

March 15, 1966

D. BOYKO

3,241,006

ELECTROMAGNETIC ACTUATOR

Filed July 2, 1963

FIG. 1.

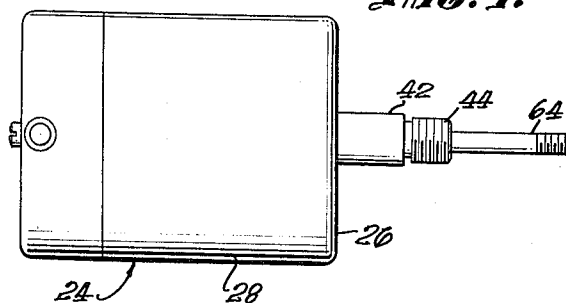


FIG. 2.

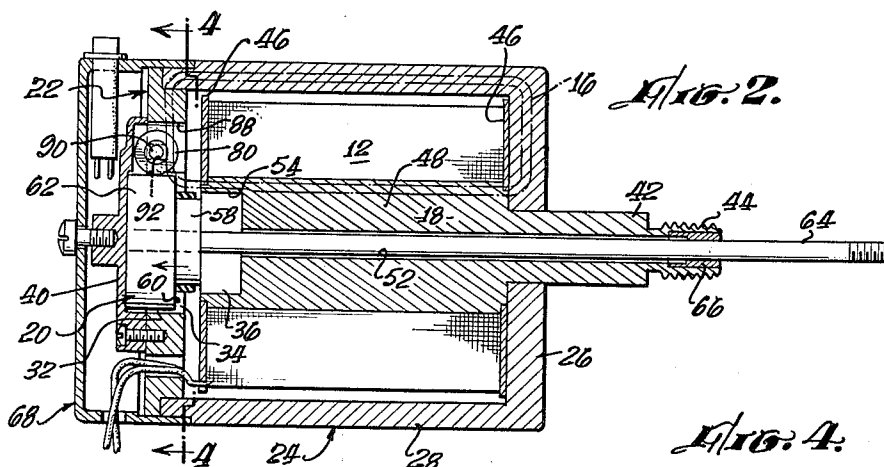


FIG. 4.

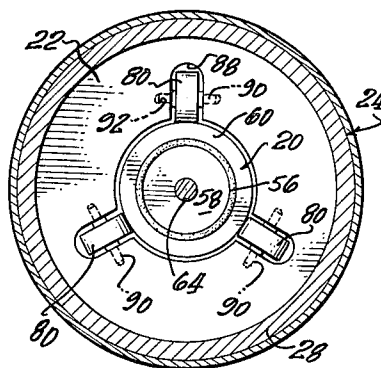
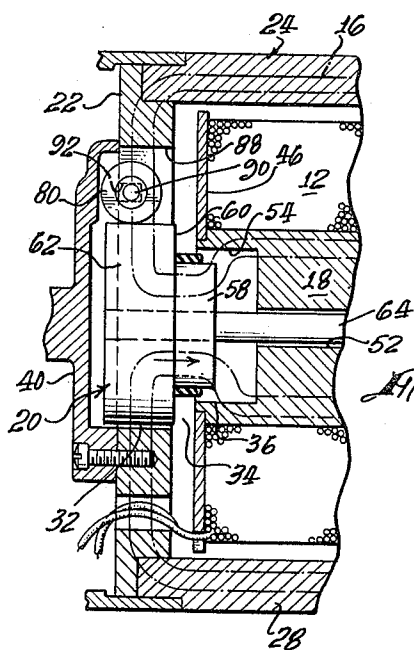


FIG. 3.

DONALD BOYKO,
INVENTOR.By *Lynn H. Latta*
ATTORNEY

1

3,241,006

ELECTROMAGNETIC ACTUATOR

Donald Boyko, Pasadena, Calif., assignor to D.B. Products, Inc., a corporation of California
Filed July 2, 1963, Ser. No. 292,343
10 Claims. (Cl. 317-199)

This invention relates to transducers and solenoids for converting electrical energy to linear mechanical force and has as its general object to provide a solenoid which provides a substantially constant output force throughout its movement range.

