

[72] Inventor **Cormac Garrett O'Neill**
Castro Valley, Calif.
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 [73] Assignee **Physics International Company**
San Leandro, Calif.

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Primary Examiner—Robert M. Walker
 Attorney—Lindinberg, Freilich & Wasserman

[54] **ELECTROSTRICTIVE ACTUATOR**
15 Claims, 10 Drawing Figs.

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 310/8
 [51] Int. Cl. F04b 19/00,
 H01v 7/00
 [50] Field of Search 103/1, 44,
 440, 44 W; 230/1; 417/383; 310/8.1, 8; 340/11

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ABSTRACT: Apparatus is disclosed for doing useful work with electroexpansive material which expands volumetrically in response to an electric field. The material is disposed in a chamber of a fixed volume slightly greater than the volume of the material at rest. The volume intermediate the material and the chamber is filled with a fluid having good insulation properties. When the material expands in response to an electrical signal, insulating fluid is forced out of a passage in a wall of the chamber and performs work by actuating a plunger or diaphragm. Means, such as an intermediate piston, may be employed to isolate the insulating fluid from the hydraulic fluid in a device being thus hydraulically driven, such as a pump valving means or fluid control valve.

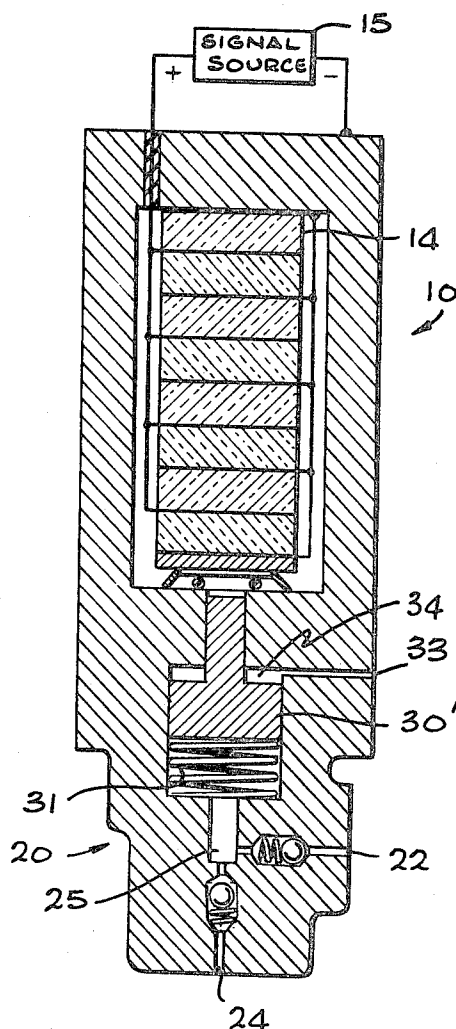


Fig. 1

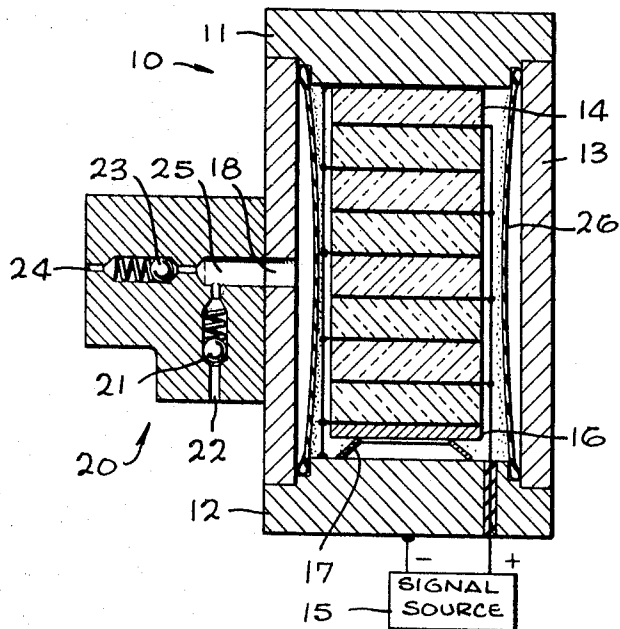


Fig. 2

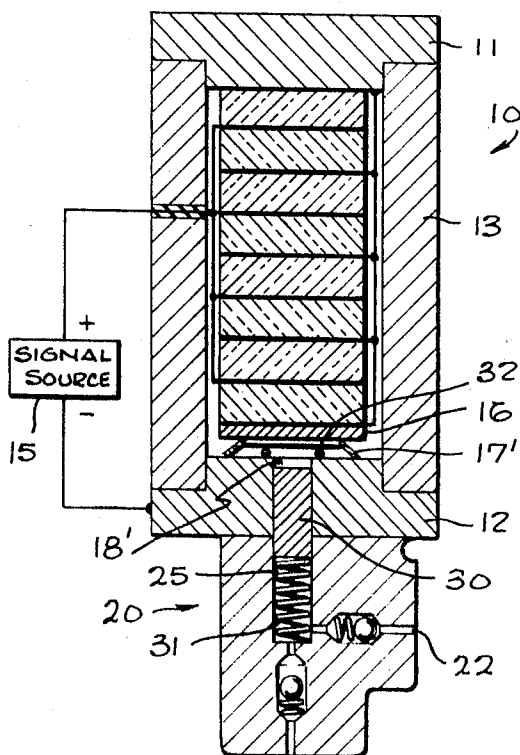
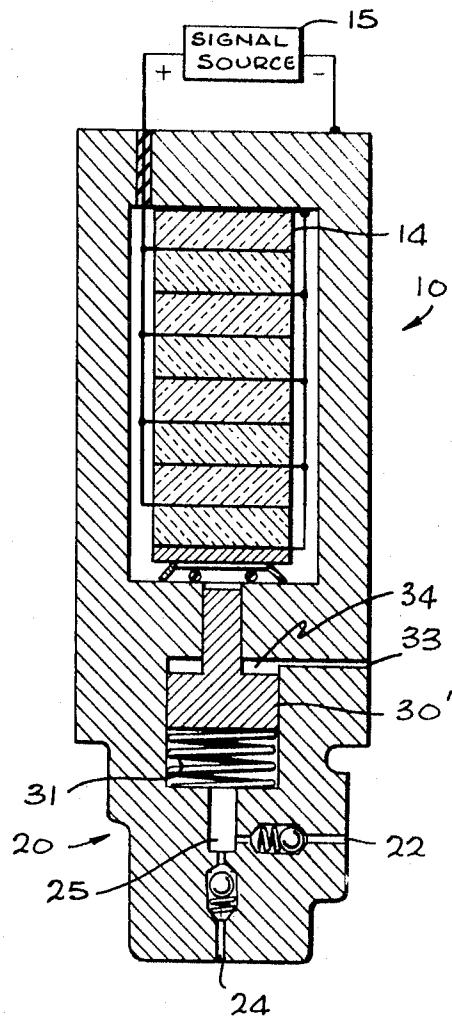


Fig. 3



CORMAC G. O'NEILL
INVENTOR.

BY *Lundberg & Freilich*

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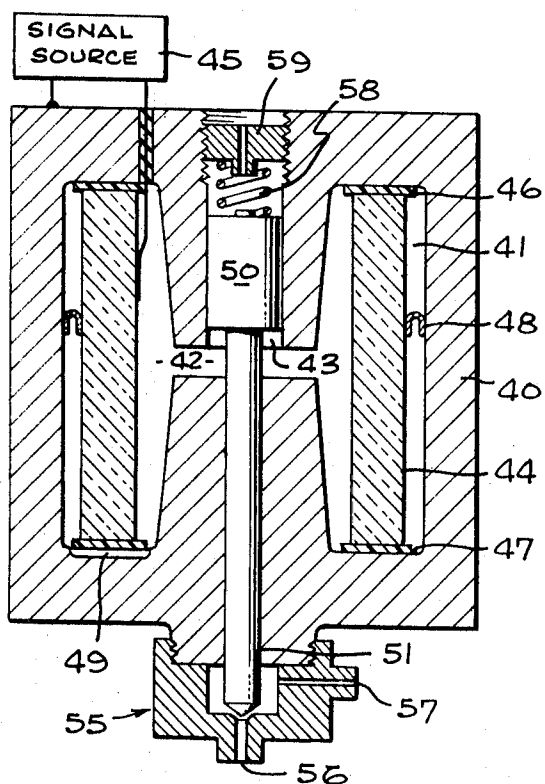


