Design & build your own solenoid

Basic Electronics

While most readers probably understand the general concept of a solenoid, few people have ever bothered to acquaint themselves with the theory or attempted to build their own. This article gives you some of the theory and shows you how to build a practical solenoid.

by JEFF SKEEN

The shape of the magnetic field surrounding a bar magnet is probably familiar to most people. A demonstration of the shape of this field using iron filings and a cardboard sheet seems to be a standard feature of science courses in secondary schools. Often the demonstration is extended slightly to show that a long coil of wire with DC current passing through it shares the same shape of field as the bar magnet.

This coil of wire is called a solenoid, which is defined by the Chambers Dictionary of Science and Technology as: "A current-carrying coil, of one or more layers. Usually a spiral of closely wound insulating wire, in the form of a cylinder, not necessarily circular. Generally used in conjunction with an iron core, which is pulled into the cylinder by the magnetic field set up when current is passed through the coil."

The third sentence of the definition concerns us the most for this is the form our solenoid will take. We use the magnetic field of the solenoid to perform work on a steel rod which in turn either operates or is part of the mechanism of a simple machine. To understand how the solenoid can move the rod and how much force the rod will apply to an external device, we require a knowledge of the basics of electromagnetism.

When dealing with electromagnetism, it is fairly common to use an analogy with electric circuits to help understanding. Since the concepts of voltage, current and resistance are familiar and easy to understand, similar concepts are used for magnetic "circuits". In magnetics, the driving force or "voltage" which creates the magnetic field is a function of the electrical current and the number of turns of wire. It is called the mmf (magnetomotive force) and given the units, ampere-turns.

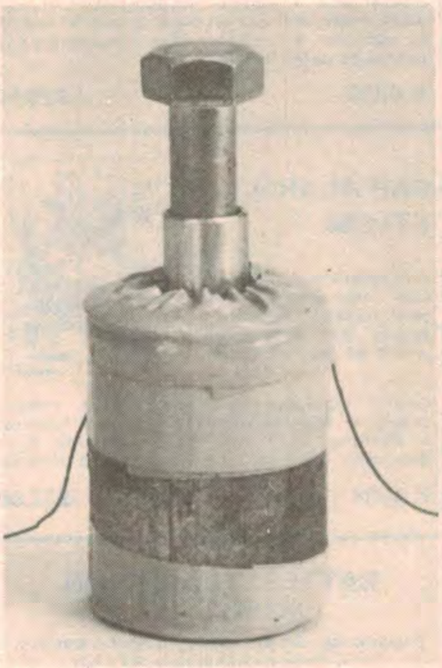
Similarly, current in a magnetic circuit is called flux (measured in webers) and magnetic resistance is called reluctance (measured in Henrys^{-1}). These terms can be be put together to form a sort of magnetic equivalent of Ohms Law.

Therefore, just as we write emf = current x resistance for the electric circuit, we can write mmf = flux x reluctance for the magnetic circuit.

The reluctance *(R)* of the magnetic circuit is calculated in terms of its magnetic length, area and conductivity (ℓ_m, A_m and $\mu_o\,\mu_r$ respectively). Thus:

$$R = \ell_m / A_m \mu_o \mu_r$$

(strictly speaking, $\mu_o \mu_r$ is termed magnetic permeability rather than magnetic conductivity). μ_o is a constant called the permeability of free space and has the value $4\pi \times 10^{-7}$ H/m. μ_r is the permeability of the materials through which the flux is flowing.



Most of the parts will be available from the garage junkbox.

Usually μ_r has a value around 1, the exception being the ferromagnetic class of materials such as iron, nickel, etc (and their alloys) which can have μ_r values approaching 1×10^6. Since μ_r is a conductivity measurement, a high value indicates that the material presents very little resistance to the passage of flux and is therefore a good magnetic conductor.

Iron transformer laminations and other iron pieces do not have μ_r values this high, a typical value being closer to 1000. This means that air, with a μ_r value of 1, forms a poor magnetic insulator around the iron and flux leakage through the air can be significant. This can prevent a simple analysis of the magnetic circuit since it is usually very difficult to determine the precise value of the leakage flux without first building and measuring the circuit!

Usually some assumptions about leakage flux and other uncertain parameters are made during the initial calculations and these values are subsequently corrected in later calculations as more data comes to hand.

To start our analysis of a solenoid we begin with the simplest case, that of a single loop of wire suspended in air. Since air has a μ_r which equals one the term $\mu_o\mu_r$ can be simplified to just μ_o. The magnetic field strength (H) along the axis of the wire loop can be determined using calculus, and is equal to $I/2r$, where I is the current in the wire and r is the radius of the loop.

