Dec. 25, 1962 E. B. ROMBERG 3,070,024

MAGNETIC DRIVE

Filed Dec. 8, 1958 2 Sheets-Sheet 1

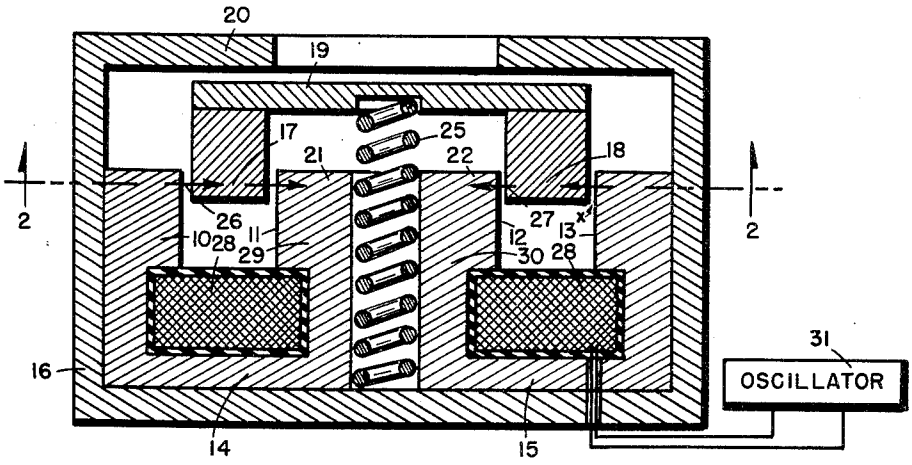


FIG. 1

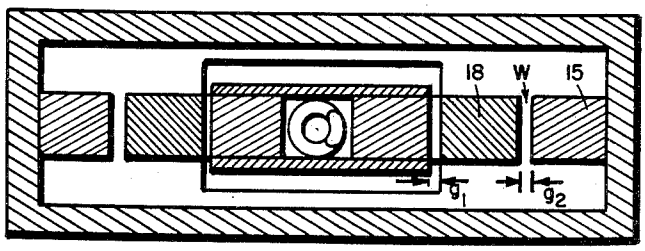


FIG. 2

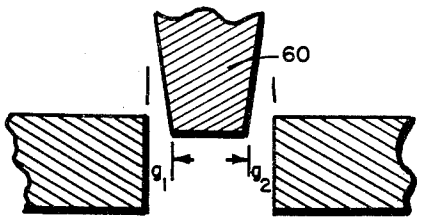


FIG. 3

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MAGNETIC DRIVE

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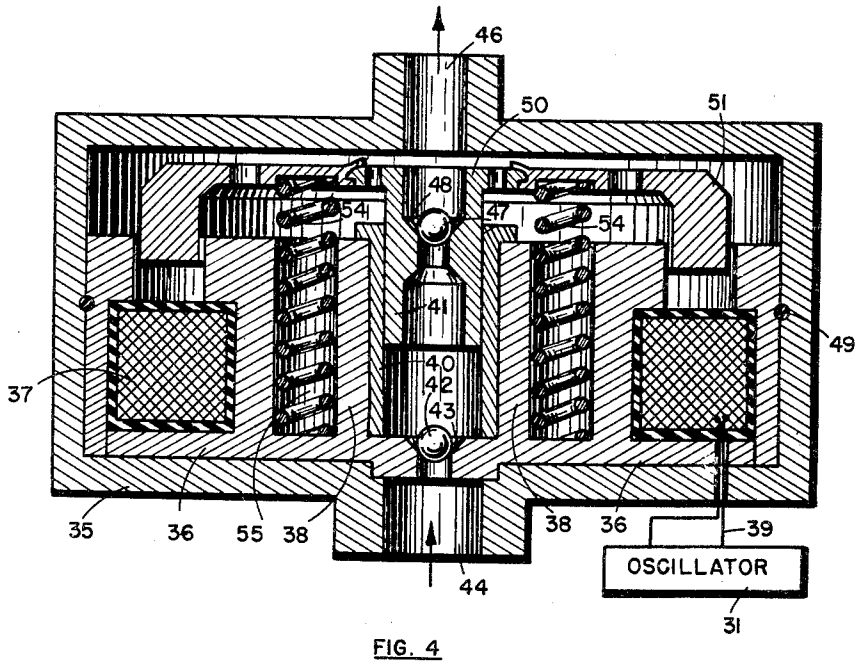


