United States Patent

Benson

[15] **3,635,016**

[45] **Jan. 18, 1972**

[54] ELECTROMECHANICAL ACTUATOR HAVING AN ACTIVE ELEMENT OF ELECTROEXPANSIVE MATERIAL

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[21] Appl. No.: **870,715**

Related U.S. Application Data

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[52] **U.S. Cl.** ....**60/23,** 60/54.5 R, 91/459

[51] **Int. Cl.** **F01k 25/00**

[58] **Field of Search** 60/23, 54.5; 310/8.7

[56] **References Cited**

UNITED STATES PATENTS

2,498,990	2/1950	Fryklund	310/8.7 X
2,548,708	4/1951	Dickey	60/23
2,649,691	8/1953	Johnson	60/54.5 HA
2,815,642	12/1957	Sherwood	60/54.5 X
3,059,417	10/1962	Sherwood	60/23
3,154,700	10/1964	McNaney	310/8.7 X
3,183,672	5/1965	Morgan	60/23 X
3,390,287	6/1968	Sonderegger	310/8.7 X
3,482,121	12/1969	Hatschek	310/8.7 X

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[57] **ABSTRACT**

An electromechanical transducer having an active module of electroexpansive material, such as piezoelectric material. A chamber filled with noncompressible fluid that is bounded by first and second plungers or diaphragms, the first plunger being operatively connected to the module. The area of the second plunger is established at a size smaller than the first plunger so as to provide for motion amplification of the relatively small mechanical displacement of the electroexpansive module. An improved electroexpansive module and a method for making the same are also disclosed.

2 Claims, 17 Drawing Figures

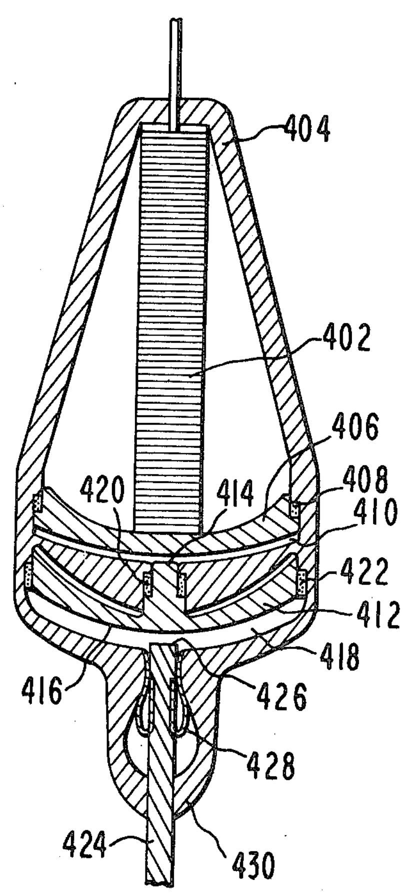
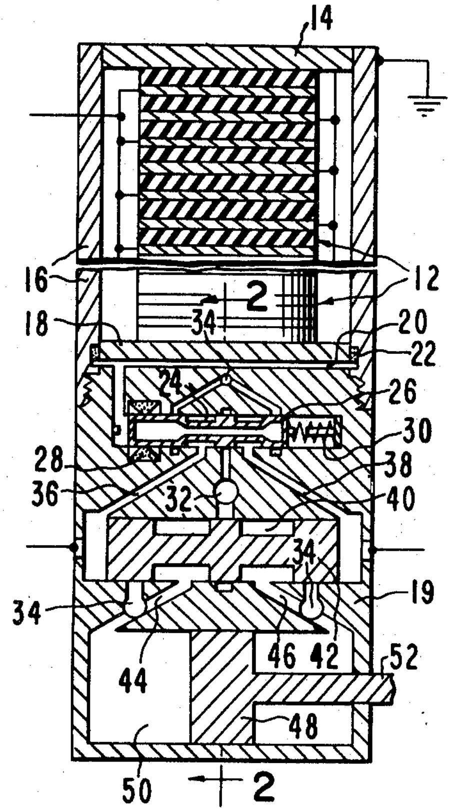


