United States Patent

[11] 3,571,769

[72] Inventor **John B. Pegram**
Los Angeles, Calif.

[21] Appl. No. **822,908**
[22] Filed **May 8, 1969**
[45] Patented **Mar. 23, 1971**
[73] Assignee **Bell Aerospace Corporation**

[54] ELECTROMAGNETIC FORCE MOTOR HAVING ADJUSTABLE MAGNETIC SATURATION

8 Claims, 20 Drawing Figs.

[52] U.S. Cl. 335/230, 335/227, 335/279
[51] Int. Cl. H01f 7/13
[50] Field of Search 336/132, 135; 335/227, 229, 230, 279

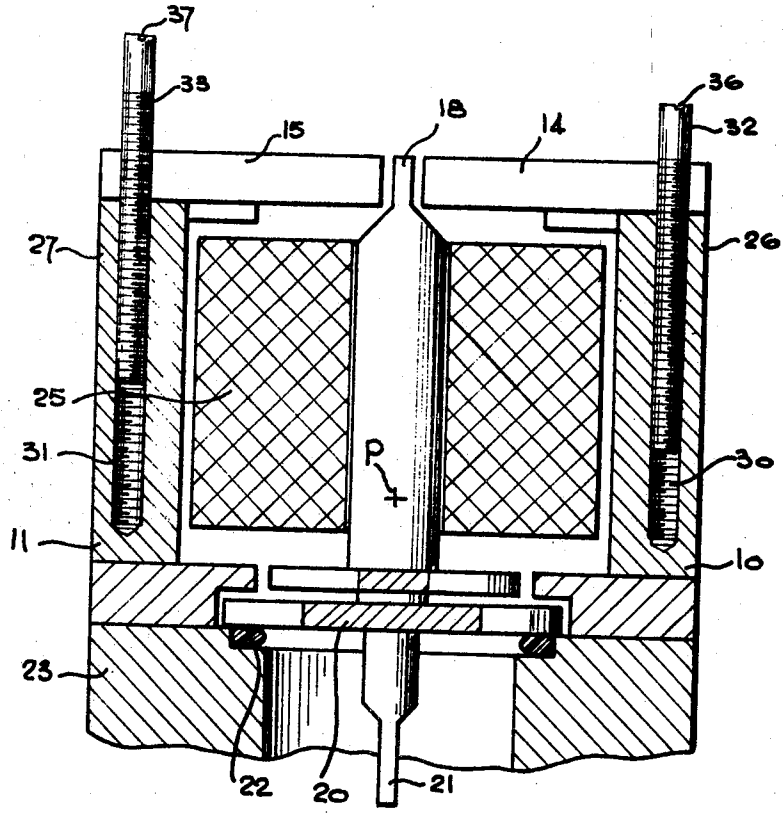
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Primary Examiner—G. Harris
Attorney—Nilsson & Robbins

ABSTRACT: An improvement in electromagnetic force motors in which the force versus input signal characteristic is adjustable by providing in the flux path regions of magnetically saturable material defining magnetic saturation paths and members of magnetically permeable material insertable in the regions to decrease the lengths or cross-sectional areas of the saturation paths.



