

July 25, 1967

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3,333,162

SOLENOID ACTUATOR

Filed Jan. 23, 1964

2 Sheets-Sheet 1

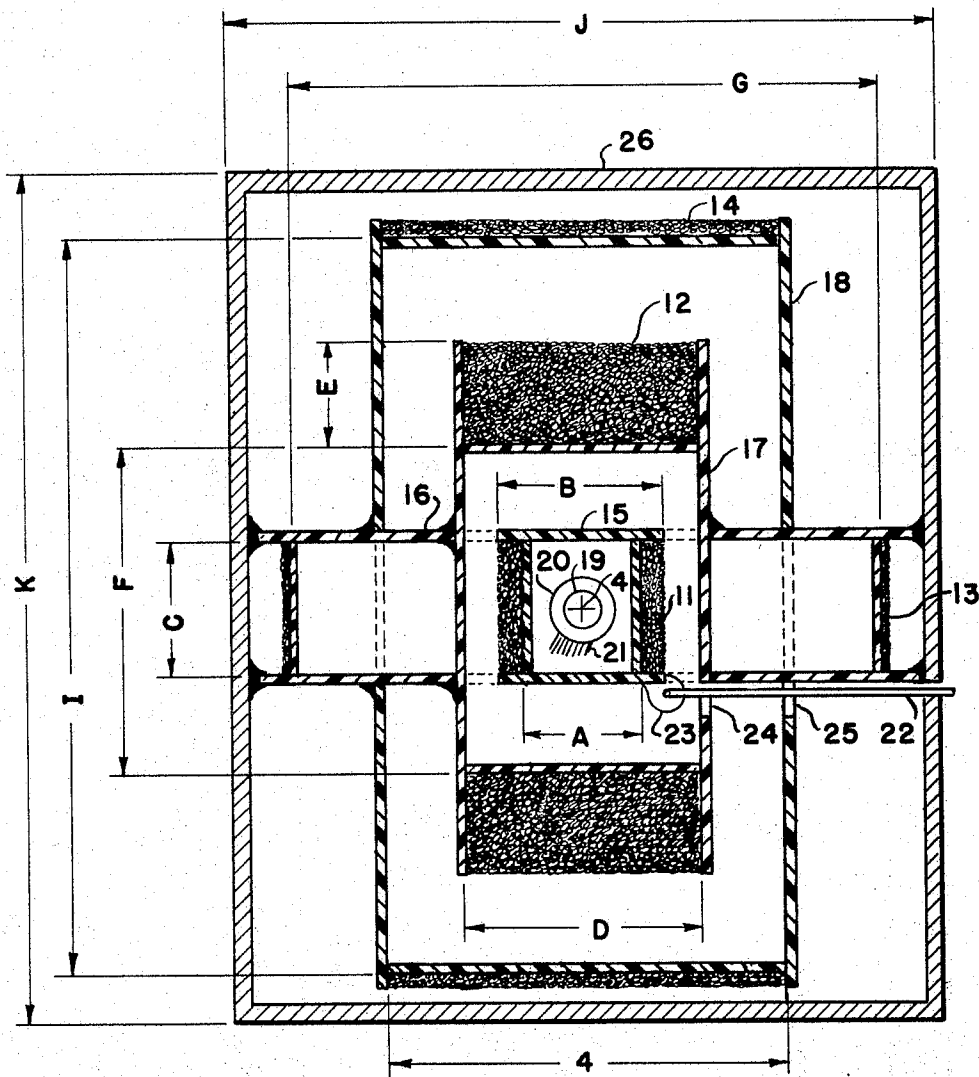


FIG 1

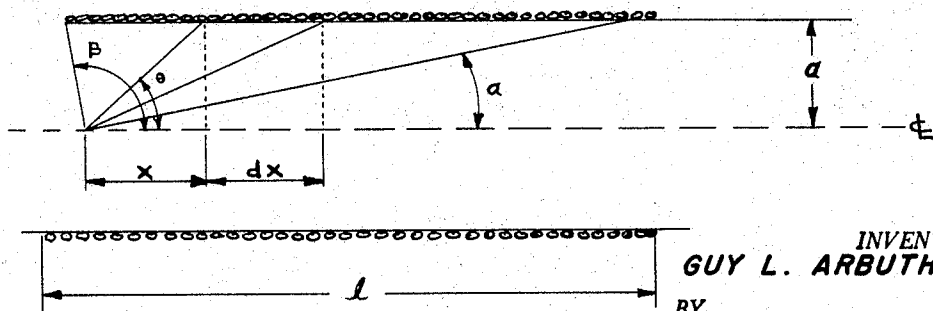


FIG 3

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2 Sheets-Sheet 2

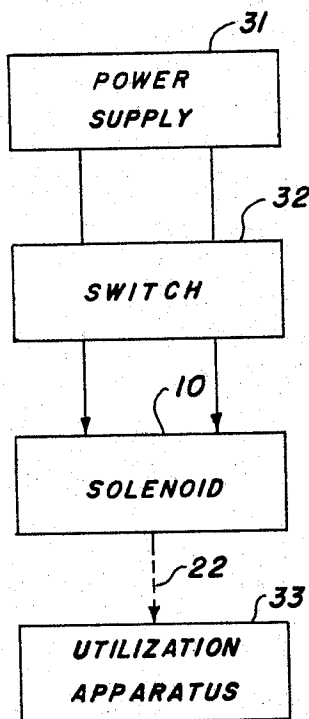


FIG 5

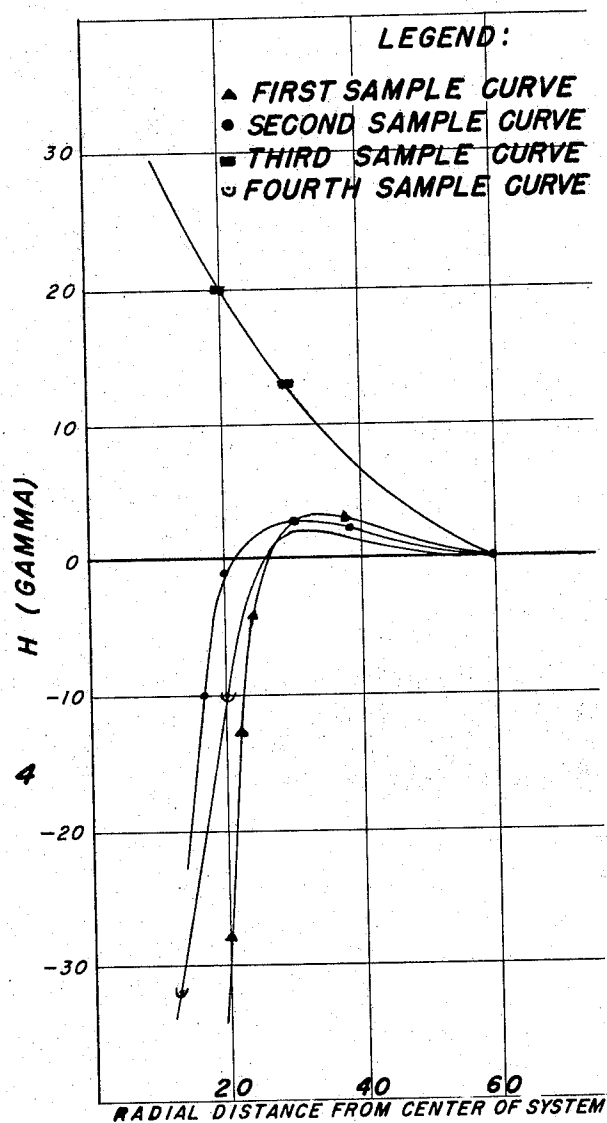


FIG 4

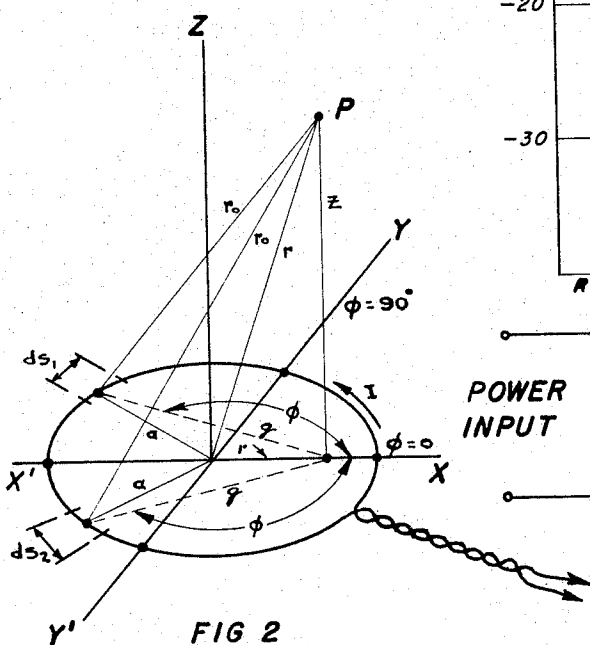


FIG 2

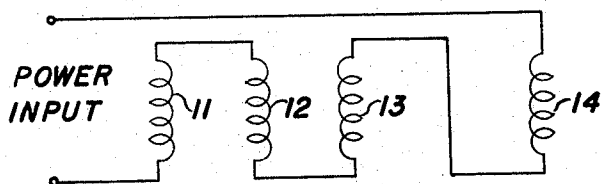


FIG 6

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3,333,162

SOLENOID ACTUATOR

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4 Claims. (Cl. 317-155.5)

The invention described herein may be manufactured and used by or for the Government of the United States of America for governmental purposes without the payment of any royalties thereon or therefor.

The present invention relates generally to solenoids and in particular is a non-ferrous solenoid actuator which operates within a negligible self-generated ambient electromagnetic field for most practical purposes.