If we cascade the wire loop to form a long air-cored solenoid, the formula for the magnetic field strength becomes, $H = NI/\ell$, where N is the number of turns in the solenoid, I is the current passing through the turns and ℓ is the length of the solenoid.

Since the amount of magnetic pull we can create with the solenoid is related to the field strength, the above formula tells us how we should wind the coil. The length term in the denominator should be made as small as possible in order that the field in the centre of the coil be as large as possible. This indicates that a short fat coil will produce more field strength than a long skinny coil.

The disadvantages of a short, fat coil are that it will only exert a strong force over a short distance, and that the outer turns use proportionally more wire per turn than do the turns on a thinner coil. On the other hand, the long solenoid while acting over a greater distance, will produce less pull and may need more turns to compensate for this.

The trick then, is to balance the coil dimensions and produce a coil with enough pull over the required distance while using the least wire.

By now some readers will be saying "why not encase the coil in an iron jacket so that the flux does not have to pass through the high reluctance of the air?" This is precisely what we do as our next trick for increasing the field strength. The net increase in field strength, however, is not as strong as we might first expect due to the behaviour of the field when outside the solenoid.

As the flux emerges from the centre of the solenoid it spreads out (in theory to infinity) into the surrounding air. Although air has a high reluctance, the flux is travelling through such a large area that the effective reluctance becomes quite low. The electrical anology of this is with wire, where a large cross sectional area will have less resistance than a small cross sectional area of the same wire. The use of an iron jacket therefore, does not produce the large decrease in reluctance (with attendant increase in field strength) one would first suppose.

PARTS LIST

1 100g spool of .5mm enamelled wire
1 15cm length of 12mm aluminium tubing
1 steel bolt, 70mm long, 9mm diameter
1 threaded female waterpipe coupling, 40 x 25mm
1 piece of galvanised iron sheet, 100 x 100mm

The use of a jacket does however produce a neat unit which can be clamped into position with "U" brackets. This allows the solenoid to be used for projects such as electronic locks where the ability to mount the lock securely on or in a wall is a must.

The end cheeks of the coil are used to prevent the wire from unravelling and to provide a low reluctance path for the flux, away from the bottleneck of the solenoid core. In addition, the solid end-cheek forms a magnet which locks the metal bolt into position when the power is applied.

By making a few assumptions about the magnetic flux path around the

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solenoid, an estimate can be made of the pull required to separate the bolt from the bottom end cheek. The assumptions are: that all the flux flows through the iron and none through the surrounding air, that there are no airgaps between iron pieces, that the μ_r (permeability) of the iron is 1000 and that none of the iron pieces carry so much flux that they saturate.

The assumptions are of course incorrect, but they do give us a maximum value of force which we could achieve with our present setup if conditions were ideal.

Using the following data from our prototype solenoid:

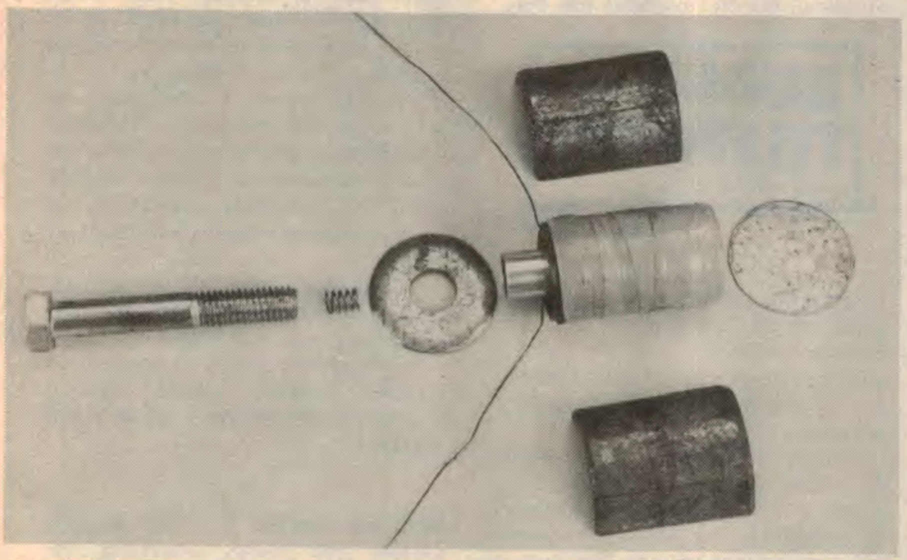
Number of turns, N; 1000
Magnetic path length, l_m; 11cm
Current, I; 2A
Cross sectional area of bolt, A; $6.36 \times 10^{-5} m^2$

the magnetic field strength (H) was calculated to be:

$$\begin{aligned} H &= NI/\ell_m \\ &= (1000)(2)/(0.11) \\ &= 1.82 \times 10^4 \text{ A/m} \end{aligned}$$

