April 2, 1974 R. E. ROSENSWEIG Re. 27,955

BEARING ARRANGEMENT WITH MAGNETIC FLUID DEFINING BEARING PADS

Original Filed Jan. 23, 1970 4 Sheets-Sheet 1

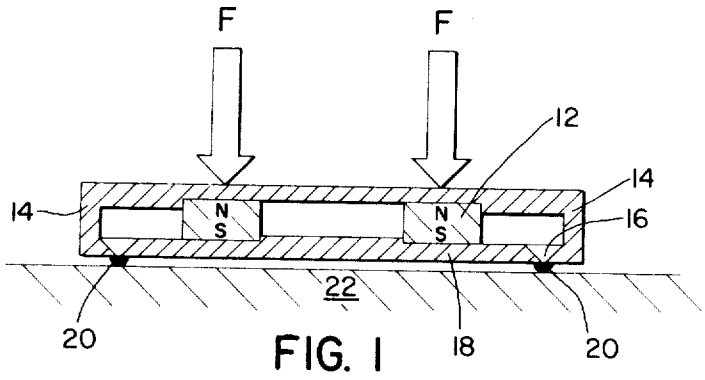


FIG. 1

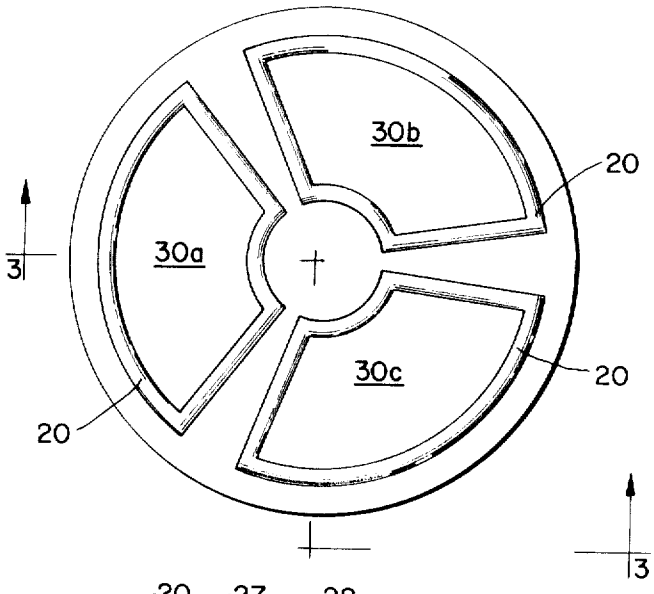


FIG. 2

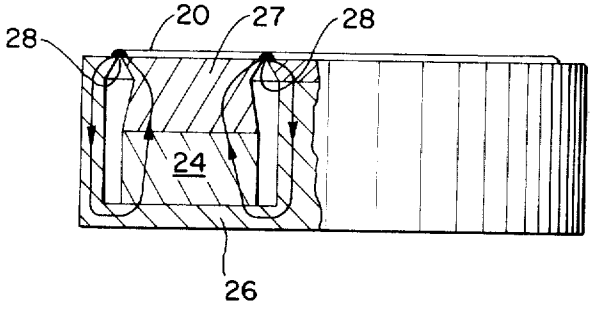


FIG. 3

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BEARING ARRANGEMENT WITH MAGNETIC FLUID DEFINING BEARING PADS

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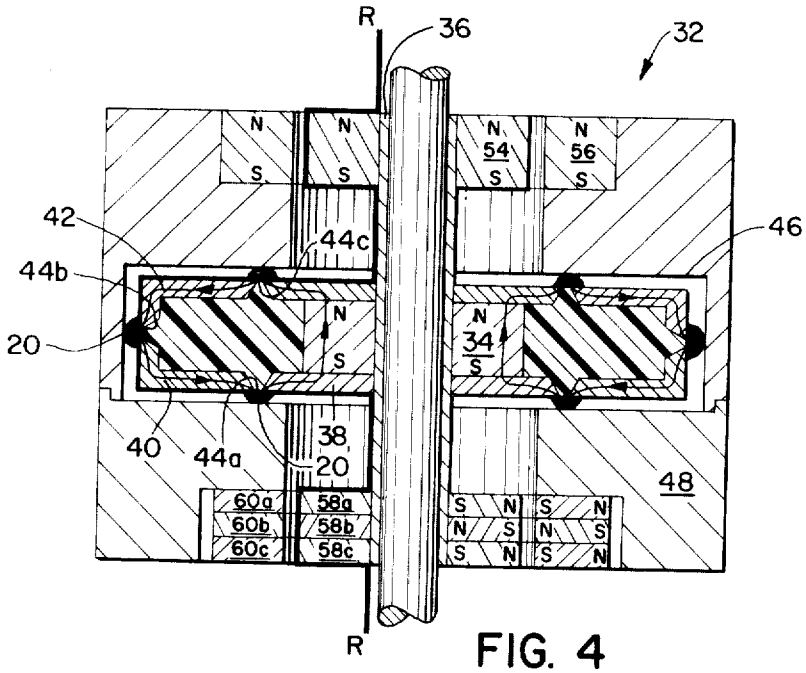