In the past, solenoids consisted of an electrically energized coil that acts as an electromagnet and produces a magnetic field which attracts an iron or other ferrous material plunger. Operationally, such an electrically energized coil pulls the plunger into it with sufficient force that any mechanism or apparatus mechanically connected thereto is likewise moved in a similar manner at some other useful location. Unfortunately for many practical purposes, such arrangement also creates a considerable external magnetic field which adversely affects or limits its use. For example, in magnetometer operations, mine hunting operations, or any other operation where the presence of spurious magnetic fields may interfere with the object or things being determined or hunted, it is definitely undesirable to have magnetic fields emanating from the equipment used in the determining or hunting process. Such interference may not only be distracting and error producing, it may defeat the operation entirely. In the case of the hunting of mines of unknown response characteristics, such magnetic fields may also present a safety hazard to the personnel involved because they may cause said mines to be prematurely or inadvertently exploded, in event they are of the magnetic type.

The instant invention overcomes most of the disadvantages of the prior art solenoids using ferrous material plungers, in that only a negligible magnetic field of the order of $.03 \times 10^{-5}$ gauss is produced thereby at a five foot radius therefrom.

It is, therefore, an object of this invention to provide an improved electromagnetic actuator.

Another object of this invention is to provide an improved solenoid type actuator having only a negligible ambient magnetic field.

Still another object of this invention is to provide a solenoid actuator that does not magnetically interfere with or adversely affect apparatus associated or contiguously disposed therewith.

Another object of this invention is to provide a non-ferrous electromagnetic solenoid type of mechanism actuator.

Another object of this invention is to provide an improved solenoid actuator for a snap valve.

Another object of this invention is to provide a non-ferrous plunger control mechanism for a controllable valve.

Still another object of this invention is to provide an improved method and means of providing motor force to a mechanism in the presence of magnetometers, magnetic mines, and other magnetic or electromagnetic equipment which will not interfere therewith or cause same to become a safety hazard.

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Another object of this invention is to provide an improved method and means for producing a mechanical force from electrical power.

Another object of this invention is to provide an improved, non-ferrous, non-interfering actuator for relay switches or the like.

Another object of this invention is to provide an improved electromagnetic solenoid type actuator that is easily and economically manufactured, maintained, and operated.

Other objects and many of the attendant advantages will be readily appreciated as the subject invention becomes better understood by reference to the following detailed description when considered in conjunction with the accompanying drawings and wherein:

FIG. 1 is a diagrammatical representation with parts broken away of the solenoid constituting this invention;

FIG. 2 is a graphical representation of the theory of a single loop of wire which provides the basis for a mathematical definition of the invention;

FIG. 3 depicts the geometry for calculation of the internal field of a solenoid of the type incorporated in this invention;

FIG. 4 is a graphical representation of field strength (H) values along four selected radial lines;

FIG. 5 is a block diagram illustrating the subject invention being operationally connected to any appropriate utilization apparatus; and

FIG. 6 is a schematic representation of the electrical interconnections of the coils incorporated in this invention.

Referring now to FIG. 1, the subject solenoid 10 is shown as having a first inner coil 11 that rotates about a fixed axis X when activated by a current in the field of a second coil 12 which surrounds coil 11 and is wound in a direction normal thereto. A third coil 13 partially surrounds coil 12 and completely surrounds coil 11, and a fourth coil 14 completely surrounds coils 11 and 12 and partially surrounds coil 13. Coils 13 and 14 are wound in opposite directions to coils 11 and 12, respectively, in order to insure the minimum possible external magnetic disturbance. Furthermore, coils 11, 12, 13 and 14 are connected in series, preferably in that order.

Coils 11 through 14 are each respectively wound on round forms or spools 15 through 18 with the material thereof being non-ferrous and, therefore, not responsive to or reactive with magnetism or electromagnetic fields of any kind. Examples of suitable materials for such forms are plastic, wood, paper, aluminum, magnesium, or the like, that have the appropriate shape and strength characteristics. Of course, each of coils 12 through 14 are held in place with respect to each other by any conventional supporting materials such as cement, potting material, or the like, likewise not containing any ferrous or other magnetically responsive material. Furthermore, the entire invention may be incased within any suitable non-ferrous nonmagnetic housing 26 or any metallic or nonmetallic shielding which may, for instance, insulate it electrically, electromagnetically, and physically from its ambient environment.

Because coil 11 is intended to rotate about axis X, it may be conventionally mounted on an appropriate shaft 19, which, in turn, may rotate in suitable bearings 20 located within and mounted on frame 17 of coil 12 by any appropriate conventional mounting means 21. So doing would be obvious to one skilled in the art having the benefit of the teachings herein presented. Likewise, other suitable arrangements which perform as desired would also be obvious to the artisan. Consequently, these con-

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ventional and well known structural features are not considered to be necessary to disclose the inventive aspect of this invention and are, therefore, omitted from FIG. 1 to prevent its being cluttered with unnecessary details.

The design of coils 11 through 14 is of some importance in this particular case. The following exemplary table of preferable parameters are thus presented:

Coil No.	No. of Turns	No. of Layers	Wire Size
11	240	6	22
12	1,190	22	20
13	12	1	14
14	303	4	18

The wire material is preferably copper, but it may be of aluminum or any other suitable non-ferrous material that is electrically conductive.