FIG.1



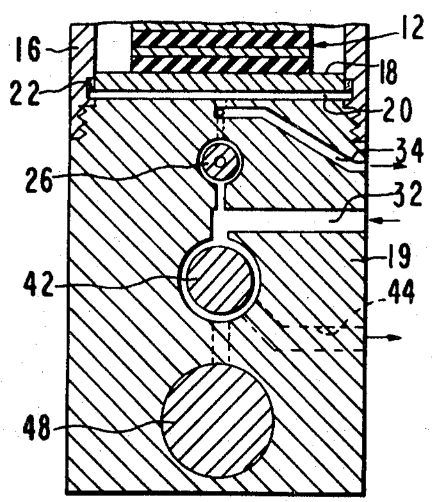


FIG.2

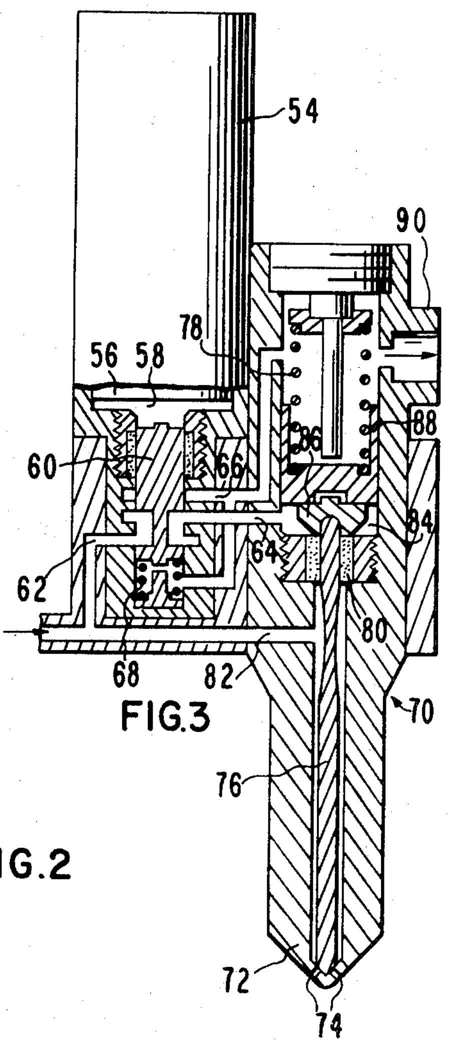


FIG.3

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FIG. 4

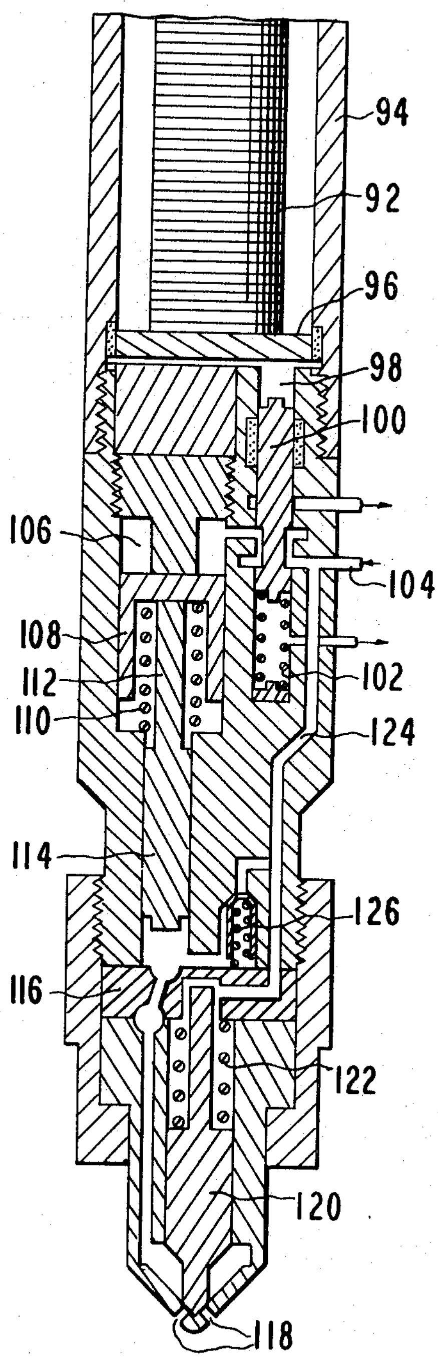

FIG. 5

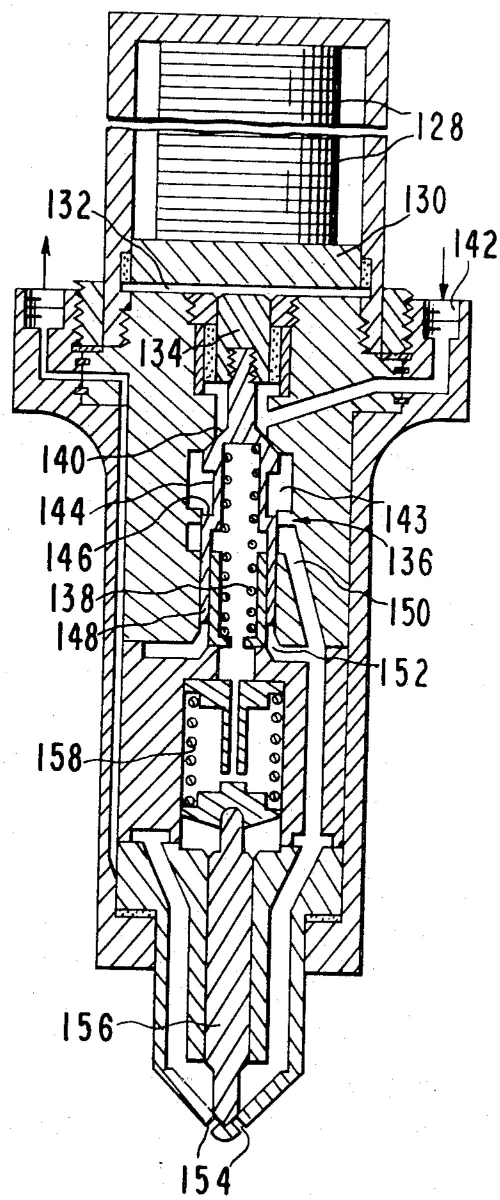

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FIG.5A

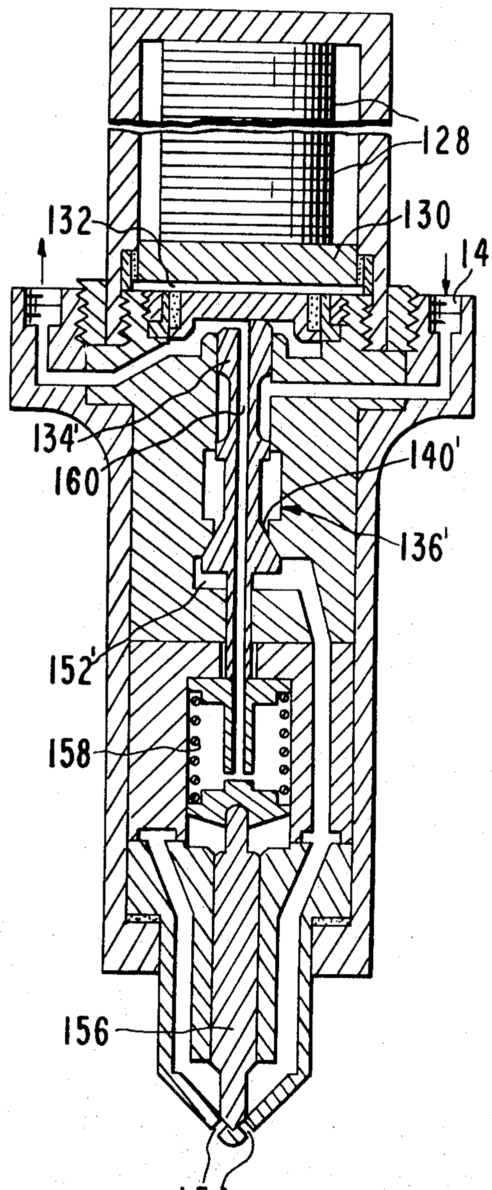

FIG. 6

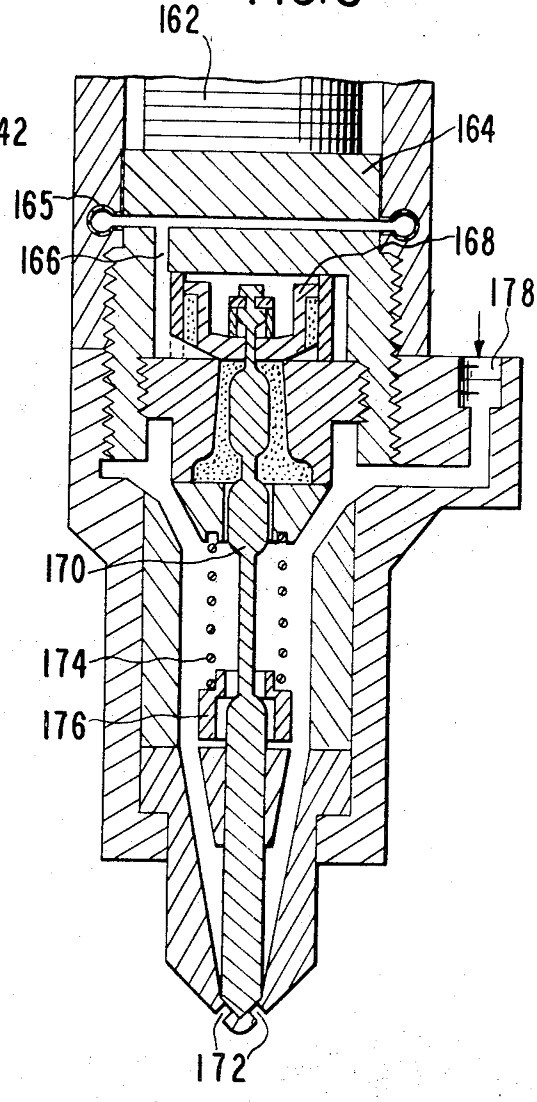

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FIG.7

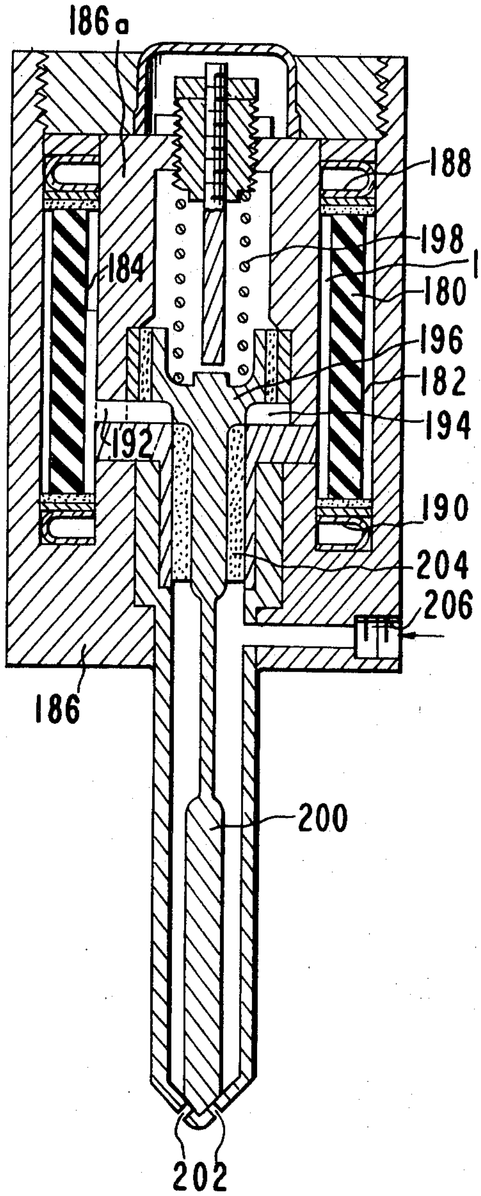

FIG.8

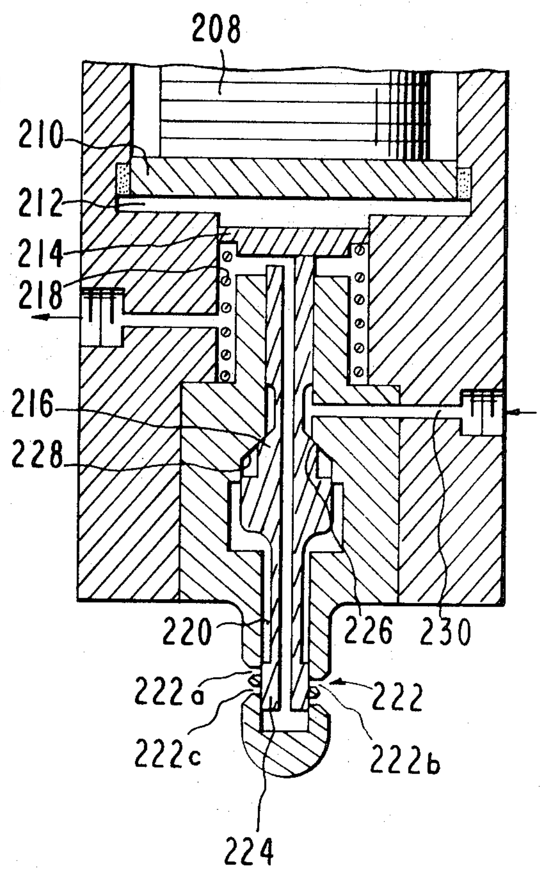

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FIG.9

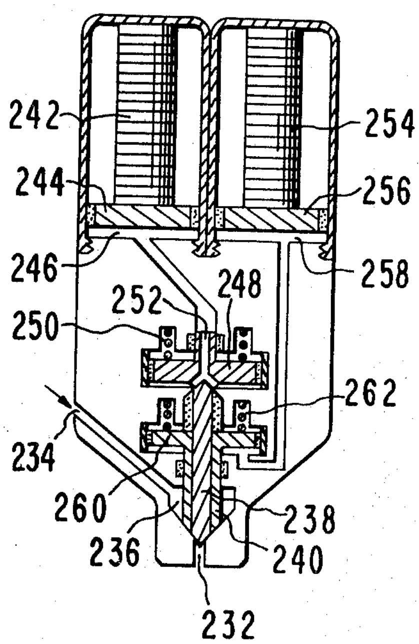
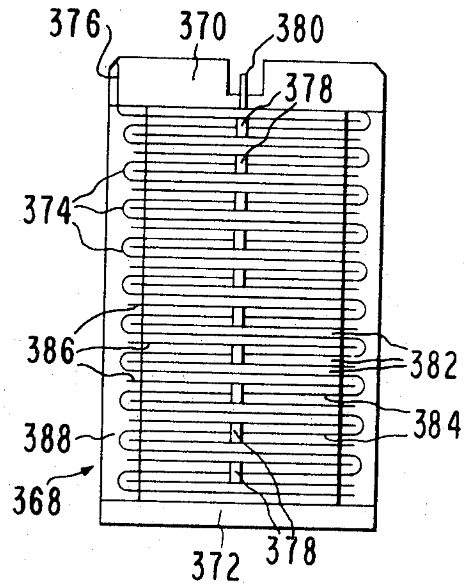