FIG. 4

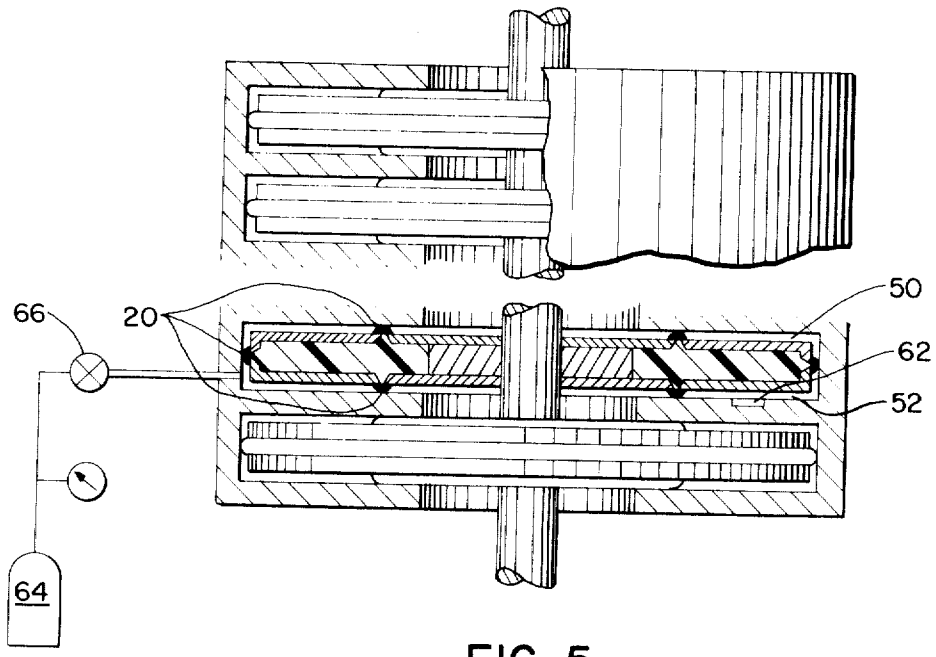


FIG. 5

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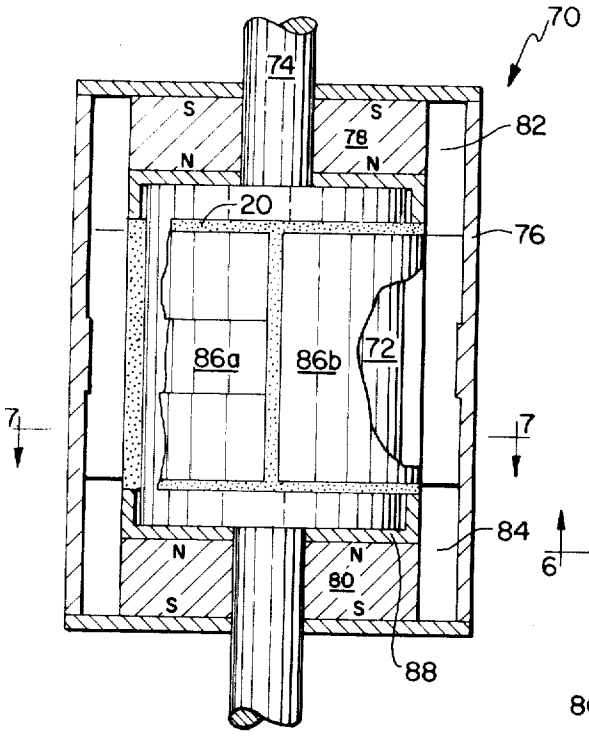