FIG. 4

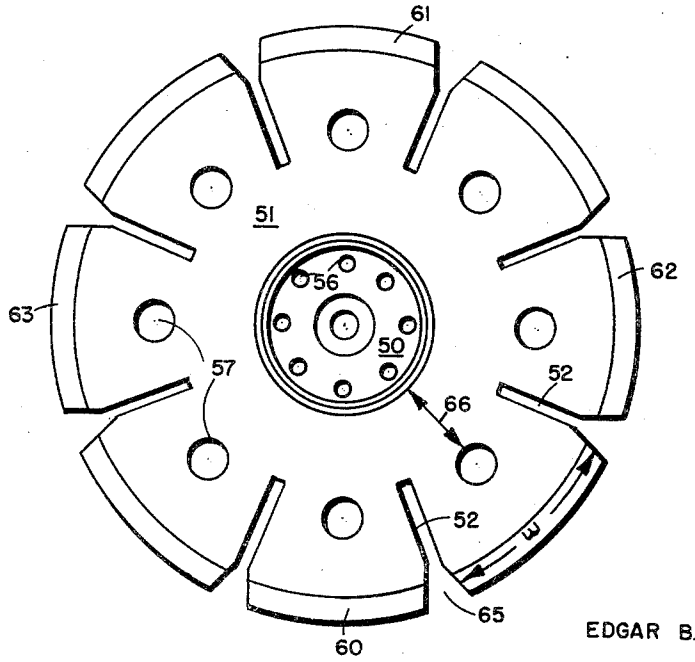


FIG. 5

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MAGNETIC DRIVE

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This invention relates to magnetic circuits, and more particularly concerns apparatus for electromagnetically driving a driven element with maximum efficiency.

Electromagnetic solenoid devices are commonly arranged so that the length of the air gap changes with motion of the armature. This results in a reluctance change and consequently provides a force which is proportional to the square of the displacement of the armature. With such an arrangement, there are excessive forces during part of the motion of the armature which inherently requires more input power and more core material and windings than is necessary to produce the force achieved at those positions where the gap length is maximum. Furthermore, in the magnetic circuits of most solenoid devices, the area of the air gap is generally relatively small as compared to the size of the core and windings whereby increased size, weight and cost are required.

In accordance with the present invention, there is provided a magnetic circuit in which the length of the air gap, or flaps, may remain fixed while the area of the gap, or gaps, is caused to change directly with armature motion. Thus, the reluctance of the magnetic circuit varies directly with the armature motion and a relatively constant magnetic force can be achieved. An armature is mounted for reciprocation within an air gap formed between two magnetic pole faces so as to replace such air gap with two smaller length gaps in series. In order to obtain maximum driving force for a given size of parts, a plurality of interconnected armature elments are utilized to provide a plurality of pairs of gaps in series whereby total gap area is substantially increased. The several armature elements are magnetically isolated from each other in order to minimize binding of the armature elements within the gaps due to the flow of flux between different armature elements.

In one embodiment, there is provided a toroidal or annular magnetic core having an annular magnetic gap. An armature ring of discontinuous magnetic material is mounted coaxially of the core for axial motion within the annular gap. Suitable means are provided to selectively or repetitively energize the core. For use as a reciprocating pump, this magnetic drive structure is provided with a piston secured to the armature ring and having a diameter considerably smaller than the diameter of the armature ring whereby maximum force is obtainable with a given amount of iron and copper in the core and its coil. The piston is, of course, operably mounted in a suitable fluid-containing chamber or cylinder and resiliently urged in a direction opposing the direction of the magnetic forces.

It is an object of this invention to provide a magnetic drive of increased efficiency.

A further object of the invention is to provide an improved fluid pump.

Another object of the invention is to provide a magnetic circuit of maximum gap area.

Still another object of the invention is to provide a magnetic circuit in which the reluctance will vary directly with relative motion of the parts.

A further object of the invention is to eliminate radial binding forces from a magnetic circuit having an annular armature.

A still further object of the invention is to provide a magnetically driven fluid pump in which the magnetic gap area is considerably greater than the piston area.

These and other objects will become apparent from the following description taken in connection with the accompanying drawings in which:

FIG. 1 depicts a structure illustrating certain principles of the invention;

FIG. 2 is a section on line 2—2 of FIG. 1;

FIG. 3 illustrates an arrangement for varying the linearity of the reluctance;

FIG. 4 shows a fluid pump constructed in accordance with the concepts of the invention;

And FIG. 5 is a second view of the armature of the pump of FIG. 4.