Fig. 4

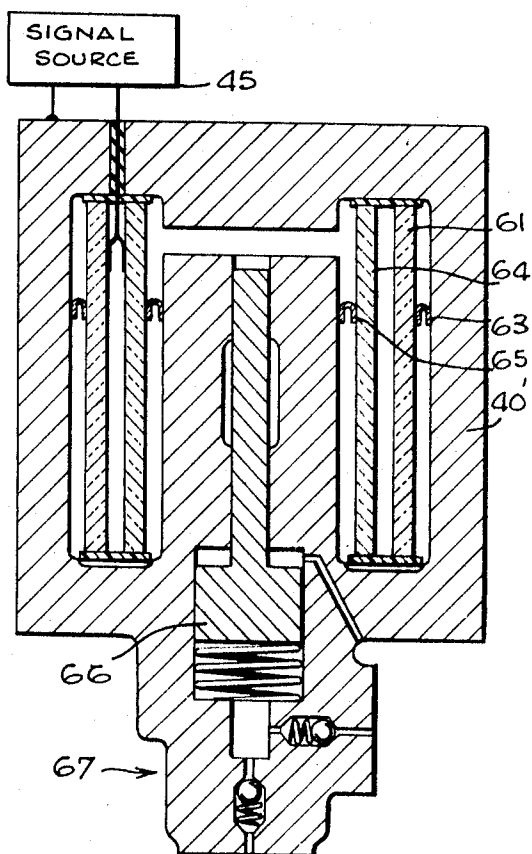


Fig. 6

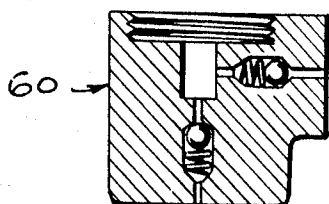


Fig. 5

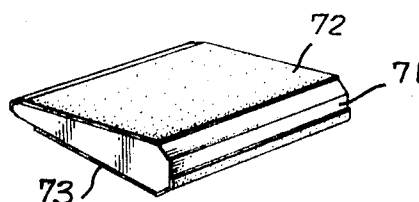


Fig. 8

CORMAC G. O'NEILL
INVENTOR.

BY *Lundberg & Freibach*

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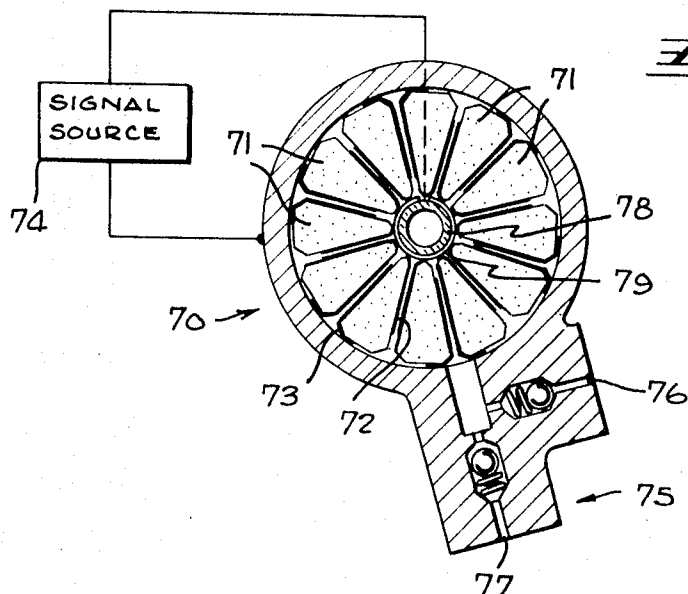


Fig. 7

Fig. 10

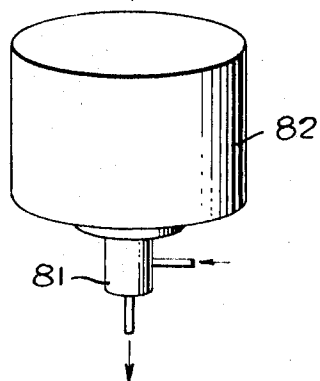
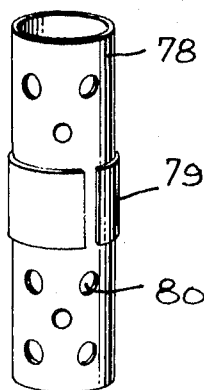


Fig. 9



CORMAC G. O'NEILL
INVENTOR.