FIG. 6

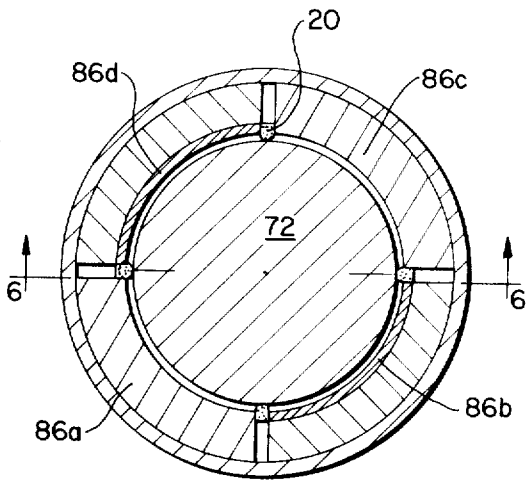


FIG. 7

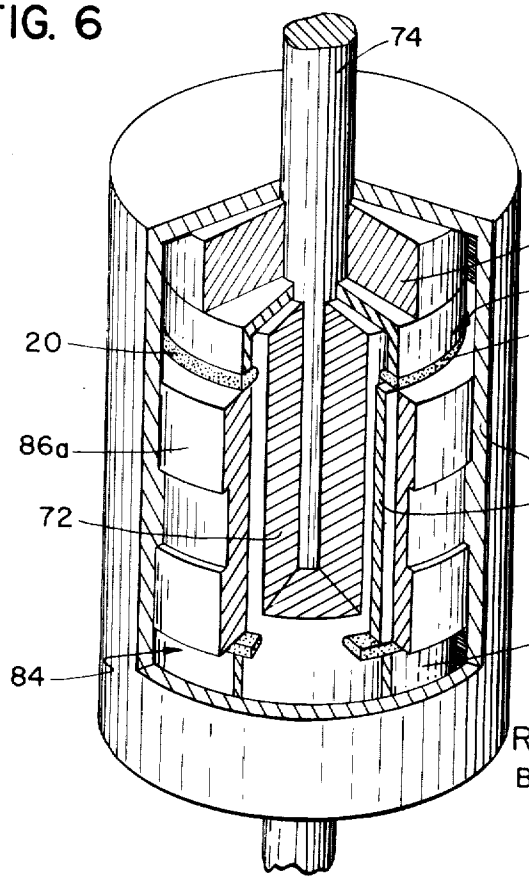


FIG. 8

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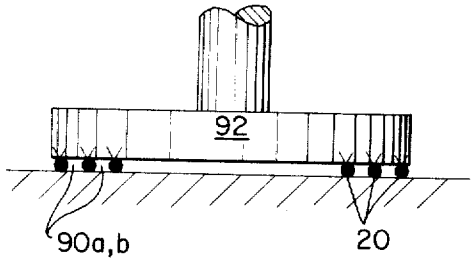


