SOLENOID MAGNETICS

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Overview -

It has been observed by inquiries and discussions online that the interest in solenoid magnetics is alive and well but without a clear concept as how to deal with the non-linearities that are attendant in solving the solenoid model for force output. See article A.5 below for more on this subject.

This article describes the basic physics and mathematical solutions for calculating and predicting the forces generated by an electromagnet to a high degree of accuracy without the aid of finite element analysis (fea) software. This methodology was practiced up through the latter half of the 20th century (and prior) for iron core solenoids due to the absence of fea software. When computers became available to ordinary manufacturing facilities and individuals in the 1980's the burden of relating the magnetic flux density (B) in iron to its magnetization (H), but still without fea software, was greatly reduced as will be presented. Prior to the computer, "solving" was approximate due to the tedious referral to a BH graph or lookup table to obtain H and then making the equation calculations perhaps many times depending upon the skill of the analyst to estimate the next trial flux level to achieve a suitable convergence of the dependent and independent magnetomotive force levels as will be explained.

Background: James Clerk Maxwell's equations as related to electromagnetics, in the mid-1800's, were presented as partial differential equations and were prior to any significant industrial manufacturing of electromagnets. The first U.S. patent for a practical electromagnet solenoid was by I.A. Timmis in 1893.[1] In 1941 Dr. Alan Hazeltine, at Stevens Institute of Technology, commissioned Herbert C. Roters to author a textbook[2] for engineering students there and to simplify Maxwell's mathematical rigors into equivalent algebraic identities. This article uses these guidelines, without the exhaustive detail as found in his text, to provide a straight forward understanding of force calculations. It is sometimes the intensive mathematical focus in later texts that discourages the pursuit of this field of study by otherwise interested persons and entering university students. The approach herein is principally algebraic but iterative in a simple computer routine that captures the accuracy of differential analysis.

Induction and Flux Propagation: Solenoid electromagnets, also classified as work solenoids, have the purpose of producing significant force or work on another object to move it against an opposing force or to accelerate it within a required time period. An iron based core and armature (plunger) greatly increases the force potential otherwise not realized strictly from a copper coil alone and therefore are principal components of a work solenoid. This amplifying effect is due to induction. Induction in iron (and a few other elements)[3] is possible due to the fact that the iron atom (Fig.1)

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1 U.S. patent no. 506,282

2 Electromagnetic Devices by Herbert C. Roters, 1941, published by John Wiley & Sons. References in this article are used by permission of the publisher.

3 The ferromagnetic atoms are elemental iron, cobalt, nickel, gadolinium, and dysprosium. Modern Technical Physics, Beiser, 1966.

has an imbalance of electron spins; specifically the third electron shell has an imbalance of four unpaired electrons which gives the atom a net magnetic moment.[4]

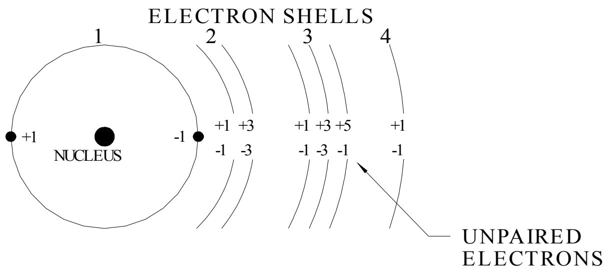


Fig.1 - Unpaired Electrons in the Iron Atom

The iron atoms tend to magnetically self align in series and parallel forming small clusters called domains, however, the domains are randomly aligned relative to each other and thus give the iron a neutral magnetic moment and the iron is said to be demagnetized (at least from the measuring ability of an external observer). That is, until the solenoid coil's magnetic field induces the domains to align according to the coil's polarity and field strength. Individual atoms and domains alone are very weak in magnetic force but when aligned in large numbers the iron's magnetic force greatly exceeds that of the coil alone; i.e., the iron atoms are the dominant magnet. When coil current is removed the domains return to mostly randomness.[5] In a solenoid the magnetic flux thus produced follows the iron path as though longitudinal end to end through the inside diameter of the coil and around thru the case wall forming a continuous loop. Figure 2 represents the cross section of a simple, though common, cylindrical solenoid. Ideally, the iron areas thru the base pole, plunger, and case walls are approximately equal to allow flux to propagate with minimal losses (elsewhere denoted as mmf drops, as will be explained). The main air gap is variable in accord with the design stroke of the solenoid. Here the flux is essentially the same as in the iron path and it is here that magnetic energy is converted to mechanical energy (work) as the air gap closes. In addition, a non-working gap between the end flange and plunger allows freedom of motion. The flux propagates about this loop.