Using the aforementioned coil designs, it has been found preferable also to use certain physical dimensions which aid in the practice of the invention. Both theoretical calculations and experimental tests predict the optimum embodiment to contain the following dimensions, although for some purposes where slightly lower efficiency is tolerable other appropriate corresponding dimensions may be employed:

Table of dimensions in inches:

A=0.85	G=4.48
B=1.25	H=3.00
C=1.00	I=5.34
D=1.75	J=approx. 5.0
E=approx. 0.25	K=approx. 6.25
F=2.30	

It should, therefore, be understood that all of the foregoing preferable parameters are merely exemplary and that other operable designs may be employed if operational circumstances so warrant. Hence, the invention disclosed herein should not be considered as being limited to the above preferable design parameters.

A plunger 22, which preferably has a one ounce weight, is connected to a bearing 23 which, in turn, is integrally or otherwise attached to form 15 of coil 11. Apertures 24 and 25 respectively are located in frames 17 and 18, in order to allow plunger 19 to moveably extend there-through. The aforesaid housing 26 may likewise contain a similar aperture to allow plunger 22 to extend there-through. Of course, plunger 22 is also made of any suitable non-ferrous material having the desired strength characteristics for proper operation and is adapted for connection to and actuation of any pertinent associated apparatus.

To facilitate understanding the actual operation of the subject invention, which is to be discussed subsequently, the theory for calculating the respective parameters of a minimum external magnetic field solenoid is now presented. The symbols used in this theoretical and mathematical presentation are as follows:

- A—Vector potential
- B—Magnetic induction
- Δ —Vector operator
- μ —Permeability
- I—Current
- F—Force
- τ —Torque
- a—Radius of solenoid
- l—Length of solenoid
- N—Number of turns of solenoid
- γ — 10^{-5} gauss (in air)
- =—Equal
- >—Greater than
- >>—Much greater than
- <—Less than
- $\equiv$ —Defined as
- $\rightarrow$ —Vector characteristic

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- ϕ —Angle
- θ —Angle
- P—Point
- r—Distance
- X—Axis distance
- Y—Axis distance
- Z—Axis distance

The purpose of the system illustrated in FIG. 1 is to raise plunger 22, having a weight of one ounce or less, a very small distance with a minimum magnetic disturbance external to the system. As previously mentioned, Coil No. 11 rotates about a fixed axis x when activated by a current in the field of Coil No. 12. Coil Nos. 13 and 14 are wound in opposite directions to No. 11 and No. 12 respectively to insure the minimum possible external disturbance.

It is desired that the combined B's of the four solenoids be less than 0.03, (3×10^{-7} gauss in air) five feet from the system. Two minor assumptions were made but the number of turns in solenoid No. 13 and No. 14 may be adjusted for the desired effect in actual construction. The following theoretical calculations are based on a steady current flow; however, the results may be applied to reasonably low frequency alternating current, certainly within construction limitations.

The theory of a solenoid is based on the theory of a single loop of wire which is where this calculation begins. Using FIGURE 2 and a basic electromagnetic fact, namely that the magnetic induction B is given by

$$\vec{B} = \Delta \times \vec{A} \quad (1)$$

where A, the vector potential is defined by

$$\vec{dA} = \frac{\mu}{4\pi} \frac{I ds}{r_o} \quad (2)$$

It should be noted that $\vec{dA}$ and $\vec{ds}$ are in the same direction, and from FIGURE No. 2 a component of $\vec{A}_1$ cancels one component of $\vec{A}_2$ leaving from all the differential elements only the $\cos \phi$ component for the total $\vec{A}$. Equation 2 is now rewritten as

$$\vec{A}\phi = \frac{\mu I}{4\pi} \oint \frac{\vec{ds}}{r_o} = \frac{\mu I}{4\pi} \oint \frac{a d\phi (\cos \phi)}{r_o} = \frac{\mu I}{2\pi} \int_0^\pi \frac{a \cos \phi}{r_o} d\phi \quad (3)$$

It has been shown in FIGURE No. 2 by the Law of Cosines that

$$q^2 = a^2 + p^2 - 2ap \cos \phi$$

also

$$r_o^2 = Z^2 + q^2$$

thus

$$r_o = \sqrt{a^2 + p^2 + Z^2 - 2ap \cos \phi} \quad (4)$$

Substitution of (4) into (3) yields

$$\vec{A}\phi = \frac{\mu I}{2\pi} \int_0^\pi \frac{a \cos \phi d\phi}{\sqrt{a^2 + p^2 + Z^2 - 2ap \cos \phi}} \quad (5)$$

At a distance much greater than the radius of the coil, a^2 may be neglected in comparison to $Z^2 + p^2$, or

$$r^2 \approx Z^2 + p^2 \gg a^2 \quad (6)$$

and (5) becomes

$$\vec{A}\phi = \frac{\mu I}{2\pi} \int_0^\pi \frac{a \cos \phi d\phi}{\sqrt{Z^2 + p^2 - 2ap \cos \phi}} \quad (7)$$

By using the first part of (6)

$$\vec{A}\phi = \frac{\mu I}{2\pi} \int_0^\pi \frac{a \cos \phi d\phi}{\sqrt{r^2 - 2ap \cos \phi}} \quad (8)$$