From this the force (F) holding the bolt to the end cheek is:

$$\begin{aligned} F &= H^2 A\, \mu_o \mu_r / 2 \\ &= (1.82 \times 10^4)^2 (4.5 \times 10^{-3})^2 \pi\, (4\pi \times 10^{-7})\, (1000)/(2) \\ &= 13.21 \text{ Newtons} \end{aligned}$$



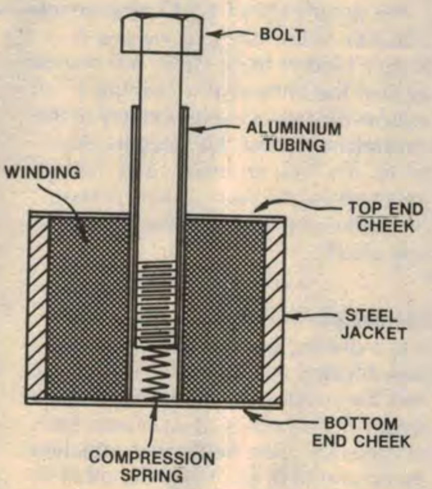
This view shows the various parts of the solenoid prior to assembly.

In the old Imperial system this is equivalent to a force of 3lb. In practice we could suspend just on 2kg (about 4.5lb in the old units) with our prototype.

If a compression spring is included between the bolt and the end cheek, there will be less force developed due to the high reluctance of the airgap around the spring. The best spring to use is one which will compress very flat, resulting in the least gap between the end of the bolt and the end cheek.

The solenoid has been designed to work with a 12V power supply capable of delivering 2A. If no supply is available, a 12V car battery will suffice. Lower voltages can be used, however the force developed on the bolt will be correspondingly less.

The coil is wound around a piece of 12mm (outside diameter) aluminium tubing. This tubing was selected since it provides a reasonable fit for a 9mm bolt. There is no reason why other diameters of tubing cannot be used provided they are made from a non-ferrous material. It is not advisable to use plastic tubing since the heat generated in the solenoid may melt the plastic if the solenoid is operated for longer than a few seconds.



The assembly details are shown in this cross-section diagram.

The outer jacket of the solenoid was constructed from a threaded female coupling normally used to connect two pieces of water pipe together. The coupling is made of galvanised steel with a length of 40mm and an inside diameter of 25mm.

The end cheeks of the solenoid are produced by cutting out three circular discs from a sheet of flat 24G galvanised iron with a pair of tinsnips. The discs should have a diameter equal to the outside diameter of the solenoid jacket. Two end cheeks should have a 12mm hole drilled through their centres to enable them to be slid over the aluminium tubing.

The two end cheeks with holes in them are now slid over the aluminium tubing and held 40mm apart by building up the diameter of the aluminium tubing on the outside of the cheeks with electrician's tape. The wire can now be wound onto the aluminium tubing between the end cheeks. If wound neatly it is possible to fit almost an entire 100g spool of 0.5mm wire into the solenoid jacket.

The easiest way to wind the wire is to place the aluminium tube in the chuck of a hand drill and then place the body of the drill in a vice. One hand can now be used to turn the drill while the other guides the wire. The high gear ratio of the drill will also make winding the wire much quicker. The wire should be built up until its diameter is just less than the inside diameter of the solenoid jacket. A layer of electrician's tape is now wound tightly around the wire to prevent it unravelling.

Carefully remove one of the end cheeks and place a piece of tape over the end of the coil to prevent turns falling off. Use a hacksaw to cut off the aluminium tubing flush with this end of the coil. Slide the solenoid jacket into position over the coil, then tape the solid end cheek to the exposed end of the coil. The other end cheek can now be taped to the jacket and the aluminium tube cut to a suitable length.

If a more permanent arrangement is required the end cheeks can be glued to the jacket with epoxy resin adhesive. The wires from the coil can be run out between the end cheeks and the jacket.

The solenoid is not intended to be run continuously for more than about 30 seconds at a time. About 25W is dissipated in the solenoid when it is operated from 12V and the resulting heat is far too much to be radiated from such a small package. This time limit is not really a disadvantage since in most applications, such as the mechanism of an electronic lock, the solenoid is only required to operate for short periods