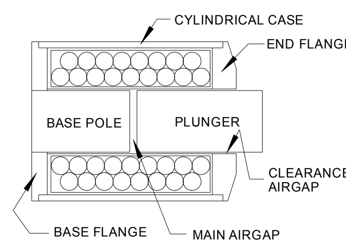
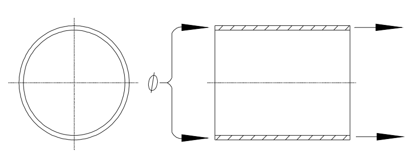


Fig. 2

Magnetic Calculations: For the following discussions the MKS system of units is assumed. Refer to appendix A.1 for symbols used in this article. Suppose a magnetic flux is passed (propagated) uniformly thru the ferrous case tube as shown in Fig. 3. This case tube is representative of that shown in Fig. 2. Let the case dimensions, o.d., i.d., and length, be known as well as the type of steel. The steel area thru which the flux propagates is $A = \frac{\pi}{4}(od^2 - id^2)$. Initially, a current in the coil multiplied by its number of turns, creates an energizing mmf measured in ampere turns given by $\Im = Ni$. The presence of a flux, ϕ , within the steel causes an mmf (magnetomotive force) potential, also given in ampere-turns, across the length of the tube.

Fig. 3 Flux Propagation in Case Tube



4 Encyclopedia Britannica, vol. xiv, Magnetism, p.660. (Other references may differ due to alternative forms of iron.)

5 An incomplete reversion to random domain orientation accounts for residual magnetism, seen as Br on a BH magnetization curve for the steel.

Likewise, each steel component in the solenoid produces an mmf, also termed as a drop, due to the same propagation of flux. In addition, each air gap produces an mmf drop across the gap as flux crosses the gap. At any static plunger position the sum of all mmf drops of the iron and gaps will equal the mmf originating in the coil. This is key for solving the solenoid.

The flux, ϕ (found below), in each of the iron elements and air gaps has a density, B, given by $B = \phi / A$ where ϕ and A are in webers and meters squared (m^2) respectively. For the iron flux density, the type of steel will have a corresponding value, H (in ampere turns per meter of length), from which to compute its mmf drop, $\Im = H\ell$. For the air gaps the mmf drop is computed by $\Im = \phi\ell / (\mu_o A)$ where ℓ is the gap length in meters; A, the area across which the flux crosses, and μ_o is the permeability of space; $4\pi \cdot 10^{-7}$ (weber/amp turn·meter). The numerical value of H is a tested and documented relationship to its value for B and typically appears in the form of a graph or data table. This data relationship can be converted to an algebraic equation (below) for use in a computer calculation.

B and H in Iron: The magnetic permeability of iron is non-linear and is given by $\mu = B / H$ (weber/amp turn·meter). Its non-linear curve is shown here in Fig. 4. (Note that the H axis is logarithmic). Each type of ferromagnetic steel has a unique BH curve and also is dependent upon its hardness and grain structure. For purposes of this article, the steel used in commercial solenoids are typically those with >99% iron such as SAE-1016, 12L14 or 1215.