FIG.11



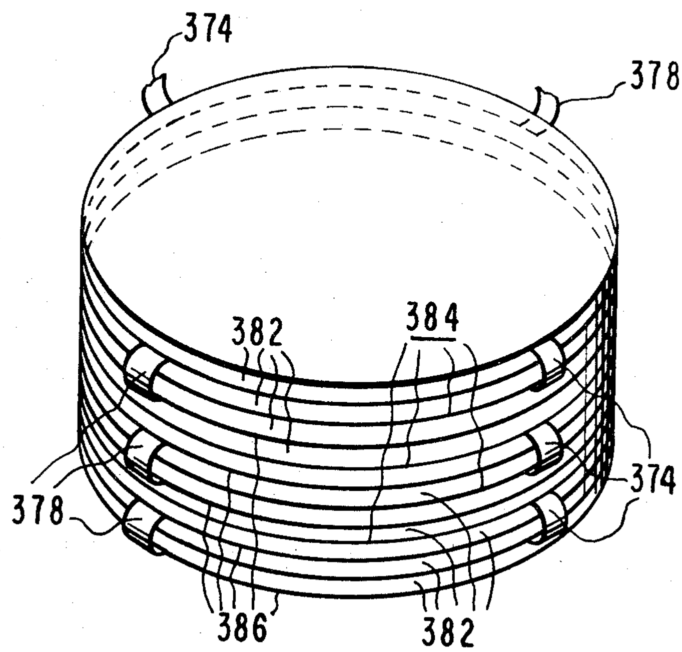


FIG.12

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FIG. 10

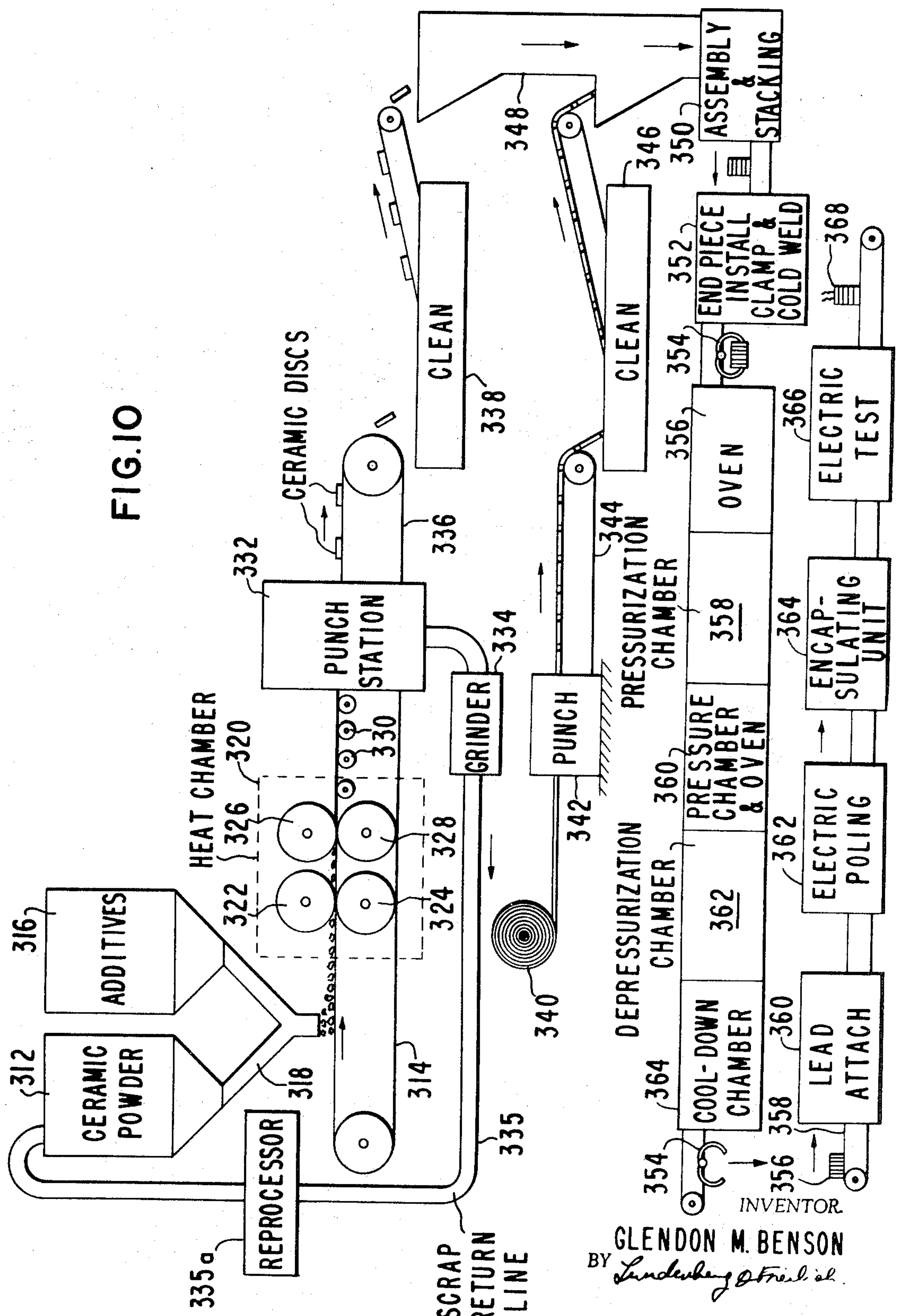

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FIG. 13

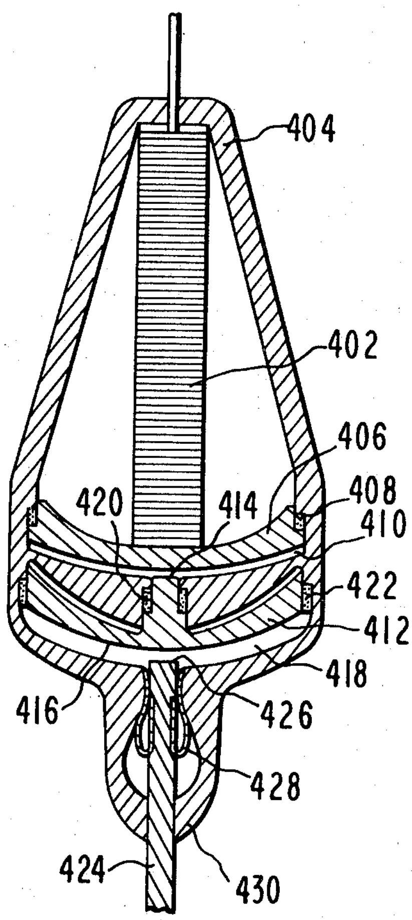
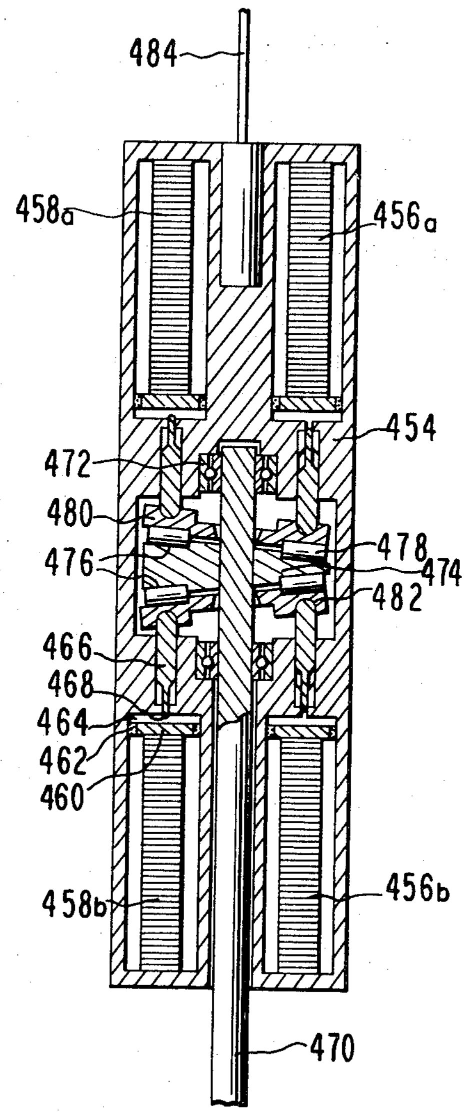


