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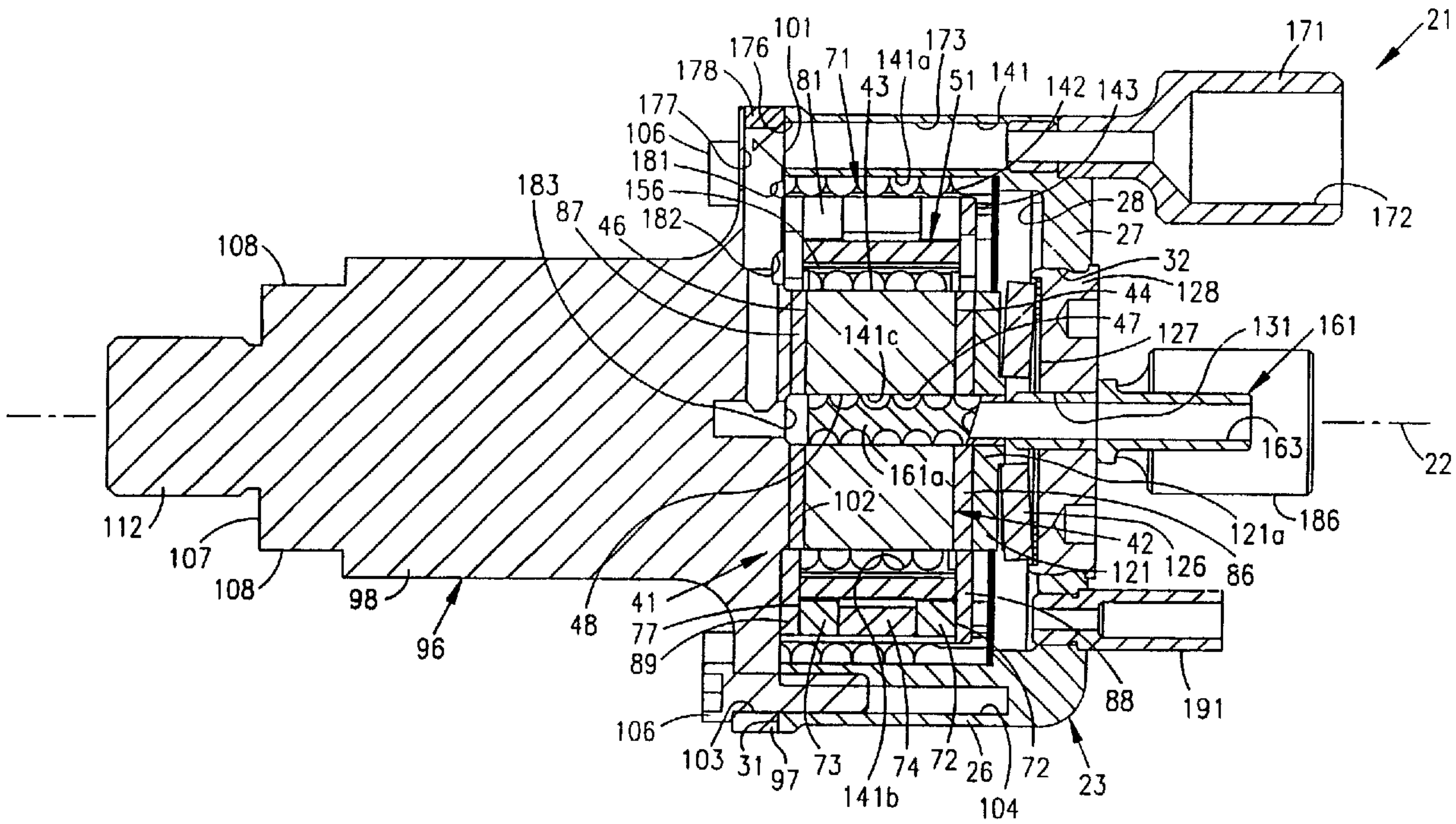

(57) Abrégé/Abstract:
A high power ultrasonic motor (21). The motor includes a housing (23) having a predetermined geometry and a transducer (41). The transducer has an active element (42) made from a magnetostrictive material and a coil (51) for producing an electromagnetic filed which extends through at least a portion of the active element. The active element is changeable between a first shape when in the absence of the electromagnetic field and a second shape when in the presence of the electromagnetic field. An electrical signal is provided to the coil for producing the electromagnetic field. An acoustic element (96) is connected to the transducer for providing ultrasonic energy to perform work.

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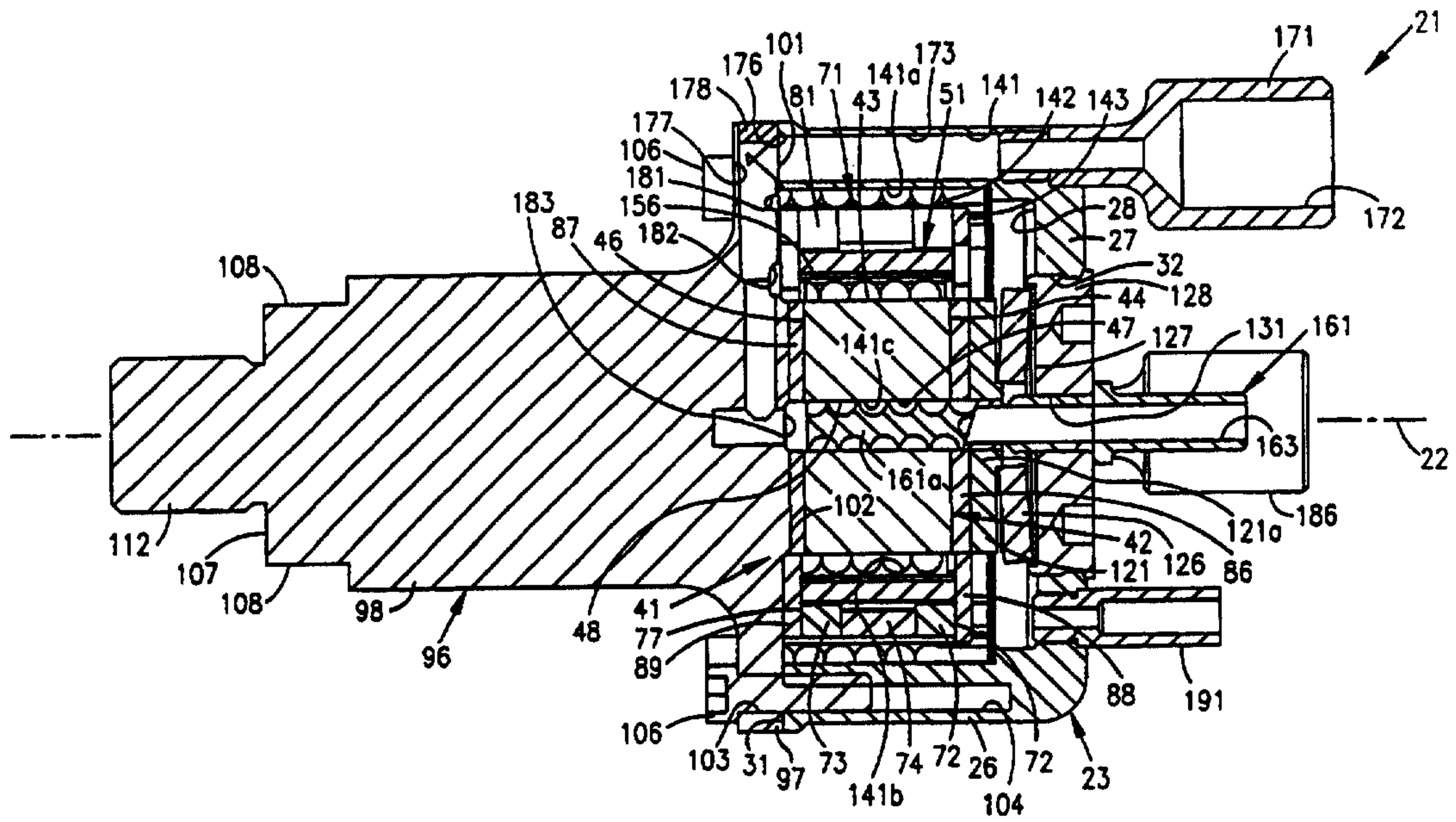

(57) Abstract

A high power ultrasonic motor (21). The motor includes a housing (23) having a predetermined geometry and a transducer (41). The transducer has an active element (42) made from a magnetostrictive material and a coil (51) for producing an electromagnetic filed which extends through at least a portion of the active element. The active element is changeable between a first shape when in the absence of the electromagnetic field and a second shape when in the presence of the electromagnetic field. An electrical signal is provided to the coil for producing the electromagnetic field. An acoustic element (96) is connected to the transducer for providing ultrasonic energy to perform work.