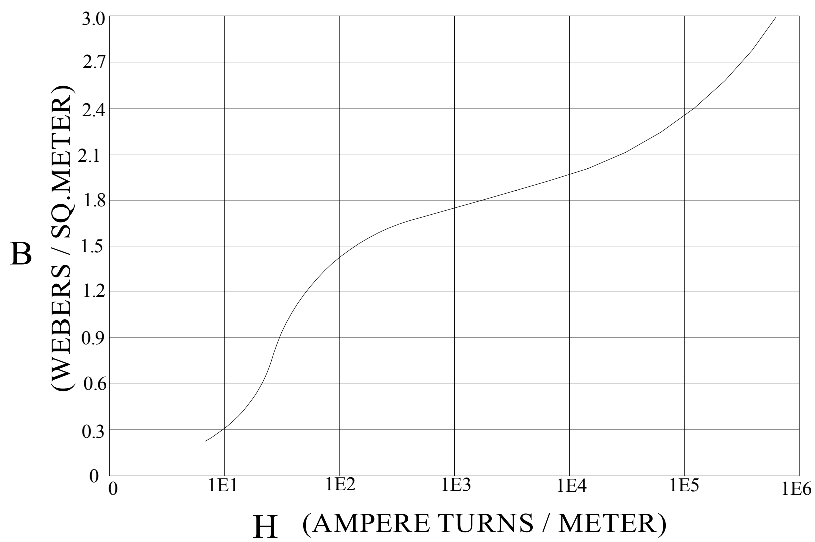


Fig. 4 Typical Ferromagnetic Steel BH Profile

BH graphs and lookup tables of BH data are not expedient for a timely modeling of magnetic circuits as suggested in the overview above. For this exercise a computer routine, having calculated B, will then find H from the equation shown below. Before 1964 and possibly later an equation seems to be non-existant [6].

$$H = a + b * B + c * B^2 + d * B^3 + e * B^4 + f * B^5 + g * B^6$$

where: a =110.529, b = -1700.2762, c = 14226.658, d = -41673.495, e = 57423.444, f = -37223.825, g = 9235.1829.

[6] The Feynman Lectures on Physics, Vol.II, 1964 - p.36-7: "Now all we need is an equation which relates H to B. But there isn't any such equation." p. 36-10: "We still have two unknowns. To find B & H we need another relationship - namely the one which relates B to H in the iron."

Where does the value for flux come from for finding the flux density B ? To begin solving the solenoid, set the flux (ϕ , webers) to an arbitrary value (such as $1{\cdot}10^{-5}$) as a starting point and solve for B, H and mmf in the iron and air gap elements of the model. After each element is solved for its mmf drop as computed above, the summation of mmf drops is then compared to the coil mmf. If the summation is greater than the coil mmf by more than 1% then incrementally lower the flux value and vice versa if the summation is less than the coil mmf. Upon convergence of these values within ±1% the true flux for the model has been found for next computing the force. Note that this sequence is repeated for any change in gap length or change in coil mmf. By these simple routines a full table of force and stroke data can be produced. A software routine can include as much detail as desired including data for inductance, force & stroke, moving mass, kinetic energy of the mass, acceleration, velocity, and coil data. Refer to appendix A.2 for a solenoid force program example.

Magnetic Tractive Energy: Work is produced by the solenoid due to the energy in the main working air gap. It is generally allowed that if the gap length is short relative to its area then the flux crossing the gap is at the same density as in the adjacent steel poles. Air gap energy, measured in joules, is proportional to the flux thru the gap and the mmf drop across the gap. Both values have been determined in the above sequence. This energy is $W_G = \Im_G \cdot \phi / 2$ joules. Mechanical work energy, also in joules, is the force times the distance moved, $W = F{\cdot}ds$. In terms of the computed magnetics this becomes newtons of force at any increment of plunger position; $F = B^2 A / 2\mu_o$. Work energy therefore is extracted from the magnetic energy as the air gap closes.

Coil Design: Most solenoid coils are wound on nylon or other plastic bobbins; some on anodized aluminum bobbins and some are insulated with tape or paper. Lead wires or terminals are welded or soldered to the copper magnet wire. The insulated coil is sized to have only a small fraction of a millimeter of clearance between the case tube i.d., the base pole and plunger o.d., and even less at the ends to prevent coil movement. Winding calculations therefore depend upon the bobbin size and the number of windings that will fit based upon their awg diameter[7]. It is advised to calculate a table of coils all having the same dimensions and spread over several awg wire sizes so as to select a coil resistance that will conform with the power limitations of the design. The coil ampere turns (mmf) can then be found from this table of data. Refer to appendix A.3 for a coil winding example.