Applying the binomial expansion to $(r^2 - 2a\rho \cos \phi)^{-1/2}$ and retaining only the significant terms the following is obtained:

$$(r^2 - 2a\rho \cos \phi)^{-1/2} = \frac{1}{r} + \frac{a\rho}{r^3} \cos \phi + \dots \quad (9)$$

Thus using (9) in (8) and performing the indicated integration

$$\begin{aligned} \vec{A}_\phi &= \frac{\mu I}{2\pi} \oint a \cos \phi \left[\frac{1}{r} + \frac{a\rho}{r^3} \cos \phi + \dots \right] d\phi \\ \vec{A}_\phi &= \frac{\mu I}{2\pi} \left[\frac{a \sin \phi}{r} \right]_0^\pi + \frac{\mu I a^2 \rho}{2\pi r^3} \left[\frac{\phi}{2} + \frac{\sin^2 \phi}{4} \right]_0^\pi \\ \vec{A}_\phi &= \frac{\mu I a^2}{4r^2} \sin \theta \end{aligned}$$

where

$$\sin \theta = \frac{\rho}{r} \quad (10)$$

The problem of choosing a convenient coordinate system now presents itself. In the preceding discussion, it is noted that spherical coordinates seem to be convenient. The coil, having a cylindrical shape, might lead one to cylindrical coordinates, however, in this case, the results involve complete elliptic integrals of the first and second kind. Cylindrical coordinates present the results in such a complicated form, the functional relation of physical parameters are obscure. Since the problem will presently involve four hypothetical solenoids, listed as No. 1, No. 2, No. 3, and No. 4, each presenting three parameters and two field components, the simplest original expression is most desirable.

The curl of any vector $\vec{\chi}$ in spherical coordinates is given by

$$\Delta \times \vec{\chi} = \frac{1}{r \sin \theta} \left\{ \left[\frac{2(\chi_\phi \sin \theta)}{2\theta} \right] - \frac{2\chi_\theta}{2\phi} \right\}_r + \frac{1}{r} \left[\frac{1}{\sin \theta} \frac{2\chi_r}{2\phi} - \frac{2(r\chi_\phi)}{2r} \right]_\theta + \frac{1}{r} \left[\frac{2(r\chi_\theta)}{2r} - \frac{2\chi_r}{2\theta} \right]_\phi \quad (11)$$

Since only the $\vec{A}_\phi$ component is present

$$\vec{B} = \Delta \times \vec{A}_\phi = \frac{1}{r \sin \theta} \left[\frac{2}{2\theta} (\sin \theta A_\phi) \right] - \frac{1}{r} \frac{2}{2r} (r A_\phi) \quad (12)$$

$$\vec{B} = \frac{2}{r \sin \theta} \left[\frac{\mu I a^2}{4r^2} \sin \theta \cos \theta \right]_r - \left[\frac{\mu I a^2 \sin \theta}{4r^3} - \frac{\mu I a^2 \sin \theta}{2r^3} \right]_\theta \quad (13)$$

Thus, where $r \gg a$ (outside of the loop),

$$\vec{B}_{\text{outside}} = \left(\frac{\mu I a^2}{2r^3} \cos \theta \right)_r + \left(\frac{\mu I a^2}{4r^3} \sin \theta \right)_\theta \quad (14)$$

and for a solenoid of N turns and $r \gg a$

$$\vec{B}_{\text{outside}} = \left(\frac{\mu a^2 N I}{2r^3} \cos \theta \right)_r + \left(\frac{\mu a^2 N I}{4r^3} \sin \theta \right)_\theta \quad (15)$$

For future reference, the field inside a solenoid is given by FIGURE 3 and the following

$$d\vec{B}_{\text{inside}} = \frac{\mu N I}{2l} \frac{a^2}{(a^2 + x^2)^{3/2}} dx \quad (16)$$

Using the fact that $x = a \cot \phi$; $dx = -a \cos^2 \phi d\phi$

$$\vec{B}_{\text{inside}} = \frac{-\mu H I}{2l} \int_\beta^\alpha \sin \phi d\phi \quad (18)$$

$$\vec{B}_{\text{inside}} = \frac{\mu N I}{2l} [\cos \alpha - \cos \beta] \quad (19)$$

Thus, inside the solenoid

$$\vec{B} \simeq \text{constant} = \frac{\mu N I}{l} \quad (20)$$

and at the ends

$$B = \frac{\mu N I}{2l} \quad (21)$$

The above neglects the "shielding effect" of outer solenoids on inner solenoid, which is functionally proportional to the current. The system involves 2 pairs of solenoids perpendicular to each other. For reasons presented later, in the discussion of the torque on solenoid No. 1, it is possible to treat the pairs of solenoids separately, remembering that one may practically null the field of No. 1 by No. 3 at some distance, resulting only in a net field

of $\vec{B}_2 - \vec{B}_4$ to rotate coil No. 1, hence the lifting plunger.