Electromagnetic operators of the solenoid type are generally characterized by a coil encircling a cylindrical core arbor of magnetic material fitted with a plunger type armature which is drawn into the core arbor when current is supplied to the coil. A standard method of using such an operator is to attach the object to be operated to the armature so that movement of the armature causes a corresponding movement of the thing operated thereby.

Prior art electromagnetic operators are characterized by a highly variable output force over their movement range. A typical prior art operator would have relatively little force at the beginning end of stroke where the armature is away from the solenoid coil arbor, and an extremely high force capable of causing life-shortening impact and strain at the end of the stroke where the armature is adjacent or in contact with the solenoid coil arbor. Where a constant force application is desired, as for any kind of proportional linear control, the relatively short part of the stroke where the force is approximately constant, must be utilized. This linear movement, constant force range is so short in most prior art operators that is severely limits the utility of such an operator for control uses.

The present invention has as its general object to provide an electromagnetic operator having a substantially constant output force throughout its movement range. The invention provides an electromagnetic operator embodying a means for shunting magnetic flux lines across a neutral force path so as to provide a substantially constant output force throughout its movement range.

More specifically the invention provides an electromagnetic operator of the solenoid type with an armature and coil arbor structure for shunting flux across a neutral force path so as to provide a substantially constant output force throughout its linear movement range in addition to providing increased linear movement range and greater life expectancy.

In accordance with the preferred embodiment of the invention the armature and coil arbor structure of the electromagnetic operator are provided with connected axial and radial air gaps which interrupt the magnetic circuit of the operator. The axial gap contains the actuating flux which provides the operating force and the radial gap serves as a variable flux-shunting path across a balanced or neutral force path.

A primary feature of the present invention involves electromagnetic armature and coil arbor members movable in relation to each other so as to close an axial gap between them while maintaining a substantially constant force between their gap faces as the gap is closed.

The novel features which are believed to be characteristic of the invention both as to its organization and method of construction and operation, together with further objects and advantages thereof, will be better understood from the following description, considered in connection are disclosed by way of example. It is to be expressly understood that the drawing is for the purposes of illustration and description only and does not constitute a limitation of the invention.

2

In the drawing:

FIG. 1 is a plan view of a solenoid embodying the invention;

FIG. 2 is a longitudinal sectional view of the same, with the armature in the deenergized, retracted position;

FIG. 3 is a fragmentary axial sectional view of the same, on an enlarged scale, showing the armature in an energized, projected position; and

FIG. 4 is an end view of the inner faces of the armature and the housing end plate around the armature.

Electromagnetic operators including the familiar solenoid work on the principle that magnetic flux lines will seek the lowest reluctance path possible to complete a magnetic circuit. Reluctance is a measure of the resistance to magnetic flux. Therefore if an armature of magnetic material characterized by a low reluctance in relation to air is placed in a magnetic circuit in such a way that it completely closes the magnetic circuit, flux lines will seek a circuit-completing path through such armature in preference to an alternate higher reluctance path through the air.

When there is an air gap in a circuit of magnetic material, flux lines will flow from one surface of the gap to the other. Such flux line flow will create a magnetic force between the faces which is proportional to the number of lines of force passing through a unit area of each of the gap surfaces. An increase of flux lines per unit area, called flux density, will increase the magnetic force between the surfaces and vice versa.

In the case of an armature which partially completes a magnetic circuit except for a small air gap, all of the flux lines in the circuit will not pass between the armature face and pole faces comprising the gap. Furthermore, many of the lines which do cross the gap out of one face into the other will not leave and enter normal to the faces. Thus the attractive force between the surfaces of the gap will not be proportional to the total number of flux lines flowing in the magnetic circuit, and this will result in a force less than the maximum possible for the surface areas of the gap and the total number of flux lines flowing in the circuit. If the armature is free to move and the gap is sufficiently small so that this lesser than maximum force is sufficient to move the armature, the armature will be pulled toward the pole face.