HIGH POWER ULTRASONIC MOTOR

This invention pertains generally to actuators and, more particularly, to ultrasonic actuators.

According to one aspect the invention provides a high power ultrasonic motor comprising a housing having a predetermined geometry, a transducer having an active element made from a giant magnetostrictive material and means for producing an electromagnetic field which extends through at least a portion of the active element, the active element changeable between a first shape when in the absence of the electromagnetic field and a second shape when in the presence of the electromagnetic field, biasing means for biasing the active element, flux path means for capturing magnetic flux through the active element, means for providing an electrical signal to the means for producing an electromagnetic field and an acoustic element connected to the transducer for providing ultrasonic energy to perform work.

According to another aspect the invention provides a high power ultrasonic motor comprising a housing having a predetermined geometry, means carried by the housing for providing power in excess of three kilowatts, including a transducer having a cylindrical actuation element made from a magnetostrictive material and a coil made from electrically conductive wire concentrically disposed about the cylindrical element for producing an electromagnetic field that extends through at least a portion of the cylindrical element, the cylindrical element changeable between a first shape when in the absence of the electromagnetic field and a second shape when in the presence of the electromagnetic field, biasing means for biasing the cylindrical element, flux path means for capturing magnetic flux through the cylindrical element, means for supplying an electrical signal to the coil, cooling means for actively cooling the cylindrical element and an acoustic element connected to the transducer for vibrating at an ultrasonic frequency in response to the transducer for performing work.

According to another aspect the invention provides a high power ultrasonic motor comprising a housing having a predetermined geometry, a transducer having a rod-like element made from a magnetostrictive material and a coil made from electrically conductive wire concentrically disposed about the rod-like element changeable between a first shape when in the absence of a magnetic field and a second shape when in the presence of the magnetic field, tubular magnetic means concentrically disposed about the coil for biasing the rod-like element and having first and second opposite end portions and a central portion between the first and second end portions, the first and second end portions having a radial thickness which is less than the radial thickness of the end portions, means for supplying a sinusoidal electrical signal to the coil, means for actively cooling the transducer which includes an electrical insulator for forming a fluid-carrying helical passageway which extends about the transducer, the rod-like element having first and second ends, first and second flux return means carried by the housing adjacent to the first and second ends of the rod-like element for capturing magnetic flux through the rod-like element and an acoustic element connected to the transducer for vibrating at an ultrasonic frequency in response to the transducer for producing useable work wherein the first and second flux return means are adjacent to the first and second end portions of the tubular magnetic means and are made from a material having an electrical resistivity ranging from 0.01 to 50 ohm-cm and a magnetic saturation flux density greater than 8,000 gauss.

According to another aspect the invention provides a high power magnetostrictive ultrasonic actuator comprising an active element made from a giant magnetostrictive material having first and second ends, the magnetostrictive element changeable from a first shape to a second shape in the presence of a magnetic field, means for producing the magnetic field which extends through at least a portion of the active element and first and second flux return elements adjacent to the first and second ends of the magnetostrictive element for capturing magnetic flux through the magnetostrictive element, wherein the high power magnetostrictive ultrasonic actuator contains a cooling system for cooling the active element.

According to another aspect the invention provides a high power ultrasonic motor comprising: a housing having a predetermined geometry; a transducer disposed within the housing, the transducer having an active element made from a giant magnetostrictive material, the active element changeable between a first shape when in the absence of the electromagnetic field and a second shape when in the presence of the electromagnetic field; a coil for producing an electromagnetic field, the coil extending through at least a portion of the active element; a permanent magnet concentrically disposed about the active element for biasing the active element; flux return elements adjacent to the active element for capturing magnetic flux through the active element; and an acoustic element connected to the transducer for providing ultrasonic energy to perform work.

According to another aspect the invention provides a system comprising: a high power magnetostrictive ultrasonic transducer capable of generating power in excess of three kilowatts comprising an active element made from a giant magnetostrictive material having first and second ends, the giant magnetostrictive element changeable from a first shape to a second shape in the presence of a magnetic field; a coil extending through at least a portion of the active element; first and second flux return elements adjacent to the first and second ends of the magnetostrictive element; a cooling system disposed within the transducer; and an acoustic element connected to the transducer for providing ultrasonic energy to perform work.

FIG. 1 is an isometric view of an ultrasonic actuator of the present invention.

FIG. 2 is a plan view of the ultrasonic motor of FIG. 1.

FIG. 3 is a cross-sectional view of the ultrasonic motor of FIG. 1 taken along the line 3-3 of FIG. 2.

FIG. 4 is an exploded view of the ultrasonic motor of FIG. 1.

FIG. 5 is a sectional view of the ultrasonic motor of FIG. 1 taken along the line 5-5 of FIG. 4.

FIG. 6 is a cross-sectional view of the ultrasonic motor of FIG. 1 taken along the line 6-6 of FIG. 5.

FIG. 7 is a sectional view of the ultrasonic motor of FIG. 1 taken along the line 7-7 of FIG. 4.

FIG. 8 is a cross-sectional view of the ultrasonic motor of FIG. 1 taken along the line 8-8 of FIG. 7.

FIG. 9 is a sectional view of the ultrasonic motor Of FIG. 1 taken along the line 9-9 of FIG. 4.

FIG. 10 is a cross-sectional view of the ultrasonic motor of FIG. 1 taken along the line 10-10 of FIG. 9.

FIG. 11 is a side elevational view of a portion of the ultrasonic motor of FIG. 1.

The high power ultrasonic actuator or motor 21 of the present invention is cylindrical in conformation and concentrically disposed about a central longitudinal axis 22 (see FIGS. 3 and 4). Apparatus or motor 21 is relatively small in size and has a diameter of approximately three inches and a length of approximately four inches. A housing member or motor housing 23 of predetermined geometry is included within motor 21. Motor housing 23, shown in FIGS. 1-4 and separately in FIGS. 5 and 6, has an outer cylindrical wall 26 which is circular in cross-section and has a generally planar end wall 27 extending across one end of cylindrical wall 26. The other end of cylindrical wall 26 is open for accessing internal chamber 28 of motor housing 23. The internal chamber is formed by walls 26 and 27. The open end of cylindrical wall 26 is provided with an annular planar face 31 extending at a right angle to longitudinal axis 22. A central circular opening 32 extends through end wall 27 into internal chamber 28. Motor housing 23 is made from any suitable material such as 6-2-4-2 titanium. Cylindrical wall 26 has an outer diameter of approximately 2.85 inches and an inner diameter of approximately 2.3 inches and a length from end to end of approximately 1.45 inches. End wall 27 has a thickness of approximately 0.25 inch and central opening 32 has a diameter of approximately 1.5 inches. Motor housing 23 is provided with a radially-extending slit 33 which extends longitudinally through the housing 23 for precluding electrical currents from traveling circumferentially around the motor housing. Any such currents in the motor housing produce unwanted electromagnetic fields and heat which disrupt the efficiency of ultrasonic motor 21. Slit 33 has a thickness of approximately 0.04 inch and extends radially inwardly from the outside of motor housing 23 a distance of approximately 0.60 inch.

A transducer assembly or transducer 41 is carried by motor housing 23 and, more specifically, is disposed within internal chamber 28. Transducer 41, as shown in FIGS. 3 and 4, includes a cylindrical or rod-like member in the form of drive rod 42 made from any suitable active or smart material which changes shape when energized by being placed in an electromagnetic field. Such active materials include magnetostrictive materials which change shape in response to an applied magnetic field. A magnetostrictive material is preferred because such a material can tolerate high mechanical stress so as to have a relatively high energy density. High energy density enables more mechanical power output from a given electrical power input and volume of smart material which thus reduces the size and weight of ultrasonic motor 21. Preferred magnetostrictive materials are rare earth materials and rare earth-transition metal materials. Preferred rare earth-transition metal materials are rare earth-iron materials of the type disclosed in U.S. Patent Nos. 4,308,474; 4,609,402; 4,770,704; 4,849,034 or 4,818,304 and commonly referred to as TERFENOL-D. TERFENOL-D is a metal alloy formed from the elements terbium, dysprosium and iron and has the formula of $Tb_xDy_{1-x}Fe_{1.92}$. The preferred formula for the TERFENOL-D material of drive rod 42 is $Tb_{.3}Dy_{.7}Fe_{1.90\text{-}1.95}$. Magnetostrictive materials such as TERFENOL-D have a desirably wide operating temperature environment ranging from approximately -100 to +380 °C. TERFENOL-D is also advantageous in that it has a relatively high thermal conductivity ranging from 10.5 to 10.8 W/m-K.