Consider 2 concentric solenoids I and II by way of illustration:

$$\begin{array}{ll} \text{\#I} & \text{\#II} \\ \vec{B}_{rI} = \frac{\mu I_I N_I a_I^2 \cos \theta}{2r^3} & \vec{B}_{rII} = \frac{\mu I_{II} N_{II} a_{II}^2 \cos \theta}{2r^3} \end{array} \quad (22)$$

$$\begin{array}{ll} \vec{B}_{\theta I} = \frac{\mu I_I N_I a_I^2 \sin \theta}{4r^3} & \vec{B}_{\theta II} = \frac{\mu I_{II} N_{II} a_{II}^2 \sin \theta}{4r^3} \\ \text{outside} & \text{outside} \end{array}$$

and if the solenoids are connected in series

$$I_I = I_{II} = I \quad (23)$$

also if they are wound in opposite directions, the total

$\vec{B}_t$ is given by

$$\vec{B}_t = \sqrt{(\vec{B}_{rI} - \vec{B}_{rII})^2 + (\vec{B}_{\theta I} - \vec{B}_{\theta II})^2} \quad (24)$$

Substituting (22) and (23) into (24)

$$\begin{aligned} \vec{B}_t &= \sqrt{\left[\frac{\mu I}{2r^3} [N_I a_I^2 - N_{II} a_{II}^2] \cos \theta \right]^2 + \left[\frac{\mu I}{4r^3} [N_I a_I^2 - N_{II} a_{II}^2] \sin \theta \right]^2} \\ \vec{B}_t &= \frac{\mu I}{2r^3} [N_I a_I^2 - N_{II} a_{II}^2] \sqrt{\cos^2 \theta + (1/2 \sin^2 \theta)} \end{aligned} \quad (25)$$

outside

$$\vec{B}_t = \frac{\mu I}{2r^3} [N_I a_I^2 - N_{II} a_{II}^2] [\cos^2 \theta + 1/4 \sin^2 \theta]^{1/2}$$

outside

Adding

$$\left(\frac{3}{4} - \frac{3}{4} \right) \sin^2 \theta$$

under the radical

$$\begin{aligned} \vec{B}_t &= \frac{\mu I}{2r^3} [N_I a_I^2 - N_{II} a_{II}^2] [\cos^2 \theta + 1/4 \sin^2 \theta + \left(\frac{3}{4} - \frac{3}{4} \right) \sin^2 \theta]^{1/2} \\ \vec{B}_t &= \frac{\mu I}{2r^3} [N_I a_I^2 - N_{II} a_{II}^2] \left[\cos^2 \theta + \sin^2 \theta - \frac{3}{4} \sin^2 \theta \right]^{1/2} \end{aligned}$$

outside

But $\cos^2 \theta + \sin^2 \theta = 1$

$$\begin{aligned} \vec{B}_t &= \frac{\mu I}{2r^3} [N_I a_I^2 - N_{II} a_{II}^2] \left[1 - \frac{3}{4} \sin^2 \theta \right]^{1/2} \\ \vec{B}_t &= \frac{\mu I}{2r^3} [N_I a_I^2 - N_{II} a_{II}^2] \left[\frac{4 - 3 \sin^2 \theta}{4} \right]^{1/2} \end{aligned} \quad (26)$$

outside

$$\vec{B} = \frac{\mu I}{4r} [N_I a_I^2 - N_{II} a_{II}^2] [4 - 3 \sin^2 \theta]^{1/2}$$

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B_{total} is a maximum, with respect to θ , when

$$\frac{d\vec{B}_{\text{total}}}{d\theta} = 0 = \frac{\mu I}{4r^3} [N_1 a_1^2 - N_{11} a_{11}^2] \frac{d}{d\theta} [4 - 3 \sin^2 \theta]^{1/2} \quad (27)$$

or

$$\frac{d}{d\theta} [4 - 3 \sin^2 \theta]^{1/2} = 0$$

$$\frac{1}{2} [4 - 3 \sin^2 \theta]^{-1/2} [-6 \sin \theta \cos \theta] = 0$$

hence, $\sin \theta = 0$; $\theta = n\pi$ where $n = 0, 1, 2, 3, \dots$. Using the above in (26), the maximum value for B_{total} is

$$\vec{B}_{\text{total}} = \frac{\mu I}{2r^3} [N_1 a_1^2 - N_{11} a_{11}^2]; \quad r > a_{11} > a_1 \quad (28)$$

Max. outside

Thus, if it is possible to hold the maximum

$$\vec{B}_t$$

outside

to $\leq 0.03\gamma$ at 5 feet, the purpose of the calculation has been accomplished.

The following deals entirely with the application of the preceding results, the use of certain assumed practical parameters and calculation of others. The field of solenoid No. 1, itself, has no use; hence, we wish to completely null it with No. 3, thus at $r > a_3 > a_1$ (28) is given by

$$\vec{B}_{1-3} = \frac{\mu I}{2r^3} (N_1 a_1^2 - N_3 a_3^2) = 0 \quad (29)$$

outside

$$\text{Thus, at } r > a_3, N_1 a_1^2 = N_3 a_3^2 \text{ or } \frac{N_1}{N_3} = \left(\frac{a_3}{a_1}\right)^2 \quad (30)$$

Inside the solenoids No. 1 and No. 3, from (20)

$$[\vec{B}_1 - \vec{B}_3]_{\text{inside}} = I \left[\frac{N_1}{l_1} - \frac{N_3}{l_3} \right] \quad (31)$$