This movement will lower the reluctance of the gap and cause more flux lines to pass between the gap surfaces of the armature and coil arbor and will cause other flux lines to straighten, and enter and leave the surfaces in a direction normal to the surfaces. This increase in the number of flux lines passing between the surfaces, and normal to them, increases the attractive force between the armature and coil arbor faces which in turn increases the number of flux lines. This cumulative action causes the force to increase exponentially as an inverse function of gap space until the force may reach explosive proportions just before the gap is closed by contact between the surfaces. Thus the force during operation ranges from a very small force to a very large force.

In a standard electromagnetic operator the number of lines of flux in the magnetic circuit is called the flux density, and is determined by the number of turns in the electromagnetic coil and by the number of amperes flowing in the coil. Usually the coil is connected to a fixed voltage source so that the number of ampere turns and hence the flux density is constant.

With a constant flux density in the magnetic circuit, the operation of a magnetic operator will be as described above and the operating force will vary through a very wide range. For many applications this large force variation is very undesirable. In many cases it is necessary to have a substantially constant force over a rela-

tively wide range of linear movement. The present invention makes this possible.

In the present invention a standard solenoid coil 12 serves as a magnetic flux generating source. The coil is wound with sufficient turns of conductive wire to create the desired magnetic field when a predetermined current is applied to its terminals. The generated flux 16 is confined to a well defined path determined by the configuration of a low reluctance (in relation to the surrounding medium e.g. air,) magnetic circuit comprising the coil arbor member 18, an armature member 20, an end plate 22 and a coil housing 24. Magnetic ingot iron has been successfully used for these parts in an experimental model. In the present invention, the magnetic circuit can operate with a constant flux density predetermined by the number of ampere-turns in the coil 12.

As is shown in the cross-sectional view of FIG. 2, flux lines 16 generated in the center of the coil 12 flow axially along the coil arbor member 18, radially in the annular end disk 26 of the coil housing 24, along the tubular lateral wall 28 of the coil housing, down the end plate 22, across a constant reluctance gap 32 between the end plate 22 and the armature member 20, and then axially along the armature member 20 until they encounter two interconnecting variable reluctance gaps 34, 36 (FIG. 3) which control the operation of the present invention.

As was pointed out above, the attractive magnetic force across a gap is proportional to the number of flux lines crossing the gap per unit of surface area, and entering both surfaces in a normal direction. The number of flux lines acting in this way is in turn dependent on the reluctance of the gap in relation to alternate paths which the flux lines are able to take. The reluctance of a particular gap in a magnetic circuit is dependent on several variables including the permeability of the gap material, e.g. air, the separation of the gap surfaces, the shape of the gap surfaces, and the area of the gap surfaces. In the present invention the gap surfaces are parallel and the material used in all gaps is air, therefore the important variables are the separation of the gap faces and the aggregate surface area of the opposing gap faces. If both of these are constant then the reluctance of the gap is constant. If either varies, then the reluctance of the gap varies. The gap 32 between the end plate and the armature member is a substantially constant reluctance gap because both the gap separation and the gap surface area are substantially constant as devices are provided to maintain constant gap separation and a substantially constant area of the armature surface is always presented to the opposing end plate gap surface.

However, the two interconnecting gaps 34, 36 between the armature member 20 and the coil arbor member 18 are not constant reluctance gaps. As is described in detail below, the armature 10 and coil arbor 18 members are adapted for axial movement relative to each other and the reluctance of both gaps 34, 36 varies in accordance with the relative movement between the members.

The means by which these variable reluctance gaps 34, 36 control the operation of the invention herein described is best understood by reference to the physical configuration of the parts relating to the gaps.

Referring to the drawings in detail there is shown therein, as an example of one form in which the invention may be embodied, an electromagnetic operator embodying generally a coil 12, a coil housing 24, a coil arbor member 18, a movable armature member 20 and housing 40 therefor.

A coil arbor 18 of magnetic material suitable for forming the magnetic core of a standard solenoid coil is provided with a shank 42 on one end, terminating in a bearing gland 44. Suitable flanges 46 are provided for retaining the coil on the body of the arbor 18 adjacent the shank. These flanges may be thin washer-like disks of aluminum or other non-magnetic material.