Drive rod 42 is formed with an outer cylindrical surface 43 and first and second planar end surfaces 44 and 46 extending perpendicular to longitudinal axis 22 and parallel to each other. Drive rod 42 has a diameter of approximately 1.25 inches and a length between end surfaces 44 and 46 of approximately 0.7 inch. A bore 47 extends along central longitudinal axis 22 between end surfaces 44 and 46 and is formed from an internal cylindrical surface 48 having a diameter of approximately 0.25 inch. Drive rod 42 is laminated to control eddy currents therein.

Transducer 41 includes a drive coil 51 which serves as means for producing an electromagnetic field extending through at least a portion of active drive rod 42 (see FIGS. 3 and 4). Coil 51 is concentrically disposed about drive rod 42 within internal chamber 28 and generates an electromagnetic field which extends through the entire drive rod 42. Coil 51 is made from 18 AWG S build square copper wire 52 wound in place with Duralco 128 epoxy made by Cotronics of Brooklyn, New York. The electrically conductive wire 52 has a direct current resistance at 22° C of approximately 0.09 ohms. Coil 51 is wound with two layers of wire 52 and has 17 turns per layer. The wire wound coil 51 has a length of approximately 0.74 inch, an external diameter of approximately 1.7 inches and an internal diameter of approximately 1.5 inches.

High power source 56 is included within the means of ultrasonic motor 21 for providing an electrical signal to transducer 41 (see FIG. 1). Electrical source 56 provides power in the range from 10 watts to 50 kilowatts to the transducer and preferably in excess of three kilowatts. Power source 56 most preferably provides approximately six kilowatts of power to transducer 41 in the form of an ultrasonic three phase sinusoidal signal of approximately 150 volts and 40 amps. An electrical wire 57, shown for simplicity only in FIG. 1, couples power source 56 to the free end of coil wire 52. End wall 27 of motor housing 23 is provided with first, second and third angularly spaced-apart bores 61, 62 and 63 for communicating with internal chamber 28 (see FIG. 5). The angular spacing between first and second bores 61 and 62 and between second and third bores 62 and 63 is each approximately 90°. A tubular strain relief 66 is disposed at one end in first bore 61. Wire 57 extends from power source 56 through strain relief 66 and first bore 61 and is electrically connected to wire 52.

Magnetic means or tubular magnetic means 71 is provided in ultrasonic motor 21 for continuously biasing drive rod 42 (see FIGS. 3 and 4). The tubular magnetic means 71 has first and second opposite end portions consisting of first and second annular bias magnets 72 and 73 and a central portion consisting of third or central annular bias magnet 74. Central bias magnet 74 is disposed between first and second bias magnets 72 and 73. The bias magnets 72-74 are made from a hard magnetic material and can be of any suitable type such as many of the different grades of neodymium iron boron magnets. Alternatively, the bias magnets 72-74 can be made from materials such as samarium cobalt.

Tubular magnetic means 71 is sized and shaped to produce a uniform dc magnetic field through drive rod 42. The greater radial thicknesses of first and second bias magnets 72 and 73 relative to the radial thickness of central bias magnet 74 provides such a uniform dc magnetic bias. First and second bias magnets 72 and 73 each have a longitudinal dimension or length of approximately 0.2 inch and outer and inner diameters of approximately 2.1 inches and 1.72 inches, respectively. Central bias magnet 74 has a length of approximately 0.35 inch and outer and inner diameters of approximately 2.1 inches and 1.79 inches, respectively. As can be seen, central bias magnet 74 has a radial thickness which is less than the radial thickness of first and second bias magnets 72 and 73 resulting from an inner diameter which is greater than the inner diameter of magnets 72 and 73.

As shown in FIG. 3, tubular magnetic means 71 is concentrically disposed about coil 51. Bias magnets 72-74 have an aggregate length closely approximating the length of coil 51. First bias magnet 72 has an outer, planar end surface 76 which is longitudinally aligned with one end surface of coil 51. Second bias magnet 73 has an outer, planar end surface 77 which is longitudinally aligned with the other end surface of coil 51. First and second bias magnets 72 and 73 each have a slit 81 with a thickness of approximately 0.04 inch extending radially therethrough. Central bias magnet 74 is provided with a slit 82 having a thickness of approximately 0.04 inch extending radially therethrough. Slits 81 and 82 are longitudinally aligned and extend in a direction parallel to longitudinal axis 22 for precluding electrical currents from traveling circumferentially around the bias magnets. As discussed above, such currents can create unwanted magnetic fields and heat which disrupt the desired performance of transducer 41.

First and second flux return means are carried by motor housing 23 within internal chamber 28 for capturing the dc magnetic field created by bias magnets 72-73 and directing this dc field through drive rod 42 (see FIGS. 3 and 4). The first and second flux return means also capture the ac magnetic field generated by coil 51 and channel this ac field into drive rod 42. The first and second flux return means include first and second inner annular disk-like members or magnetic disks 86 and 87 and first and second annular ring members or magnetic rings 88 and 89.

Disks 86 and 87 and rings 88 and 89 are each made from any suitable ferromagnetic or soft magnetic material having a relatively low electrical conductivity and a relatively high electrical resistivity. The flux return elements 86-89 also have a relatively high magnetic saturation flux density. It is preferred that the material of elements 86-89 has an electrical resistivity greater than 1000 ohm-cm, although a more practical electrical resistivity range is between 0.01 to 1000 ohm-cm. It is preferable that the magnetic saturation flux density be greater than 8,000 gauss, more preferably greater than 12,000 gauss and most preferably greater than 20,000 gauss.

A suitable material for elements 86-89 is the material marketed under the trade name High Flux by Arnold Engineering of Marengo, Illinois and Magnetics of Butler, Pennsylvania. High Flux is a nickel and iron alloy having the composition of .5 nickel and the balance iron. The nickel and iron elements of the High Flux material are ground into micron and sub-micron particle sizes. A dielectric is sprayed on the particles to electrically insulate them and that powder mix is compressed at roughly 200 tons per square inch to make a solid component which is the equivalent of a sandstone structure. Another suitable material is iron powder marketed by MMG-North America of Paterson, New Jersey. The iron powder has a composition of greater than 95% iron. The iron powder is produced in a manner similar to the method for producing High Flux described above. Briefly, the iron elements are ground into micron and sub-micron particle sizes. A dielectric is sprayed on the particles to electrically insulate them and that powder mix is compressed to make a solid component which is the equivalent of a sandstone structure. Each of these materials has an electrical resistivity ranging from 0.01 to 50 ohm-cm and a magnetic saturation flux density ranging from 12,000 to 15,000 gauss. High flux has a high relative permeability which makes it a better magnetic flux conductor.

First magnetic disk 86 has a longitudinal dimension or thickness of approximately 0.1 inch and outer and inner diameters of approximately 1.255 inches and 0.25 inch, respectively. Second magnetic disk 87 has a longitudinal dimension or thickness of approximately 0.07 inch and outer and inner diameters of approximately 1.255 inches and 0.25 inch, respectively. Disks 86 and 87 are each centered on longitudinal axis 22 with first magnetic disk 86 abutting first end surface 44 of drive rod 42 and second magnetic disk 87 abutting the second end surface 46 of the drive rod 42.

First and second magnetic rings 88 and 89 each have a longitudinal dimension or thickness of approximately 0.08 inch and outer and inner diameters of approximately 2.095 inches and

1.31 inch, respectively. Each of the rings 88 and 89 is provided with a cutout 91 in the shape of a half-moon on the inside thereof and a radially-extending slit 92 extending therethrough and having a thickness of approximately 0.12 inch. Cutout 91 in first ring 88 permits coil wire 52 to pass ring 88 and exit internal chamber 28 for electrical coupling to wire 57 and thus power source 56. Slits 92 preclude electrical currents from traveling circumferentially around the rings 88 and 89 for the same reasons discussed above with respect to slits 33, 81 and 82. The first magnetic ring 88 abuts end surface 76 of first bias magnet 72 and the corresponding end of coil 51 and the second magnetic ring 89 abuts end surface 77 of the second bias magnet 73 and the corresponding end of coil 51.