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SHEET 1 OF 3

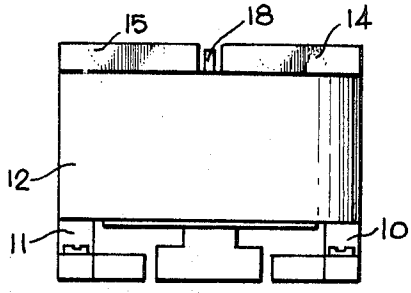


Fig-1

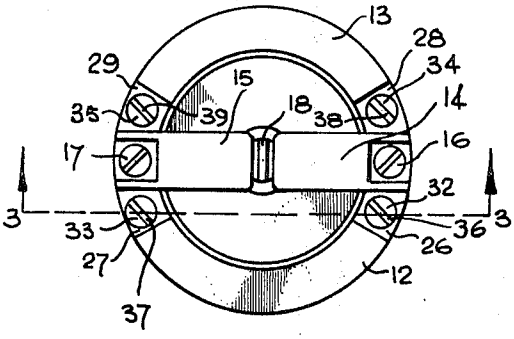


Fig-2

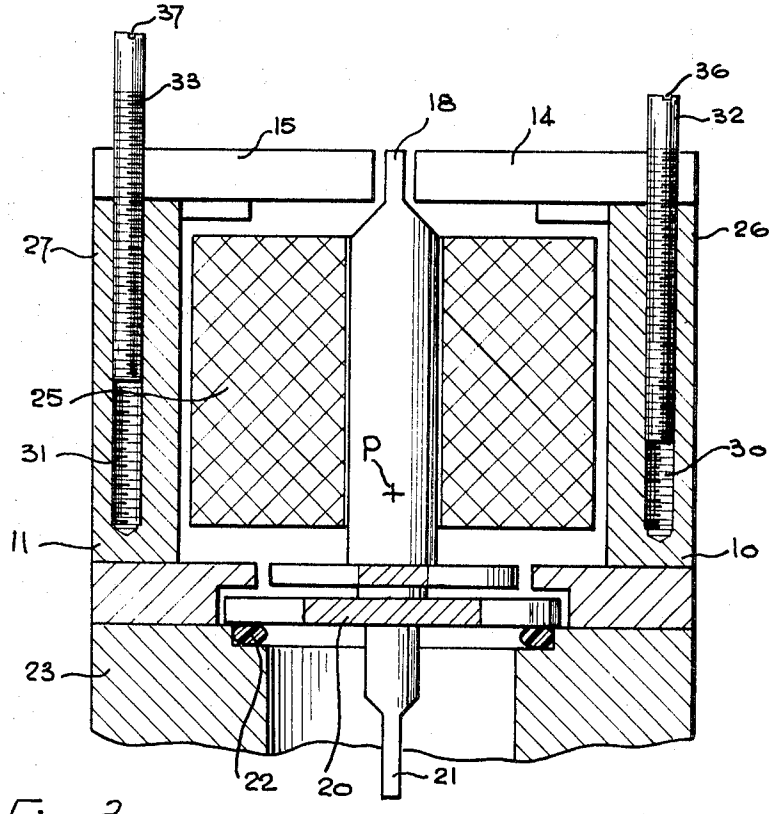


Fig-3

INVENTOR.
JOHN B. PEGRAM
BY Nilsson & Robbins
Attorneys.

Fig-4

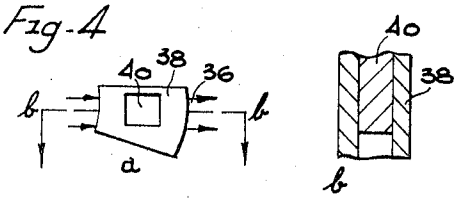


Fig-7

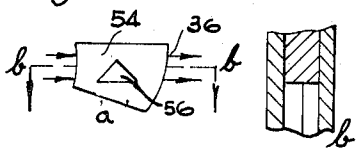


Fig-5

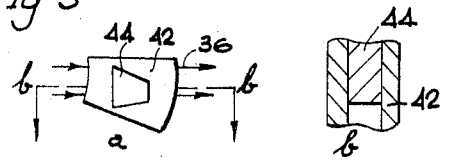


Fig-8

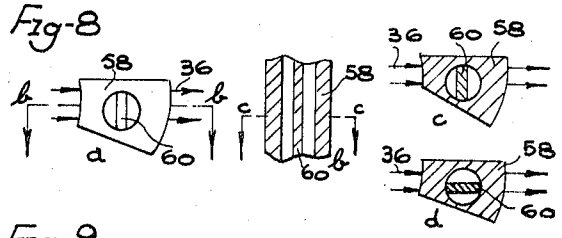


Fig-6

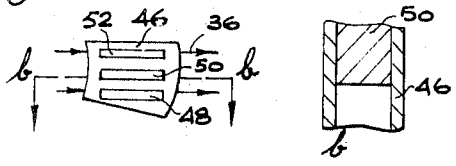


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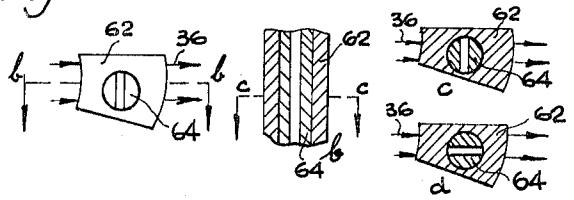