Coil arbor 18 has an axial bore 52, and a counterbore 54 at the inner end thereof. The cylindrical inner surface of counterbore 54 functions as one face of the annular cylindrical gap 36, the other face being provided by the cylindrical periphery (FIG. 3) of a reduced neck 58 which constitutes the inner end portion of armature 20. A flat radial annular shoulder 60 occurs as an offset between the peripheral surface of neck 58 and the cylindrical periphery of an enlarged head 62 which constitutes the outer end portion of armature 20. This cylindrical surface of head 62 forms one face of the constant-reluctance gap 32. The radial shoulder 60 forms one face of the variable axial gap 34, the other face of this gap being provided by the adjacent end of coil arbor 18. Magnetic ingot iron has been successfully used in an experimental model for the armature 20 and arbor 18 as well as for the other parts making up the magnetic circuit of the operator.

An actuator rod 64 is axially secured to the armature member 20 as by press fit and extends outwardly from the neck 58. The rod 64 is slidably mounted in the arbor bore 52 with the neck 58 slidably associated with the counterbore 54 in constant annular gap relationship and the rod 64 extending through the plunger bore 52 and out the other end of the arbor 18 after slidably passing through the close fitting bearing surface of a bearing bushing 66 inserted in the threaded end 44 of the arbor 18. Said bearing 66 may be of oilite bronze or other suitable bearing material. The device to be actuated and controlled is suitably attached to the protruding end of the actuator rod 64.

When the neck 58 enters the counterbore 54 it forms the annular radial gap 36 between the neck 58 and the coil arbor counterbore 54 as one of the two variable reluctance interconnecting gaps 34, 36 referred to above. The radial gap 36 does not appear in the usual electromagnetic operator. Its function is to shunt flux, as the armature member 20 is drawn toward the coil arbor member 18, in order to prevent the exponential force buildup characteristic of the prior art. The gap separation of the faces of radial gap 36 is kept constant by maintaining coaxiality through supporting devices described in detail later. However, the surface area of the gap 36 increases as the neck 58 is inserted further into the counterbore 54 when the armature member 20 is drawn toward the coil arbor member 18. This increase in surface area of the radial gap 36 lowers its reluctance and causes the desired flux-shunting effect. It should be noted that the radial forces exerted between the armature neck 58 and core arbor surface 54 as the number of flux lines crossing the gap 36 increases, are equal and opposite around the circumference of the armature neck 58, and hence the net resultant force on the armature member 20 is neutral and has no effect on its movement. The only operating effect is the flux-shunting effect referred to above.

The axial gap 34 formed between the annular end surfaces of the arbor, is also a variable reluctance gap; however, unlike the radial gap 36 it has a constant surface area and a variable separation of gap faces. This constant surface area is equal to the surface area of the annular end of the core arbor cylinder. The gap 34 narrows as the armature head 62 moves closer to the end of the core arbor member 18. The attractive force which is developed across this gap is of course the actuating force of the electromagnetic operator. Without the flux-shunting effect of the radial gap 36, the actuating force developed across the gap 34 would undergo an exponential buildup as in prior art devices and the desired constant force output over a relatively wide range of linear movement would not be obtained.

In operation when the axial gap 34 is at a maximum (the armature head 62 being retracted) the coil 12 is designed to generate sufficient flux, when current is applied, to exert the desired actuating force on the armature 20.

5

This force will be kept constant as the armature head 62 is drawn toward the end of the coil arbor member 18. This force is proportional to the flux density across the axial gap 34. At this time the total flux lines 16 flowing in the magnetic circuit are dividing between the axial gap 34 and the radial gap 36. The axial gap 34 decreases as the armature member 20 moves toward the core arbor member 18 and consequently the reluctance of the gap 34 decreases. This would normally cause more of the total circuit flux lines to bridge the axial gap and thus increase the actuating force. However, as the axial gap reluctance decreases, so does the reluctance of the radial gap 36. This is because of the increased surface area of the radial gap 36 as the neck 58 enters more deeply in the counterbore 54. This action of the radial gap 36 causes the flux lines to continue to divide between the axial and radial gaps in approximately the same proportion, thus keeping the flux across the axial gap 34 approximately constant so as to result in approximately constant actuating force throughout the range of armature member movement. In practice the radial gap is also designed to compensate for end effects of the axial gap so the division of flux lines does not remain quite the same throughout the movement range.

