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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON, D.C. 20546

REPLY TO ATTN OF: GP

SEP 0 5 1973

TO: KSI/Scientific & Technical Information Division
Attention: Miss Winnie M. Morgan

FROM: GP/Office of Assistant General Counsel for Patent Matters

SUBJECT: Announcement of NASA-Owned U.S. Patents in STAR

In accordance with the procedures agreed upon by Code GP and Code KSI, the attached NASA-owned U.S. Patent is being forwarded for abstracting and announcement in NASA STAR.

The following information is provided:

U.S. Patent No. : 3,750,067

Government or Corporate Employee : Cal/Tech, Pasadena, CA

Supplementary Corporate Source (if applicable) : JPL

NASA Patent Case No. : NPO-11738-1

NOTE - If this patent covers an invention made by a corporate employee of a NASA Contractor, the following is applicable:

Yes [X] No [ ]

Pursuant to Section 305(a) of the National Aeronautics and Space Act, the name of the Administrator of NASA appears on the first page of the patent; however, the name of the actual inventor (author) appears at the heading of column No. 1 of the Specification, following the words ". . . with respect to an invention of . . ."

Elizabeth A. Carter

Elizabeth A. Carter
Enclosure
Copy of Patent cited above

United States Patent [19]

Fletcher et al.

[11] 3,750,067

[45] July 31, 1973

[54] **FERROFLUIDIC SOLENOID**

[76] Inventors: **James C. Fletcher**, Administrator of the National Aeronautics and Space Administration with respect to an invention of; **Eric E. Sabelman**, Palo Alto, Calif.

[22] Filed: **Mar. 16, 1972**

[21] Appl. No.: **235,295**

[52] **U.S. Cl.** **335/296,** 335/297

[51] **Int. Cl.** **H01f 3/00**

[58] **Field of Search** 335/281, 296, 297, 335/303, 1, 209

[56] **References Cited**

UNITED STATES PATENTS

2,667,237	1/1954	Rabinow	335/209 X
2,917,599	12/1959	Oushinsky	335/1
3,467,927	9/1969	Macy	335/296
2,532,876	12/1950	Asche et al.	335/303 X
2,792,536	5/1957	Immel	335/279

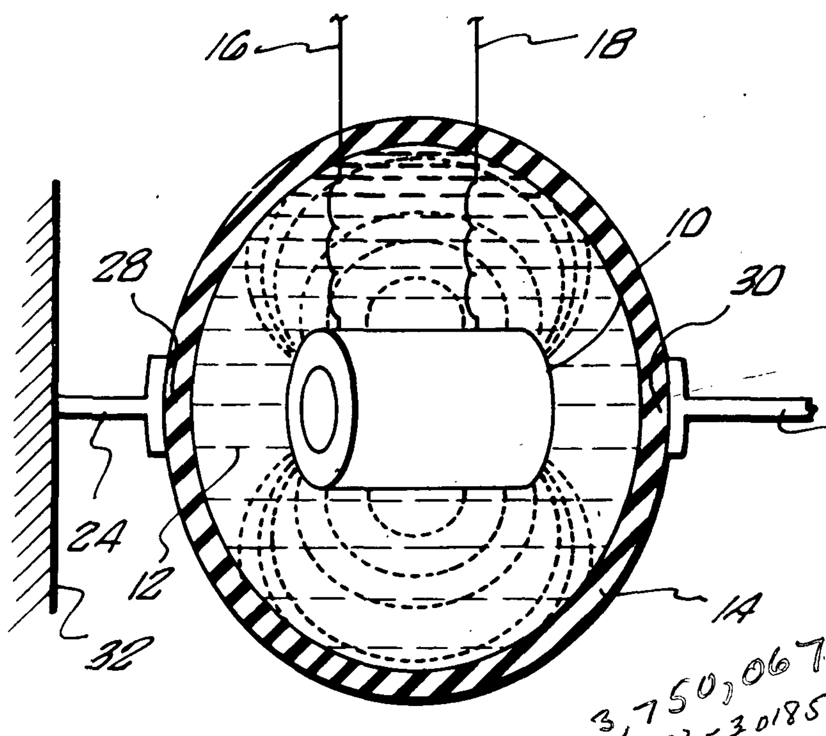
Primary Examiner—George Harris
Attorney—Monte F. Motte et al.