An acoustic element or extension 96 is included within ultrasonic motor 21 and, among other things, serves to close the open end of motor housing 23. As shown most clearly in FIGS. 3 and 4, acoustic extension 96 includes a flange portion 97 and a cylindrical portion 98 each of which are centered on longitudinal axis 22. Disk-like flange portion 97 has a longitudinal dimensional or thickness of approximately 0.225 inch and an external diameter of approximately 2.9 inches. The flange portion 97 has a generally planar surface or face 101 which abuts and mates with annular planar face 31 of motor housing 23. A central planar surface 102 is provided at the center of face 101. Central surface 102 has an outer diameter of approximately 1.255 inches and is parallel to face 101. Central surface 102 is spaced outwardly from face 101 a distance of approximately 0.035 inch. A plurality of 12 circumferentially spaced-apart bores 103 extend longitudinally through flange portion 97 and longitudinally align with an equal plurality of threaded bores 104 extending longitudinally into planar face 31 of motor housing 23. A cap screw 106 extends through each of flange bores 103 and threadably engages a bore 104 in the motor housing to secure the acoustic extension 96 to motor housing 23.

Cylindrical portion 98 is integral with flange portion 97 and extends from the flange portion 97 in a direction away from face 101. An annular planar surface 107 extending parallel to face 101 forms the other end of acoustic extension 96. Two oppositely aligned cutouts or flats 108 are formed in cylindrical portion 98 adjacent end surface 107 for facilitating gripping and rotating of ultransonic motor 21 with a wrench. A threaded stub 112 protrudes perpendicularly from end surface 107 a distance of approximately 0.7 inch.

Acoustic extension 96 is made from any suitable material such as an acoustic metal. Suitable acoustic metals are aluminum alloys, magnesium alloys and titanium alloys. A magnesium alloy is preferred for the material of acoustic extension 96. Preferred magnesium alloys for forming acoustic extension 96 are high Q/low damping materials and include materials being of the following American Society for Testing and Materials (ASTM) type: AZ31B-F[c] and AZ31B-H24 each having percentage compositions of aluminum, zinc and magnesium ranging from 2.5 to 3.5, 0.7 to 1.3 and at least 0.20, respectively; AZ61A-F having percentage compositions of aluminum, zinc and magnesium ranging from 5.8 to 7.2, 0.4 to 1.5 and at least 0.15, respectively; AZ80A-T5 having percentage compositions of aluminum, zinc and magnesium ranging from 7.8 to 9.2, 0.2 to 0.8 and at least 0.15, respectively; ZK60A-T5 having percentage compositions of zinc and zirconium ranging from 4.8 to 6.2 and at least 0.45, respectively; and HK31A-H24 having percentage compositions of thorium and zirconium ranging from 2.5 to 4.0 and 0.45 to 1.0, respectively. These materials each have a Q (quality factor) which is greater than 100 and a high fatigue strength ranging from 18,000 to 30,000 psi. AZ80A-T5, ZK60A-T5, AZ31B and AZ61A-F are more preferable materials for acoustic extension 96 and AZ80A-T5 is most preferable because it has a relatively high electrical resistivity of approximately 12.2 μohm-cm.

Acoustic extension has a longitudinal dimension or length measured from central face 102 to end surface 107 of approximately 2.5 inches, which is equal to the quarter resonant wavelength of the material of the acoustic extension. Accordingly, the acoustic extension is sized to vibrate from transducer 41 at its resonant frequency.

The stack of second magnetic disk 87, drive rod 42 and first magnetic disk 86 are disposed in internal chamber 28 (see FIG. 3). Second magnetic disk 87 abuts central surface 102. Coil 51 extends around drive rod 42 and is stacked between first and second magnetic rings 88 and 89. The second magnetic ring 89 abuts face 101 of flange portion 97. First bias magnet 72, central bias magnet 74 and second bias magnet 73 are stacked between first and second magnetic rings 88 and 89 outside coil 51. A disk-like reaction mass 121 centered along longitudinal axis 22 abuts first magnetic disk 86. Reaction mass 121 is made from any suitable material such as 17-4 PH stainless steel and has a longitudinal dimension or thickness of approximately 0.1 inch and outer and inner diameters of approximately 1.255 inches and 0.245 inch, respectively. The reaction mass 121 has a raised central portion 121a with a diameter of approximately 0.45 inch. The central portion 121a has a longitudinal dimension or thickness of approximately 0.04 inch. The reaction mass 121 is sized with a specific mass so that the combined mass of the reaction mass 121 and first magnetic disk 86 make drive rod 42 operate at its resonant frequency.

Means is included within ultrasonic motor 21 for imparting a preload on drive rod 42 and includes a belleville spring 126, a preload disk 127 and a preload plate 128. Belleville spring 126 can be of any suitable type such as part number BEL-2401-2410 made by HK Metalcraft of Lodi, New Jersey. Preload disk 127, which precludes the belleville spring 126 from embedding within preload plate 128, can be made from any suitable material such as 1.95 blue hardened spring steel. The disk 127 has a longitudinal dimension or thickness of approximately 0.03 inch and outer and inner diameters of approximately 1.4 inches and 1.0 inch, respectively. Preload plate 128 is disk-like in shape and made from any suitable material such as 6-2-4-2 titanium. Preload plate 128 has an outer cylindrical surface which is threaded and diametrically sized to threadably engage central opening 32 of motor housing 23. A threaded bore 131 extends through the center of preload plate 128. Preload plate 128 is rotatably tightened within central opening 32 so as to provide a preload on drive rod 42 ranging from 1500 to 2800 lbs and preferably approximately 2300 lbs.

Active cooling means is provided in ultrasonic motor 21 for extending the duty cycle of the motor 21 and enhancing the performance thereof. The active cooling means includes a fluid passageway 141 having portions extending about drive rod 42, coil 51 and tubular magnetic means 71. Fluid passageway 141 is adapted to permit any suitable dielectric cooling fluid to flow through ultrasonic motor 21 for cooling transducer 41 and other motor components. Any synthetic heat transfer fluid, such as the fluid having the trade name Multitherm 503 made by Multitherm Corporation of Colwyn, Pennsylvania, is a suitable cooling fluid for ultrasonic motor 21.

Fluid passageway 141 has three helical portions consisting of first or outer helical portion 141a, second or middle helical portion 141b and third or central helical portion 141c. Outer helical portion 141a, as shown in FIG. 3, extends circumferentially around the outside of tubular magnetic means 71 and is formed in part by the inner surface of cylindrical wall 26. Outer helical portion 141a is further formed by a tubular member consisting of outer cooling fixture 142, illustrated separately in FIGS. 7 and 8, which extends around the tubular magnetic means 71. Cooling fixture 142 has a longitudinal dimension or length of approximately 0.99 inch and outer and inner diameters of approximately 2.298 inches and 2.1 inches, respectively. A disk-like ring 143 is formed at one end of the cooling fixture 142. Ring 143 is provided with a central opening 146 having an internal diameter of approximately 1.75 inches. The outer cylindrical surface of cooling fixture 142 is formed with a helical channel 147 provided with at least six turns (see FIGS. 4 and 8). Channel 147 has a radius of approximately 0.06 inch. Two diametrically opposed cutouts 148 are provided in ring 143 for communicating with helical channel 147. Outer cooling fixture 142 is disposed in internal chamber 28 so that ring 143 is positioned close to end wall 27 of motor housing 23.

Ultrasonic motor 21 has means which includes a second tubular member or cooling fixture 156 for forming middle helical portion 141b of fluid passageway 141. Cooling fixture or inner cooling fixture 156, as shown separately in FIGS. 9 and 10, has a longitudinal dimension or length of approximately 0.74 inch and outer and inner diameters of approximately 1.5 inches and 1.26 inches, respectively. The inner cylindrical surface of cooling fixture 156 is formed with a helical channel 157 having at least five turns. Channel 157 has a radius of approximately 0.06 inch. As shown in FIG. 3, inner cooling fixture 156 is disposed between drive coil 51 and drive rod 42. Outer cylindrical surface 43 of the drive rod 42 forms the inner surface of middle helical portion 141b of the fluid passageway 141.

Outer and inner cooling fixtures 142 and 156 are each made from an electrically insulating or nonconductive material. Suitable materials are ceramics such as boron nitride, alumina, silicon carbide, boron carbide, titanium diboride, tungsten carbide, silicon nitride, spinel, pyrolitic graphite, pyrolitic boron nitride, beryllia, graphite and silicon, including all compositions, variations and grades of the foregoing. Another suitable material is aluminum nitride. The preferred material of the cooling fixtures 142 and 156 is hot pressed boron nitride. The aforementioned materials are good thermal conductors and thus enhance the removal of heat from motor housing 23 and the components therein. Specifically, the materials have a relatively high thermal conductivity of greater than 1 W/m-K and preferably greater than 30 W/m-K.