If (31) is to be approximately zero also, this means that

$$\frac{N_1}{N_3} = \frac{l_1}{l_3} \quad (32)$$

Combining (32) and (30)

$$\frac{N_1}{N_3} = \frac{l_1}{l_3} = \frac{a_3^2}{a_1^2} \quad (33)$$

The next requirement is for

$$\vec{B}_{2,4} \leq 0.03\gamma$$

outside

at its maximum possible value at 5 feet. One cannot arbitrarily set $\vec{B}_{2,4} \text{ max} = 0$ at this distance as was done for No. 1 and No. 3 since $(\vec{B}_{2,4} \text{ inside solenoid \#2})$ must be above a certain minimum to insure rotation of solenoid

No. 1. For an approximate answer $\vec{B}_{2,4}$ (outside) is set to equal 0.03γ at 5 feet and it turns out that experimentally the field tends to zero past this point.

$$\vec{B}_{2,4} = 0.03\gamma = \frac{\mu I}{2(5 \text{ ft.})^3} [N_2 a_2^2 - N_4 a_4^2] \quad (34)$$

Max. outside

The following conversion factors to mks system are now used:

$$1 \text{ gauss} = 10^{-4} \text{ webers/meter}^2$$

$$5 \text{ ft.} \approx 1.5 \text{ meters}$$

$$\mu_0 \approx \mu \approx \mu_{\text{air}} \approx \mu_{\text{plastic}} = 4\pi \times 10^{-7} \frac{\text{Henrys}}{\text{meter}}$$

[This is good to 1 part in 100,000,000]

$$1 \text{ inch} = 2.54 \times 10^{-2} \text{ meters.}$$

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Then,

$$0.03 \times 10^{-5} \text{ gauss} \frac{\left(\frac{10^{-4} \text{ Weber}}{\text{meter}^3} \right)}{\text{gauss}} (2) (1.5 \text{ meter})^3 = \frac{(2.54 \times 10^{-2})^2 4\pi I \times 10^{-7} \frac{\text{Henry}}{\text{meter}}}{[N_2 a_2^2 - N_4 a_4^2]} \quad (35)$$

Thus,

$$N_2 a_2^2 - N_4 a_4^2 = \frac{6(3.375) \times 10^{-11}}{I(12.57)(6.45) \times 10^{-11}}$$

Note: a_2 and a_4 have units of inches

and

$$N_2 a_2^2 - N_4 a_4^2 = \frac{0.25}{I} = \frac{1}{4I} \quad (36)$$

The above is outside the system. Inside the system the

torque that $\vec{B}_{2,4}$ inside must exert on solenoid No. 1 must be $(1 \text{ oz}) \times a_1 \text{ oz-inches}$.

Since the torque is given by

$$T = d\vec{F} \times r = d\vec{F} \times a \sin \phi$$

$$T_{\#1} = (N_1 I) B_{2,4} (a_1^2 \pi) \quad (37)$$

inside

Rewritten

$$T_{\#1} = \pi a_1^2 (N_1 I) \vec{B}_{2,4} \quad (38)$$

inside

The field inside No. 2 acting on solenoid No. 1 is given by

$$\vec{B}_{2,4} = \mu I \left[\frac{N_2}{l_2} - \frac{N_4}{l_4} \right] \quad (39)$$

inside #2

Combining (38) and (39)

$$T_{\#1} = \pi a_1^2 (N_1 I) \mu I \left[\frac{N_2}{l_2} - \frac{N_4}{l_4} \right]$$

$$T_{\#1} = \pi a_1^2 I^2 \mu N_1 \left[\frac{N_2}{l_2} - \frac{N_4}{l_4} \right] \quad (40)$$

$$T_{\#1} = \left(9.8 \frac{\text{M}}{\text{sec.}^2} \right) (1 \text{ oz.}) \left((2.83 \times 10^{-2} \frac{\text{kilogram}}{\text{oz.}}) \right)$$

$$a_1 = \pi a_1^2 I^2 \mu N_1 \left[\frac{N_2}{l_2} - \frac{N_4}{l_4} \right]$$

$$(9.8) 2.83 \times 10^{-2} = \pi a_1 I^2 \mu N_1 \left[\frac{N_2}{l_2} - \frac{N_4}{l_4} \right] \quad (41)$$

$$(9.8) \frac{2.83 \times 10^{-2}}{(3.14)(12.57 \times 10^{-7})} = a_1 I^2 N_1 \left[\frac{N_2}{l_2} - \frac{N_4}{l_4} \right]$$

$$(9.8) 7.07 \times 10^3 = a_1 I^2 N_1 \left[\frac{N_2}{l_2} - \frac{N_4}{l_4} \right] \quad (42)$$

$$69.2 \times 10^3 = a_1 I^2 N_1 \left[\frac{N_2}{l_2} - \frac{N_4}{l_4} \right]$$

At this point, it is very useful to collect all known relationships.

$$\frac{N_1}{N_3} = \frac{l_1}{l_3} = \left(\frac{a_3}{a_1}\right)^2$$

$$N_2 a_2^2 - N_4 a_4^2 = \frac{1}{4I}$$

$$a_1 I^2 N_1 \left[\frac{N_2}{l_2} - \frac{N_4}{l_4} \right] = 69.2 \times 10^3$$

where a_1 and l_1 are given in inches, I in amps, and N_1 in turns.