Power Considerations: Solenoid wattage limitations are a function of the solenoid size, the degree of close fit internally of the coil and whether or not the coil is molded or encapsulated within the housing. Some solenoids have exposed coils and very little contact with heat sinking components. Each type should be tested for final coil temperature at their expected environment temperature, supply voltage and operational duty cycle. Appendix A.4 gives an empirical estimate of solenoid power dissipation capability for purposes of establishing a new design.

Copper to Iron Volume Ratio:

At the outset of a new solenoid design the designer may be faced with a decision of how much volume should be allocated to iron and how much to copper volume. Sufficient iron area must allow the starting force, which is usually the lowest point of the force curve, to be adequate for the lowest voltage and highest coil temperature to successfully energize the solenoid. This effort requires the solenoid to operate at or near the knee on the BH curve of the iron. Two fundamental factors benefit: (a) The domain alignments of the iron atoms can be viewed as an amplification factor of the coil mmf

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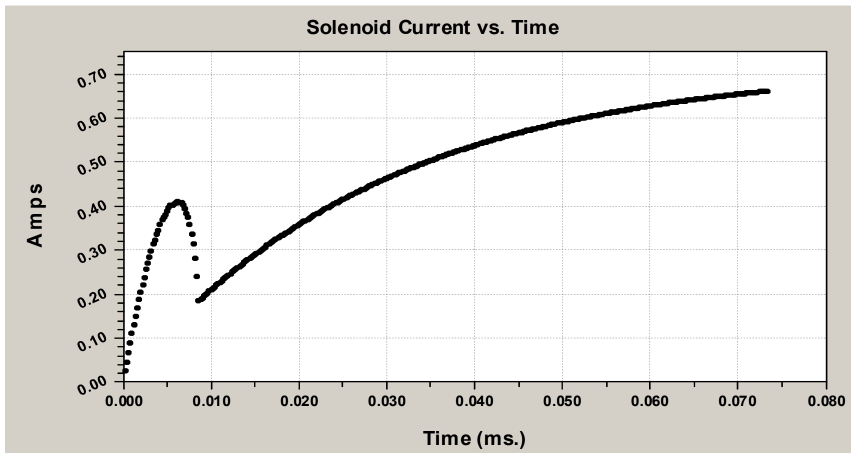
7 In 1857 J.R. Brown of Brown & Sharpe developed the magnet wire gauge sizes (awg; American Wire Gauge). Each bare wire size diameter can be calculated directly from the awg number by the equation $d = 0.46/92^{(awg+3)/39}$ (**d** is in inches). (For awg 0000 use -3 in the exponent, etc.). Standard Handbook for Electrical Engineers, 8th edition, p.244, A.E. Knowlton, McGraw Hill publisher.

which peaks at maximum permeability (B/H). (b) Minimum required coil power is achieved resulting in a lower coil temperature rise and its attendant minimized coil resistance. If the designer writes a software routine that incrementally trades iron volume and copper volume within the allowable volume for the solenoid the force will be seen to peak at the optimum ratio. Included in this approach would be the recalculation of the coil at each incremental step of volume ratios.

It should be noted that optimization of a solenoid intended for high response, driving its own plunger mass or to impact a target may differ from the one moving a spring or friction load which relies on the static force at the start of the solenoid stroke. When accelerating only against the inertia of a mass the rapid acceleration will create a significant counter emf in the coil that prohibits the current, flux, and force from rising to their optimum levels. The graph of Fig.5 shows a typical dynamic plot where the peak current during plunger movement reaches only about 57% of its steady state level. If the flux density, B, at the peak is well below μ_{MAX} then some improvement is response time may be possible by adjusting the copper/iron ratio.