FIG. 10

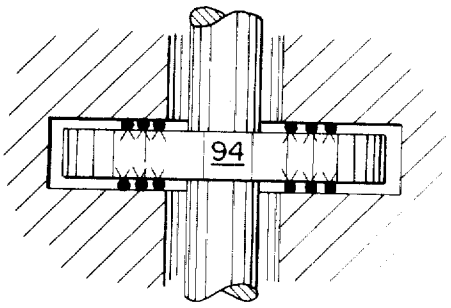


FIG. 11

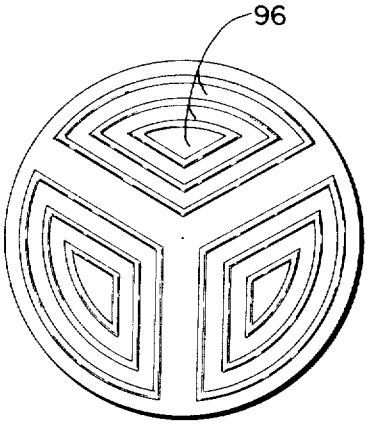


FIG. 12

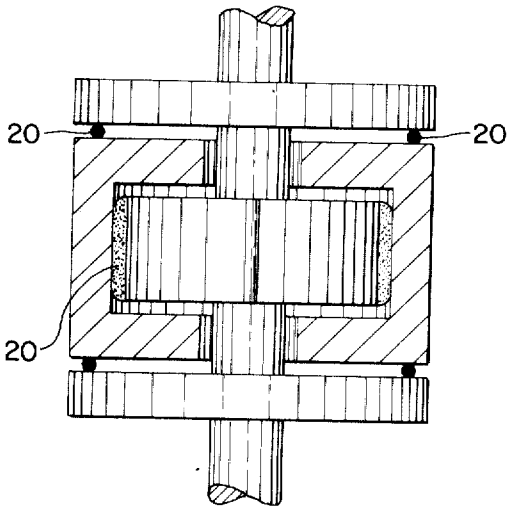


FIG. 9

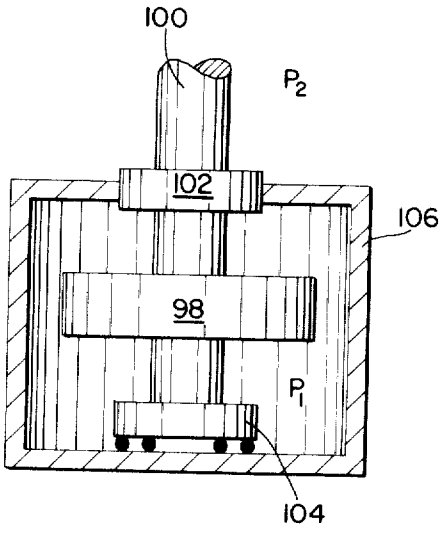


FIG. 13

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BEARING ARRANGEMENT WITH MAGNETIC FLUID DEFINING BEARING PADS

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Original No. 3,612,630, dated Oct. 12, 1971, Ser. No. 5,167, Jan. 23, 1970. Application for reissue May 19, 1972, Ser. No. 255,247

Int. Cl. F16c *39/06*

U.S. Cl. 308—10 25 Claims

Matter enclosed in heavy brackets [ ] appears in the original patent but forms no part of this reissue specification; matter printed in italics indicates the additions made by reissue.

ABSTRACT OF THE DISCLOSURE

A bearing wherein a fluid bearing pad is sealed between two bearing surfaces, such as between an inner race and an outer race. A permanent magnet and permeable pole pieces define a magnetic circuit which circuit provides for the flow of magnetic flux across at least one of the bearing surfaces. A magnetic gap on the bearing surface through which the magnetic flux flows defines a predetermined continuous peripheral pattern. The magnetic flux is concentrated at the gap and a magnetic fluid is captured therein. The other bearing surface engages the magnetic fluid in sealing relationship and the fluid-bearing pad is sealed between the bearing surfaces and within the periphery defined by the magnetic fluid seal.

SUMMARY OF THE INVENTION

Hydrostatic bearings are characterized by a particular load support feature and low stiction at low or zero surface speed. However, hydrostatic bearings are generally complex to construct and operate since a fluid flow of a gas or a liquid must be provided with the attendant requirement for pumps, orifice control, valves, conduits, energy sources, etc.

I have discovered a novel concept for bearings which employs some of the principles or features of a hydrostatic bearing and magnetic fluid seals. Briefly, my invention includes providing a fluid pad or pads between two surfaces such as first and second surfaces having relative motion one with the respect to the other. The pad is sealed between the surfaces by defining a magnetic gap continuously along a predetermined periphery. Magnetic flux passes across the gap and a magnetic fluid is captured therein. The magnetic fluid seals the pad within the predetermined area defined by the periphery and allows for relative movement of the surfaces one to the other. The entrapment of the pad by magnetic fluids may be incorporated into radial bearings, thus bearings, or combinations of both. My bearing supports radial and/or torque loads concomitant with the support of loads which are almost purely thrust loads.

Any fluid material may be utilized in the pads such as gases like air, carbon dioxide, and nitrogen etc., or liquid such as water, oil, etc. In my invention all the bearings, as will be described in the preferred embodiments, have the distinct advantages and features of no solid surface contact resulting in no wear and long life, low friction with the attendant low loss of either the fluid which comprises the bearing pad or the magnetic fluid which is used as the sealing medium. The novel bearings as will be described are similar to hydrostatic bearings but require not active fluid supply. The various thrust or radial bearings may be combined with each other or with conventional bearings such as ball bearings, roller bearings, jewel bearings, journal bearings, magnetic bearings with or without active feedback, etc.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a sectional view of one embodiment of the invention employed with a thrust bearing;

FIG. 2 is a sectional view of three padded bearing member providing thrust and moment supports;

FIG. 3 is a sectional view of FIG. 2 taken along lines 3—3;

FIG. 4 is a sectional view of a thrust bearing in combination with radial repulsive magnetic support;

FIG. 5 is a sectional view of a staged thrust bearing;

FIG. 6 is a sectional view of my invention employed in a radial bearing concept;

FIG. 7 is a sectional view of FIG. 6 taken along lines 7—7;

FIG. 8 is a perspective view with sections broken away of the concept shown in FIGS. 6 and 7;

FIG. 9 is a schematic illustration of thrust and moment pads incorporated in a bearing with multiple seals;

FIGS. 10 and 11 are schematic illustration of multistaged seals capturing a plurality of pads in a thrust bearing;

FIG. 12 is a schematic illustration of multistaged seals capturing a plurality of pads in a thrust bearing capable of supporting large forces; and

FIG. 13 is a schematic illustration of one of my bearing embodiments employed in a definite environment.