It should be noted that another gap in the magnetic circuit is formed by the end face of the neck and the bottom of the counterbore 54; however, the length of the plunger and the cylinder depth are chosen so as to make the reluctance of this gap very much higher than the reluctance of the other gaps so that this gap is of little effect in operation as the force exerted across it is negligible due to the lack of flux lines bridging it.

To sum up the foregoing, the shunting effect diverts a portion of the flux field away from the radial gap 34, where the flux density would normally increase as the radial armature face 60 approaches the end of the pole piece (coil arbor 18). The diversion of flux may be sufficient to maintain substantially constant flux density in gap 34. On the other hand, in some installations, it may be desirable to have a small increase or decrease in axial force as the armature approaches "home" position (of maximum approach to arbor 18) which can be accomplished by suitably adjusting the relationships between the characteristics of gaps 34 and 36.

Referring now to FIG. 2 and the remainder of the structure, the coil housing 24 has two parts, the first comprising a short tubular section closed at one end by an annular disk 26 adapted to receive the shank 42 of the arbor 18 in close fitting relationship through its center hole. The other part consists of an annular end cap 68 adapted to cap the other end of the tubular section 28 and adapted to encircle the head 62 of the armature in slideable and supporting relationship. Said supporting relationship is accomplished by the use of at least three bearing rollers 80 spaced around the circumference of a circular opening in the end plate 22, through which the armature disk slides. These bearing rollers allow the armature head 62 to slide through the end plate 22 on roller bearing surfaces which serve the dual purpose of lessening friction and maintaining a constant annular radial gap 32 between the armature disk and the end plate. Since the end plate 22 is concentrically fastened to the end of housing cylinder 28, these roller bearings 80 serve to maintain the width of the radial gap 36 circumferentially uniform in order to produce the desired neutral force and flux shunting effect. If it were not for these roller bearings 80, the radial gap 36 would be of varying width around the circumference of the armature neck 58, thus causing the reluctance of the gap 36 to vary, and this would in turn apply non-balancing magnetic forces to the plunger in a radial direction and cause it to "seize" on the counterbore 54 as well as interfering with its intended controlled flux shunting effect. The end plate 22 and coil housing 24 also serve as a major portion of the magnetic circuit and provide a return path

6

for the flux lines 16 flowing across the gaps 32, 34, 36, between the armature and arbor members.

The armature cap 40 of non-magnetic material such as aluminum is provided to receive the armature head 62 when the armature member 20 is withdrawn from the arbor member 18 the maximum amount possible. This housing is axially and concentrically secured to the end plate 22 so as to seal off the movable armature member 20 from the outside environment. The face of the armature cap 40 contacting the end plate 22 has respective recesses 88 to receive the portions of the roller bearings 80 extending beyond the face of the end plate 22. The cap face is also adapted to act as a retainer for the axles 90 (FIG. 4) on which the roller bearings rotate. These axles are located in tangential slots 92 cut in the face of the end plate 22 to a depth equal to the diameter of the axles 90. The cover cap 68, of non-magnetic material, is used to close the end of housing 24 adjacent armature cap 40.

It is to be understood that the above described arrangements are illustrative of the application of the principles of the invention. Numerous other arrangements may be devised by those skilled in the art without departing from the spirit and scope of the invention. Thus by way of example and not of limitation, the electromagnetic operator may give constant force over a wide range of movement which is curved, the gap configurations may be changed or the gaps displaced from each other so that they are not interconnecting, the magnetic circuit may consist of materials of differing permeability throughout the length of the circuit, or different magnetic materials may be used. Accordingly, it is to be understood that the present invention is to be limited only by the spirit and scope of the appended claims.