Fig. 5 - Coil current during and following plunger movement.



During plunger acceleration, the counter emf voltage is attributed to the changing levels of current, total ampere turns in the circuit, flux, and inductance following an increment of time, dt. These factors are implicit in the equation $y = 1 - e^{-tR/L}$ where **y** is the fraction of the steady state current at the time **t**. The equivalent equation demonstrates the factors associated with this effect.

$$y = 1 - e^{\frac{-tRi^2}{\Im\phi}}$$

Optimization of a high response solenoid then would look for the shortest energizing time which occurs at the cusp of the negative-going current curve (at t = 8ms in fig.5). If used as an impact device, optimizatIon would also consider the ending kinetic energy ($W_{KE} = mv^2/2$, joules).

Appendix:

A.1 - Symbols, units and identities.

A: area in meters² for iron cross sections, etc.
B: flux density in webers/meter².
d : diameter; in meters or inches as applicable.
e : base of natural logarithms, e = 2.7182818.
F: linear force in newtons; 1 newton = 0.2248 lbf.
$\Im$:ampere-turns (mmf); as in a coil or the drop across an air gap, or drop across a length of steel.
H: ampere-turns/meter; as used in a BH graph or the mmf drop per meter of iron length.
i : current in amperes

ℓ : length in meters or inches as applicable.
N: number of winding turns in a coil.
ϕ : flux, webers
P: permeance
μ, μ_O, μ_{MAX} : permebility of iron or air as applicable.

DEFINITION	EQUATION	UNITS
flux density	$B = \phi / A$	webers/m² (Tesla) (T)
force, magnetic	$F = B^2 A / 2\mu_o$, $F = \Im^2 / 2 \frac{dp}{ds}$	newtons (N)
torque, magnetic	$T = \Im^2 / 2 \frac{dp}{d\theta}$	newton·meters (Nm)
magnetomotive force	$\Im = \phi / p$	ampere turns (NI)
permeance	$p = uA / \ell$	webers/amp·turn
permeability	$\mu = B/H$	weber/amp·turn meter (henry/meter)
magnetic intensity	$\Im = H\ell$	amp·turn/meter
inductance	$L = 2w/I^2$, $L = \Im\phi / i^2$	henry (H)
airgap energy, magnetic	$w = \Im^2 p/2 = \phi^2/2p$	joules (j)

A.2 - Solenoid Force. This sample software routine solves the text example from footnote 2 (above). For simplicity and clarity the format of pcbasic is used below.