Central helical portion 141c extends through central bore 47 of drive rod 42. Means for forming central helical portion 141c includes an elongate member in the form of cooling tube 161. Inner cylindrical surface 48 of the drive rod also serves to form the central helical portion 141c of fluid passageway 141. Cooling tube 161 is made from any suitable nonelectrically conducting material such as a polyamide/imide, for example Torlon, and has a first end portion or helical portion 161a and an opposite second end portion in the form of fitting 161b (see FIG. 11). A central or threaded portion 161c is disposed between helical portion 161a and fitting 161b. Helical portion 161a is sized and shaped for disposition within drive rod bore 47, as shown in FIG. 3, and has a longitudinal dimension or length of approximately 0.75 inch and an outer diameter of approximately 0.21 inch. A helical channel 162 having at least four turns extends circumferentially around helical portion 161a. The helical channel 162 has a radius of approximately 0.06 inch. Cylindrical central portion 161c of cooling tube 161 is externally sized and shaped to threadably engage threaded bore 131 of preload plate 128 to secure helical portion 161a within drive rod 42. A central bore 163 extends longitudinally through fitting 161b and central portion 161c to an opening 164 in helical channel 162 (see FIG. 11). Bore 163 extends through the open end of fitting 161b.

The cooling fluid is introduced into ultrasonic motor 21 by means of a tubular inlet fitting 171 having a bore 172 extending therethrough (see FIGS. 1-4). An inlet line (not shown) is connected to fitting 171 in this regard. Inlet fitting 171 is threadably secured to an inlet bore 173 extending longitudinally through cylindrical wall 26 of motor housing 23 (see FIGS. 3 and 5). Longitudinal inlet bore 173 communicates by means of an opening 176 in flange face 101 with a radially-extending bore 177 entering the side of flange portion 97 of acoustic extension 96. Radial bore 177 extends approximately to the center of flange portion 97. A plug 178 serves to close the opening of radial bore 177 in the outer cylindrical surface of flange portion 97. First, second and third openings 181, 182 and 183 further extend through flange face 101 for communicating with transverse bore 177 (see FIGS. 3 and 4). First opening 181 is radially positioned on flange face 101 so as to permit fluid within radial bore 177 to communicate with outer helical portion 141a of fluid passageway 141. Second and third openings 182 and 183 are similarly positioned to permit cooling fluid to access middle and central helical portions 141b and 141c of the fluid passageway. Cutouts 91 facilitate the flow of the cooling fluid past the first and second magnetic rings 88 and 89.

The cooling fluid flowing through outer end middle helical portions 141a and 141b of the fluid passageway 141 recombines in internal chamber 28 at the other longitudinal ends of outer and inner cooling fixtures 142 and 156. The fluid within outer cooling fixture 142 exits outer helical portion 141a by means of cutouts 148 in this regard. The cooling fluid from passageway portions 141a and 141b exits motor housing 23 through third bore 63 in end wall 27. A tubular member in the form of outlet fitting 186 extends longitudinally from motor housing 23 and is provided with a bore 187 in communication with third bore 63. The cooling fluid traveling through central helical portion 141c of fluid passageway 141 enters central bore 163 in cooling tube 161 through opening 164 to exit ultrasonic motor 21 means of the cooling tube. Exit lines (not shown) are secured to outlet fitting 196 and fitting 161b of the cooling tube 161 for carrying the cooling fluid away from ultrasonic motor 21.

The temperature within internal chamber 28 can be monitored by means of any suitable temperature sensor (not shown) such as a thermistor or thermocouple disposed in slit 92 in first magnetic ring 88 atop drive coil 51. A tubular strain relief 191 is secured to motor housing 23 and communicates with second bore 62 for permitting an electrical wire 192 to enter the motor housing for connection to the temperature sensor.

In operation and use, motor 21 uses a drive rod made from a magnetostrictive material such as TERFENOL-D to produce vibratory motion at threaded stub 112 of acoustic extension 96. This vibratory motion is in the ultrasonic frequency range, that is, greater than 17 kilohertz. In general, drive rod 42 is changeable between a first shape in the absence of a magnetic field and a second shape when in the presence of a magnetic field. More specifically, the magnetic domains in the giant magnetostrictive material of the drive rod 42 align with longitudinal axis 22 when a magnetic field parallel to axis 22 is applied to the drive rod. This alignment of the magnetic domains causes the drive rod 42 to elongate. A sinusoidal input signal is provided to coil 51 for producing a changing electromagnetic field which has the same frequency as the input signal and extends through the drive rod 42.

Belleville spring 126 serves to create a longitudinal preload on drive rod 42 which remains constant at approximately 2300 lbs throughout the actuation and deactuation of the drive rod 42. The preload externally causes the magnetic domains to be more perfectly oriented perpendicular to the longitudinal axis 22 of drive rod 42. A much longer linear operation region on the strain versus magnetic field strength curve for the drive rod is thus provided resulting in a much higher strain for a magnetic field of given strength in comparison to a drive rod having no prestress thereon.

Tubular magnetic means 71 provides a dc magnetic bias to drive rod 42 which causes the magnetic domains within the drive rod to strain to roughly one-half of their maximum possible value. With the material of drive rod 42 now at one-half of its total strain, the ac magnetic field from coil 51 adds to and subtracts from the dc magnetic bias field which, through magnetostriction, causes the drive rod 42 to expand and contract from its magnetically biased strain. The magnetic biasing of drive rod 42 increases the overall efficiency of the magnetostrictive material of the drive rod and decreases the required strength of the input signal to drive coil 51 and the resulting heat generated by the drive coil by a factor of two.

The sizing and shaping of tubular magnetic means 71 provides for a dc magnetic bias in drive rod 42 which is substantially uniform. As discussed above, the radial thickness of central bias magnet 74 is smaller than the radial thickness of first and second bias magnets 72 and 73 disposed on either side of the central bias magnet. This thickness reduction is caused by the relatively larger inner diameter of central bias magnet 74. The relatively thinner central bias magnet 74 reduces the intensity of the dc magnetic bias field at the longitudinal center of drive rod 42. The uniform dc bias from tubular magnetic means 71 enhances the performance of drive rod 42 and the magnetic coupling of the drive rod to drive coil 51.

The substantially uniform magnetic bias through drive rod 42 is further facilitated by the use of flux return elements 86-89. As discussed above, first and second magnetic disks 86 and 87 are disposed on respective end surfaces 44 and 46 of drive rod 42. First and second magnetic rings 88 and 89 are disposed on respective end surfaces 76 and 77 of the tubular magnetic means 71. These flux return elements serve to capture the dc magnetic field generated by bias magnets 72-74 and direct the field through drive rod 42 thereby reducing magnetic flux leakage in the drive rod 42 and thus enhancing the dc biasing of the drive rod.

The sinusoidal input signal provided by power source 56 to ultrasonic motor 21 has a power of approximately six kilowatts and a frequency of 20 approximately kilohertz. The input signal passes through helically wound wire 52 of drive coil 51 and causes an alternating electromagnetic field to be generated by the coil through drive rod 42. This magnetic field has a maximum field strength ranging from -600 to +600 oersted and preferably approximately 500 oersted. The magnetic domains in the magnetostrictive material of drive rod 42 respond to the induced magnetic field by straining, causing the length of the drive rod to elongate and contract in phase with the frequency of the induced magnetic field generated by drive coil 51.

Ultrasonic motor 21 operates on the principle of conservation of momentum. Motor housing 23 and transducer 41 and the other components therein constitute the motor section of the apparatus 21. Acoustic extension 96 serves as the momentum reactionary section of the apparatus 21. The oscillatory movement of drive rod 42 causes a corresponding oscillatory force to be exerted by the drive rod 42 against reaction mass 121. As the reaction mass is driven in one direction against belleville spring 126, acoustic extension 96 must respond in an opposite direction to conserve momentum. The longitudinal velocity of ultrasonic motor 21 at flange face 101 is approximately zero. The maximum longitudinal velocity of the motor 21 is at end surface 107. The acoustic extension 96 is in the direct load path of drive rod 42 and, as discussed above, is longitudinally sized so as to operate at its resonant frequency. Accordingly, a resonant one-half wavelength standing wave is established to cause threaded stub 112 to oscillate at an ultrasonic frequency in response to transducer 41. The established standing wave is 180° out of phase with the oscillating drive rod 42. Stub 112 can be attached to other systems to produce usable work.