BY *Lindenberg & Freilich*

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ELECTROSTRICTIVE ACTUATOR

BACKGROUND OF THE INVENTION

This invention relates to drivers for pumps, valves, actuators and the like, and more particularly to electroexpansively powered drivers.

Such devices as pumps and fuel injectors have been devised based upon the piezoelectric effect of certain materials. Upon application of an electric field across such material, the material expands or contracts along known axes, depending upon the polarity of the electric field. Therefore, in such piezoelectric devices the expanding and contracting material is generally so disposed in a housing that the mechanical load is transmitted directly by the material, thereby requiring a precise configuration and low compliance for the load surfaces. Another disadvantage of directly driven devices is that the travel of the load surfaces is quite limited. To overcome that disadvantage, it has been common practice to so stack a plurality of piezoelectric elements that their cumulative piezoelectric expansion is more substantial. But that, of course, compounds the first problem since more precise load surfaces with low compliance are then required.

Some materials known as electrostrictive material exhibit the property of a positive dimension change in a direction parallel to the applied electric field regardless of the polarity of the applied field, with only a second order reduction in dimensions along two complementary (orthogonal) directions. In other words, given the direction of the applied electric field as the principle axis, the material will expand along that axis regardless of the polarity of an applied voltage with very little contraction along second and third mutually perpendicular axes. Consequently, upon application of a voltage of either polarity, the material increases in volume sufficiently to perform useful work.

The present invention concerns the performance of useful work through use of any material, referred to hereinafter as "volumetric electroexpansive material," that is known to exhibit an increase in volume in response to an electric field regardless of whether the increase in volume is due to the piezoelectric effect or the electrostrictive effect. The performance of work is best carried out hydraulically to avoid having mechanical loads transmitted through material interfaces.

An important advantage of a hydrostatically driven device using elements of volumetric electroexpansive material is that the elements may be easily produced, such as by casting, with loose tolerances in respect to surface finish, compliance of interfaces, and mechanical strength of the ceramic material, as well as dimensions. But of all the advantages of such a device, the most important is that displacement amplification may be readily achieved hydraulically even though that use of electroexpansive material would produce lower strains along a given axis for a certain voltage gradient than in directly driven devices.

SUMMARY OF THE INVENTION

According to the invention, an electroexpansively powered fluid driver is provided by a body having a chamber of a given volume and a passage in a wall thereof communicating with that chamber. Volumetric electroexpansive material is disposed in that chamber but not to its full capacity. The space intermediate the volumetric electroexpansive material and the chamber is filled with a fluid so that when an electric field is applied across the electroexpansive material, the material may undergo a total volume increase to perform work by forcing fluid from the chamber through the passage in its wall. Such a fluid driver may be employed to pump fluid, either directly or by means of a piston.

A plurality of electroexpansive elements may be used to increase the total change in volume, i.e., to increase the hydraulic displacement produced in response to an electrical signal.

The driver chamber may be of any suitable elongated configuration, such as a cylinder to accommodate a stack of elements. The driver chamber may also be annular and the electroexpansive elements tubular.

Another configuration for the electroexpansive elements for the use in a cylindrical chamber is a substantially segmental section. A plurality of segmental sections are disposed in the cylindrical chamber such that each makes electrical contact with a split tube spring at the center. The split tube spring urges each of the segmental sections against the cylindrical wall of the chamber where a second electrical contact is made to provide an electrical field in response to an electrical signal.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 shows a longitudinal cross section of a first embodiment of the present invention. 2 illustrates a variant of the first embodiment shown in FIG. 1.