[57] **ABSTRACT**

An electromechanical actuator for producing mechanical force and/or motion in response to electrical signals applied thereto, is disclosed. The actuator includes a ferromagnetic fluid and a coil which are contained within an elastomeric capsule. Energization of the coil by application of current to a pair of coil electrodes extending through the walls of the elastomeric capsule produces distortion of the capsule, i.e., radial expansion and axial contraction. This distortion is caused by the redistribution of the ferromagnetic fluid within the capsule under the influence of the magnetic field produced by the energized coil. Variation of the current input will produce corresponding variations in the degree of capsule distortion.

11 Claims, 6 Drawing Figures

402



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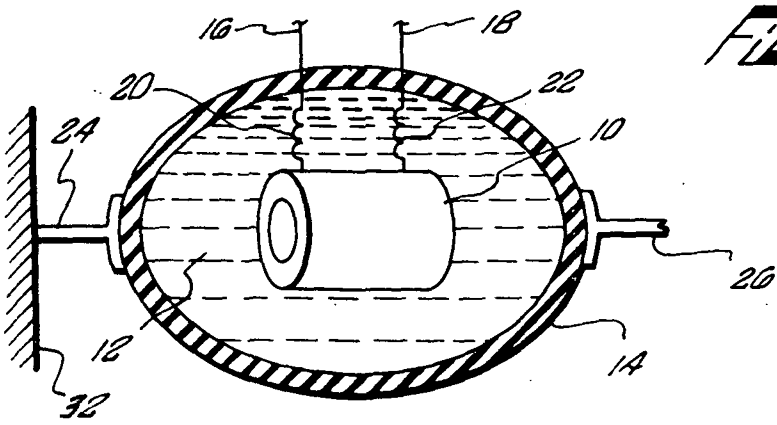