The formation of acoustic extension 96 from the various magnesium alloys set forth above enhances the ultrasonic vibratory motion produced by acoustic extension 96. In general, these magnesium alloys have relatively low density and thus, in accordance with the conservation of momentum principle, increase the velocity of the vibration amplitude output at threaded stub 112 relative to other acoustic metals such as titanium alloys. The magnesium alloy material of extension 96 also has relatively high strength which contributes to the life of motor 21.

The flux return elements 86-89 also serve to capture the ac magnetic field created by drive coil 51 and channel that field through drive rod 42 so as to increase the ac magnetic field intensity in the drive rod and thus enhance the performance of transducer 41. The magnetic rings 88 and 89 are positioned at the longitudinal ends of drive coil 51 and the magnetic disks 86 and 87 are positioned at the longitudinal ends of drive rod 42 for this purpose. As discussed above, disks 86 and 87 and rings 88 and 89 are each made from soft magnetic materials which have low electrical conductivity. These elements are ferromagnetic at ultrasonic frequencies and have very low energy losses. The relatively high electrical resistivity of these elements precludes the creation of appreciable eddy currents therein which reduce the ability of the flux return elements to conduct and direct magnetic flux. Such eddy currents also disrupt the intensity of the alternating magnetic field through the drive rod 42 and thus negatively affect the efficiency of transducer 41. The capturing and redirecting of the ac magnetic field by flux return elements 86-89 serves to increase the efficiency of ultrasonic motor 21 by a factor of two to five times.

The active cooling of transducer 41 and tubular magnetic means 71 within ultrasonic motor 21 by means of fluid passageway 141 further enhances the performance of the motor. The active cooling also permits continuous operation of ultrasonic motor 21 at full power. The incorporation of helical passageway portions in and around drive rod 42, drive coil 51 and bias magnets 72-74 increases the ability of the cooling fluid to carry heat away from the motor. In this regard, the utilization of helical channels 147, 157 and 162 increases the heat transfer area encountered by the cooling fluid. Helical portions 141a-c increase the fluid flow speed in and around transducer 41 to enhance chaotic flow patterns and turbulence and thus further increase the convection coefficient of the cooling fluid. Specifically, the velocity and convection coefficient of the cooling fluid through helical portions 141a-c are increased approximately 10 times and 45 times, respectively.

The construction of outer and inner cooling fixtures 142 and 156 from an electrically insulating or dielectric material further serves to enhance the operating efficiency of transducer 41. Deleterious eddy currents from the high frequency magnetic field generated by drive coil 51 are not produced in cooling fixtures 142 and 156. Eddy currents can disrupt the intensity of the ac magnetic field extending through drive rod 42. Such undesirable eddy currents are also not generated in the nonconductive cooling fluid of ultrasonic motor 21. In addition, fixtures 142 and 156 are good heat conductors and thus enhance the transfer of heat from the various components in the motor section of ultrasonic motor 21 to the cooling fluid. The dielectric material of cooling fixtures 142 and 156 further protects against electrical shorts within motor 21.

The ultrasonic energy generated by motor 21 can produce usable work in many applications. For example, ultrasonic motor 21 can be used for the excitation of solids, fluids and gases. In the excitation of chemical mixtures, motor 21 can cause physical, structural and chemical changes in the mixture. As an example, motor 21 can be used for the curing of polymers such as industrial epoxy or for the devulcanization of rubber. Motor 21 can be easily scaled larger or smaller for use in other applications. For example, a smaller motor could be used for various surgical or other medical tools. Examples include medical tools for dental cleaning, bone prosthesis insertion and removal, sonic imaging and surgery. Other applications include using motor 21 for disrupting biological cells. Motor 21 can further be used for degassing soda pop, beer or wine, for ultrasonically machining materials or welding components together and for sonicating seed.

In an alternative design of the high power ultrasonic motor of the present invention, the transducer can be operated in quarter-wave mode wherein one end of the motor section is fixed and the other end of the motor section is free to move. In this design, no acoustic extension is needed. In other embodiments, less effective flux concentrating soft magnetic materials such as ferrites or molybdenum permalloy powder can be used in place of the materials of the high flux return elements described above and be within the scope of the present invention. It should also be appreciated that other embodiments of the ultrasonic motor herein can include less than all of the components described above and be within the scope of the present invention. In addition, transducers utilizing some or all of the features described above can be provided for use in applications other ultrasonics and be within the scope of the present invention.

From the foregoing, it can be seen that a new and improved ultrasonic motor has been provided. The ultrasonic motor utilizes a smart material actuation element made from a magnetostrictive material such as TERFENOL-D and has a momentum reactionary section made from a material of relatively low density. Reliable and continuous high power in excess of three kilowatts can be generated by the motor. The motor is relatively compact in size and is easily scalable. Active cooling with a dielectric fluid can be provided. The actuation element can be magnetically biased with a substantially uniform dc magnetic field and flux return elements made from a low electrical conductivity material can be utilized. A displacement at the wave guide tip of approximately 20 micrometers peak-to-peak can be generated. The motor can provide a pressure on the wave guide face of approximately 2500 psi.

CLAIMS:

1. A high power ultrasonic motor comprising a housing having a predetermined geometry, a transducer having an active element made from a giant magnetostrictive material and means for producing an electromagnetic field which extends through at least a portion of the active element, the active element changeable between a first shape when in the absence of the electromagnetic field and a second shape when in the presence of the electromagnetic field, biasing means for biasing the active element, flux path means for capturing magnetic flux through the active element, means for providing an electrical signal to the means for producing an electromagnetic field and an acoustic element connected to the transducer for providing ultrasonic energy to perform work.

2. The ultrasonic motor of Claim 1 wherein the means for providing an electrical signal includes means carried by the housing for providing power in excess of three kilowatts, said means including the transducer.

3. The ultrasonic motor of Claim 1 wherein the active element is a cylindrical element and wherein the means for producing an electromagnetic field is a coil made from a conductive material concentrically disposed about the cylindrical element.

4. The ultrasonic motor of Claim 3 wherein the biasing means is a magnetic means.

5. The ultrasonic motor of Claim 4 wherein the magnetic means includes tubular magnetic means concentrically disposed about the cylindrical element, the tubular magnetic means having first and second opposite end portions and a central portion between the first and second

end portions, the first and second end portions having a radial thickness and the central portion having a radial thickness which is less than the radial thickness of the end portions for producing a substantially uniform bias over the length of the cylindrical element.

6. The ultrasonic motor of Claim 5 wherein the first and second end portions having an inner diameter and the central portion has an inner diameter which is less than the inner diameter of the end portions.

7. The ultrasonic motor of Claim 6 wherein the first and second end portions are first and second annular members and wherein the central portion is a third annular member disposed between the first and second annular members.

8. The ultrasonic motor of Claim 3 wherein the cylindrical element has first and second opposite ends, further wherein the flux path means comprises first and second flux return elements carried by the housing, the first and second flux return elements located adjacent to the first and second ends of the cylindrical element.

9. The ultrasonic motor of Claim 8 wherein the first and second flux return elements are first and second disk-like elements made from a material having an electrical resistivity ranging from 0.01 to 50 ohm-cm and a magnetic saturation flux density greater than 8,000 gauss.

10. The ultrasonic motor of Claim 1 wherein the acoustic element is mounted on the transducer and is made from a material having a quarter resonant wavelength, the acoustic element having a length equal to the quarter resonant wavelength of the material.

11. The ultrasonic motor of Claim 1 wherein the acoustic element is made from an acoustic metal.

12. The ultrasonic motor of Claim 11 wherein the acoustic element is made from a magnesium alloy.

13. The ultrasonic motor of Claim 1 further comprising cooling means for cooling the active element, the cooling means comprising a passageway about the transducer adapted to receive a cooling fluid, the passageway formed from a material which is an electrical insulator.