FIG. 3 illustrates another variant of the first embodiment illustrated in FIG. 1.

FIG. 4 shows a longitudinal cross section of a second embodiment of the present invention.

FIG. 5 shows a cross section of a pump valving means for use with the embodiment of FIG. 4 in place of a valve element shown.

FIG. 6 illustrates a variant of the second embodiment illustrated in FIG. 4.

FIG. 7 shows a cross section of a third embodiment of the present invention.

FIG. 8 shows an isometric view of a segmental section of electroexpansive material employed in the embodiments of FIG. 7.

FIG. 9 illustrates a central column of nonconductive material with holes throughout and a split ring of conductive spring material for use in the embodiment illustrated in FIG. 7 at the center of a plurality of segmental sections.

FIG. 10 illustrates in an isometric view a variant of the embodiment illustrated in FIG. 7.

The novel features that are considered characteristic of the invention are set forth with particularity in the appended claims. The invention will best be understood from the following description with reference to the accompanying drawings.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

Referring now to FIG. 1, there is shown an electroexpansive driver body 10 comprising end plates 11 and 12 and a cylindrical tube 13. Disposed within the driver body are a plurality of stacked elements made of volumetric electroexpansive material, such as element 14, each in the form of a disc. There are a number of different materials commercially available that exhibit a volumetric electroexpansive effect in response to an electrical signal. Some suitable ceramic materials are "Thin Loop" by Channel Industries of Santa Barbara, California, and "Skinny Loop" by Honeywell of Minneapolis, Minnesota.

A signal source 15 is connected across each of the stacked elements by, for example, soldering one terminal of the source 15 to the plate 12 and the other terminal of the source 15 to a thin metal electrode interposed between each of the opposing faces of adjacent discs as shown. Alternate pairs of opposing faces are connected to the positive and negative terminals of the source 15 in such a manner that each disc shares a positive electrode with one neighbor and a negative electrode with the other neighbor, the two electrodes at the stack extremities being of the same polarity as the terminal of the source source 15 connected to the end plate 12. The plate 12 is made of suitable conductive material. The plate 11 is in direct contact with the top of the stacked elements while the plate 12 is in contact with the bottom of the stack through a metal disc 16 and a metal spring washer 17. The metal spring 17 holds the elements of the stack in electrical contact with the thin metal electrodes interposed between adjacent discs. As electrical signals from the source 15 are applied, the stack continually

expands, thereby continually flexing the spring 17. The disc 16 protects the stack of electroexpansive elements from damage due to forces against the spring 17.

When an electrical signal is applied to the stack of electroexpansive elements from the source 15, the total volume of the electroexpansive material disposed within the chamber of the body 10 increases. Fluid within the chamber of the body 10 is thereby forced to flow under pressure through a passage 18 in the tubular wall 13 of the chamber. As the electrical signal is removed, the total volume of the electroexpansive material decreases, thereby causing a reduction in pressure on the remaining fluid in the chamber of the body 10.

In order to pump fluid continually in response to electrical pulses, pump valving means 20 is connected to the passage 18. A one-way valve 21 at the fluid inlet port 22 prevents fluid being forced from the chamber of the body 10 from being returned to its source. A one-way valve 23 in the outlet port 24 similarly prevents fluid from flowing in the opposite direction.

If the fluid being pumped is an electrical conductor, fluid in the chamber of the body 10 would provide a short circuit across the electroexpansive elements. Accordingly, to pump conductive fluid, a sleeve 26 of flexible material is provided around the stack of electroexpansive elements, from the plate 11 to the plate 12, to isolate the fluid (which has suitable insulation properties) in contact with the stack of elements from the fluid pumped. In either case, a predetermined minimum feed pressure at the inlet 22 would be required to insure filling a pumping chamber 25.

FIG. 2 illustrates a variant of the first embodiment illustrated in FIG. 1. The variation is substitution of a piston 30 for the flexible sleeve 26 in the first embodiment of FIG. 1 to isolate the fluid being pumped through the pump valving means 20 from fluid in the drive chamber of the body 10. The volumetric electroexpansive elements, such as the elements 14, are connected to a signal source 15 as before.