FIG. 16



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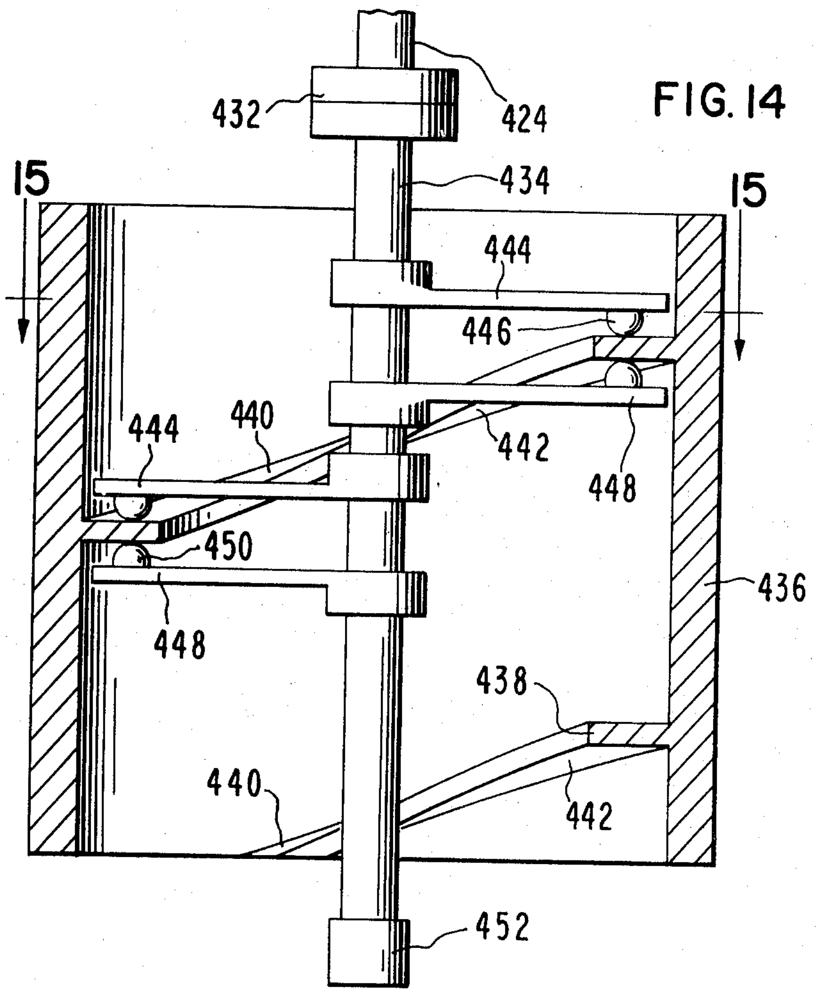

FIG. 14

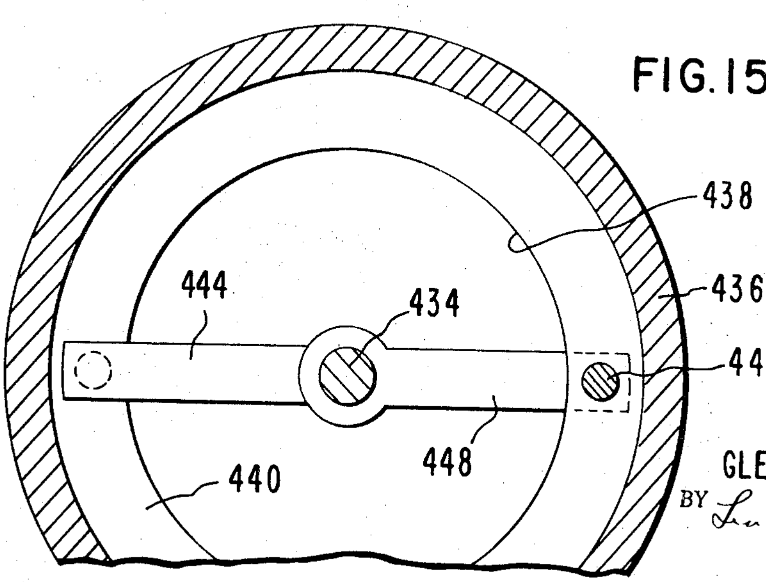

FIG. 15

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ELECTROMECHANICAL ACTUATOR HAVING AN ACTIVE ELEMENT OF ELECTROEXPANSIVE MATERIAL

This application is a divisional application of Ser. No. 671,065, filed on Sept. 27, 1967 for ELECTROMECHANICAL ACTUATOR HAVING AN ACTIVE ELEMENT OF ELECTROEXPANSIVE MATERIAL now U.S. Pat. No. 3,501,099.

This invention relates to electromechanical transducers or actuators which have as the active element thereof an electroexpansive module so arranged that accurate high speed mechanical movement is generated in response to electrical excitation. Such transducers are useful in any environment wherein precise and rapid mechanical movement in response to an electric signal is required.

An object of the present invention is to provide an electromechanical transducer or actuator that has improved precision of mechanical movement and response time. This object is achieved by providing an actuator that employs as an active element material that exhibits strain when subjected to an electric field, such as piezoelectric material, in combination with a coupling or linkage system for coupling a load to the active element.

The coupling or linkage affords substantial motion amplification so that the relatively small magnitude of strain typical of such electroexpansive elements as piezoelectric elements is multiplied to a significant amount. In achieving such motion amplification according to the present invention, a fluidtight chamber is provided. The chamber contains noncompressible fluid, such as mercury, and is bounded by a piston having a large surface area and a piston having a small surface area. Attached in driving relation to the large area piston is an electroexpansive module; attached to the small area piston is a load. When the large area piston moves in response to electrical excitation of the electroexpansive module, the load attached to the small area piston moves a greater amount. Because the unit forces developed by state-of-the-art electroexpansive materials is high, the pressure of the fluid in the chamber is adequate to drive the load.

Another object of the present invention is to provide an improved method for making a piezoelectric module that constitutes the active element of such actuator. The improved method lends itself to automated production of the modules with a high degree of reproducibility of characteristics and parameters.

Still another object is to provide an improved piezoelectric module.

The foregoing as well as other objects will be more apparent after referring to the following specification and accompanying drawings in which:

FIG. 1 is a partially schematic side elevation view of an electroexpansive actuator according to the present invention;

FIG. 2 is a view taken along line 2—2 of FIG. 1;

FIG. 3 is a fuel injection valve controlled by an actuator of the present invention;

FIG. 4 is another form of injection valve controlled by an actuator of the present invention;

FIG. 5 is still another form of injection valve exemplifying the present invention;

FIG. 5A is a valve substantially identical to that shown in FIG. 5 with certain fluid sealing characteristics being modified;

FIG. 6 is yet another fuel injection valve exemplifying the present invention;

FIG. 7 is yet another fuel injection valve illustrating the present invention;

FIG. 8 is a further fuel injection valve that embodies this invention;

FIG. 9 is a dual controlled injection valve illustrating this invention;

FIG. 10 is a diagrammatic view illustrating a novel process for making electroexpansive modules according to the present invention;

FIG. 11 is a diagrammatic view of a module formed by the method; and

FIG. 12 is a fragmentary perspective view of the module of FIG. 11;

FIG. 13 is a sectional view of another form of electromechanical actuator according to the present invention;

FIG. 14 is a cross-sectional view of a reciprocal-to-rotary motion converter for operative association with the structure of FIG. 13;

FIG. 15 is a sectional top view taken along line 15—15 of FIG. 14; and

FIG. 16 is a cross-sectional view of an electromechanical actuator according to the invention that develops a rotary output.

Referring more particularly to the drawings, reference numeral 12 indicates an electroexpansive module having one end thereof secured to an end plate 14 of a cylindric housing 16. In the present specification and claims the term "electroexpansive" denotes the characteristic of exhibiting or producing a strain in response to excitation by an electric field. In this sense, piezoelectric material is electroexpansive. Thus, when module 12 is electrically excited, strain is produced at the lower end thereof with respect to the upper end thereof, i.e., with respect to end plate 14. Secured to the lower end of module 12 is a piston 18. A manifold housing 19 is threadedly joined to casing 14 and is formed to define a chamber 20 below piston 18. Piston 18 is provided with a peripheral elastomer seal 22 so that chamber 20 is fluidtight. Communicating with chamber 20 is a valve compartment 24 in which is slidably carried a primary valve body 26. At the entry end of compartment 24, valve body 26 is provided with an elastomer seal 28 for preventing the fluid in chamber 20 from passing the valve body into the compartment. In FIG. 1 valve body 26 is shown in a neutral position, a position obtaining when module 12 is in a discharged or deenergized state. At the right-hand end of valve compartment 24 is a coil spring 30 which is balanced by an equal force on the left-hand side of the valve body from fluid within chamber 20. Thus, it will be seen that when piston 18 moves downwardly in response to expansion of module 12, valve body 26 is moved rightwardly against the force of spring 30. Conversely, when piston 18 is moved upwardly, decrease of pressure within chamber 20 will permit the force stored in spring 30 to move the valve leftwardly.

It can be seen in the drawing that the area of piston 18 that is exposed to chamber 20 is much greater than the exposed area of valve body 26. This disparate area relationship accomplishes motion amplification to a degree that is proportional to the ratio of the two surface areas. Because such electroexpansive material as piezoelectric material has a high unit force when expanded in response to electrical excitation, adequate pressure is present in chamber 20 for moving valve body 26 through its desired travel.

Manifold housing 19 includes a fluid inlet opening 32 and a fluid outlet opening 34. Connected to inlet opening 32 is a pump (not shown) of conventional form which supplies pressurized fluid from a reservoir (not shown) which is connected to outlet opening 34. Inlet 32 communicates with compartment 24 at the central region thereof and outlet opening 34 communicates with the compartment at the lateral regions thereof. Intermediate the central and lateral regions of the compartment are transfer passages 36 and 38 through which fluid is transferred between compartment 24 and a secondary valve compartment 40. Within secondary compartment 40 is a secondary valve body 42 which is moved rightwardly in response to delivery of fluid through passage 36 and leftwardly in response to delivery of fluid through passage 38. Fluid inlet opening 32 communicates with the central region of compartment 40 from which fluid can be transferred through one or the other of a pair of lower transfer passages 44 and 46 which communicate to opposite sides of an actuator piston 48 carried in a piston chamber 50. The piston is moved laterally in a direction determined by the position of secondary valve 42. An actuator rod 52 is attached to piston 48 and extends exterior of manifold housing 19 so as to afford attachment of a load to the actuator.