14. The ultrasonic motor of Claim 13 wherein the material has a thermal conductivity greater than 1 W/m-K.

15. The ultrasonic motor of Claim 13 wherein the passageway is formed from hot pressed boron nitride.

16. The ultrasonic motor of Claim 13 wherein the passageway is a helical passageway within the transducer.

17. A high power ultrasonic motor comprising a housing having a predetermined geometry, means carried by the housing for providing power in excess of three kilowatts, including a transducer having a cylindrical actuation element made from a magnetostrictive material and a coil made from electrically conductive wire concentrically disposed about the cylindrical element for producing an electromagnetic field that extends through at least a portion of the cylindrical element, the cylindrical element changeable between a first shape when in the absence of the electromagnetic field and a second shape when in the presence of the electromagnetic field, biasing means for biasing the cylindrical element, flux path means for capturing magnetic flux through the cylindrical element,

means for supplying an electrical signal to the coil, cooling means for actively cooling the cylindrical element and an acoustic element connected to the transducer for vibrating at an ultrasonic frequency in response to the transducer for performing work.

18. The ultrasonic motor of Claim 17 wherein the cooling means includes a fluid-carrying passageway which extends about the transducer, wherein the passageway is an electrical insulator.

19. The ultrasonic motor of Claim 18 wherein the fluid-carrying passageway is a helical passageway which extends through the cylindrical element.

20. The ultrasonic motor of Claim 17 wherein the magnetostrictive material is a giant magnetostrictive material.

21. The ultrasonic motor of Claim 17 wherein the transducer is capable of performing work on a continuous basis.

22. A high power ultrasonic motor comprising a housing having a predetermined geometry, a transducer having a rod-like element made from a magnetostrictive material and a coil made from electrically conductive wire concentrically disposed about the rod-like element changeable between a first shape when in the absence of a magnetic field and a second shape when in the presence of the magnetic field, tubular magnetic means concentrically disposed about the coil for biasing the rod-like element and having first and second opposite end portions and a central portion between the first and second end portions, the first and second end portions having a radial thickness which is less than the radial thickness of the end portions, means for supplying a

sinusoidal electrical signal to the coil, means for actively cooling the transducer which includes an electrical insulator for forming a fluid-carrying helical passageway which extends about the transducer, the rod-like element having first and second ends, first and second flux return means carried by the housing adjacent to the first and second ends of the rod-like element for capturing magnetic flux through the rod-like element and an acoustic element connected to the transducer for vibrating at an ultrasonic frequency in response to the transducer for producing useable work wherein the first and second flux return means are adjacent to the first and second end portions of the tubular magnetic means and are made from a material having an electrical resistivity ranging from 0.01 to 50 ohm-cm and a magnetic saturation flux density greater than 8,000 gauss.

23. The ultrasonic motor of Claim 22 wherein the magnetostrictive material is a giant magnetostrictive material.

24. The ultrasonic motor of Claim 22 further comprising means carried by the housing for providing power in excess of three kilowatts.

25. The ultrasonic motor of Claim 22 wherein the electronic insulator for forming the fluid-carrying passageway is a ceramic material.

26. The ultrasonic motor of Claim 25 wherein the ceramic material is selected from the group consisting of boron nitride, aluminum nitride, alumina, silicon carbide, boron carbide, silicon nitride, pyrolitic boron nitride, beryllia and silicon.

27. A high power magnetostrictive ultrasonic actuator comprising an active element made from a giant

magnetostrictive material having first and second ends, the magnetostrictive element changeable from a first shape to a second shape in the presence of a magnetic field, means for producing the magnetic field which extends through at least a portion of the active element and first and second flux return elements adjacent to the first and second ends of the magnetostrictive element for capturing magnetic flux through the magnetostrictive element, wherein the high power magnetostrictive ultrasonic actuator contains a cooling system for cooling the active element.

28. The actuator of Claim 27 wherein the means for producing a magnetic field includes a coil concentrically disposed about the magnetostrictive element.

29. The actuator of Claim 27 further comprising a permanent magnet concentrically disposed about the magnetostrictive element for providing a DC magnetic bias to the magnetostrictive element, the permanent magnet having first and second ends, the first and second flux return elements adjacent to the first and second ends of the permanent magnet for capturing magnetic flux produced by the permanent magnet and directing said flux through the magnetostrictive element.

30. The actuator of Claim 27 wherein the actuator is capable of providing power in excess of three kilowatts.

31. A high power ultrasonic motor comprising:

a housing having a predetermined geometry;

a transducer disposed within the housing, the transducer having an active element made from a giant magnetostrictive material, the active element changeable between a first shape when in the absence of the electromagnetic field and a second shape when in the presence of the electromagnetic field;

a coil for producing an electromagnetic field, the coil extending through at least a portion of the active element;

a permanent magnet concentrically disposed about the active element for biasing the active element;

flux return elements adjacent to the active element for capturing magnetic flux through the active element; and

an acoustic element connected to the transducer for providing ultrasonic energy to perform work.

32. The ultrasonic motor of claim 31 wherein the transducer is capable of providing power in excess of three kilowatts and the ultrasonic motor further comprises a cooling system for cooling the active element.

33. The ultrasonic motor of claim 31 wherein the flux return elements comprise first and second flux return elements.

34. A system comprising:

a high power magnetostrictive ultrasonic transducer capable of generating power in excess of three kilowatts comprising an active element made from a giant magnetostrictive material having first and second ends, the giant magnetostrictive element changeable from a first shape to a second shape in the presence of a magnetic field;

a coil extending through at least a portion of the active element;

first and second flux return elements adjacent to the first and second ends of the magnetostrictive element;

a cooling system disposed within the transducer; and

an acoustic element connected to the transducer for providing ultrasonic energy to perform work.