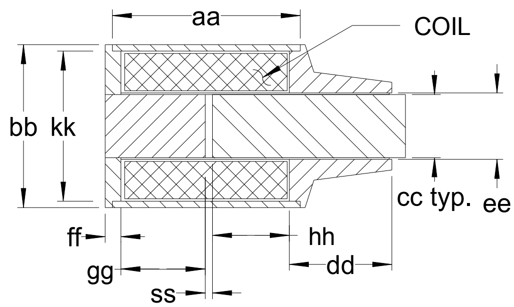


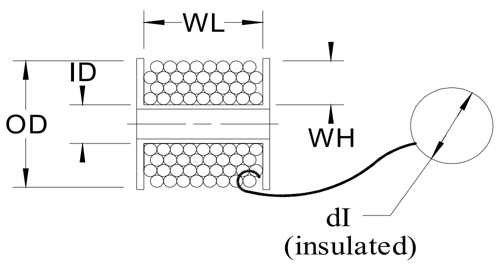
Fig. 6 - Roters Electromagnetic Devices, vol.1, pp.73 & 232.

```
 5  'Roters.bas  mohler  Aug. 1982 and May-Jun 2019
10 PI=3.14159: UO=.0000004*PI: Q=.00045:Z=0:M=39.37
20 AC=.0008234: AB=.0008722:AP=AB:LP=.0508
30 LC=.0889:LB=.0508:DP=.0333:RT=.038:RL=.0008128
40 PR=UO*PI*DP*RT/RL
50 FX=2040:' coil amp turns, also 1020 and 3825 are in Roters' text.
60 FOR SS=.505 TO .015 STEP -.005:'inches
70 S=SS/M:'meters
80 PG=UO*AP/S:'main air gap permeance
90 B=Q/AC
100 GOSUB 300
110 FC=H*LC
120 B=Q/AB
130 GOSUB 300
140 FB=H*LB
150 B=Q/AP
160 GOSUB 300
170 FP=H*(LP-S)
180 FR=Q/PR
190 FG=Q/PG:'main air gap mmf
200 FT=FC+FB+FP+FR+FG:'total mmf drops
210 IF FT/FX>1.01 THEN Q=Q*.993:GOTO 90
220 IF FT/FX<.99 THEN Q=Q*1.012:GOTO 90
230 IF Z=0 THEN PP=PG:FF=FG:Z=1:GOTO 270
240 F=((FF+FG)/2)^2*(PG-PP)/2/(.005/M)
250 PP=PG:FF=FG:'holds the previous pp & ff for line 240.
260 PRINT "ss=";INT(SS*1000)/1000;"in.";"    F=";INT(F*.2248*100!)/100!;"lbf.";"    Q=";Q;" webers"
262 N=N+1:IF N=15 THEN PRINT "Hit any Key":N=0:X$=INPUT$(1):CLS
270 NEXT SS
280 END
300 A=110.529:Y= -1700.2762:C=14226.658:D= -41673.495:E=57423.444
302 F= -37223.825:G=9235.1829
304 H=A+Y*B+C*B^2+D*B^3+E*B^4+F*B^5+G*B^6:RETURN
```

Code keys: Lines 10-50 set physical constants and dimensions taken from Roters' example but in MKS units. Final stroke and derived force units revert to imperial units in keeping with the text.

A.3 - Coil Calculation Method.. Each wire size diameter can be calculated directly from the awg number by the following equation which can be conveniently implemented into a computer routine: **d** = $0.46/92^{(awg+3)/39}$ **.** Here **d** is in inches. (For awg 0000 use -3 in the exponent, etc). This is the bare copper diameter and which must then be modified to include the insulation layer, before calculating the coil, by equation : **di** = **d**+4.38727E-03***d**^0.343976 (Insulated wire diameter)

Fig. 7 - Bobbin wound coil



For computing a coil, lines 5 to 8 must be modified to input a magnet wire size of up to 40 awg which will become **d** in line 12; the bobbin winding diameter **id,** the maximum winding diameter **od**, and the bobbin winding length **wL**. The insulated magnet wire diameter **di** will be computed at line 14.

The coil calculation routine reiterates until the bobbin is filled. Note that line 90 for resistance uses the bare copper diameter **d**, not the insulated diameter, **di**. Dimensions are in inches.

```
 4  'User must input id, od, wL, awg
 5  awg=27:' modify this line for preferred magnet wire awg.
 6  id = .625:' bobbin winding diameter
 7 od = 1.375:' max.winding diameter of coil
 8 wL = .875:' bobbin winding length
10 pi=3.14159: rad=pi/180
12 d=.46/92^((awg+3)/39):' bare magnet wire dia.
14 di =  d+4.38727E-03*d^0.343976 :' insulated magnet wire dia.
20 wh=(od-id)/2
30 tL=int(wL/di)-1: 'turns/layer
40 xwh=di: nL=1: goto 60
50 xwh=xwh+di*cos(30*rad): nL=nL+1
60 if xwh+di*cos(30*rad)<wh then goto 50
70 if nL/2>int(nL/2) then nL=nL-1:' for even no. layers
80 nt=nL*tL:'total turns
90 R=(xwh+id)*nt*6.787388E-07/(d^2/4):' coil res.@20C
100 print "No.Turns=";nt;"  Res.@20C=";R;" ohms"
110 end
```