In operation, the embodiment of FIGS. 1 and 2 actuates a load in response to expansion and/or contraction of electroexpansive module 12. Upon application of an electrical signal of appropriate polarity to the electroexpansive module, piston 18 is driven downwardly, as a consequence of which valve body 26 is driven rightwardly against the force of spring 30. In such position, inlet opening 32 communicates with transfer passage 36 so that the pressure on the left side of valve body 42 is increased, thereby driving the valve body rightwardly. As a consequence of such rightward movement, fluid inlet 32 communicates fluid through transfer passage 44 to the left side of piston 48 so as to move the piston rightwardly; the load attached to piston rod 52 is moved in a corresponding direction. When electroexpansive module 12 is discharged, piston 18 moves upwardly, and the pressure on the left side of primary valve body 26 is removed, thereby permitting spring 30 to move the valve body to a central neutral position so as to interrupt delivery of fluid through transfer passage 36. Further rightward movement of valve body 42 is terminated, but the valve is not returned to the central neutral position until module 12 is energized with a signal of the opposite polarity.

On energization of the module with a signal of opposite polarity, piston 18 is moved upwardly thereby permitting compression spring 30 to move valve body 26 leftwardly in compartment 24. Responsive to such movement, fluid entering inlet 32 is admitted to transfer passage 38 thus moving valve body 42 toward a central position at which movement of piston 48 is terminated. It can be seen that very precise movement of actuator rod 52 is possible because the response time of the electroexpansive module is very fast, and further because the physical expansion and contraction of the module is amplified by the relatively small cross-sectional area of valve body 26 as compared with the cross-sectional area of piston 18. Because the structure is symmetrical rod 52 can be moved in either direction, thus providing a double acting device.

Referring now to FIG. 3, wherein an embodiment of the present invention is shown in driving relation to a fuel injection valve, there is provided an electroexpansive module 54 which is drivably connected as described hereinabove to a piston 56 below which is defined a chamber 58. In direct communication with chamber 58 is a control valve body 60. The area of valve body 60 that is exposed to the fluid in chamber 58 is substantially less than the area of piston 56 that is exposed to the chamber so that the valve body experiences a relatively large amount of movement in response to a relatively small amount of movement by piston 56.

Control valve body 60, when in the lower or open position, communicates fluid at an inlet port 62 to an outlet port 64 and, when in the closed or upper position, interrupts such fluid flow to outlet port 64. In the upper or closed position of the valve body, port 64 is connected to a discharge port 66. Valve body 60 is biased toward the upper or closed position by a compression spring 68 so that inlet port 62 is normally closed thereby permitting maintenance of high pressure at inlet port 62.

Outlet port 64 communicates to an injection valve assembly designated generally as 70, which valve typically has a nozzle portion 72 for installation into communication with the cylinder of an internal combustion engine. The valve has one or more injection ports 74 through which fuel is injected when the valve is open. The injection ports are normally closed by an injector needle 76 which needle is biased downwardly by a spring 78 to so normally close the injection ports. The needle is supported by an elastomer seal 80 below which fuel under high pressure enters through a fuel line 82 and above which outlet port 64 from control valve body 60 communicates. Above elastomer seal 80 a chamber 84 is defined; within the chamber an actuator 86 is secured to injection needle 76 and has a downwardly-directed surface area so that when pressurized fluid is conveyed through port 64 in response to downward movement of control valve body 60, actuator 86 and needle valve 76 are lifted upwardly against force of spring 78 so as to inject fuel through injection port 74. Such action occurs in response to energization of module 54 by an electric signal so as to drive piston 56 downwardly. Fuel injection continues so long as the module is strained or electrically charged. Chamber 84 is delimited at the upper extremity thereof by a cup 88 above which resides spring 78 and above which discharge port 66 communicates. Communicating with the volume above cup 88 is an outlet fitting 90 which returns fuel to the low-pressure side of the fuel source.

In operation the device of FIG. 3 normally resides in the position shown in the figure. In such position high-pressure fuel is maintained at inlet opening 62 of the actuator valve and at the lower end of injector needle 76, ready for injection through injector ports 74. When an electrical signal is applied to module 54, piston 56 is driven downwardly thereby compressing the fluid in chamber 58 to drive control valve body 60 downwardly against the force of spring 68. This action moves the annular excision on valve body 60 into interposition between inlet port 62 and outlet port 64 so as to apply high pressure fluid to chamber 84. Thus, piston 86 and injector needle 76 are lifted to permit injection of fuel through ports 74 into the engine to which the device is installed. Fuel injection continues for as long as module 54 is energized or charged. When the application of an electrical signal is interrupted and when the electroexpansive module is discharged so as to move piston 56 upwardly, control valve body 60 experiences a corresponding movement. Upward movement of the control valve body interrupts the inflow of fuel through inlet port 62 and connects outlet port 64 through the annular excision in the control valve body to discharge port 66. Consequently, the fluid pressure within chamber 84 and the upward force against piston 86 are abruptly terminated so that the injector needle 74 is moved downwardly to the closed position. Because the injector valve of FIG. 3 is very fast acting and closes securely, over supply of fuel and/or nozzle weep are avoided.

The valve of FIG. 3 illustrates the versatility of an injector valve embodying the present invention. The distance that control valve body 60 travels is proportional to the magnitude of the voltage applied to electroexpansive module 54. If the magnitude of the voltage applied to the module is large, control valve body 60 moves a relatively large distance and fuel is applied to chamber 84 rapidly. If the magnitude of the electric signal applied to the module is of relatively low magnitude, control valve body 60 experiences a shorter travel so that outlet port 64 is not fully opened. Accordingly, the time required for application of fluid pressure to chamber 84 is lengthened. Because the time of opening and closing injector needle 76 is proportional to the time required for fuel pressure buildup within chamber 84, the actuating time of the injector valve is proportional to the magnitude of the electric signal applied to the electroexpansive module. Thus, it will be seen that the injection characteristics of the valve can be controlled by simple control devices capable of varying the voltage applied to the electroexpansive module in proportion to operating characteristics of the engine with which the device of FIG. 3 is used.

It will be observed that the valve of FIG. 3 is driven by the pressure present in the combustion fuel supply system. This characteristic materially simplifies the control system without sacrificing accuracy or versatility. In the valve of FIG. 3 the fuel injection pressure is limited to the supply pressure of the fuel. In the modification of the invention shown in FIG. 4, mechanisms for materially increasing the pressure are provided.

In FIG. 4 an electroexpansive module 92 having characteristics described hereinabove is mounted in a housing 94 and is provided with a piston 96 which is driven downwardly in response to electrical energization of the module. The piston 96 forms one side of a fluid chamber 98 which chamber communicates with a control valve body 100. The valve body is biased toward an upward position by a compression spring 102, and when the valve body moves downwardly in response to energization of the module 92, an inlet fluid connection 104 is connected to a plunger chamber 106 by a suitable annular excision in the control valve body. Below chamber 106 is carried a first plunger 108 which is resiliently biased in an upward position by compression spring 110. Spring 110 resides below the first plunger in a lower plunger chamber 112 in which is also disposed a second plunger 114 of lesser diameter than first plunger 108. Below second plunger 114 is a fuel compression chamber 116 which communicates at the lower end thereof with an injector port 118. An injector needle 120 is biased by a spring toward a position at which the needle closes port 118. Communicating with fuel chamber 116 from inlet 104 is a fluid passage 124 having a check valve 126 therein. The check valve affords one-way fuel flow into chamber 116 and prevents backflow of fuel from the chamber.

The operation of the embodiment of FIG. 4 can be appreciated by assuming that chamber 116 is filled with fuel from inlet port 104. When electroexpansive module 92 is energized by an electric pulse, downward movement of piston 96 results, which in turn moves valve body 100 down to admit fuel into plunger chamber 106. The pressure applied to plunger 108 is equal to the supply pressure of the fuel. The consequent downward force on the plunger is substantial because the upper surface area of the plunger is large. Such force causes downward movement of plunger 108 and secondary plunger 114 which compresses the fuel in fuel chamber 116 to such an extent that injector needle 120 is raised so as to open the valve and forcefully inject fuel through ports 118.

The pressure at which the fuel is injected is very high, because the surface area of lower plunger 114 is small compared to the upper surface of plunger 106. Equal force transmission from the upper plunger to the lower plunger renders inversely proportional the pressure on the respective surfaces. In one valve designed according to the present invention, a surface area ratio of 10 to 1 (upper plunger, 10; lower plunger, 1) affords a tenfold pressure increase so that fuel will be injected to the engine cylinders at 10,000 p.s.i. in a system wherein the fuel supply pressure is 1,000 p.s.i.

Fuel injection terminates either when secondary plunger 114 completes its stroke or when electroexpansive module 92 is discharged to permit upward movement of valve body 100 at which time the force of spring 110 moves secondary plunger 114 upwardly. Thus, it can be seen that the quantity of fuel injected through injecting ports 118 can be established by selecting the appropriate size secondary plunger 114 or in the alternative can be adjusted by adjusting the timing of the signal applied to electroexpansive module 92. A circuit suitable for so controlling the energization of the module is shown in U.S. Pat. application, Ser. No. 671,060, now U.S. Pat. No. 3,500,799 filed concurrently herewith and entitled "Electromechanical Control System." Thus, the embodiment of FIG. 4 combines extremely high injection pressure with versatility in timing and quantity of fuel injection.