FIG. 1A

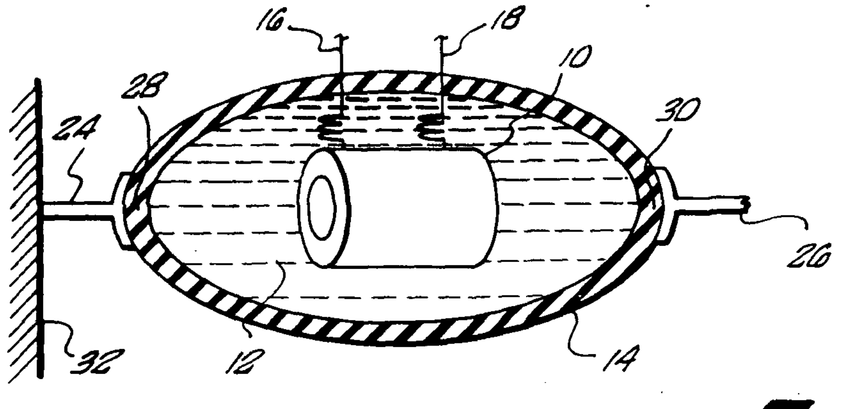

FIG. 1B

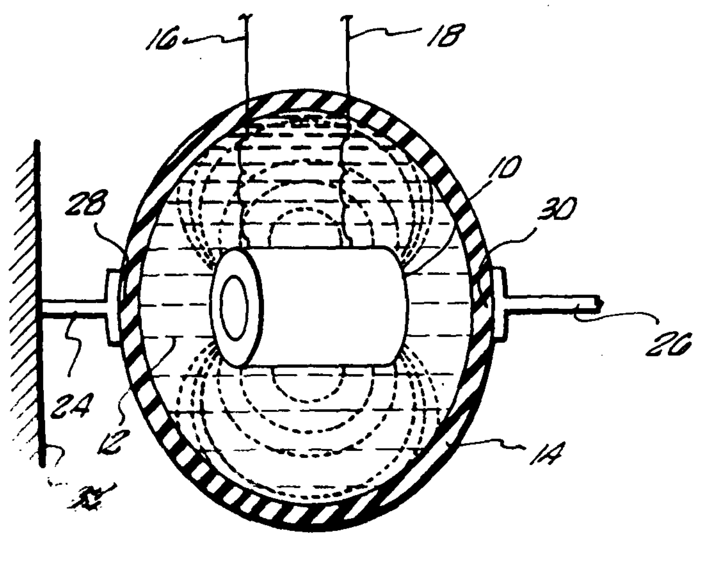

FIG. 1C

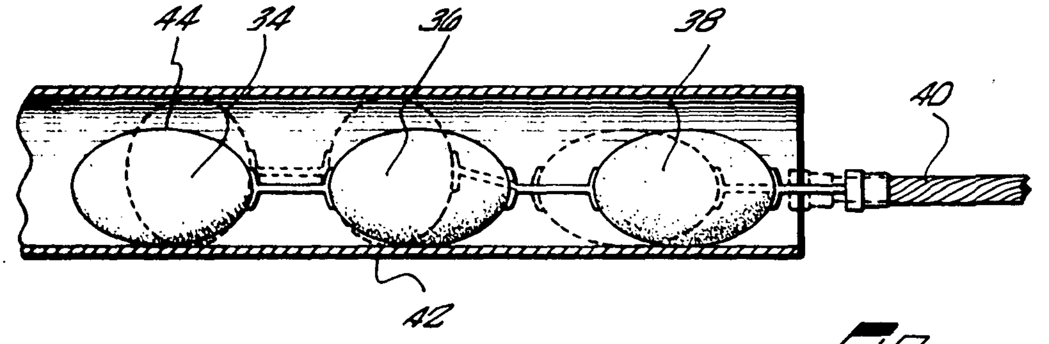

FIG. 2

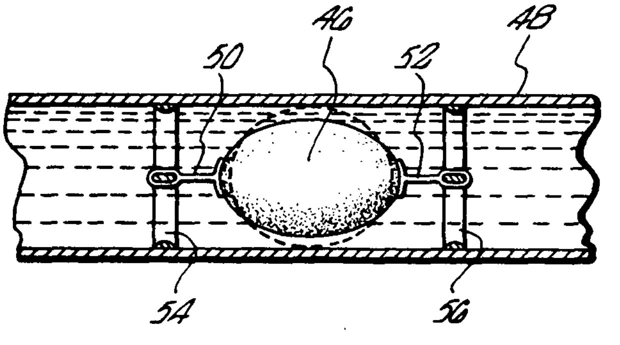

FIG. 3

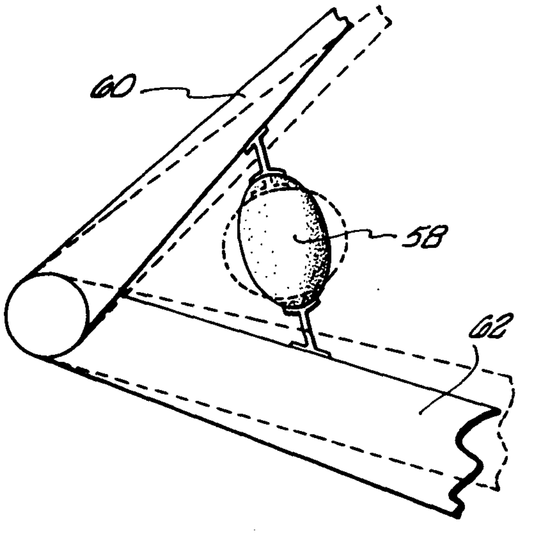

FIG. 4

FERROFLUIDIC SOLENOID

ORIGIN OF THE INVENTION

The invention described herein was made in the performance of work under a NASA contract and is subject to the provisions of Section 305 of the National Aeronautics and Space Act of 1958, Public Law 85-568 (72 Stat. 435; 42 U.S.C. 2457).

BACKGROUND OF THE INVENTION

1. Field of the Invention

This invention generally relates to electromechanical devices for producing predetermined mechanical movements, or reactions, in response to the application of electrical energy. More specifically, the present invention concerns ferrofluidic actuators that will readily serve as a current-to-pressure transducer, i.e., variable force at constant displacement, or as a current-to-motion transducer, i.e., variable displacement at constant force.