DESCRIPTION OF THE PREFERRED EMBODIMENT(S)

FIG. 1 is an illustration of a thrust bearing which includes a ring magnet **12** magnetized across the face which produces magnetic induction which is conducted by a cup pole piece **14** which focuses the lines of magnetic flux to an intense value at an annular gap **16**. The gap is formed by the undercut portion of the pole piece to provide a greater fringing condition. The flux traverses the gap and returns to the magnet via the flat pole piece **18**. A magnetic fluid **20**, which may include those magnetic fluids which comprise a carrier fluid such as water, hydrocarbons, fluorocarbons, etc., a surface active agent such as fatty acids, for example, a monounsaturated fatty acid like oleic acid and any magnetic-type particles like ferrous materials such as ferrite, chromium dioxide, magnetic, etc., is introduced into the gap and is evenly distributed in a ring defined by the fringing field of the gap with the rim of the fluid extending outwardly from the bottom face as shown.

The fluid filled model may then be laid flat on a nonmagnetic surface **22** with the result that a pad of air or fluid bearing pad is trapped within the enclosure defined by the nonmagnetic surface **22**, the flat pole piece **18**, and the peripheral ring of sealing magnetic fluid. As shown in FIG. 1 and in the following embodiments as wil be described, the trapped fluid, such as air, creates a net support force and when it is compressed as by a small displacement it allows rotative and lateral movement of the surface **22** with respect to the surface **18** without contact between the moving surfaces.

Accordingly, FIG. 1 represents a low friction thrust bearing for slide or rotary motion which has little resistance to upsetting torques. If desired, it may be inverted wherein the device will react as a liquid suction cup clinging to the surface and capable of supporting its own weight and further retain its function as a rotary or slide bearing. In this embodiment it may be used as a tiltometer or an accelerometer of the inertial sensor class.

Any type of permanent magnetic material may be used with my novel bearings. For example, aluminum, nickel, cobalt compounds such as Alnico V and VIII; cobalt-samarium materials, rubber-bonded magnets, ce-

ramics, and other iron containing materials such as magnetite and ferrite may also be used. In addition, the pole pieces to which the magnetic flux passes have been described in regard to a material capable of being magnetized. Such materials are generally characterized by being soft magnetically or being very responsive to magnetism, that is, capable of high magnetic saturation although having no inherent magnetic characteristics of their own. For example, ferrous materials such as iron, cast iron, etc., may be used as well as iron alloys such as 400 series stainless steel.

FIG. 2 is a top view of a three-padded bearing member providing thrust and moment supports and FIG. 3 is a sectional view of FIG. 2 taken along lines 3—3. Referring first to FIG. 3 a continuous ring magnet **24** in combination with pole pieces **26** and **27** describes a magnetic circuit. The lines of flux are shown by the arrows and pass through the gap **28**. By segmenting the air pads as shown in FIGS. 2 and 3, this prevents or inhibits the support fluid in the pad from displacing from an opposite side when off center loading is applied. Thus the upsetting torque is balanced by a restoring torque accompanying the angular displacement.

FIG. 4 illustrates a still further embodiment of my invention utilizing captured fluid pads and radial repulsive magnetic support. The bearing is shown generally at **32** and comprises an inner race which includes a sleeve **36**, a permanent magnet **34** secured to the sleeve **36** for rotation therewith, pole pieces **38**, **40**, and **42** which define gaps **44**a, b, and c respectively. Magnetic fluid **20** is captured in the gaps as described before and defines in combination with an inner surface **46** of an outer race **48** air pads **50** and **52**.

The line R—R defines the surface of rotation between the inner race and the outer race **48** which may be secured to a fixed or moving surface such as a housing (not shown). This embodiment creates separate air pads as shown at **50** and **52** circumscribed by the peripheral magnetic fluid seal **20** on either side of the structure containing the magnet **40**. Any axial displacement compresses the captured pad on one side while at the same time a pressure reduction is created in the captured fluid on the other side. Thus a push-pull pair or set of forces is set up, or in other words, a thrust pair is created for axial displacement in either direction. To achieve radial as well as thrust support, the novel thrust bearing is combined in this embodiment with radial repulsive magnetic support. As shown, a pair of axially magnetized ring magnets **54** and **56** are adapted to inhibit lateral and/or oscillatory movement (cocking) or upsetting torque. Magnet **54** is secured to sleeve **36** while magnet **56** is disposed within the outer race **48**. Another means to resist an upsetting torque is illustrated by the use of alternate concentric magnets which are radially magnetized shown as **58**a, b, and c and **60**a, b, and c. The surface revolution of the inner race to the outer race is shown by the surface line R—R. Although this embodiment has been shown with radial repulsive magnetic support, other radial support may be utilized, such as journal bearings, ball bearings, etc.