In the drawings, like reference characters refer to like parts.

Referring now to FIGS. 1 and 2, there is shown a magnetic drive comprising an electromagnet forming first and second pairs of opposing mutually-spaced magnetic pole faces 10, 11 and 12, 13, provided by magnetic cores 14, 15, which are of substantially C-shaped configuration. As illustrated, the cores 14, 15 may be suitably affixed to a case or support 16. A pair of armature elements 17, 18 are mounted for reciprocation between the pole face pairs 10, 11 and 12, 13, respectively. The armature elements 17, 18 are rigidly or fixedly interconnected by an arm 19 which is positioned to abut a top wall 20 of the case 16 in the upper limiting position of the armature and to abut the surfaces 21, 22 of the cores 14, 15 in the lower limiting position. The armatures 17, 18 are of any suitable low-reluctance magnetic material while the arm 19 is formed of high reluctance or a non-magnetic material to minimize or prevent flux flow between the armatures. The armature assembly 17, 18, 19 is resiliently urged to the upper limiting position thereof by any suitable means such as spring 25 mounted to abut at its respective ends the arm 19 and the bottom wall of case 16.

Means are provided for repetitively energizing the cores 14, 15 to provide a flux flow such as in the directions indicated by arrows 26, 27 (or in directions opposite to those indicated) between the faces of each pair of pole faces in substantially alined but in opposite directions. Specifically, a winding 28 is wound about the legs 29, 30 of cores 14, 15 and connected to be cyclicly energized by some suitable source of fluctuating electrical energy such as the oscillator 31. The oscilllator 31, for example, may be a conventional 60-cycle supply. It will be readily appreciated that a direct-current source may be utilized by providing a normally closed switch arranged to be opened upon downward motion of the armature as is well known in the art.

It will be seen that the relatively long gap between pole faces 12, 13 is replaced by a pair of gaps g_1 and g_2 in series each of which is of an unvarying length during reciprocal motion of the armature. Upon energization of the coil 28, the force f, tending to pull the armature further down into the gap, is given by the expression

$$f=KNI\frac{d\phi}{dx} \tag{1}$$

where K is a constant, N is the number of turns of the coil, I is the current flow in the coil, ϕ is the total number of flux lines linking the coil and x is distance measured in the direction of armature motion. The quantity ϕ is defined as

$$\phi=\frac{.4\pi NI2A}{g}=\frac{.4\pi NI2wx}{g} \tag{2}$$

where g is the total gap length (g_1+g_2) and A is the gap area which is the product of gap width w and the distance x of penetration of the armature into the gap. Substitution of Equation 2 into Equation 1 yields

$$f=\frac{K_1(NI)^2}{g}\cdot\frac{dx}{dx} \qquad (3)$$

where K_1 is a constant including the term $.4\pi w$. Examination of Equation 3 indicates that the magnetic force is constant for a constant gap length.

It is desirable in the arrangement of FIGS. 1 and 2 that each armature element be centered within the long gap formed by the cooperating pole faces so that the series gaps g_1 and g_2 are equal. A difference in length of gaps g_1 and g_2, in the illustrated arrangement utilizing a plurality of armature elements, would cause increased lateral forces tending to displace the armature in one direction or the other toward an adjacent magnetic pole face. For example, if the armature **18** were displaced toward the right in FIG. 1, flux would flow across gap g_2 from pole face **13** to armature **18**, thence through the arm **19** (if it were low magnetic reluctance) to armature element **17** and across the narrow gap to the pole face **11** of core **14**. Thus, the lateral radial forces would be inordinately increased by the use of plural armature elements if the connecting arm **19** were not of high reluctance material.