2. Description of the Prior Art

Electromechanical actuators including the use of a ferromagnetic fluid have heretofore been fabricated. The magnetic fluid is generally maintained in a container which is positioned to allow controlled magnetic forces to act on the magnetic fluid and thereby cause mechanical movement.

Such electromechanical actuators using a magnetic fluid present several advantages over conventional solenoids which include a core and a concentrically positioned coil. Among these advantages are the provision of maximum force at the extreme end of a work stroke, and the production of variable force or displacement in response to variations in electrical current applied thereto. A further advantage provided by ferrofluidic solenoids is the reduction, or elimination, of sliding or rotating parts thereby enabling the lifetime of the solenoid to be limited only by fatigue, puncture or corrosion of the capsule containing the magnetic fluid.

An example of a prior art electromechanical actuator including the use of a magnetic fluid is disclosed in U.S. Pat. No. 2,792,536. Briefly, the referenced prior art device involves a ferromagnetic fluid that is sealed in a container having flexible walls to form the core of a solenoid. A coil is situated in close proximity to the container such that the application of electric current to the coil produces deformation of the container.

Such prior art ferrofluidic solenoids have been found to be bulky and are, by design, limited to producing forces that are generally resolvable along a single axis or plane. Further, these prior art devices are generally unacceptable for employment in spacecraft due to their undesirable levels of magnetic flux leakage which may cause deleterious affects on adjacent scientific instrumentation.

It is accordingly the intention of the present invention to provide an improved ferrofluidic solenoid which is principally characterized by compactness, simplicity, low magnetic flux leakage, and the provision of useful mechanical forces along multiple axes or planes.

OBJECTS AND SUMMARY OF THE INVENTION

It is a primary object of the present invention to provide an improved ferrofluidic solenoid for producing mechanical forces or movement in response to the application of electrical energy.

It is another object of the present invention to provide a ferrofluidic solenoid characterized by compactness, simplicity and low magnetic flux leakage.

It is a further object of the present invention to provide a ferrofluidic solenoid that will produce useable mechanical forces along multiple axes or planes.

It is a yet further object of the present invention to provide a ferrofluidic solenoid that is suitable for employment in multiples.

Briefly described, the present invention involves an electromechanical actuator embodied as a ferrofluidic device for producing a mechanical force, or displacement, in response to the application of electrical energy.

More particularly, the subject electromechanical actuator includes a ferromagnetic fluid and an electric coil which are both contained within an elastomeric capsule. Electrodes of the coil extend through the capsule walls to permit the application of electric current to the coil. The magnetic field produced by the coil, when energized, causes redistribution of the fluidic mass within the capsule and, as a consequence, deformation of the capsule.

Further objects and the many attendant advantages of the invention will be more readily appreciated as the same becomes better understood by reference to the following detailed description which is to be considered in connection with the accompanying drawings wherein like reference symbols designate like parts throughout the figures thereof.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1A is a schematic diagram of an electromechanical actuator in accordance with the present invention.

FIG. 1B is a schematic diagram illustrating the actuator of FIG. 1A in an unenergized condition and maintained under a pretensioning load.

FIG. 1C is a schematic diagram illustrating the actuator of FIG. 1B in an energized condition.

FIG. 2 is a schematic diagram illustrating an exemplary manner in which multiple electromechanical actuators, in accordance with the subject invention, may be used to provide a peristaltic device.

FIG. 3 is a schematic diagram illustrating an electromechanical actuator, in accordance with the subject invention, employed as a valve.

FIG. 4 is a schematic diagram illustrating how an electromechanical actuator, in accordance with the subject invention, may be employed as a "muscle" for prosthetic devices.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

Referring now to FIG. 1 of the drawings, a ferrofluidic solenoid in accordance with the present invention essentially includes a coil **10**, a ferromagnetic fluid **12** and an elastomeric capsule **14**. As shown, both the coil **10** and the ferromagnetic fluid **12** are contained within the capsule **14**.

The coil **10** may be of any conventional and well known type and may either be encased or exposed. The coil **10** is connected to receive electrical current via a pair of terminal wires **16** and **18** which are appropriately extended through the wall of the capsule **14**. The terminal wires **16** and **18** are preferably looped, as shown at **20** and **22**, within the capsule **14** to prevent breakage when the capsule **14** is deformed in a manner to be described hereinafter.