By starting with the desired current and dimensions of the solenoid, it is possible with the equations in (43) to

calculate the number of turns needed in each coil. The numerical calculation for the solenoids described herein as coils 11 through 14 are shown in the foregoing table of parameters. It is important to note, however, that (42) is valid only for a one ounce weight thus in general case (42) is written

$$a_1 I^2 N_1 \left[\frac{N_2}{l_2} - \frac{N_4}{l_4} \right] = 69.2 \times 10^3 \text{ [Number of oz.]} \quad (44)$$

The size of the solenoid shown in FIGURE 1 can be decreased; the exhibited dimensions represent sizes that were easy to work with to establish feasibility. The calculated values and the experimental values were very close, which established that neglecting the size of the coils for field calculations was practical, as may be discerned by inspection of FIGURE 4.

Briefly, the actual operation of the subject invention will now be discussed in connection with FIGS. 1, 5, and 6.

As shown in FIG. 5, a power supply 31 (which may be either a direct current or alternating current power supply, depending on the selection of parameters mentioned above and the frequency involved), has its output coupled through a switch 32 to the input of solenoid 10 to timely supply electrical energy thereto.

This electrical energy, in turn energizes each of the series connected coils 11 through 14, depicted schematically in FIG. 6, which, then, act as a plurality of interacting inductances. The magnetic fields generated by coils 11 and 12 react in such manner as to apply a torque to coil 11 and its associated rotatable form 15, thereby causing it to turn on axis X an amount sufficient to move plunger 15. For the foregoing theoretically proven reasons this occurs, even though no ferrous material cores or plungers are employed. Plunger 22, of course, as a result of its connecting rod action, actuates any appropriate utilization apparatus 33 by applying a substantially unidirectional force thereto.

Because coils 13 and 14 are wound in opposite directions to 11 and 12, respectively, their magnetic fields interact to effectively cancel the magnetic fields, if any, that escape the physical periphery of coil 12. In this way, the total spurious external magnetic disturbance is held to a minimum; in this case, 3×10^{-7} gauss in air, five feet from the system. For most practical purposes, including being used in magnetic mine hunting vehicles and mine countermeasure devices, this amount of ambient magnetism is negligible and presents practically no danger and no adverse operational effects. Accordingly, for such purposes, it is considerably safer and better than most of the prior art solenoid type electromagnetic actuators in operation at the present time.

Obviously, many modifications and other embodiments of the subject invention will readily come to the mind of one skilled in the art having the benefit of the teachings presented in the foregoing description and drawing. Therefore, it is to be understood that this invention is not to be limited thereto and that said modifications and embodiments are intended to be included within the scope of the appended claims.

What is claimed is:

1. Means for producing a force along a predetermined path comprising in combination:
 - rotatable means for producing a first electromagnetic field;
 - means spatially disposed around said first electromagnetic field producing means for producing a second electromagnetic field capable of interacting with said first electromagnetic field in such manner as to effect

rotation of said rotatable first electromagnetic field producing means;

means spatially disposed around said first and second electromagnetic field producing means for producing a third electromagnetic field that is in opposition with said first electromagnetic field an amount sufficient for the effective cancellation thereof only at a predetermined radial distance external to and substantially surrounding the outer periphery of said second electromagnetic field;

means spatially disposed around said first, second, and third electromagnetic field producing means for producing a fourth electromagnetic field that is in opposition with said second electromagnetic field an amount sufficient for the effective cancellation thereof only at a predetermined radial distance external to and substantially surrounding the outer periphery of said third electromagnetic field;

means hinged to said first electromagnetic field producing means for converting the rotary movement thereof to proportional motion and force along a predetermined path; and

means effectively connected to each of the aforesaid electromagnetic field producing means for the disposition thereof in a predetermined operable geometrical configuration.

2. The invention according to claim 1 further characterized by a non-magnetic housing incasing said electromagnetic field producing means in such manner as to effect electromagnetic and physical insulation thereof from their ambient operational environment.

3. A solenoid comprising in combination:

- a first electrically inductive means;
- a second electrically inductive means surrounding said first electrically inductive means;
- a third electrically inductive means surrounding said first and second electrically inductive means and having a polarity that is opposite the polarity of said first electrically inductive means;
- a fourth electrically inductive means surrounding said first, second, and third electrically inductive means and having a polarity that is opposite the polarity of said second electrically inductive means;

means interconnecting said first, second, third, and fourth electrically inductive means for electrically connecting same in series;

means effectively connected to said first and second electrically inductive means for providing relative rotation capability therebetween; and

means effectively connected to all of the aforesaid electrically inductive means for maintaining each thereof in operational dispositions relative to the others to effect substantially magnetic field neutralization at a predetermined distance from the outer periphery thereof, while enabling relative rotation to occur between the aforesaid first and second electrically inductive means when a predetermined electrical energy is supplied thereto.

4. The invention of claim 3 further characterized by means connected to said first electrically inductive means for converting the rotation thereof into a force proportional thereto along a predetermined linear path.

References Cited

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