Referring to FIG. 5, an alternative embodiment of FIG. 4 is shown (radial support means not shown). The two-sided thrust bearing is cascaded in series to provide n stages of pads in series with the resulting factor of n greater restoring thrust. If desired, a cascade may also be fashioned of the configuration illustrated in FIG. 2 in which case exceptional ability to support cocking loads or offsetting torques is achieved.

An optional feature is also shown to maintain constant vapor pressure within a particular pad. For example, a sublimating material **62** such as dichlorobenzene, naphthalene, etc. may be incorporated into the air pad e.g. embedded into the wall prior to sealing by the magnetic fluid, which sublimating material may be used to control the vapor pressure in the pad in the event that there is some loss of vapor pressure through accidental loss of gas pressure from the pad through movement, diffusional mass loss, thermal expansion effect, etc. Of course, if desired pressure may be maintained through other means such as an air cylinder **64** in communication with the fluid pad including a check valve **66** disposed on a conduit **68**.

A bearing having a magnetic arrangement for capturing four fluid pads on the inside of a cylindrical surface which illustrates the radical bearing concept as opposed to the thrust bearing concept is shown in FIG. 6. A front cross-sectional view of a bearing wherein pads are sealed on the inside of a cylindrical surface is shown generally at **70** and comprises an inner race which in this embodiment is a cylindrical type element **72** secured to a shaft **74**. The outer housing **76** comprises two annular permanent magnets **78** and **80** and nonmagnetic annular support elements **82** and **84**. Adjacent the magnets **78** and **80** are permeable distributor pole pieces **86** and **88**. Secured to the support elements **82** and **84** are four cylindrical type permeable plates **86**a, b, c and d, the inner surface of which are spaced apart from the outer cylindrical surface of element **72**. The perimeter of the cylindrical plates in combination with the pole pieces **86** and **88** define gaps in which are captured magnetic fluid **20**. Referring to FIG. 7 which is a sectional view taken along lines 7—7 of FIG. 6, the gaps are clearly shown as filled with a magnetic fluid **20**. The arrows indicate the flow of the flux lines across the gap and through the permeable return piece **76**. FIG. 8 is a perspective view of the embodiment represented by FIGS. 6 and 7. The magnetic fluid **20**, the outer cylindrical surface of the element **72**, and the inner surfaces of the cylindrical plates are the mediums which define the boundaries and seal the four fluid pads.

In FIG. 9 is shown a combination of the radial bearing concept of FIGS. 6 and 7 combined with the thrust bearing of FIG. 2 to provide a stable bearing support against angular displacement or offsetting torques and axial and radial displacements. Another embodiment, of course, would be to combine the radial gearing concept of FIGS. 6 and 7 with the thrust bearing of FIG. 12 to provide a plurality of fluid pads.

In FIG. 10 is shown a variation of the embodiment of FIG. 1 wherein a plurality of air pads **90**a and b are provided on a simplified thrust bearing **92** utilizing multiple seals **20** to achieve greater load support. The face of the permeable piece is shown as having knife edges to define the magnetic gaps. However, in this embodiment if desired, the pole pieces employed in my invention may also be doubly beveled, singly beveled, internally veed, etc.

FIG. 12 is a generalization of FIG. 2 and shows another embodiment of my bearing having thrust and moment support through the use of multiple peripheral seals **96**. The same multiple seal arrangement may be used in the embodiment shown in FIG. 6 by the employment of multiple concentrically arranged knife edges to define the magnetic gaps.

FIG. 13 is a schematic illustration which shows the use of one of two of my bearing embodiments in an inertial fly wheel system. A flywheel **98** is disposed within a housing **106** in a vacuum environment P_1. A shaft **100** passes through bearing **102**, flywheel **98** and is secured to thrust bearing **104**. Bearing **104** supports the load and is constructed in a similar manner as shown in FIG. 10, that is having multiple fluid bearing pads. The bearing **102** is constructed in accordance with FIG. 6 and in addition to providing the fluid pads as previously described also seals the vacuum environmental P_1 form the atmosphere P_2 where the shaft intersects the housing. More specifically, the bearing **102** also acts as a magnetic fluid seal in a manner as disclosed in my copending application Ser. No. 865,281, filed Oct. 10, 1969, which is hereby incorporated by reference in this application in its entirety. The shaft power

may be supplied or removed electrically, hydraulically, mechanically, etc.