Still another form of the present invention is shown in FIG. 5 wherein the electroexpansive module is designated by reference numeral 128, the module functioning to drive a piston 130 associated with a fluid chamber 132 which in turn drives an actuator valve body 134 having an upper surface communicating with the fluid in the chamber. The actuator valve body is slidably supported in a valve chamber designated generally at 136; a spring 138 is provided for biasing the valve body upwardly to the position shown in the drawing. In such upward position, an upwardly converging valve face 140 on the valve body seats against a corresponding seat portion of chamber 136 and prevents fuel entering inlet opening 142 from passing. Below upwardly converging valve face 140 a fuel compression chamber 143 is defined between an annular excision 144 on valve body 134 and the wall of chamber 136. Chamber 143 at its lower extremity is bounded by an annular face 146 formed on the valve body. Below annular face 146 the valve body has a cylindric or tubular skirt portion 148 which in the position shown in the figure closes a fluid outlet passage 150. Valve chamber 136 at the bottom thereof includes an annular section 152 which also communicates with fuel outlet opening 150. At the lower end of the structure a plurality of injection openings 154 are provided and are normally closed by an injector needle valve 156 which is biased downwardly by a spring 158.

In operation, the embodiment of FIG. 5, when the electroexpansive module is energized by an electric signal, injects fuel by the following sequence of actions: the increase of pressure in chamber 132 moves the valve body 134 downwardly so as to retract converging face 140 from its seat and thereby admit fuel therebelow.

Downward movement of valve body 134 moves tubular skirt portion 148 downward within annular chamber 152 so as to compress the fuel in the annular chamber. Injector needle valve 156 is thereby loaded by an upwardly directed force that is almost equal to the opposing downward force of spring 158. When annular face 146 of valve body 134 passes below the upper extremity of fuel passage 150, a fuel path from inlet opening 142 down to the lower end of injector needle 156 is provided so that the needle is unseated and fuel is injected through ports 154. As described hereinabove, the injection continues until module 128 is discharged to permit piston 130 to move upwardly.

As in the preceding embodiments, the quantity of fuel injected depends upon the time between the energization of the electroexpansive module and the discharge of the module. Moreover, the physical geometry of plunger 134 can be modified to effect variations in fuel injection quantity.

FIG. 5A depicts a valve identical in most respects to that shown in FIG. 5. Because of the substantial identity, similar characters of reference are used in many respects in the two figures. Corresponding parts that are rearranged from FIG. 5 are primed in FIG. 5A. It will be noted, however, that centrally of valve body 134' in FIG. 5A is a longitudinal passage 160 which affords a drainage path for whatever minor amount of fuel may leak past the relatively moving parts of the system. When module 128 is pulsed to compress fluid in chamber 132 and drive valve body 134' downwardly, converging valve face 140' is unseated so as to admit fluid below the shoulders on needle valve 156. Pressure on the shoulders unseats the valve and permits egress of fluid from ports 154 at a pressure equal to that of the source applied at inlet 142. Such pressure is less than that of FIG. 5; the lower pressure permits simplification of valve body 134' (as compared with valve body 134) and elimination of spring 138. The presence of longitudinal passage 160 unloads all downward force on needle valve 156 except that of spring 158. Consequently, the needle valve is efficiently opened because the upward force on the shoulders from fluid pressure exceeds the downward force of spring 158. Such construction shortens response time of the structure. For example, a device designed according to FIG. 5A has a response time in the order of 100 microseconds, by which is meant the valve is opened and is injecting fuel within 100 microseconds after electrical excitation of module 128 occurs. This is approximately 100 times faster than any known prior electrically driven valves.

Yet another modification of the present invention is shown in FIG. 6, wherein an electroexpansive stack 162 drives a piston 164 which compresses fluid in a chamber 166. Communicating with chamber 166 is a plunger 168 having a downwardly-directed surface exposed to the chamber interior. Connected to plunger 168 is an injection needle 170 the lower end of which is adapted to normally close off a fuel injection port 172. The injection needle is retained in such normally closed condition by a compression spring 174 that exerts a force on a collar 176 which is operatively connected to the injector needle. The force of spring 174 is sufficient to move the valve toward a closed position and retain it there even in the presence of fuel supplied at significant pressures to a fuel inlet opening 178.

In operation the valve of FIG. 6 opens in response to application of an electric signal to an electroexpansive module 162, because on such application the pressure within chamber 166 is increased so that plunger 168 is lifted as is injector needle

170. When the electroexpansive module is discharged, the force of spring 174 is sufficient to reseat the injector needle to interrupt fuel injection through port 172.

In FIG. 6, seal 165 is a metal bellows of Omega seal which prevents fluid leakage from chamber 166 into the upper electroexpansive module 162. Such seals are leaktight, reliable seals that easily withstand the high pressures and the large number of operating cycles experienced.

As shown in FIG. 7 the present invention can be embodied with an electroexpansive module 180 of generally cylindric configuration. The module has an outer face on which is disposed a conductive layer 182 that defines an electrode. Another conductive layer 184 is provided on the inner face of the cylindric module 180 so that connection of an electric signal across electrodes 182 and 184 will effect a radial strain in the module. The axial ends of the module are sealed off with respect to a housing 186 by an upper flexible metallic seal member 188 and a lower flexible metallic seal member 190. Between the seal members is defined an annular chamber 191. Housing 186 includes a rigid core member 186*a* that defines a radial passage 192 communicating annular chamber 191 with a pressure chamber 194. The top surface of pressure chamber 194 is defined by the lower face of a plunger 196 which is biased downwardly by a compression spring 198. The surface of plunger 196 that is exposed to chamber 194 is less than the area of module 180 that is exposed to annular chamber 191 so that motion amplification is achieved. Attached to or integral with plunger 196 is an injector needle 200, the lower end of which is adapted normally to close an injection port 202. A suitable seal 204 is provided for isolating chamber 194 from fuel entering an inlet opening 206.

In operation, the embodiment of FIG. 7 is caused to open by application of an electrical signal of suitable magnitude to the electrodes 182 and 184. Module 180 expands inwardly in response to such signal. Inward expansion of the module compresses the fluid in chamber 194 which in turn exerts an upward force on plunger 196. Valve needle 200 is thereby lifted so as to open port 202 and permit injection of fuel therethrough.

Further demonstrating the versatility of the present invention is the embodiment depicted in FIG. 8. An electroexpansive module 208 has at the lower end thereof a piston 210 that forms the upper wall of a fluid chamber 212. Also forming a part of the chamber is a plunger 214 to which is affixed a valve body 216. Plunger 214 has an area less than piston 210. A compression spring 218 is provided for biasing plunger 214 upwardly, it being understood that the plunger 214 and valve body 216 will be driven downwardly in response to electrical excitation of module 208. The valve body is supported for slidable movement in a bore 220 which at the lower end thereof has a plurality of outlet injection ports 222. It will be noted that a port 222*a* is at a level higher than a port 222*b* which in turn is higher than a port 222*c*. Opposite the ports, valve body 216 is formed with a cylindric portion 224 that in the uppermost position, as shown in the figures, closes all of injection ports 222. Also in the uppermost position, a valve face 226 seats on a downwardly diverging seat 228 in bore 220 to arrest fuel flow entering at inlet 230 from entering the lower region of bore 220.

By employment of the structure of FIG. 8, rate of fluid delivery can be controlled in proportion to the magnitude of voltage applied to energize electroexpansive module 208.

When electroexpansive module 208 is deenergized, valve body 216 resides in the position shown in FIG. 8, a position in which upwardly converging surface portion 226 seats against downwardly diverging seat portion 228 so as to prevent entry of fuel below the seat. Additionally, injection ports 222 are closed because cylindric portion 224 of the valve body closes the inner terminus of the ports. When the module is pulsed, the fluid in chamber 212 is compressed so as to move plunger 214 and valve body 216 downwardly. The amount of downward movement is proportional to the voltage of the pulse applied to the module. The number of ports 222 uncovered in response to downward movement of the valve body is proportional to the amount of downward travel of the valve body. Because the rate of fuel injected is proportional to the number of ports uncovered, the rate of fuel injected is proportional to the amplitude of the voltage pulse applied to module 208. Accordingly, the rate of fuel injected is very readily controlled since many techniques are known in the art for controlling the magnitude of the voltage applied to the module in proportion to engine speed or like engine operating parameters. Several such techniques are described in my copending application titled "Electromechanical Control System," and filed concurrently herewith.

Illustrating the versatility of the present invention in an extremely high speed accurate fuel injection actuator is the fuel injection valve of FIG. 9. The valve includes an outlet opening 232 and a fuel inlet opening 234. Intermediate the openings is a chamber 236 that defines a valve seat closable by either a central valve body 238 or an outer valve body 240 which is concentric with the central valve body and axially movable relative thereto. Valve bodies 238 and 240 are driven independently of one another so that the time duration of fluid flow from inlet opening 234 to outlet opening 232 can be made extremely short without requiring high valve body accelerations and excessive consumption of power necessary for such acceleration. For controlling the valve bodies independently an electroexpansive valve module is provided for each valve body. A module 242 is associated with central valve body 238 and is connected in driving relation to a piston 244 below which is a fluid chamber 246. The fluid chamber communicates with a secondary piston 248 which is biased downwardly by compression spring 250. Piston 248 is preferably integral with valve body 238 and has a fluid passage 252 therethrough for communicating fluid from chamber 246 to the volume below the piston. Thus, when module 242 is electrically pulsed, the fluid in chamber 246 is compressed and piston 248 as well as valve body 238 are lifted against the force of spring 250.