Fig-10

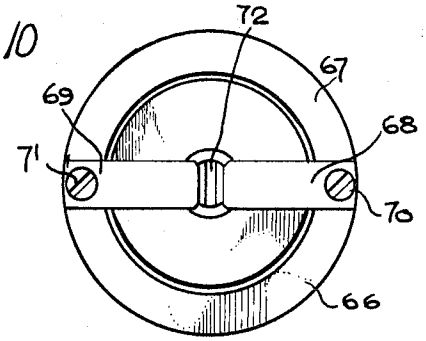


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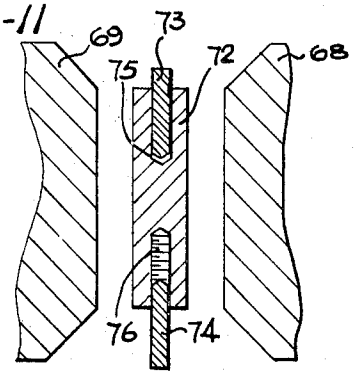


Fig-12

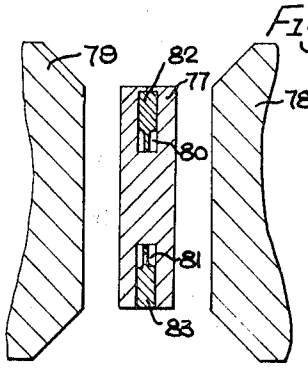


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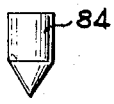
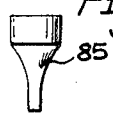


Fig-14



INVENTOR.
JOHN B. PEGRAM
BY
Nilsson & Robbins
Attorneys.