It will be seen that the arrangement illustrated in FIGS. 1 and 2 provides a force which does not vary during the length of the stroke of the armature and at the same time provides a substantial increase in gap area by providing plural armature elements each with two working gaps g_1 and g_2. It will be readily appreciated that additional symmetrically disposed armature elements may be provided for cooperation with additional pairs of magnetic pole faces. Such an arrangement is illustrated in FIGS. 4 and 5 which show the concept of this invention as applied to a reciprocating fluid pump. Mounted within a completely closed, sealed pump housing **35** is a toroidal or annular core **36** which is of substantially C-shaped cross section. A toroidal coil **37** is wound about the inner annular leg **38** of the core. The coil is connected to an oscillator **31** via leads **39** extending through suitable apertures in the housing **35** and the core **36**. Coaxially fixed within the core **36** is cylinder sleeve **40** in which is reciprocably mounted an axially bored piston **41**. The fluid chamber, or cylinder, is provided with a unidirectional inlet valve comprising ball **42** and valve seat **43** for communication with an inlet port **44** formed in the housing **35**. An outlet port **46**, formed in the housing **35**, is in fluid communication with the interior of the cylinder which receives fluid upon the downward (intake) stroke of the piston through a unidirectional valve comprising a ball **47** and a valve seat **48** formed within the piston **41**. Suitable means such as the O-ring **49** is provided to seal the inlet port **44** from the cylinder pressure chamber.

The piston is formed with circumferential flange **50** to which is fixedly secured, as by swaging, an annular armature ring **51** of discontinuous magnetic material. The magnetic discontinuities of the armature ring **51** are provided by a plurality of radial slots **52** which may, if desired, extend completely to the piston flange **50**. Resilient means which may be a single annular spring, or the illustrated plurality of springs **54**, are mounted in apertures **55**, bored in the core **36** to abut the surface of the armature **51**. A plurality of apertures **56**, **57** are formed in the piston flange **50** and the armature ring **51** in order to decrease the viscous drag on the piston and armature.

It will be seen that the annular armature **51** in effect comprises a plurality of armature elements arranged in diametrically-opposed pairs **60—61**, **62—63**, etc., each of which pairs is substantially similar to the single armature element pair **17—18** of FIGS. 1 and 2. The slots **52**, which provide a high reluctance magnetic path between the several armature elements, are wedge shaped as indicated at **65**, in order to equalize gap width w of the gaps g_1 and g_2 on the radially inner and outer sides of the individual armature elements. It has been found that it is not necessary to extend the high reluctance slots **52** the full distance to the center of the armature since it is merely

necessary to minimize the cross-sectional area of the flux path **66** between the respective armature elements. The thickness of the portion **66** of the armature ring **51** is made small enough so as to effect saturation thereof when the coil is energized.

For a pump such as illustrated in FIG. 4, which is particularly adapted to provide pressurized fluid to aircraft carried instruments such as gyroscopes and distance meters, the energization of the coil may be most conveniently effected by utilizing a synchronized bistable multivibrator or flip-flop as the oscillator **31**. This is desirable by reason of the fact that the conventional aircraft power supply of 400 c.p.s. is of too high a frequency for optimum operation of such a pump. It has been found convenient to operate a pump such as that illustrated in FIG. 4 having a housing diameter on the order of 1 inch at a frequency of about 10 cycles per second by the use of a flip-flop which energizes the solenoid coil for a period such as 20 percent of the cycle. The 20 percent energizing period of the 10 c.p.s. frequency is chosen so as to be just long enough to pull the armature fully down into the annular gap of the core to complete the intake stroke. During the following 80 percent of each cycle, the springs return the armature and piston to their upper limiting position (in abutment with the top wall of the casing **35**) for the pumping stroke. A pump such as illustrated in FIG. 4, providing an output pressure of 20 to 40 pounds per square inch, has operated over five-thousand hours without appreciable wear. Such long life may be attributed largely to the minimization of the radial forces which are largely eliminated by the discontinuity of the annular armature.

On the intake stroke, the springs are compressed. The force exerted thereby increases to some extent. Consequently, for the highest efficiency, the magnetic forces acting against the spring forces should increase in proportion. Thus, each of the armature elements **60** through **63** may be tapered as illustrated in FIG. 3 so that the gap lengths g_1 and g_2 will decrease during the intake stroke of the pump in direct proportion to the increase in spring force. With such an arrangement, the magnetic force can at all times be made equal to or a small fixed amount greater than the spring forces for all armature positions.

It will be readily appreciated that while a specific embodiment of the invention has been illustrated as providing the reciprocal magnetic drive for a miniaturized reciprocating fluid pump of maximum efficiency, the principles of the disclosed invention may equally well be practiced in any arrangement wherein a constant driving force is required to provide a linear motion of a driven element. The variety of uses of the disclosed reciprocating magnetic motor will be readily apparent to those skilled in the art.