Associated with valve body 240 is an electroexpansive module 254 which is connected in driving relation to a piston 256 that bounds a fluid chamber 258. Chamber 258 communicates with the lower side of a secondary piston 260 which is integral with outer valve body 240 and which is resiliently biased downwardly by a compression spring 262. Thus, when module 254 is pulsed, thereby compressing fluid in chamber 258, piston 260 is moved upwardly against the force of spring 262 so as to lift outer valve body 240 from its seat in chamber 236.

The operation of the form of my invention shown in FIG. 9 is as follows: Voltage is applied to one of the electroexpansive modules, e.g., module 242. The fluid in chamber 246 is compressed thereby unseating central valve 238. Outer valve 240, in a down or seated position, arrests fluid flow from inlet opening 234 to outlet opening 232. In order to initiate a short injection of fluid, a voltage pulse is applied to module 254, as a consequence of which outer valve body 240 is lifted from its seat. A short interval after such energization of module 254 module 242 is discharged, thereby permitting central valve body 238 to seat and to arrest fluid flow from outlet opening 232. In a specific valve designed according to the invention as depicted in FIG. 9, a flow duration of 100 microseconds (1×10^{-4} seconds) is readily achieved. It will be appreciated by those skilled in the art that control circuitry for pulsing and discharging the modules in an appropriate sequence is well within the competence of the present state of the art. Moreover, examples of novel control circuitry can be found in my concurrently filed copending application.

Thus, it will be seen that the present invention provides an electromechanical actuator or transducer that is capable of being driven electronically with great precision and speed. Because the transducer is a solid state device it possesses the advantageous characteristics inherent in such devices. Moreover, the operating characteristics of the actuator can be readily predicted in view of the simple relationship between the area of the piston driven by the electroexpansive module and in the area of the follower or secondary piston which communicates with the first mentioned piston.

Further contributing to the excellent operating characteristics of the actuator of the present invention is a method for making the electroexpansive module which method permits automated production of the modules. The method also affords a high degree of predictability of characteristics, so that modules with desired characteristics are readily reproducible. The steps of the method can be more fully appreciated by reference to FIG. 10. A hopper **312** for ceramic material having desired electroexpansive, piezoelectric, or ferroelectric properties is supported over an endless conveyor **314**. The particles of which the ceramic powder is constituted are preferably in the diameter range of approximately 1 to 50 microns mean diameter. Oxides of lead, titanium, zirconium or the like exemplify materials having the necessary electrical and mechanical characteristics. A second hopper **316** is provided for holding such additives as may be necessary to enhance the electroexpansive character of the ceramic material. Such additives are exemplified by the oxides of niobium, strontium, and the like. Suitable mechanical blending and mixing equipment is identified schematically at **318**; the specific nature of such equipment forms no part of the invention. Conveyor **314** is part of a hot rolling mill, which according to the present invention, produces a continuous sheet of ceramic material preferably in the thickness range of about 5 to 50 mills. The hot rolling mill portion of the apparatus includes a heat chamber **320** and opposed pinch rolls **322** and **324** between which the ceramic material is conveyed from conveyor **314**. Rolls **322** and **324** are designed so that the combined effect of the pressure exerted by the rolls and the temperature within chamber **320** cooperate to compact the ceramic material to a degree that the density range of the ceramic material is about 80–99 percent of the theoretical density after the material exits from the hot rolling segment of the apparatus. A second rolling station formed by pinch rolls **326** and **328** is provided to further compact the material so as to increase the density thereon. The compacted ceramic material is fed in a continuous sheet by a conveyor **330** to a punch station **332**. At punch station **332** the ceramic material is formed into discs or rings as desired for the particular form of module desired. The excess sheet stock produced from punch **332** is ground at a grinder indicated at **334** and returned to hopper **312** for reuse by a conveyor line **335**, in which is interposed apparatus **335*a*** for reprocessing the material.

The ceramic discs or rings, as the case may be, are conveyed from punch **332** by a conveyor **336** to a cleaning bath **338**. In bath **338** the discs are cleaned and chemically treated so as to prepare the surfaces thereof for bonding.

Simultaneous with the formation and preparation of the ceramic discs or rings, conductive electrodes are prepared. A sheet or roll of material such as nickel, platinum, tungsten or like compatible material is provided as indicated schematically at **340**. The material preferably has a thickness of less than a mil. A punch **342** is provided to form the conductive material into discs or rings, the specific configuration depending on the specific configuration of the ceramic discs. Punch **342** is adapted so that the discs or rings are continuously connected one to the other for electrical continuity therebetween. The formed electrode rings or discs are transported by a conveyor **344** to a cleaning bath **346** so as to prepare the electrodes for bonding to the ceramic discs. From baths **338** and **346** are delivered respectively the disc and electrodes along a conveyor indicated schematically at **348** to an assembly and stacking station **350**.

At assembly and stacking station **350** the ceramic discs are assembled into stacks with the continuous disc electrodes alternately disposed therebetween so that an electrode is disposed between each adjacent ceramic disc and further so that alternate sets of electrodes are electrically continuous. To each stack so formed are applied ceramic end plates, one functioning as a plunger or piston, for example the piston designated by reference numeral **18** in FIG. **1**.

The formed assembly is then clamped as at **354** for mechanical conveyance through succeeding steps in the process. The clamp retains axial compression on the stack during subsequent hot isostatic treatment thereof. The pressure from the clamp and the extreme smoothness of the discs and electrodes can be combined with a hard vacuum in a chamber at **352** to effect cold welding between the parts.

The stacked and clamped assembly enters a continuous oven having an oxidizing atmosphere therein. Preferably the oven has a temperature gradient therein so that as the clamped stack progresses, it is gradually brought up to the appropriate temperature. The temperature desired is in the range of about 1,000°–1,400° C. The stacks are accumulated at the downstream or outlet end of **356** for admission as a group or batch into a pressurization chamber **358**. The pressure within chamber **358** is rapidly increased to several thousand p.s.i., as a consequence of which the entire stack is subjected to uniform radial loading as well as axial loading additional to that provided by clamping structure **354**. However, such pressure does not cause ambient gas to be diffused into the stack because a gas impervious glaze is formed only on the outer surface of the stack as a result of the elevated temperature in oven **356**. From pressurization chamber **358** the batch of stacks is transferred to a high temperature pressurized chamber **360** in which the batch is maintained at the same temperature and pressure for a required time interval. After the transfer, pressurization chamber **358** is decompressed and is ready to accept another batch of stacks from oven **356**.

The elevated temperature and pressure in chamber **360** effect bonding together of the elements of the stacks. When the stacks within chamber **360** have assumed the requisite bonding characteristics between the individual elements and after the ceramic has assumed the required domain structure, the batch is moved to a depressurization chamber **362** which is gradually reduced to ambient pressure. Thereafter, the batch is transferred to a cool-down chamber **364** for controlled cooling to ambient temperature. At the outlet end of cool-down chamber **364** clamp **354** is released so that a formed stack, indicated at **356** in FIG. **10**, is deposited onto a conveyor **358** for further processing.

Conveyor **358** first delivers the stack to a lead attaching station **360** at which a common lead is connected to one group of electrodes formed by alternate electrodes and another lead is attached to another group of electrodes formed by the remaining electrodes. Accordingly, the leads permit establishment of electric field across each ceramic disc between the electrodes. An appropriately polarized DC voltage is applied across the leads in an electric polling station **362** which includes an insulative liquid bath, for example peanut oil, that is maintained at a temperature of about 100°–200° C.

Electric polling unit **362** operates by first raising the temperature of the stack by immersion in the hot insulating liquid and then by applying a DC voltage across the previously attached leads. The magnitude of the DC voltage is established in accordance with such parameters as the specific composition of the ceramic material, the temperature of the bath, and the thickness of the individual ceramic discs that constitute the stack. A skilled artisan will appreciate the specific voltage magnitude required, a typical magnitude being approximately 100 volts per mil (0.001 inch) thickness of the discs across which the voltage is established. Duration of voltage application also depends on the above mentioned parameters, 10 to 50 minutes being a typical time range. When electric polarizing is completed in unit **362**, the module is cleaned and dried after which it is transferred to an encapsulating station **364**. Exemplary of suitable encapsulating material is a plastic insulative cover such as silicon rubber or urethane, the encapsulation being performed so that the end pieces of the module are exposed. In an automated production line the encapsulation material can be most expeditiously applied by continuous extrusion of insulative material concentrically with the stack.

The encapsulated unit is then subjected to testing procedures at a test station **366** and is then discharged at the output of the apparatus, a completed module being indicated at **368**. Module **368** can then be incorporated into the piezoelectric actuators described hereinabove.