Fig-15

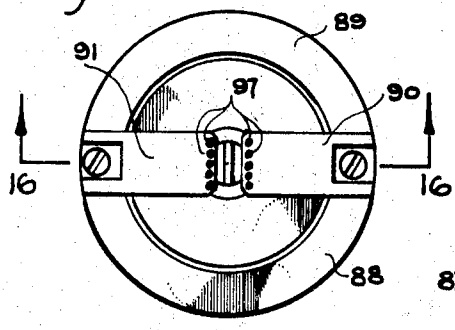


Fig-16

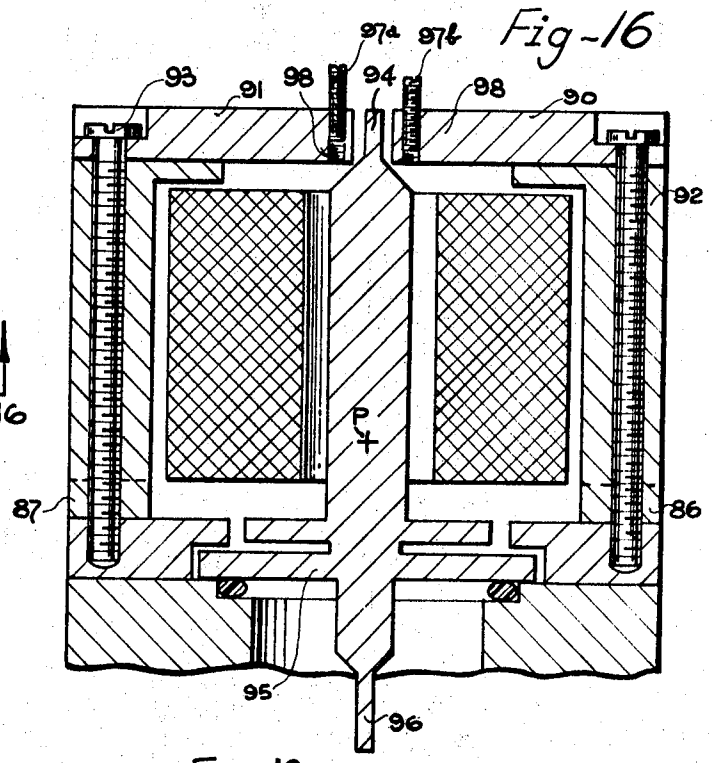


Fig-17

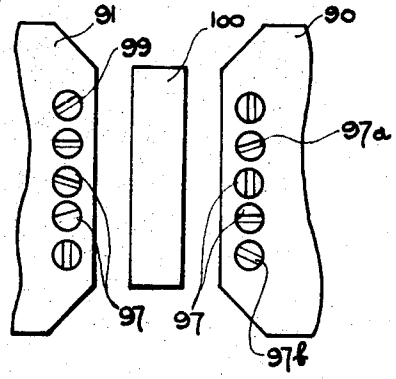


Fig-18

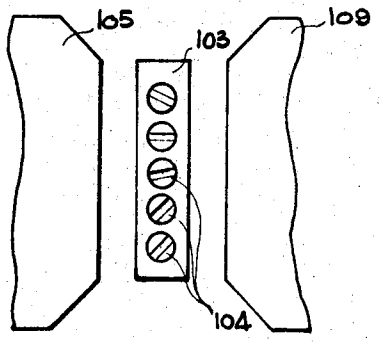
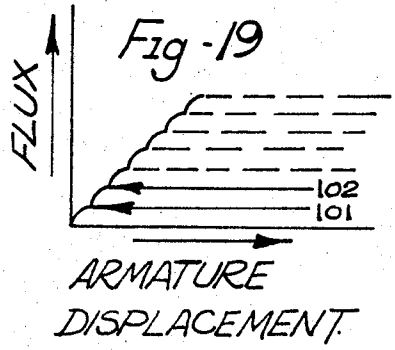


Fig-19



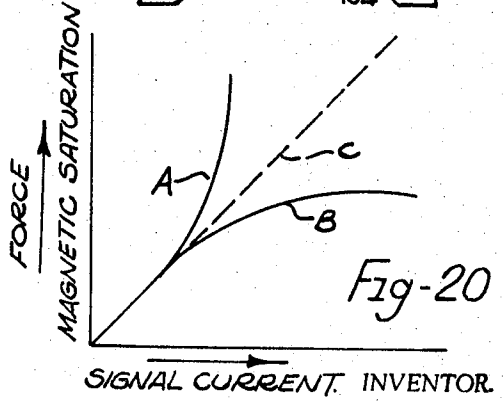


Fig-20

INVENTOR.
JOHN B. PEGRAM
BY
Nilsson & Robbins
Attorneys.

ELECTROMAGNETIC FORCE MOTOR HAVING ADJUSTABLE MAGNETIC SATURATION

BACKGROUND OF THE INVENTION

1. Field of the Invention

The fields of art to which the invention pertains include the fields of torque motors, fluid handling, valve and valve actuation.

2. Description of the Prior Art

The use of force motors in the prior art has long been known. One example of the utility of force motors is in the positioning of the pilot valve such as a flapper or spool of a hydraulic servovalve. The force motor in such applications is used as an element of a control system and is adapted by its operating characteristics to convert an electrical input signal into a desired mechanical position of the spool valve. Force motors also have a wide variety of other uses, for example, in automatic control systems for industrial machinery.

Such force motors typically utilize a large percentage of the air gap for armature motion. In various of the prior art applications it has long been desirable to provide force motors which bear a linear relationship to the applied input signal and wherein the force exerted upon the armature remains substantially linear as it approaches the pole faces. This would permit displacement of the armature over the entire gap.

A variety of schemes have been proposed to accomplish such linearization, for example, reducing the effective length or the cross-sectional area of a part of the armature and keeping that portion always saturated magnetically, as illustrated in U.S. Pat. No. 3,071,714. Another linearization scheme provides recesses on the face of the armature and a plurality of mating teeth on the face of the pole pieces, for example, as shown in U.S. Pat. No. 2,930,945. A more recent and improved method of linearization is described in application Ser. No. 565,237, filed Jul. 14, 1966 by Samuel A. Gray, entitled "Electromagnetic Force Motor Having Linear Output Characteristics," now U.S. Pat. No. 3,517,360.

Each of the foregoing devices utilizes magnetic saturation to obtain linearization. However, problems arise in manufacturing such torque motors. Variations in effective pole areas, magnetic saturation characteristics, leakage path variations, magnetic strength variations, hysteresis curve characteristics, normal production tolerances for air gaps, and the like, make the manufacture of acceptable devices very costly. There is a need, therefore, for a simple method of assuring the attainment of magnetic saturation appropriate to the linearization of the force versus input signal characteristic of the force motor.

SUMMARY OF THE INVENTION

The present invention enables the manufacture on a production basis of electromagnetic force motors in which the magnetic saturation of each motor is adjustable so as to linearize the force versus input signal characteristic of the motor and compensate for all manufacturing tolerances. The present invention provides means whereby the length and/or cross-sectional area of the saturation path may be adjusted during a test of the motor to appropriately modify the force versus input signal characteristic of each motor. A motor is provided of the electromagnetic force type, that is, having a pair of pole pieces spaced apart to provide an air gap therebetween, an armature within the air gap and permanent magnetic means defining a magnetic circuit. The improvement of this invention comprises providing at least one region of magnetically saturable material in the flux path of the magnetic circuit and providing a discrete member of magnetically permeable material for association therewith. The region of magnetically saturable material is constructed to define a magnetic saturation path and to define means for receiving the discrete member thereat to thereby decrease the length or cross-sectional area of the saturation path. At a selected armature position polarizing flux from the permanent magnet and signal coil is sufficient to magnetically saturate the region in the absence of the discrete member, but is insufficient to magnetically saturate portions of the region that are occupied by the discrete member.