Although the invention has been described and illustrated in detail, it is to be clearly understood that the same is by way of illustration and example only and is not to be taken by way of limitation, the spirit and scope of this invention being limited only by the terms of the appended claims.

I claim:

1. A pump comprising a casing having inlet and outlet ports, a magnetic core mounted in said casing and spaced from one side thereof, said core having an annular magnetic gap having inner and outer annular faces, a coil on said core, said core having an axial bore providing a pumping cylinder, valve means for providing communication between said cylinder and said ports, a piston slidably mounted in said cylinder, an armature fixed to said piston and extending in the space between said core and casing, said armature having a peripheral flanged projecting substantially normal to the armature body and into said gap to provide an annular magnetic armature having inner and outer faces respectively adja-

cent said inner and outer gap faces, said armature body and flange having a number of slots extending substantially radially thereof to minimize flow of magnetic flux circumferentially of said armature.

2. The structure of claim 1 wherein said slots are outwardly divergent to equalize the circumferential length of inner and outer portions of said flange between adjacent slots.

3. An annular magnetic core having an annular magnetic gap, an armature having a disc portion coaxial with said core and mounted for axial reciprocation relative thereto, said disc portion fixedly carrying an annular magnetic armature flange of low reluctance magnetic material positioned to reciprocate within said annular gap, said disc portion and armature flange having a plurality of radially extending slots providing high reluctance to circumferential flow of flux around said armature, and a coil on said core, the sides of each said slot mutually diverging from inner to outer surfaces of said flange so as to equalize said inner and outer gap widths.

4. An annular magnetic core having an axial bore and an annular magnetic gap, said gap having mutually facing inner and outer pole faces, a coil on said core, a reciprocable member slidably mounted in said core bore, an armature having a disc portion fixed to said member and extending radially outwardly to said gap, said armature having a peripheral flange of low reluctance magnetic material projecting substantially normal to the disc portion thereof to and within said gap, said flange having inner and outer surfaces respectively adjacent said inner and outer pole faces to provide equal-length inner and outer magnetic gaps, said flange having a plurality of slots each diverging outwardly from inner to outer surfaces thereof so as to decrease the difference in area between said inner and outer magnetic gaps.

5. The structure of claim 4 wherein said flange is tapered in the direction of its projection so as to effect decrease of gap length upon motion of said flange into said core.

6. A magnetic core comprising an annular magnetic gap having inner and outer annular faces, a coil on said core, an armature mounted for reciprocation relative to said gap faces in a direction substantially parallel to said faces, said armature having a central web portion, a peripheral flange of low reluctance magnetic material projecting substantially normal to the web portion into said gap to provide an annular magnetic armature portion having inner and outer faces respectively adjacent said inner and outer gap faces, said armature having a number of slots extending substantially radially thereof to minimize flow of magnetic flux circumferentially of said armature.

7. A magnetic drive comprising electromagnetic means forming first and second opposing mutually spaced magnetic pole faces of endless configuration, means for energizing said electromagnetic means to provide flux flow between said faces in a direction normal thereto, a plurality of mutually spaced armature elements of low reluctance magnetic material arranged in diametrically opposed pairs, said elements being fixedly related to each other and being mounted for reciprocation between and relative to said pole faces in a direction substantially parallel to said faces and normal to said direction of flux flow.

8. A magnet core having inner and outer pole faces forming an endless magnetic gap providing a flux flow in a direction extending between said faces, a coil on the magnet core, a segmented armature mounted for reciprocation relative to said magnet in a direction substantially parallel to said faces and normal to said direction of flux flow, said armature having segments of low reluctance magnetic material extending into said gap so as to vary magnetic gap area between said pole faces and the segments as the armature reciprocates, each said segment having a cross-section which varies in the direction of said reciprocation so as to effect some decrease in gap length, upon reciprocation, due solely to such varying cross-section.

9. An annular magnetic core having an axial bore and an annular magnetic gap, said gap having mutually facing inner and outer pole faces, a coil on said core, a reciprocable member slidably mounted in said core, an armature having a web portion fixed to said member and extending radially outwardly to said gap, said armature having a peripheral flange of low reluctance magnetic material projecting substantially normal to said web portion to and within said gap, said flange having inner and outer surfaces respectively adjacent said inner and outer pole faces to provide inner and outer magnetic gaps, said flange having a plurality of slots and being smaller at its projecting end portion so as to decrease the gap lengths upon motion of said flange into said core.

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