The ferromagnetic fluid **12** is preferably a colloidal, non-flocculating, suspension of high permeability particles in an inert liquid. Such a ferromagnetic fluid **12** is marketed by Ferrofluidics Corp., Burlington, Massachusetts. It is to be understood that although the above-described ferromagnetic fluid is preferred, any other appropriate medium such as a mixture of particulate material may be used.

The elastomeric capsule **14** may be a moderately elongated hollow shell having a closed wall as shown. The capsule is sized to permit enclosure of the fluid **12** and the coil **10** which is roughly centered within the capsule. Any appropriate and well known elastomeric material may be used.

As shown in FIG. **1A**, a pair of end arms **24** and **26**, or other mechanical connections, are attached to the respective ends **28** and **30** of the capsule **14**. These end arms **24** and **26** may be attached to the respective ends **28** and **30** in any well known manner, and may be stiff or flexible as necessary to accommodate the particular use of the solenoid.

Operationally, the net force and stroke produced by the ferrofluidic solenoid are dependent on a complex relation of elastic, hydrostatic and magnetic effects. Application of current to the coil **10** results in an effective pressure increase in the fluid **12**. If this pressure is considered to be transmitted hydrostatically through the fluid **12**, the elastomeric capsule **14** expands in diameter and contracts in length analogously to blowing up a toy balloon. This deformation of the capsule **14** is illustrated by FIG. **1C** showing a substantially spherical shape.

As an example, the capsule **14** may be maintained under a pretensioning load as illustrated by FIG. **1B**. The end arms **24** and **26** are useful for this purpose. As shown, such a pretensioning load will cause the capsule **14** to be longitudinally expanded. This may be accomplished, for example, by having one of the end arms **24** mechanically grounded by connection to an effectively stationary object **32**. The opposing end arm **26** may then be pulled away from the stationary end **28** to have the longitudinal dimension of the capsule **14** increased.

Referring again to FIG. **1C**, energization of the coil **10** by application of electrical current to the terminal wires **16** and **18** creates a magnetic field, the flux lines of which are generally illustrated by the dotted lines within the capsule **14**. The magnetic field operates to, in effect, redistribute the magnetic fluid **12** within the capsule **14** to thereby deform the shape of the capsule **14**. As shown this deformation of the capsule **14** is characterized by having the ends **28** and **30** thereof withdrawn and the central wall area protruded, i.e., axial compression and radial expansion. Simply considered, the stronger the magnetic field created by the current **10**, the more pronounced will be the deformation of the capsule **14**. The strength of the magnetic field is, of course, dependent on the amount of current applied to the coil **10** via the terminals **16** and **18**. Accordingly, the ferrofluidic solenoid of the present invention may act as a current-to-motion transducer in that an increased application of current will produce a corresponding larger displacement of the end **30** with respect to the end **28**. In the alternative, the ferrofluidic solenoid may be viewed as a current-to-force transducer in that the increased application of current will produce larger forces at the ends **28** and **30**.

Considering the subject solenoid in greater detail, the following assumptions are made: the elastomer is considered to be Gaussian, anisotropic, in the non-crystalline extension range ($X<\sim4$), a right circular cylindrical shell, and of constant volume ($X_1\ X_2\ X_3 = 1$); and the fluid **12** is assumed to be homogeneous and incompressible.

Considering the contribution of the capsule **14** to solenoid operation, the extension of an elastomer sheet under biaxial tensile stresses, S_1 and S_2, is described by the equation:

$$S_1 - S_2 = G(X_1^2 - X_2^2) \qquad \text{Eq. 1}$$

where X_1 and X_2 are the extension ratios and G is an elastic modulus derived from the free energy of the elastomer:

$$G = N_c kT = \rho R_0 T/M_c \qquad \text{Eq. 2}$$

where N_c is the number of polymer chains per unit volume, K is Boltzmann's constant, T is absolute temperature, ρ is the mass density, M_c is the chain molecular weight (between crosslinks), and R_0 is the gas constant.