A.4 - **Allowable Coil Watts:** During the design phase and before a final model is available for testing, the heat dissipating ability can be estimated by knowing the overall size of a cylindrical, steel housed solenoid. The computation below is based upon empirical data of solenoids up to 4 inch diameter and anticipates a final stabilized coil temperature of about 105°C when the computed wattage is the cold starting wattage (at about 20°C) and power is then on continuously. This rating does not include the improvement possible by mounting the solenoid to a heat sink which greatly improves the heat dissipation and continuous duty power rating. This implies a free flow of ambient air at normal air pressure about the solenoid. Solenoids at low air pressure or the vacuum of space are an entirely different matter where cooling depends upon conduction into a surrounding mass and/or by radiation

into space (review the Stefan-Boltzmann radiation constant). In such cases solenoid heating is very rapid, being a function of the thermal mass of the copper, surrounding steel and incoming wattage, and cooling is very slow.
What is inferred by continuous power rating is that the joule energy dissipated in heat is in equilibrium with the electrical joule energy entering the solenoid and within the thermal limits of its insulating materials..

Method: For computing the continuous power rating (P), first calculate the total volume (vol) of the solenoid (volume is in cubic inches).

If vol=> 2.06 then P=1.213*vol + 6.0 (watts).
If vol=> 0.186 and vol<2.06 then P=3.772*vol + 0.73 (watts).
If vol<0.186 then P=7.709*vol (watts).

A.5 - Conclusions and Additional Thoughts -

The methods outlined above are not being recommended as a substitute for fea when such software is available but gives some insight into how magnetics problems can be solved and were solved in industry before fea became available to the individual designers. These are some of the methods used up until the 1980's when fea began to become available and affordable. Primarily this article hopefully gives some insight into how magnetic circuits can be solved and to help answer questions posed online by frustrated inquirers that are getting false advice in a fruitless effort to find that elusive formula for magnetic forces.

An example of misleading online shortcuts found in some calculators uses the equation

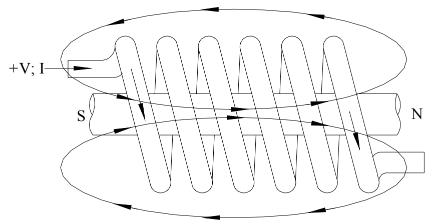
$$F = ni^2 * \mu_O * A/(2*G^2).$$

Implied in this equation is that 100% of the amp-turns and the attendant flux is impressed across the air gap between the core and the iron being lifted. Since (amp-t * flux/2) is the gap energy available for lifting there are no losses based upon this implication. The resulting force, especially at close air gaps (G), will have large errors as the solenoid flux levels incur no accountable core losses. In reality, the solenoid must have some significant circuit of core iron in the stator to focus the flux at the air gap and the flux in this core produces amp-turns drops (losses) that prevent 100% of the magnetomotive force from appearing across the air gap while also causing a lowering of the flux level. When analyzing the solenoid of Fig.6 using this equation, the force errors at a gap length of 0.5 inch are 5% too high; at a gap length of 0.1 inch the force is 24% too high; and at a gap of .025 inch the force is over 6.4 times too high and much worse at or near zero air gap. Without an accounting of the true flux and energy stored in the flux path the incremental inductances are unknown along with any attendant dynamic response times of the electromagnet.

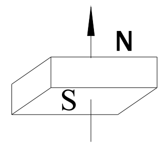
The ASEE reports that 40%-50% of engineering students drop out of engineering studies due to some perceived complexity of the subject material. It is interesting to note that technical writer and editor Ronald Kohl, as an engineering student, had contempt for the way textbooks and academia obfuscated technical material. He felt that professors often cloaked engineering material with a mystique designed to build their reputations as wizards.[8] He was not alone. It is frustrating to have an instructor show a complex equation and conclude with "...and it is obvious therefore that...". This may be a factor in the dropout problem where for lack of clear teaching the student cannot follow the "obvious" in practical terms. Academic articles couched in terms of Maxwell's and Faraday's equations do not, by themselves, answer students' questions.

[8] "Ronald Kohl Made Technical Magazines Readable" by Machine Design editor Leland Teschler, Jan.12, 2006; from Mr. Kohl's self-penned obituary.