A completed module **368** is depicted, partially schematically, in FIGS. **11** and **12**. The module includes an upper end plate **370** and a lower end plate **372**. The upper end plate serves to support the electrical terminations to the electrodes, and the lower end plate acts as a piston, for example, see piston **18** of FIG. **1**. Alternate electrodes are interconnected to one another to form one group by straps **374** which as described hereinabove are integral with the electrodes which they interconnect. The group of interconnected electrodes is terminated at a ground connection **376**. Alternate electrodes are interconnected by straps **378** so as to form a second group of electrodes, which second group of electrodes is terminated at a high voltage terminal **380** located centrally of upper end plate **370**. Ceramic discs or rings of electroexpansive material are indicated at **382**. An exemplary ground electrode is indicated at **384** and an exemplary high voltage electrode is indicated at **386**. The assembly is completed, as described above, by enclosure in a insulative encapsulation layer **388**. Accordingly, the module is self-contained and is readily mountable into an electroexpansive actuator or transducer housing.

An alternate electrode design employs a thin electrode deposited on each ceramic by conventional techniques in such a manner that the electrode covers the flat surface of the disc except for a narrow margin or border that exists for approximately 330°, with the remaining 30° having the electrode extend to the edge. The processing is identical to that described above except that in lead attaching station **360**, a thin strip electrode is placed on each side of the stack in such a manner as to connect the tabs of the individual electrodes to the strip electrode thereby forming two integral electrode systems, one for ground and the other for voltage application.

Employment of the foregoing method for producing electroexpansive ceramic stacks results in increased performance measured in terms of dielectric constant, coupling coefficient, loss factors, and other piezoelectric coefficients.

Construction of electroexpansive modules by employing a plurality of extremely thin discs or like bodies affords increased stack performance measured in terms of dielectric constant, coupling coefficients, loss factor, and other piezoelectric coefficients. Using the methods of this invention on advanced ceramic compositions produces even greater performance. As an example, producing, by piezoelectric action, axial strains of over 0.5 per centum in large stacks is presently feasible while the attainment of one per centum unit strain appears achievable.

Modules or stacks produced by the method can be incorporated into many forms of actuators. For example, in FIG. 13 there is shown an electroexpansive stack **402** fixed at its upper end to a housing **404** and at its lower end to a primary piston **406**. The piston is sealed within body **404** by an elastomer seal **408**. Such seal permits primary piston **406** to move in response to electrical excitation of stack **402**. The lower face of piston **406** defines one surface of a fluid tight chamber **410**. A secondary piston **412** has a surface **414** communicating with chamber **410**; the area of surface **414** is small with respect to the area of piston **406** so that the amount of movement of secondary piston **412** is greater than the amount of movement of piston **406**. Secondary piston **412** has a lower face **416** that bounds a second fluid tight chamber **418**. The piston **412** is supported in housing **404** by an upper elastomer seal **420** and a lower elastomer seal **422** so that both chambers **410** and **418** are fluid tight. A rod **424** is supported for slidable movement in body **404** and has a surface **426** communicating with chamber **418**. The area of surface **426** is much less than surface **416** of secondary piston **412** so that the rod moves a greater distance than does secondary piston **412**. Rod **424** is supported in fluidtight relationship to chamber **418** by a Bellowfram or rolling bellows seal **428** or the like and is supported for reciprocal movement by guide extension **430** that extends from main body **404** and is integral therewith.

The operation of the embodiment of FIG. **13** is as follows: An electric pulse is applied to stack **402** so as to cause the stack to expand and drive piston **406** downwardly. Fluid in chamber **410** is compressed thereby applying pressure to surface **414** of secondary piston **412** so as to urge the secondary piston downwardly by an amount proportional to the ratio of areas between piston **406** and surface **414**. Consequently, fluid in chamber **418** is compressed so that a force is applied against surface **426** of rod **424**. The rod is thus driven downwardly. A load attached to the rod is driven correspondingly. Because rod surface **426** is smaller than surface **416**, substantial motion amplification is achieved by the device. When the stack **402** is electrically discharged, piston **406** moves upwardly, piston **412** moves upwardly, and rod **424** and load attached thereto is moved upwardly.

An exemplary load device for attachment to the rod **424** of FIG. **13** is shown in FIGS. **14** and **15**. The device functions to change reciprocal movement of rod **424** to rotary movement. Attached to the outer end of plunger rod **424** is a swivel connection **432** which joins to the actuator rod for axial movement therewith a shaft **434** and which permits shaft **434** to rotate relative to the actuator rod. Shaft **434** extends into a motion converter housing **436**. Housing **436** includes a helical ramp **438** that has an upper surface **440** and a lower surface **442**. Radiating from shaft **434** is one or more upper arms **444**. Each arm has at its outer extremity an antifriction member, such as a ball bearing **446**, for affording rolling contact with upper ramp surface **440**. Also radiating from shaft **434** is one or more lower arms **448**, each of which is provided with a ball bearing **450** for bearing on lower ramp surface **442**. Shaft **434** has a fitting **452** that extends exterior of housing **436** to permit attachment of a load to the device.

The structure of FIGS. **13–15** operates as follows: electrical excitation of module **402** effects axial movement of rod **424** as previously described. Such movement is transmitted through swivel **432** to shaft **434** which in turn forces upper arm **444** down ramp surface **440**. Swivel **432** permits shaft **434**, and load fitting **452**, to rotate. The load attached to the outlet portion **452** is correspondingly rotatively driven. When module **402** is discharged and rod **424** moves in the opposite axial direction, rotative movement in the opposite sense is effected because ball bearings **450** move up ramp surface **442** so as to apply torque to shaft **434** through arm **448**.

FIG. **16** depicts a somewhat more sophisticated rotary actuator or motor in which a main housing **454** supports axially opposed right-hand electroexpansive modules **456*a*** and **456*b***, and lower axially opposed left-hand electroexpansive modules **458*a*** and **458*b***. Because each module has a substantially identical plunger structure, only the plunger structure associated with the module **458*b*** will be explained in detail, it being understood that the plunger structures associated with the other modules are substantially identical. A piston **460** is attached to one end of module **458*b*** and is supported for movement with respect to housing **454** by a peripheral elastomer seal **462** so that a fluid tight chamber **464** is formed above the piston. A secondary plunger **466** is supported in housing **454** and has a surface portion **468** in communication with chamber **464**. The area of surface portion **468** is much smaller than the area of piston **460** so that on movement of piston **460** resulting from expansion or contraction of module **458*b***, plunger **466** will move a greater amount.

Mounted centrally of housing **454** is a shaft **470**. The shaft is supported for rotation on bearings **472**. Mounted on the shaft is a generally wedge shaped body **474** which has annular faces **476** thereon, body **474** being so constructed that annular faces **476** are spaced axially from one another by a large distance at one point, are spaced close to one another at a point 180° from the first mentioned point, and converge smoothly from the first mentioned point to the last mentioned point. The surface **476** forms one race of a roller bearing that has rollers

478. The other race is formed by a disc **480** that, on the outer surface thereof, has a depression **482** for engaging each plunger **466** associated with the electroexpansive modules. Each of the modules **456*a*, 456*b*, 458*a*** and **458*b*** is connected through an electrical wire harness **484** to external control circuitry not shown.

The operation of this embodiment of the invention can be understood by assuming that shaft **470** resides in the position shown in the drawing and by further assuming that left-hand modules **458*a*** and **458*b*** are pulsed. When the modules are so pulsed, they expand so that each plunger **466** associated with the modules is moved inwardly toward member **474**. Forces are thereby applied to the portion of surface **476** that are separated from one another by the greatest amount, and because of the gradual taper inwardly from such point, member **474** and shaft **470** will be rotatively driven as a consequence of such force. Simultaneously with such action modules **468*a*** and **468*b*** are discharged so that the plungers **466** associated with the latter modules are urged away from member **474**. When the shaft has been rotatably driven through approximately 180°, modules **458*a*** and **458*b*** are discharged and modules **456*a*** and **456*b*** are supplied with electric pulses. Consequently, the rotative force on shaft **470** is continued and the shaft continues to rotate.

The device described above is simplified for convenience of description; an actual device made in accordance with this invention has more than two pairs of electroexpansive modules so that torque can be delivered smoothly and continuously to shaft **470** by appropriate charging and discharging of the modules in sequence. The speed of rotation of shaft **470** can be controlled by controlling the frequency at which the modules are charged and discharged.

Thus, it will be seen that the present invention provides an improved electromechanical actuator that has characteristics not heretofore achievable. The excellent electromechanical characteristics of the device are achieved in part by employing a novel method for producing a module that constitutes the active part of the actuator.

Although several embodiments of the invention have been shown and described, it will be apparent that other adaptations and modifications can be made without departing from the true spirit and scope of the invention.

What is claimed is:

1. Apparatus for actuating a load comprising:
an electroexpansive body having a surface,
means for forming walls that define in cooperation with said surface a fluidtight chamber,
a plunger having a face communicating with said chamber, said face having an area less than said surface of said electroexpansive body,
noncompressive fluid in said chamber,
means for applying an electrical field across said electroexpansive body, and
means for coupling said load to said plunger including a second face on said plunger having an area which is larger than said first plunger face,
means including said second face for defining a second fluidtight chamber,
a noncompressible fluid in said second chamber, and
a rod coupled to said load having an end surface in said second chamber that has an area less than said second plunger face.

2. Apparatus according to claim 1 wherein said electroexpansive body comprises: a plurality of discs of ceramic electroexpansive material having a thickness no greater than about one millimeter, a plurality of conductive discs, one of said conducting discs being interposed between each said ceramic disc, said discs and said electrodes being bonded together in a unitary assembly, first conductive means for electrically connecting together every alternate conductive disc, second electric circuit means for interconnecting all other conductive discs, whereby application of an electric field between conductive circuit means places an equal voltage across every disc in parallel so that the mechanical expansion of each said disc is in series.

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