent-magnet motor. Unlike a permanent-magnet motor, a separately excited motor can have its flux changed by a change in field current. If ϕ is **decreased,** the following behavior will be observed:

- Based on Eq. 3-9, a decrease in ϕ will cause a decrease in the internally generated voltage E_A.
- Based on Eq. 3-10, a decrease in E_A will cause an increase in armature current I_A.
- Based on Eq. 3-11, an increase in I_A will tend to cause an **increase** in the induced torque τ_{ind}. However, the original decrease in ϕ will tend to cause a **decrease** in τ_{ind}. Which way will τ_{ind} change? In most practical situations, the increase in I_A will be many times larger than the decrease in ϕ, so τ_{ind} will increase.
- As the increase in τ_{ind} makes $\tau_{ind} > \tau_{load}$, the motor will increase its speed ω.
- Based on Eq. 3-9, an increase in ω causes E_A to increase.
- Based on Eq. 3-10, the increase in E_A will cause I_A to decrease.
- The armature current I_A decreases until $\tau_{ind} = \tau_{load}$, and the motor continues to operate at the new increased speed.

Another way to look at the impact of decreasing ϕ involves the speed-versus-torque characteristic given by Eq. 3-12. A decrease in ϕ causes the vertical intercept (no-load speed) to increase, and the slope becomes steeper as shown in Fig. 3-10.

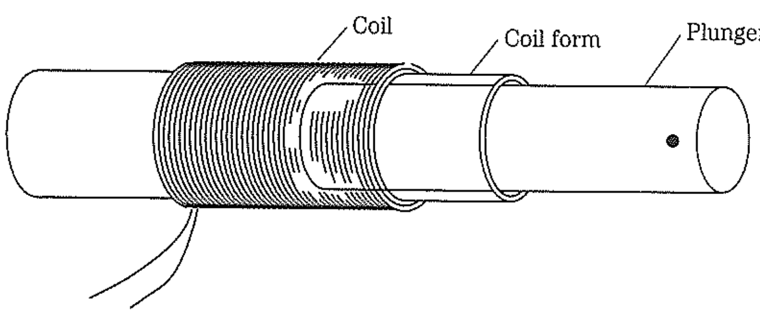


3-10 Speed-versus-torque characteristics of a separately excited dc motor for two different values of field flux.

6
CHAPTER

Solenoids

Strictly speaking, a *solenoid* is any helical winding of wire. Within the context of electromechanical devices, the term is more often used to identify a coil and plunger arrangement such as the one shown in Fig. 6-1. When the coil is energized, the plunger will be pulled toward the center of the coil. If everything is designed just right, there will be a significant amount of force available for this pull, and loads attached to the plunger can be moved along with the plunger. Often a spring will be used to return the plunger to its original position when the coil is de-energized. The distance moved by the plunger is called the *stroke* of the solenoid.



6-1 A simple solenoid.

Homemade solenoids

The precise design of a solenoid can be a very complicated problem, even for professional engineers. However, the design and construction of homebrew solenoids is ideally served by the methodology of "design a little, build a little, test a little, and tweak as necessary."

Design parameters

There are quite a few design parameters associated with a simple solenoid. Some of these include:

- number of turns in the coil
- gauge of the wire used in the coil
- dimensions of the coil
- dimensions of the plunger
- stroke length
- available force
- magnetic properties of the shell and plunger
- voltage across the coil
- current through the coil

As we might expect, many of these parameters are interrelated and an improvement in one parameter may come at the cost of a degradation in another parameter. The homebrew design process is not completely random; there are some guidelines and practical rules-of-thumb.

Coil turns

The force exerted by either a solenoid or an iron core electromagnet is approximately proportional to the square of the number of turns:

$$F \propto N^2$$

In other words, doubling the number of turns in the coil will approximately quadruple the available force. This of course assumes that the current remains constant. However, doubling the number of turns will approximately double the resistance of the coil and therefore halve the current, providing that nothing else is changed. The current can be held constant by either doubling the applied voltage or using a larger gauge wire to halve the resistance of the doubled coil. Everything comes at a price; increasing the voltage may lead to excessive heating in the coil.

Wire gauge

Small diameter wire allows more turns to be placed on a given core, but smaller diameter wire will have a higher resistance than larger diameter wire. Any homebrew design should definitely use enamel-insulated magnet wire of some gauge, rather than plastic-insulated bell wire or hookup wire. The thickness of the plastic insulation will make it difficult to get lots of turns packed into a small volume around the core.