As will be clear from the foregoing description, the bearing concept I have developed utilizing fluid pads such as air pads sealed with magentic fluid may be used in any great number of bearing environments. For example, this concept may be applied in an inertial fly wheel energy storage where low loss and long life are key factors. Modern composite high strength materials make possible high speed flywheel energy reservoirs which are spun in a vacuum to reduce friction losses. Seals as disclosed in this specification are advantageous to ensure vacuum in the face of the shaft penetration, such as disclosed in my copending application Ser. No. 865,281, filed Oct. 10, 1969, now abandoned. They may also be used as thrust and radial bearings for engines such as aircraft jet engines, helicopter rotors and blades; for fly wheel power sources such as silent lawn mowers, silent marine engines, central power generating plants, space vehicles, submarines, etc., particularly when using the radially segmented face seals to strongly resist upsetting torques and longitudinally disposed seals along a shaft in groups of three or more pads to achieve radial bearing supports. These practical embodiments permit the bearing to support radial and/or torque loads concomitant with the support of loads which are almost purely thrust loads.

Also, in referring to FIG. 4, the line R—R describes the surface of revolution as the shaft and inner race rotate with respect to the outer race. As can be clearly seen, the magnetic fluid maintains a complete pressure-type seal while stationary or rotating. Upon rotation of the shaft, the magnetic seal which captures the fluid pad remains pressure tight and accordingly, the fluid pad remains captured at all times whether the shaft is rotating or stationary. Although the various bearing embodiments such as the thrust bearings, the radial bearings or the combination of both radial and thrust bearings using a plurality of fluid pads captured in various embodiments have been described generally in reference to the movement of a shaft in combination with a housing or outer bearing surface, it is obvious that the housing to which the outer race is secured or the bearing surface which engages the simplified thrust bearings such as shown in FIGS. 1, 2, 3, and 10 may move at the same speed, a greater speed, or less speed than that of which the shaft is rotating and in either the same direction as the shaft or in the opposite direction of the shaft. Also, it has been generally described in reference to a solid shaft; however, the shaft may take the form of a bushing passing through the inner race and may assume various configurations in the form of a ring element, a collar, or a sleeve.

Having described my invention, what I now claim is:

1. A bearing which comprises:

(a) a first element having a first *magnetic* surface;

(b) a second element having a second *nonmagnetic* surface spaced apart from the surface of the first element and adapted to relative movement in reference thereto and further adapted to engage in sealing relationship a peripheral magnetic fluid seal;

(c) fluid support means disposed between said surfaces and providing a fluid bearing surface;

(d) magnet means to capture magnetic fluid along a periphery disposed on [at least one of said] *the magnetic surface* [surfaces]; and

(e) magnetic fluid captured along the periphery, *the magnet means providing a magnetic flux which passes through the magnetic fluid and the magnetic surface, which flux does not pass through the nonmagnetic surface,* whereby the fluid support means is sealed between the surfaces.

2. The bearing of claim **1** wherein the magnet means includes a permanent magnet in combination with permeable pole pieces disposed within the first element, and further includes gap means defined on the first surface, and wherein the second surface engages the magnetic fluid and seals in part the fluid support means.

3. The bearing of claim **1** wherein the first element is a disc-type element and the magnet means includes a ring magnet disposed within the disc-type element, and further includes at least two concentrically arranged knife edges spaced apart from one another on the first surface of the first element.

4. The bearing of claim **1** wherein the magnet means includes means to establish at least two magnetic fluid peripheries on the surface of the first element to define fluid support means therebetween.

5. The bearing of claim **1** which includes means to maintain [constant] *control of the* pressure within the fluid support means.

6. The bearing of claim **5** wherein the means to maintain the pressure within the fluid support means includes sublimating means.

7. The bearing of claim **1** wherein the first element includes an upper and a lower surface, the means to capture the magnetic fluid along a periphery includes at least one peripheral magnetic fluid seal on each of the upper and lower surfaces, and wherein the second element includes lower and upper surfaces adapted to engage respectively the peripheral magnetic fluid seals on the upper and lower surfaces of the first element to seal fluid bearing pads on the respective surfaces.

8. The bearing of claim **7** wherein the bearing pads are cascaded in a plurality of stages.

9. The bearing of claim **1** which includes means to provide radial support.

10. The bearing of claim **9** wherein the first element has an upper surface, shaft means extend upwardly from said surface, the second element extends over the upper surface of the first element and inwardly toward said shaft means, and the means to provide radial support is disposed between the shaft means and the second element.