I claim:

1. In an electromagnetic operator, in combination: a core and an armature relatively movable upon a common axis, said core including an arbor and a coil housing coaxially surrounding said arbor, said arbor and housing being secured together at their one ends, said arbor having at its other end a counterbore and said housing having at its other end an annular end plate spaced axially from said other end of the arbor and having an internal surface defining a central aperture therein; said armature including a head portion disposed within said end plate aperture and a neck portion in opposed relation to said arbor counterbore, said head portion defining a substantially radial shoulder adjoining said neck portion and in opposed, magnetically attracting relation to said other end of said arbor to provide an axial gap in which the major flow of magnetic flux effective for developing axial pull between the armature and core is developed; said neck being arranged to enter said counterbore as relative movement between the armature and core occurs, so as to develop a flux-shunting radial gap between said neck and counterbore in which magnetic flux between said armature and core is shunted to an extent which is minimal when the armature and core are at maximum spacing and which progressively increases as said armature and core approach one another, with an increase such as to provide a substantially constant pull between the armature and core throughout the range of relative movement.

2. The electromagnetic operator of claim 1, with the end face of said armature neck and the end face of said arbor arranged in parallel relation so as to form a variable separation axial gap across which the actuating flux passes between them.

3. The electromagnetic operator of claim 1, with the peripheral surface of said neck and the cylindrical inner surface of said counterbore in variably telescoping radial opposition to provide a variable area radial gap adapted to shunt from said axial gap an amount of flux substantially proportional to the amount of surface area in radially opposed relation in said radial gap.

7

4. An electromagnetic operator comprising: at least two members one of which is movable in relation to the other along a unidirectional axis; flux generator means for creating a substantially constant number of magnetic flux lines in said members; axial gap means for causing a designated amount of flux to pass between said members parallel to said unidirectional axis so as to actuate relative movement of said members; radial gap means operable with effectiveness progressively increasing with increased approach of said members for causing the remaining flux in said members to pass between said members transverse to said unidirectional axis at a rate such as to maintain the ratio of flux passing between the members in the axial direction and the transverse direction substantially constant.

5. The electromagnetic operator of claim 4 including an armature member and a coil arbor member movable in relation to each other along the longitudinal axis of the coil arbor, and flux generator means including a conductive coil adapted to encircle said coil arbor member.

6. The electromagnetic operator of claim 5 including axial gap means comprising substantially parallel surfaces on the armature and coil arbor members transverse to the longitudinal axis of the coil arbor separated by a relatively high reluctance gap, whereby said gap surfaces retain a constant area as the gap separation is varied; radial gap means comprising concentric cylindrical surfaces on the armature and coil members parallel to the longitudinal axis of the coil arbor separated by a relatively high reluctance gap, whereby said gap surfaces retain a constant gap separation as the surface area is varied; said axial and radial gap means each including parts carried respectively by said two members and operative in response to relative movement of said members to increase the surface area of the radial gap means as the axial gap separation is decreased.

8

7. An electromagnetic operator as defined in claim 1, wherein said armature head has an axially broad cylindrical surface disposed within said core end plate aperture in closely spaced, narrow-gap relation to the inner surface of said aperture such as to be operative in all positions of relative movement between the armature and core, to pass the flux between said end plate and armature head with minimal axial pull effect.

8. An electromagnetic actuator as defined in claim 7, wherein the internal surface of said core and plate defining said aperture is a substantially cylindrical surface of lesser axial extent than the opposed cylindrical surface of said armature head.

9. An electromagnetic actuator as defined in claim 8, wherein said actuator head is partially enclosed within said end plate aperture and partially projected outwardly of said end plate in the position of maximum separation of said armature and core.

10. An electromagnetic actuator as defined in claim 1, wherein the inner end face of said armature neck is disposed in a substantially radial plane which, in the position of maximum separation of said armature and core, is located externally of said counterbore so as to provide substantially no radial shunting of flux in said position.

References Cited by the Examiner

UNITED STATES PATENTS

2,859,298	11/1958	Burch	200—87
2,992,304	7/1962	Andrews	317—165
3,035,139	5/1962	Lindsay	317—191
3,142,788	7/1964	Gelenius	317—177
3,154,728	10/1964	Bordenet	317—177 X

BERNARD A. GILHEANY, *Primary Examiner*.
JOHN F. BURNS, *Examiner*.