For a section of this cylindrical shell, the longitudinal stress S_1 (directed between the ends **28** and **30**) is the sum of the longitudinal pressure stress and imposed tensile stress:

$$S_1 = PR/2t + F/2\pi Rt \qquad \text{Eq. 3}$$

The orthogonal tangential stress is the shell hoop stress:

$$S_2 = PR/t \qquad \text{Eq. 4}$$

The operating solenoid has an internal pressure, P, the sum of the initial pressure, P_I, and magnetic pressure, P_M, and is under initial plus final tensile loads, F_I and F_F. Because of the expansible nature of the shell wall, the unstressed unit length, L_o, radius, R_o, and thickness, t_o, are multiplied by the extension/compression ratios X_1, X_2, and X_3, respectively, to define initial parameters, i.e., $L_I = L_oX_1$, $R_I = R_oX_2$, and $t_I = t_oX_3$. The solenoid "on" condition is then described by the equation:

$$(F_1+F_F)/\pi X_2R_o - (P_I + P_M)R_oX_2 = 2X_3t_oG(X_1^2 - X_2^2) \qquad \text{Eq. 5}$$

Next considering the contribution of the ferrofluid **12** to solenoid operation, the Bernoulli equation for a ferromagnetic fluid includes a term for a scalar magnetic pressure:

$$P_M = \mu_0 \int_0^H M dH = \mu_0 \bar{M} H \qquad \text{Eq. 6}$$

where μ_o is the permeability of free space, M is the exact magnetization, $\bar{M}$ is the mean magnetization, and H is the magnetic field intensity. $\bar{M}$ has the asymptotes $x_iH/2$ for very small fields and saturation magnetization M_s; both M_s and x_i, the initial susceptibility, are characteristic of the particular ferrofluid (typically $125 < M_s < 1{,}000$ gauss; $0 < x_i < 4$).

The field intensity H is the quotient of the flux density B and the relative permeability. The flux density B at any section, j, in turn, is dependent on the total flux ϕ in the magnetic circuit, i.e.,

$$B_j = \phi / A_j \quad \text{Eq. 7}$$

and

$$\phi = \frac{0.4\pi\mu NI}{\sum_j \frac{l_j}{A_j}} \quad \text{Eq. 8}$$

where N is the number of turns in the coil, I is the current, l_j is the incremental circuit length, and A_j is the area along l_j. Hence it is seen that the magnetic pressure is not constant, but varies with the cross-section of the magnetic flux path, and in addition, with distance from the coil, in very large diameter solenoids.

The simplest case neglects end effects and assumes that the flux area A_c outside the coil is equal to that inside. Then, for a coil length l_c:

$$\phi = 0.2\pi\mu NIA_c/l_c \quad \text{Eq. 9}$$

and

$$H = 0.2\pi NI/l_c \quad \text{Eq. 10}$$

The magnetic pressure is then:

$$P_m = 0.2\pi\mu\ \overline{M}\ N\ I/l_c \quad \text{Eq. 11}$$

The axial extension ratio, X_1, could be divided into components for the linear stretching due to initial preload ($X_{1I} < 1$) and for contraction resulting from radial expansion ($X_{1F} < 1$) in the absence of preload; the output stroke length is the sum of these components. A similar but inverse relation exists for X_2 and stroke length. The following special cases are for unity ratios with respect to the unstressed state only; the actual "zero stroke" conditions are more complex.

The maximum output stroke is obtainable when the radial extension radio, X_2, is unity. Equation (5) then becomes:

$$(F_I + F_F)\ X_1/\pi R_o - (P_I + P_M)\ R_o X_1 = 2t_o G(X_1^2 - 1) \quad \text{Eq. 12}$$

In the absence of preload tension, F_I, and pressure, P_I, the force output is:

$$F_F = 2\pi R_o t_o G(X_1 - 1/X_1) + \pi R_o^2\ P_M X_1 \quad \text{Eq. 13}$$

A similar calculation for zero stroke length, $X_1 = 1$, gives the force output:

$$F_F = 2\pi R_o t_o G(1 - X_2^2) + \pi R_o^2\ P_M X_2^2 \quad \text{Eq. 14}$$

For comparison, the maximum force produced by a conventional solenoid is:

$$F_{MAX} = C\ A_c\ NI/l_c \quad \text{Eq. 15}$$

where C is a pull coefficient of about 0.01 and the other quantities are as previously defined.