As the electroexpansive material increases in volume, fluid is driven from the chamber of the body 10 through a passage 18' against the piston 30, thereby forcing fluid from the pumping chamber 25 through the outlet port 24 of the pump valving means 20. As the electrical signal is removed, the volume of the electroexpansive material decreases thereby allowing fluid to reenter the chamber of the body 10 as the piston 30 is driven upwardly under the feed pressure of fluid at the inlet port 22. To minimize the feed pressure that would be required to insure filling the pump chamber 25 to its maximum, a return spring 31 is provided for the piston in the pumping chamber 25. Since fluid to and from the passage 18' must pass by the spring washer 17', holes (such as hole 32) may be provided in the washer 17'. Alternatively, notches may be provided along the inner and outer edges of the washer 17', or radial bypass slots may be provided in the plate 12 or the disc 16.

Still another variant of the first embodiment of the present invention is illustrated in FIG. 3. The principle variation is the provision of a piston 30' with a larger area exposed to the fluid being pumped than to fluid in the drive chamber of the body 10. In that manner, volume amplification is obtained to increase the average flow rate from the inlet port 22 to the outlet port 24.

If force amplification were desired instead of volume amplification, the area of the piston 30' in contact with the fluid in the chamber of the body 10 would have been greater than the area in contact with fluid being pumped. In either case, the piston cylinder 34 (i.e., the cylindrical passage through the body 10 to the pump valving means 20 containing the piston 30') would have a large diameter portion of sufficient length to allow maximum travel for the piston 30'. A vent 33 is provided at the base of the enlarged portion of the piston cylinder to facilitate driving the piston 30' down in response to an electrical signal and up again in response to force of the return spring 31. Otherwise, a vacuum may be produced behind it as the piston 30' is driven toward the pump chamber 25.

Another variation illustrated in FIG. 3 is provision of the body 10 and the pump valving means 20 by integral metal castings of two longitudinal sections which are then welded, braised or otherwise fastened together in fluidtight manner after all of the internal elements have been properly placed. Electrical connections to the volumetric electroexpansive element are made in a manner similar to that described with reference to the embodiment of FIG. 1.

Referring now to FIG. 4, a second embodiment of the present invention is provided based on the dilation of volumetric electroexpansive material in the direction of applied field without significant, if any, contraction on the two complementary axes. Both inside and outside surfaces of electroexpansive material (in the form of a tube) will then act to displace fluid if the tube is placed within an annular chamber of a body having a passage through a wall thereof. Thus, in the embodiment of FIG. 4, a body 40 is provided with an annular chamber 41 with a passage 42 from the chamber 41 to a piston cylinder 43 concentric with the chamber 41. A signal source 45 is provided with one terminal connected directly to the body 40 and the other terminal passing into the chamber 41 where it is connected to the inner surface of a tube of electroexpansive material 44. The inside and outside surfaces of the tube 44 are coated with an electrically conductive coating, such as silver or nickel. The end surfaces of the tube 44 are coated with an electrically conductive coating, such as silver or nickel. The end surfaces of the tube are not coated. It should be understood that the tube 44 of electroexpansive material is electrically insulated from the body 40 as by rings 46 and 47 of dielectric material. Springs are then placed on the outside of the electroexpansive element 44, such as spring 48 formed from a band of conductive spring material, in order to maintain electrical contact between the conductive coating on the outside surface of the electroexpansive element 44 and the body 40. To assure that fluid pressure will always be equal on both sides of the electroexpansive element 44, bypass slots are provided, such as a bypass slot 49.

A piston 50 is provided with an arm or stem 51 extending from the body 40 in order to actuate a device as the piston 50 is moved up and down hydraulically in response to a signal from the source 45. As shown, the device is a valve 55 having two ports 56 and 57 through which fluid may flow from one port to the other as the piston 50 is moved upwardly in response to a signal from the source 45. A spring 58 and nut 59 are provided to adjust the position of the valve stem (arm or stem 51 of the piston 50) to close the passage to the port 56 when no signal is applied.

The embodiment of FIG. 4 may be readily adapted for pumping a fluid by substituting for the valve device 55 a pump valving device 60 is substantially the same as the valve pumping means 20 illustrated in FIG. 1, both in construction and in operation, and therefore will not be further described with reference to the second embodiment of the invention illustrated in FIG. 5.