In particular embodiments, a plurality of magnetically saturable regions is provided and a plurality of discrete members therefor. With appropriate adjustment, the magnetically saturable regions and discrete members define a plurality of discrete sections, each section being magnetically saturable at a predetermined level of magnetic flux density. The motor can be constructed so that the level of magnetic flux density at which the sections saturate is different for each section. The result is a linearization of force with input signal as each section is successively saturated.

The saturation-adjustable regions can be positioned within the armature of the motor, within one or both of the pole pieces, between the permanent magnets and the motor frame; i.e., any convenient locations.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a side elevational view of an electromagnetic force motor utilizing the present invention;

FIG. 2 is a top elevational view of the apparatus illustrated in FIG. 1;

FIG. 3 is a cross-sectional view taken about the line 3–3 of FIG. 2, in the direction of the arrows;

FIGS. 4—9 are plan and cross-sectional views, of a variety of particular magnetically saturable sections and insertable members therefor;

FIG. 10 is a top elevational view of an electromagnetic force motor constructed in accordance with another embodiment of the present invention;

FIG. 11 is an enlarged view of a portion of the apparatus illustrated in FIG. 10;

FIG. 12 is a view similar to that of FIG. 11 but of still another embodiment of this invention;

FIG. 13 and 14 are plan views of insertable members utilizable in the apparatus of FIG. 11 or 12;

FIG. 15 is a top elevational view of an electromagnetic force motor utilizing still another embodiment of this invention;

FIG. 16 is a cross-sectional view taken about the line 16–16 of FIG. 15, in the direction of the arrows;

FIG. 17 is an enlarged view of a portion of the apparatus illustrated in FIGS. 15 and 16;

FIG. 18 is a view similar to that of FIG. 17 but utilizing another embodiment of this invention; and

FIGS. 19 and 20 are curves illustrating operating characteristics of an electromagnetic force motor constructed in accordance with the present invention.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

Referring to FIGS. 1 through 3, there is illustrated an electromagnetic force motor constructed in accordance with one embodiment of the present invention. The force motor includes frame members 10 and 11 having a pair of permanent magnets 12 and 13 affixed thereto in any manner or means known to the art such, for example, as by brazing. At the upper surface of the frame members 10 and 11 there is affixed a pair of pole pieces 14 and 15. The pole pieces 14 and 15 are adjustable by way of loosening attaching bolts 16 and 17 therethrough and adjusting the position of the pole pieces 14 and 15 until they are of the desired relationship to an armature 18 disposed in the air gap formed between the faces of the pole pieces 14 and 15. The armature 18 is supported upon a support member 20 and may have any desired structure such, for example, as an elongated tube which flexes about a pivot point P to thereby position a flapper 21 which is used to control the position of a servovalve spool as above referred to. The mounting means 20 may be sealed by means of a conventional O-ring 22 to the base 23 as is well-known to the art. Positioned about the armature 18 is a coil 25 which is adapted to receive an electrical input signal and which thereby causes the armature to take a physical position depending upon the strength of the applied input signal and the polarity thereof.

Inserts 26, 27, 28 and 29 of magnetically saturable material are placed between the frame members 10 and 11 at respective ends of the permanent magnets 12 and 13. The inserts 26, 27, 28 and 29 define cavities therein, e.g., 30 and 31, threaded for the receipt of mating plugs 32, 33, 34 and 35 of magnetically saturable material, which plugs are threadable into the cavities by means of drive slots 36, 37, 38 and 39, respectively, therein. The plugs 32—35 can be of any appropriate magnetically permeable material of the same, greater or less permeability or saturation level as the surrounding material of the inserts 26—29.