The "off" condition of the ferrofluidic solenoid is described by $F_F = 0$ and $P_M = 0$. Assuming the unstressed filled capsule to be at ambient pressure, this is equivalent to a uniaxially stressed tube, such that equation (5) reduces to:

$$X_1/\pi R_o\ F_I - P_I R_o = 2t_o G(X_1^2 - 1/X_1) \quad \text{Eq. 16}$$

If the preload tension, F_I, is released, the remaining internal pressure declines, and X_1 approaches 1. Thus the isolated solenoid requires no external return spring, as do conventional solenoids.

As may be apparent from the P_M–H relation in equation (6), the assumption that pressure within the capsule **14** is hydrostatic and uniform is an oversimplification. The magnetic pressure is maximum at the section of the magnetic circuit with least area, whether within the core area of the coil **10** or the annulus area surrounding the coil **10**. This pressure is superimposed on any pre-existing hydrostatic pressure. So long as the fluid **12** is not appreciably saturated, all the flux is contained by the fluid **12**, and there will be a minimum field intensity at the extreme ends of the capsule **14**. The "on" configuration of the capsule **14** is not spherical, as if hydrostatically inflated, but is apple-shaped or toroidal, due to the tendency of the fluid to follow the lines of flux.

As the magnetic fluid **12** approaches magnetic saturation, an increasing proportion of the flux will be forced into the space surrounding the capsule **14**. This results in a lessening rate of increase in magnetic pressure, but should cause an additional traction force to be exerted across the capsule end interface, equivalent to an exterior pressure:

$$P' = \mu_o/2\ M_n^2 \quad \text{Eq. 17}$$

From the foregoing discussion it is clear that the subject ferrofluidic solenoid has several advantages over conventional solenoids and over prior art electromechanical actuators using a ferromagnetic fluid. Among these advantages are the elimination of the conventional air gap which results in greater efficiency of operation. Also, magnetic flux leakage is minimal up to the fluid saturation level since the coil **10** is completely surrounded by the magnetically permeable material in the fluid **12**. Further, the simplicity and compactness of the subject invention permits the device to be economically manufactured and readily employed, or staged, in multples or in tandem.

Referring to FIG. **2**, an exemplary peristaltic device is illustrated as including three solenoids **34, 36** and **38** connected in tandem. In operation, an end solenoid **38** may be connected to a cable **40** to be pulled through a conduit **42**. The solenoids **34, 36** and **38** may then be serially energized and then serially de-energized commencing with the leading solenoid **34**. The radial expansion of the leading solenoid **34** will cause the central portion **44** of the capsule wall to be forced against the interior surface of the conduit **42** to effectively anchor the leading end of the peristaltic device. Energization of each successive solenoid, i.e., solenoid **36** and then solenoid **38**, will cause the cable **40** to be pulled through the conduit **42** for a distance equal to the summed work strokes of the solenoids **36** and **38**. The dotted lines in FIG. **2** illustrate the movement produced after energization of the first two solenoids **34** and **36**. Upon all of the solenoids connected in tandem being energized, the leading solenoid **34** is de-energized, followed by the de-energization of each successive solenoid. Clearly, this results in the string of solenoids being extended for their full ambient length whereupon the solenoids can again be successively energized. In the de-energization cycle, the trailing solenoid **38** anchors the trailing end of the peristaltic device to permit the desired inward extension of the preceding solenoids **34** and **36**. It is to be understood that any practical number of solenoids may be staged despite the foregoing example involving only three solenoids.

Referring to FIG. **3**, a ferrofluidic solenoid in accordance with the present invention may be used as a valve. As shown, a solenoid **46** can be situated within a fluid conducting conduit **48**. The ends **50** and **52** of the solenoid **46** may be appropriately supported by a pair of supporting rings **54** and **56**, respectively, which are secured within the conduit **48**. As may be appreciated, the end connectors **50** and **52** may be somewhat flexible to permit easy axial compression of the solenoid **46** and thereby not significantly impede the radial expansion thereof upon energization. Again, the dotted lines in FIG. **3**, illustrate the solenoid **46**, when energized. As shown, the energized solenoid **46** serves to completely block the inner passage of the conduit **48** such that the flow of fluid through the conduit **48** is stopped.