FIG. 6 illustrates a variant of the second embodiment described with reference to FIG. 4. The principle variation is the provision of more than one tubular electroexpansive element. The first element 61 is substantially the same as the single element 44 shown in FIG. 4 with an electrical connection between the signal source 45 and the inside surface of the element 61 and between the outside surface of element 61 and the body 40' by a spring 63. Connections are provided for a second tubular electroexpansive element 64 in a corresponding but reverse manner with the inside surface thereof connected to the body 40' by a spring 65, and the outside surface directly connected to the signal source 45. In that manner, multiple electroexpansive elements may be used to provide increased fluid displacement. Another variation is the provision of a piston 66 and pump valving means 67 in a manner similar to that described with reference to FIG. 3 for the first embodiment of the present invention such that volume amplification is achieved.

A third embodiment of the present invention is illustrated in FIG. 7. It consists of a body 70 having a cylindrical chamber in which segmental sections of electroexpansive elements are radially disposed, such as a section 71 shown in an isometric view in FIG. 8. As viewed in that FIG. 8, the top surface is coated with a conductor 72, such as silver, around to the far, narrow end. The bottom side is similarly coated with a conductor 73 around to the near, wide end. By applying a potential across the two ends, an electric field is established between the conductors 72 and 73. Accordingly, when segmental sections have been so placed in the chamber of the body 70 that adjacent ones have their conductors 72 opposite each other and similarly have their conductors 73 opposite each other, a signal may be applied to all of the sections in parallel by a source 74. The elements expand circumferentially with little or no radial contraction for a net volume increase. In that manner, fluid may be driven out of the chamber of the body 70. A pump valving means 75 (the same as that described with reference to FIG. 1) is provided in order that the electroexpansive driver may pump fluid from an inlet port 76 to an outlet port 77.

A tube 78 is provided as a central column in the chamber of the body 70 to assure that the segmental sections remain in place substantially as shown in FIG. 7 with the wide end of each in contact with the cylindrical wall of the body 70. A split ring 79 of conductive spring material is placed around the column 78, as may be more clearly seen in FIG. 9. As the split ring 79 seeks to expand in diameter, the segmental sections are maintained in electrical contact with the cylindrical wall of the body 70. At the same time, the split ring 79 is in contact with the narrow end of each segment so that it may be employed as one electrode connected to the signal source 74 as shown in FIG. 7 while the cylindrical wall of the body 70 is employed as the other (ground) electrode. The tube 78 is provided with a plurality of holes, such as a hole 80, in order that pressures quickly equalize throughout the chamber of the body 70.

If the fluid being pumped is an electrical conductor, a nonconductive hydraulic fluid may be provided in the chamber of the body 70 and isolated from the fluid being pumped by a piston in the manner described hereinbefore with reference to FIG. 2 or, if volume amplification is desired, in a manner described hereinbefore with reference to FIG. 3. Alternatively, the pump valving means 75 may be omitted and a valve or other device attached to the body 70 for actuation through a piston in a manner similar to that described hereinbefore with reference to FIG. 4.

Although the pump valving means 75 is shown in FIG. 7 connected to a radial passage from the chamber of the body 70, it should be appreciated that such a means or other device may be connected to an axial passage as shown in FIG. 10 by a pump valving means 81 connected to a body 82 which is otherwise the same as that illustrated in FIG. 7. In that manner, the passage from chamber of the body 82 to the valving means 81 is through the center of an end wall to provide direct fluid transfer from a central tube of the form illustrated in FIG. 9. Here again, the pump valving means 81 may be isolated from the hydraulic fluid in the chamber of the body 82 by a piston, and may also be substituted with a piston actuated device if desired.

Although the present invention has been shown and described with reference to particular embodiments, it should be apparent to one skilled in the art that many changes and modifications may be made without departing from the true spirit and scope of the invention.