Current

The force exerted by either a solenoid or an iron core electromagnet is approximately proportional to the square of the current through the coil:

$$F \propto I^2$$

In other words, doubling the current will approximately quadruple the available force.

Physical dimensions

The stroke length of a solenoid depends upon the dimensions of the coil and plunger. Generally, longer plungers are capable of longer strokes. (When speaking of plunger length, we are only considering the length of the cylinder of magnetic material. The linkage that connects the plunger to the load is nonmagnetic and is not part of the plunger.) Consider the following:

- Once the plunger is completely inside the coil, the magnetic forces acting on the plunger are too weak to cause further movement of the plunger deeper into the coil. Therefore, it makes no sense to have a coil that is longer than the plunger.
- If the plunger is longer than the coil, the forces will tend to center the plunger in the coil (i.e., leave approximately equal lengths of plunger sticking out of both ends of the coil). In many designs, stops are included to prevent the leading end of the plunger from going past the end of the coil. (The leading end is the end that lies just inside the coil when de-energized, and which is the "forward" end relative to the direction of motion as the plunger moves in response to the coil becoming energized.) Just how "centered" the plunger will be depends upon the weight of the plunger and the force of the load attached to the trailing end of the plunger. Theoretically, an unloaded plunger with zero mass should center exactly. However, plungers have nonzero mass. Even when unloaded, plungers that are several times longer than their coils tend to stop moving a good bit before center.
- In the de-energized "at rest" position a part of the plunger must lie inside the coil. If the plunger is completely outside the coil, the coil will not generate sufficient magnetic force to pull in the plunger.

Figure 6-2 shows the relationships between the various dimensions and plunger positions. For the "ideal" limiting case, the stroke length L_S would be given by:

$$L_S = \frac{L_C + L_P}{2} \tag{6-1}$$

where

L_C = coil length
L_P = plunger length

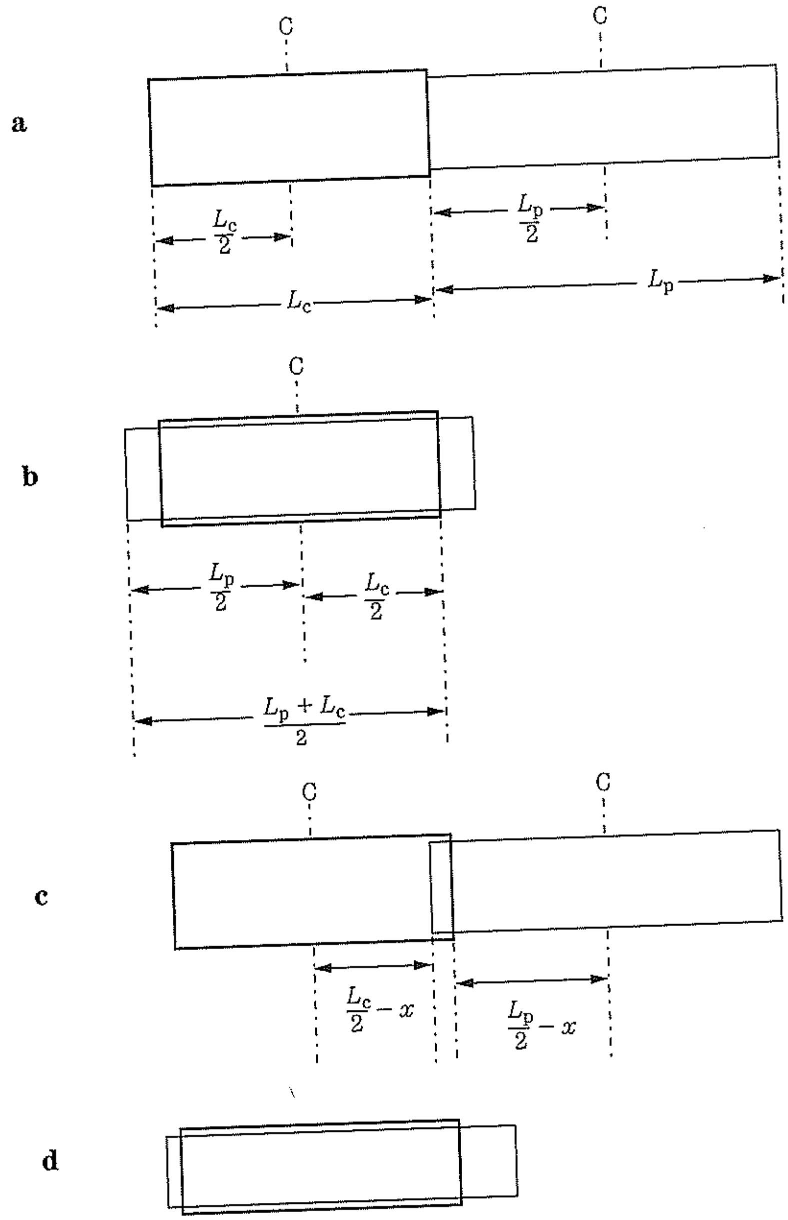
In all practical cases, the stroke length will always be shorter than the value given by Eq. 6-1. The sensible way to approach this would be to analyze the intended application to determine the **required** stroke length L_R, and then select the coil length L_C and plunger length L_P so that they satisfy:

$$\frac{L_C + L_P}{2} > K_1 L_R$$

and

$$L_P > K_2 L_C$$

where K_1 and K_2 are "fudge factors" that vary between 1.2 and 1.5. For smaller solenoids, values near 1.2 are fine. For larger solenoids, values closer to 1.5 should be

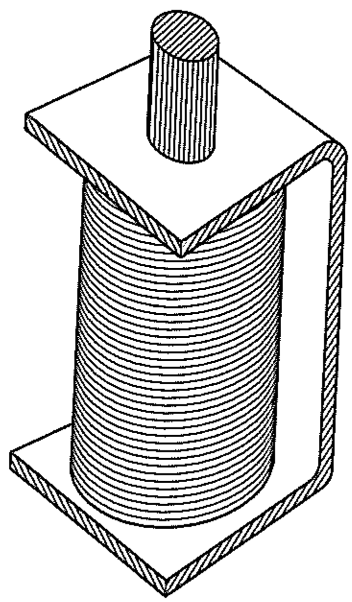


6-2 Plunger positions: (a) "ideal" de-energized position, (b) "ideal" energized position, (c) practical de-energized position, (d) practical energized position.

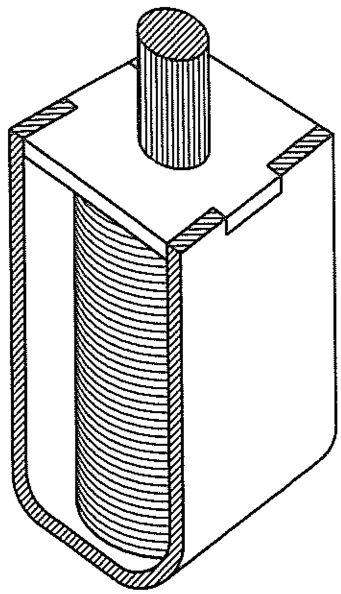
used. If in doubt, use a larger value because this will result in a longer realized stroke length. If the stroke length winds up being too long, the motion will just hit the stops a little bit harder (there should **always** be stops). If the stroke length winds up being too short, you will have to start over and build a new solenoid.

Shells

For every homebrew solenoid that I have ever made, the coils have been wound on some sort of nonmetallic core form—usually a length of small diameter plastic tube. The plungers have been pieces of steel rod stock. The most powerful commercially produced solenoids have their coils enclosed in a ferrous alloy shell which provides a low reluctance path for the coil's magnetic flux. There is a compromise design that lies between a shell-less homebrew solenoid and a commercial solenoid with a full shell. This design is called an *open frame* solenoid. An open frame solenoid will produce more force than a comparably sized shell-less solenoid and less force than a comparably sized solenoid with a full shell. There are two major variations of the basic open frame design: the C frame style shown in Fig. 6-3 and the D frame style shown in Fig. 6-4. Commercial designs achieve slightly higher forces with the D style, but for homebrew designs, the extra performance is probably not worth the increased complexity. Homebrew solenoid frames can be easily fabricated from the steel angle brackets sold in hardware stores.



6-3
An open frame solenoid with a C style frame.



6-4
An open frame solenoid with a D style frame.