In yet another exemplary application, the ferrofluidic solenoid of the present invention may be used as a "muscle", or the like, for prosthetic devices. As shown by FIG. **4**, a solenoid **58** can be connected between a pair of pivotally connected sections **60** and **62** to produce a "closing" motion when energized. De-energization of the solenoid **58** would then produce a spreading or "opening" movement of the respective sections **60** and **62**.

It is to be noted that each of the applications illustrated by FIGS. **2**, **3** and **4** are exemplary and that for simplicity of illustration, the two electrical connectors for the respective solenoids have not been shown. However, it is clear that such electrical connectors may be connected to the coils of the respective solenoids in any suitable manner and collectively situated to permit the application of current thereto.

From the foregoing description, it is now clear that the present invention provides an improved ferrofluidic solenoid that is compact and simple of construction and which is characterized by a lack of significant magnetic leakage. It is also apparent that the subject solenoid may be readily used to form tandem stages and is readily applicable to a multitude of different uses.

While a preferred embodiment of the present invention has been described hereinabove, it is intended that all matter contained in the above description and shown in the accompanying drawings be interpreted as illustrative and not in a limiting sense and that all modifications, constructions and arrangements which fall within the scope and spirit of the invention may be made.

What is claimed is:

1. An electromechanical actuator for producing mechanical movement in response to the application of electric current, the actuator comprising:

a flexible closed shell capable of omnidirectional deformation having an interior cavity formed by the wall thereof;

an electrical coil maintained unattached in said cavity so that the entire shell is relatively movable to said electrical coil;

means for energizing said electrical coil including a pair of terminals extending through said wall of said shell and connected to said electrical coil;

a magnetizable fluid completely surrounding said suspended coil and fully occupying said cavity to exert a hydrostatic pressure on said shell, said shell being deformed when a magnetic pressure is created in said magnetizable fluid within said shell by the application of current through said terminals to energize said coil.

2. The electromechanical actuator defined by claim **1**, said shell comprising an elastomeric material forming a continuous closed wall and an oblong configuration when subject to only said hydrostatic pressure, said fluid comprising a ferromagnetic fluid responsive to a magnetic field created by energization of said coil, said shell assuming a substantially spherical shape when subject to said magnetic pressure.

3. A ferrofluidic solenoid comprising:

a flexible capsule having a hollow interior area formed by the wall thereof;

a coil having an open bore positioned in said hollow interior area so that the entire wall is movable relative to said coil;

means connected to said coil for permitting the application of electrical current to said coil;

a magnetizable fluid contained within said capsule and fully immersing said coil, said open bore containing only said magnetizable fluid, said flexible capsule producing an output force by being deformed by said magnetizable fluid when the fluid pressure of said magnetizable fluid within said shell is varied by the application of current through said terminals to energize said coil.

4. The actuator defined by claim **1**, said shell comprising an elastomeric material.

5. The actuator defined by claim **1**, said fluid comprising a ferromagnetic fluid.

6. The actuator defined by claim **1**, said fluid comprising a colloidal, non-flocculating suspension of high permeability particles in an inert liquid.

7. The actuator defined by claim **1** further including output members connected at opposing points along the exterior of said shell for transmitting mechanical forces developed by deformation of said shell to articles connected thereto.

8. The actuator defined by claim **7**, said shell comprising an elastomeric material and having an oblong spherical configuration, said coil having the longitudinal axis thereof superimposed with the longitudinal axis of said shell, said output members connected to said shell at opposing points on said shell intersecting said longitudinal axis.

9. The actuator defined by claim **8**, said fluid comprising a ferromagnetic fluid.

10. The ferrofluidic solenoid defined by claim 3, said capsule comprising an elastomeric shell having a continuous closed wall and an oblong configuration, said fluid comprising a ferromagnetic fluid responsive to introduction to a magnetic field created by energization of said coil.

11. The ferrofluidic solenoid defined by claim 10, said coil having the longitudinal axis thereof superposed with the longitudinal axis of said capsule, said solenoid further including connecting arms secured to the exterior surface of said capsule at opposing points thereon intersecting said longitudinal axis of said capsule.

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