As part of the manufacture procedure, the magnetically saturable plugs 36, 37, 38 and 39 are threaded into their respective cavities until completely inserted therein. The force versus input signal characteristic is then plotted by methods well-known to the art and will typically have an asymptotic curvature with respect to the force axis, until pole contact, representing rapidly increasing force with armature movement. The permanent magnets 12 and 13 provide sufficient polarizing flux to magnetically saturate those regions of the inserts 26—29 adjacent the cavities in the absence of the insert plugs 32—35, but the magnets provide insufficient polarizing flux to magnetically saturate portions of the inserts 26—29 occupied by the plugs 32—35. Although the intensity of the flux increases somewhat as the reluctance of the magnetic circuit decreases, this increase is insufficient to offset the relatively much larger increase in length or area of the flux path. Accordingly, when the plugs 32—35 are fully inserted, the inserts 26—29 are not magnetically saturated. The plugs 32—35 are then withdrawn until the force versus input signal obtains an S-shape, e.g., by uniformly withdrawing the plugs 32—35, partially from their cavities. The plugs 32—35 can then be individually adjusted so as to straighten out the S-shaping and linearize the force versus input signal characteristic. The basis of such adjustment will be discussed further with respect to FIGS. 19 and 20 and lies in providing varying lengths of unoccupied cavities in the inserts 26—29. Thus, discrete regions of varying cross-sectional areas are provided. As the flux density increases upon movement of the armature 18 toward one or the other of the poles 14 or 15, that discrete region having the smallest cross-sectional area is first driven into saturation. Each of the regions of magnetically permeable material that is progressively greater in cross-sectional area is then sequentially magnetically saturated to produce a stair-step type relationship between flux increase and armature displacement. By proper adjustment of the length of the cavities, a substantially linear force versus input signal curve can be obtained.

In place of the cylindrical plugs 32—35, one can utilize plugs of a variety of configurations, as illustrated in FIGS. 4—9. In each of the FIGS. 4—9, the direction of the flux path is shown by the arrows 36. FIGS. 4*a* and 4*b* show plan and cross-sectional views, respectively, of an insert 38 and plug 40 of square cross-sectional configuration that may be substituted for any of the inserts 26—29 or plugs 32—35 of FIG. 2. A generally longer length of saturation path will thereby be obtained. The plug 40 is pressed into the insert 38 and can be forcefully slid to a frictionally retained position. The same arrangement can be utilized for the plugs 32—35, rather than the screw-fit described above; or any other retention means can be utilized which allows the plugs to be raised or lowered as described.

Another alternate configuration is shown in plan and cross-sectional views in FIGS. 5*a* and 5*b*, respectively, wherein the insert 42 is formed to accommodate a trapezoidal-shaped plug 44. A generally longer saturation path is thus provided than with the plugs 32—35 of FIG. 2. The shaping of the plug 44 imparts a particular unique shape to the force versus input signal characteristic.

Alternatively, as shown in plan and cross-sectional views in FIGS. 6*a* and 6*b*, respectively, one may provide an insert 46 formed to accommodate a plurality of strip-shaped plugs 48, 50 and 52 which can be independently raised or lowered to obtain very long saturation paths with a variety of unique force versus input signal characteristics.

FIGS. 7*a* and 7*b* shown plan and cross-sectional views, respectively, of an insert 54 formed to receive a plug 56 of triangular cross section to provide a still different force versus input signal characteristic.

FIGS. 8*a* and 8*b* show plan and cross-sectional views, respectively, of an insert 58 formed to receive a rotatable vanelike plug 60. FIGS. 8*c* and 8*d* show cross-sectional views of the insert 58 and vanelike plug 60 in alternative rotational positions. The saturation area can be varied by rotating the plug 60 and/or lowering or raising the plug 60 with respect to the insert 58.

FIGS. 9*a* and 9*b* show plan and cross-sectional views, respectively, of an insert 62 formed to accommodate a slotted plug 64 therein. FIGS. 9*c* and 9*d* show alternative positions of the slotted plug 64 in the insert 62. With the plug 64 positioned as shown in FIG. 9*c* a short saturation path is provided of relatively small cross-sectional area. In the position shown in FIG. 9*d*, a relatively long saturation path is provided with a relatively large cross-sectional area. The cross-sectional area of the saturation path can be varied by raising or lowering the slotted plugs 64 and both the cross-sectional area and the length of the saturation path can be varied by rotating the plug 64.

Referring to FIGS. 10 and 11, still another alternative embodiment of this invention is illustrated. An electromagnetic force motor is constructed that is similar to the motor of FIGS. 1—3 but in which the permanent magnets 66 and 67 directly abut frame members (not shown) that support poles 68 and 69, by means of attaching bolts 70 and 71, to define an air gap with an armature 72 therein.

In the embodiment of FIGS. 1—3 plugs 26—29 were provided between the permanent magnets 12 and 13 and the frame members 10 and 11. In contrast, in the embodiment of FIGS. 10 and 11, adjustable plugs 73 and 74 are provided on the armature 72. The plugs 73 and 74 are shown threadable in and out of pockets 75 and 76, respectively, therefor but may be formed to be threadable therein. By threading the plugs 73 and 74 in and out of the pockets 75 and 76 therefor, one can vary the cross-sectional area of the saturation path in the armature to achieve desired force versus input signal characteristics.