11. The bearing of claim **10** wherein the means to provide radial support includes journal bearing means.

12. The bearing of claim **10** wherein the means to provide radial support includes repulsive magnetic support.

13. A bearing which comprises:

(*a*) a first cylindrical-type element having an outer surface, said surface adapted to engage in sealing relationship a peripheral magnetic fluid seal;

(*b*) a second element disposed about the first element and having an inner surface spaced apart from the outer surface of the first element and adapted for movement in reference thereto;

(*c*) fluid support means disposed between the inner and outer surfaces;

(*d*) magnet means [to define] *to capture magnetic fluid along* at least one *periphery* [peripheral gap] on at least one of said surfaces; and

(*e*) magnetic fluid captured [in] *along* the *periphery* [peripheral gap], *one of said surfaces being magnetic and the other nonmagnetic, the magnetic fluid captured along the periphery on the magnetic surface, the magnet means providing a magnetic flux which passes through the magnetic fluid and the magnetic surface, and which flux does not pass through the nonmagnetic surface,* whereby the fluid support means is sealed between the two surfaces.

14. The bearing of claim **13** which includes a plurality of pheripheral magnet gaps disposed [in generally rectangular form] on the inner surface of the outer element.

15. The bearing of claim **13** which includes a plurality of peripheral magnetic gaps disposed [in generally rectangular form] on the outer surface of the inner element.

16. The bearing of claim **13** wherein the second element extends radially inward and is spaced apart from at least one of the bases of the cylindrical first element, the second element further including a first bearing surface; and means to provide thrust and moment support,

said means adapted to engage in bearing relationship the first bearing surface of the second element.

17. The bearing of claim **16** wherein the means to provide thrust and moment support includes a third element having a lower surface spaced apart from the first bearing surface of the second element and adapted for relative movement in reference thereto and further adapted to engage in sealing relationship a peripheral magnetic fluid seal;

fluid support means disposed between the first bearing surface and the lower surface and providing a fluid bearing surface;

magnet means to define a peripheral gap on at least one of said surfaces disposed on one of said surfaces; and

magnetic fluid captured along the peripheral gap whereby the fluid support means is sealed between the first bearing surface and lower surface.

18. A method for providing a bearing, which method comprises:

(a) providing a first *magnetic* bearing surface;

(b) providing a second *nonmagnetic* bearing surface;

(c) *providing a magnetic field adapted* [establishing at least one periphery adapted] to capture a magnetic fluid on [one of said] *the magnetic surface* [surfaces] *along a periphery;*

(d) capturing a magnetic fluid along the periphery;

(e) engaging the *captured* magnetic fluid in sealing relationship with the other *nonmagnetic* surface; and

(f) sealing a fluid pad between *the* first and second surfaces and within the boundary defined by the *periphery of the* magnetic fluid.

19. The method of claim 18 wherein the fluid seal between the first and second surfaces is air.

20. The method of claim 18 which includes controlling the pressure of the fluid seal between the first and second surfaces.

21. The method of claim 18 which includes providing a series of staged fluid pads.

22. The method of claim 18 which includes providing a series of fluid pads in generally the same plane to inhibit the support fluid in the pads from displacing when off-center loading is applied to the bearing.

23. A low friction thrust bearing which comprises:

(a) a magnet to produce magnetic induction;

(b) a magnetic permeable pole piece characterized by a gap formed along a periphery by an undercut portion of the pole piece, the pole piece conducting the magnetic induction, and the lines of magnetic flux focusing to an intense value about the gap;

(c) a magnetic fluid captured and disposed along the periphery by the magnetic flux;

(d) a nonmagnetic surface spaced apart from and adapted for relative movement in reference to the surface of the pole piece, and adapted to engage in a sealing relationship a peripheral magnetic fluid seal; and

(e) air disposed between the surface of the pole piece and the nonmagnetic surface and sealed within the periphery of the magnetic fluid to form at least one air pad support, the magnetic flux of the magnet conducted from the magnet through the pole piece, traversing the gap and through the magnetic fluid and returning to the magnet, thereby providing a low friction bearing where the entrapped air pads provide a net support force, and movement is provided between the moving nonmagnetic and pole piece surfaces without contact.

24. The bearing of claim 23 which includes a ring magnet and a generally annular gap in the pole piece to define three separate peripheries and three separate air pads, thereby preventing the air in any pad from being displaced when off-center loading is applied to the bearing.

25. The bearing of claim 23 which includes a ring magnet and a pole piece characterized by two annular gaps on opposite surfaces to define opposite but similar peripheries, nonmagnetic surfaces being disposed opposite each surface to provide a series of cascaded air pads.

References Cited

The following references, cited by the Examiner, are of record in the patened file of this patent or the original patent.

UNITED STATES PATENTS

2,936,711	5/1960	Watt	74—5.7
3,475,975	11/1969	Sokol	308—10
2,718,157	9/1955	Schaub	192—84 PM
3,436,131	4/1969	Lode	308—10
3,530,727	9/1970	Albert	73—516 LM
3,530,728	9/1970	Evans	74—5

ROBERT SKUDY, Primary Examiner