What is claimed is:

1. An electroexpansively powered fluid driver comprising: a body having a chamber of a given volume and a passage in a wall thereof communicating with said chamber; volumetric electroexpansive material disposed in said chamber, said material being a solid and having a total volume less than said given volume of said chamber;

nonconductive fluid filling said chamber and in direct contact with said electroexpansive material on all sides free to move in response to an electric field applied to said electroexpansive material such that all of said fluid will be at the same pressure at any given time; and

means for applying an electric signal as a potential across said material to create said electric field to cause said material to undergo a total volume change to perform work by forcing fluid from said chamber through said passage.

2. Apparatus as defined in claim 1 including pump valving means comprising:

- a pump chamber having a port connected to said passage;
- fluid inlet means having a one-way valve communicating with said pump chamber; and
- fluid outlet means having a one-way valve communicating with said pump chamber.

3. Apparatus as defined in claim 1 wherein said chamber is a cylinder and said material is in the form of a plurality of segmental sections, said sections being disposed about a central spring tube through which electrical contact is made with each section while each section is being urged against the cylindrical wall of said chamber, said wall being made of electrical conductive material, and said means is connected between said spring tube and said cylindrical wall.

4. Apparatus as defined in claim 3 including pump valving means comprising:

- a pump chamber having a port connected to said passage;
- fluid inlet means having a one-way valve communicating with said pump chamber; and
- fluid outlet means having a one-way valve communicating with said pump chamber.

5. An electroexpansively powered driver comprising:

- a hydraulic cylinder;
- a body having an hydraulic fluid chamber of a given volume and a passage in a wall thereof communicating with said hydraulic cylinder;

volumetric electroexpansive material so disposed in said chamber as to provide a hydraulic drive chamber between said material and walls of said chamber;

a piston disposed in said cylinder;

fluid filling said hydraulic drive chamber and passage to said piston in said cylinder, said fluid surrounding said electroexpansive material on all sides free to move in response to an electrical field applied to said electroexpansive material such that all of said fluid will be at the same pressure at any given time; and

means for applying an electric field to said material to cause said material to undergo a total volume increase to hydraulically advance said piston in said cylinder.

6. Apparatus as defined in claim 5 including pump valving means comprising:

- a pump chamber having a port connected to said cylinder at the end thereof remote from said hydraulic drive chamber;

fluid inlet means having a one-way valve, communicating with said pump chamber; and

fluid outlet means having a one-way valve communicating with said pump chamber;

7. Apparatus as defined in claim 6 including a return spring in said cylinder between said piston and said pump valving means.

8. Apparatus as defined in claim 5 wherein said piston has a portion at one end thereof with an area that differs from the area at the other end thereof, and said cylinder is of a diameter substantially equal to that of said portion over a sufficient length thereof to receive said portion of said piston and allow maximum travel of said piston.

9. Apparatus as defined in claim 8 including means for venting said cylinder at the base of the enlarged portion thereof.

10. An electroexpansively powered fluid driver comprising: a hydraulic cylinder;

a body having an annular hydraulic fluid chamber of a given volume and a passage in a wall thereof communicating with said hydraulic cylinder;
at least one tube of volumetric electroexpansive material so disposed in said chamber as to provide a hydraulic drive chamber between said tube and walls of said body;
an actuating piston disposed in said cylinder;
fluid filling said hydraulic drive chamber and passage to said piston in said cylinder, said fluid surrounding said electroexpansive material on all sides free to move in response to an electrical field applied to said electroexpansive material such that all of said fluid will be at the same pressure at any given time; and
means for applying said electric field to said material to cause said material to undergo a total volume increase to hydraulically advance said piston in said cylinder.

11. Apparatus as defined in claim 10 including an arm ex-

tending from said cylinder for actuation of a device.

12. Apparatus as defined in claim 11 wherein said device is a valve and the end of said arm remote from said piston comprises a valving plunger.

13. Apparatus as defined in claim 11 wherein said device is a pump and the end of said arm remote from said piston comprises a pumping piston.

14. Apparatus as defined in claim 13 wherein said pumping piston has a diameter that differs from the diameter of said actuating piston.

15. Apparatus as defined in claim 10 wherein a second tube of volumetric electroexpansive material is disposed in said chamber and said means functions for said second tube in the same manner as for said one tube of volumetric electroexpansive material.

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