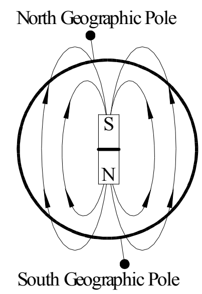
A.6 - Miscellaneous Reference -



Current and Magnetization Relationship
of Coil and Ferrous Core



A magnet's North pole face is attracted toward the north geographic pole of the earth.



The Earth's Magnetic Polarization
Signal Corp., Bureau of Standards Depiction

A.7 - The BH Equation

Why are there few, if any, published equations for the magnetic relationships of B and H in iron in spite of the availability of graphical data or data tables describing this relationship? Probably because of the wide hysteresis loop seen when plotting the data which would make any equation subjective to the degree of magnetization and also dependent upon whether the current is rising or declining on the curve. Perhaps also because we read from Richard Feynman in his 'The Feynman Lectures on Physics' (Vol.II, 1964 - p.36-7): "Now all we need is an equation which relates H to B. But there isn't any such equation." He was right, of course, because of the magnetic 'memory' in the iron. He, being a purist in the scientific world, would argue that the magnetic memory prevented one from establishing an equation that would accurately describe the magnetic state under all conditions. Yet mechanical springs exhibit a hysteresis of their own albeit so negligible as to not prevent an acurate predictive result in engineering design, whether during stressing or relaxation of the spring.

At first glance the wide hysteresis band and its attendant residual magnetism (at Br with zero current) would seem to make an equation useless. However, in a d.c. solenoid the conditions are not the same as when plotting the hysteresis curve. Such a plot dictates that the iron under test is a completely closed iron path, usually a toroidal shape or doughnut, and that the levels of current rise and decline (and reverse) are controlled and recorded to accurately describe the BH numerical relationships. The plotted curve also displays the residual magnetization (Br) (and coercivity) of the iron when the driving current is reduced and reversed. The relatively high Br, as plotted, is a result of maintaining the induced flux in a closed iron path analogous to the purpose of a keeper in some permanent magnet circuits such as the radio speaker. If the keeper is removed; i.e., the magnetic circuit is made discontinuous, the residual Br retention is lost due to the magnetic domains returning to random orientations and cannot be regained by reapplying the keeper. The same effect occurs in a solenoid when de-energized and the plunger retracts to form a large air gap between the pole pieces. These observations, before fea software, now gave substance to the fact that an equation describing the initial magnetization curve is of value for computing solenoid forces. The alternative as utilized in the subsequent commercial magnetics fea software is to use a BH lookup table, in memory, of discrete points on the curve and then to apply interpolation to find a more specific association of B and H.

The iron's magnetic retentivity after the solenoid's first cycle will not have the level of Br as produced in a BH plot (where the iron path remains completely closed) but instead is greatly reduced due to the reopening of the working air gap. At the start of a second energizing cycle the iron's initial residual B will be nearly the same as for a degaussed circuit. Subsequent cycling of the solenoid will return the iron to the same previous state and will maintain repetitive performance. All of this allows the use of an equation to describe the initial BH magnetization curve, being the dotted segment in fig. 8. The figure shown is somewhat idealized in that soft solenoid iron will show a lower Br relative to its saturation level and the coercivity points, both positive and negative, are also nearer the origin. The actual form of the initial magnetization and its corresponding equation are shown at figure 4 above.

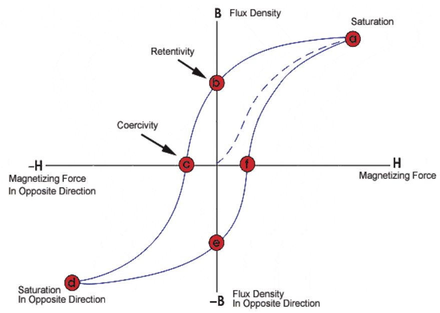


Fig. 8 Hysteresis Plot of Iron

The equation then allows an accurate prediction of solenoid forces, dynamic response times, inductance, and energy distributions when incorporated into an analytic software routine.