FIG. 12 depicts an embodiment wherein an armature 77 is positioned between poles 78 and 79 therefor in a manner similar to the embodiment of FIG. 11 but wherein pockets 80 and 81 and plugs 82 and 83, respectively, therefor are uniquely shaped to obtain particular force versus input signal characteristics. The plugs 82 and 83 are shaped so that different lengths of saturation paths are encountered therealong. FIGS. 13 and 14 illustrate still other alternative configurations for plugs 84 and 85 that can be substituted for the plugs 82 and/or 83 to obtain other unique force versus input signal characteristics. Note, that the plug 85 depicted in FIG. 14 is shaped to provide a geometrically decreasing saturation path length during insertion thereof. Each plug of FIGS. 12, 13 and 14 are merely inserted in a relatively easy fitting pocket and seated in. Pressfit plugs could be utilized, but it should be noted that it is generally undesirable to use pressfit plugs in the armature in view of the resultant widening of the hysteresis loop upon the consequent hardening of the armature.

Referring to FIGS. 15 through 17, there is illustrated an electromagnetic force motor constructed in accordance with still another embodiment of the present invention. Here too, the force motor includes frame members 86 and 87 having a pair of permanent magnets 88 and 89, but they directly abut the frame members 86 and 87. At the upper surface of the frame members 86 and 87 there is affixed a pair of pole pieces 90 and 91 which are adjustable, by means of loosening attaching bolts 92 and 93, to the desired relationship to an armature 94 disposed in the air gap formed between the faces of the pole pieces 90 and 91. Here too, the armature 94 is supported upon a support member 95 about a pivot point P to thereby position a flapper 96.

The pole faces of the pole pieces 90 and 91 are arranged to provide a substantially linear force versus signal current

characteristic to the electromagnetic force motor. With particular reference to FIG. 17, each pole 90 and 91 has provided therein a plurality of discrete threadable plugs 97 received in threaded pockets 98 (FIG. 16) therefor. Each plug 97 is provided with a drive slot 99 and is threadable into its pocket 98, each independently of the other, as shown more clearly in FIG. 16. Since each of the discrete regions defined by the particular plug 97 and pocket 98 therefor has a different cross-sectional area, the regions will be driven into saturation at different points in time by the polarizing flux provided by the permanent magnets 88 and 89 signal coil. In this particular embodiment, the plugs 97 are disposed so that the polarizing flux is not sufficient to drive any of the discrete regions defined by the plugs 97 into magnetic saturation when the armature 100 is centered. However, upon the application of an electrical signal to the coils, for example, each as to polarize the upper portion of the armature 100 as a south-magnetic pole, and assuming that the pole piece 90 is magnetized to be a north-magnetic pole, then the armature 100 moves toward the pole piece 90. As this movement occurs, the flux density between the armature 100 and the pole piece 90 increases. As the flux density increases, the magnetically saturable material in the discrete plug 97 regions sequentially become saturated in a predetermined manner. Thus, as the flux density begins to increase, that discrete region having the smallest cross-sectional area of magnetically permeable material is the first driven into saturation and then each of the regions of progressively greater cross-sectional area goes sequentially into magnetic saturation. In terms of the plugs 97, as the flux density begins to decrease, those pockets 98 having the least penetration by its plug 97 is first driven into saturation and then each of the pockets 98 having progressively greater penetration by their plug 97 goes sequentially into magnetic saturation.

By such means, discrete regions of varying cross-sectional areas can be provided and with appropriate stepping, as indicated in application Ser. No. 565,237, referred to above, stepwise linearization of the force versus input signal characteristic can be obtained. The great advantage of this invention is that the saturation sequence can be very accurately controlled. A plurality of determinations of force versus input signal characteristics can be coordinated with individualized adjustment of the depth of penetration of the plugs 97 into the pockets 98. The resultant sequence is illustrated in FIG. 19. Upon the application of the current signal the flux density present in the pole piece 90 increases as the armature 100 approaches its pole face. As the flux density approaches the first arbitrary point such as that shown at 101, a discrete region, for example at 97*a*, has reached saturation and therefore no longer has any capability of increasing the pulling force on the armature 100. As the armature, however, continues to approach the pole face of the pole 90, a second flux level such as that shown at 102 is reached at which, for example, the region at plug 97*b* goes into magnetic saturation. This produces a stair-step type curve which, however, by the proper selection and adjustment of the plugs 97 is substantially linear as is illustrated in FIG. 19.

As an additional manner of illustrating the principal upon which this embodiment is based, reference is made to FIG. 20 which is a graph illustrating force and magnetic saturation on the ordinate and input signal current on the abscissa. Curve A represents the typical force curve of prior art electromagnetic force motors showing the nonlinear relationship of the force to the input signal current. Curve B on the other hand represents the overall magnetic saturation of the various sections of the pole 90 superimposed over the curve A. By adding these two curves A and B one then obtains curve C shown in dashed line which is a substantially linear force versus signal current relationship.

The various discrete adjustable regions of magnetically saturable material need not necessarily be disposed in the poles as shown in FIGS. 15—17 but may be disposed in the armature, and this is illustrated in FIG. 18. As is therein shown, the armature 103 is positioned between the pole faces of a pair of oppositely disposed poles 105 and 109. However, in this embodiment, the armature 103 has disposed therein a plurality of threaded pockets and plugs 104 therefor of magnetically saturable material, each being individually adjustable to penetrate into its pocket a different length to provide different cross-sectional areas taken normal to the lines of magnetic flux so that each of the regions thereat saturate at a different point as above described.

In each of the alternative embodiments of an electromagnetic force motor constructed in accordance with the present invention it should be recognized that the magnetic circuit has inserted therein an adjustable dynamically varying reluctance the value of which depends upon the flux density present in the magnetic circuit. The polarizing flux from the permanent magnets and signal coil is sufficient to magnetically saturate the plug regions at least at some selected armature position within the air gap and the absence of the plug therein, but is insufficient to magnetically saturate portions of the regions occupied by the plug at that armature position. By utilizing structures of the present invention, the fringing flux normally present at the force motor gaps changes much less with the position of the armature than with ordinary torque motors. Thus, the overall efficiency and force-output of an electrical force motor in accordance with the present invention is substantially increased.

I claim:

1. In an electromagnetic force motor having a pair of pole pieces spaced apart to provide an air gap therebetween;
- an armature positioned with a portion thereof in said air gap, said armature being adapted to move in said air gap from a neutral position thereby more closely approaching one of said pole pieces;
- a magnetic circuit in said motor including said pole pieces, said armature and a permanent magnet means, said permanent magnet means providing polarizing flux;
- electrical signal receiving means operatively associated with said magnetic circuit to establish magnetic flux therein of a strength proportional to a received electrical signal;
- the improvement of apparatus for enabling adjustment of force versus input signal characteristic, comprising: and
- at least one region of magnetically saturable material disposed in the flux path of said magnetic circuit, said region defining a magnetic saturation path thereat;
- a discrete member of magnetically permeable material;
- said region defining means for receiving said discrete member thereat to thereby vary the length or cross-sectional area of said saturation path;
- said permanent magnet polarizing flux and signal receiving means magnetic flux being sufficient to magnetically saturate said region at a selected armature position within said air gap in the absence of said discrete member, but being insufficient to magnetically saturate those portions of said region that are occupied by said discrete member at that armature position.

2. An electromagnetic force motor as defined in claim 1 in which said means for receiving said discrete member is a cavity defined by said region, said discrete member being insertable in said cavity.

3. An electromagnetic force motor as defined in claim 1 in which said magnetically saturable region is positioned within said armature.

4. An electromagnetic force motor as defined in claim 1 in which said magnetically saturable region is positioned within one of said pole pieces.

5. An electromagnetic force motor as defined in claim 1 which further includes a frame member securing said pole pieces in operative association with said permanent magnet means, said magnetically saturable region being disposed in said magnetic circuit between said frame member and said permanent magnet means.

6. An electromagnetic force motor as defined in claim 1 wherein there is a plurality of said magnetically saturable regions and a plurality of said discrete members of magnetically

permeable material each independently receivable at respective ones of said regions.

7. An electromagnetic force motor as defined in claim 1 wherein there is a plurality of said magnetically saturable regions and a plurality of said magnetically saturable regions and a plurality of said discrete members of magnetically permeable material receivable at respective ones of said regions to thereby provide a plurality of discrete sections, said sections

being magnetically saturable each at a different level of flux density.

8. An electromagnetic force motor as defined in claim 7 wherein each of said plurality of discrete members is receivable independently of the others of said plurality of discrete members.