35. The system of claim 34 wherein the giant magnetostrictive material is TERFENOL-D.

36. The system of claim 34 wherein the ultrasonic transducer produces work on a continuous basis.

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PATENT AGENTS

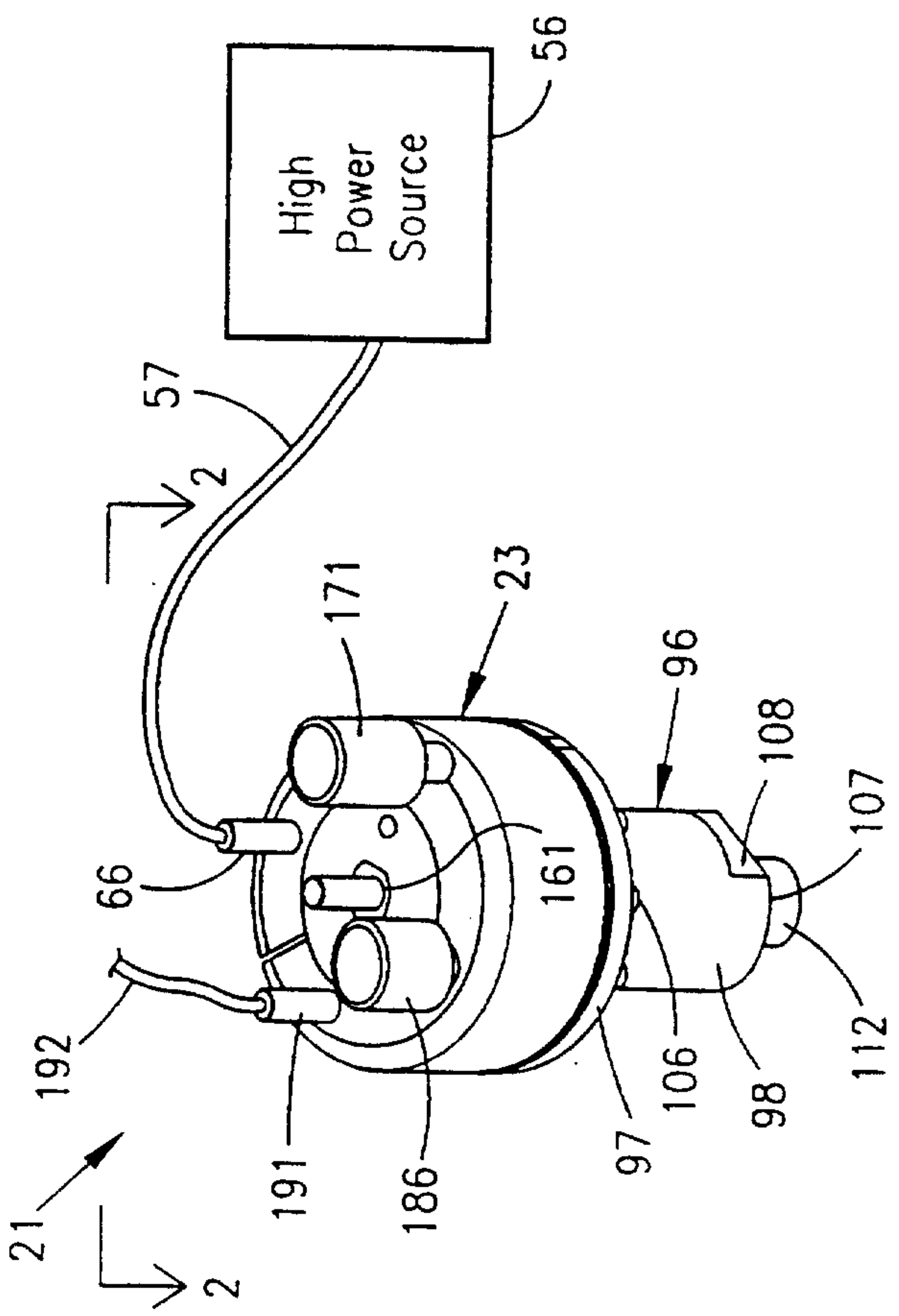

FIG. 1

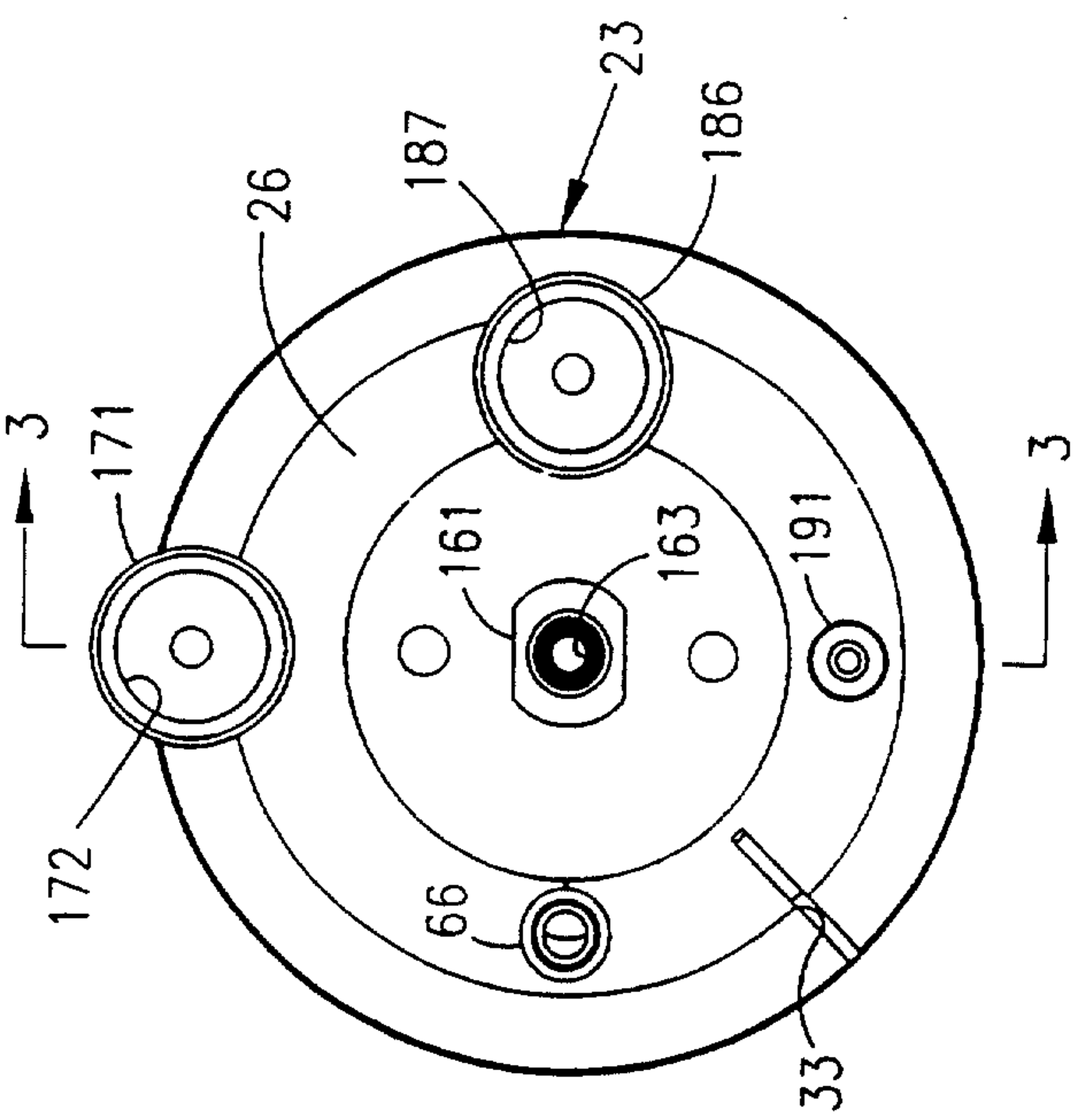

FIG. 2

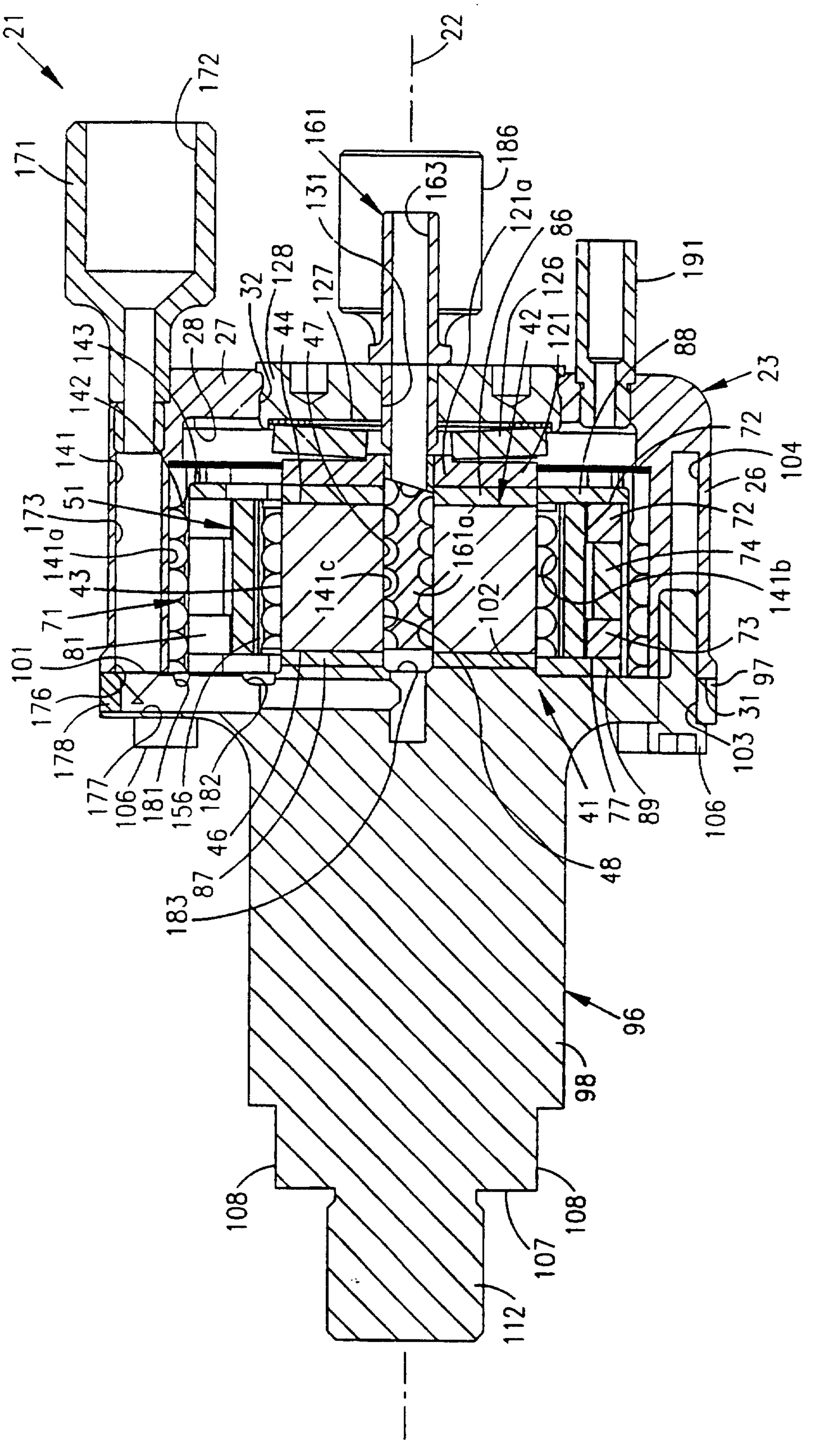
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FIG. 3

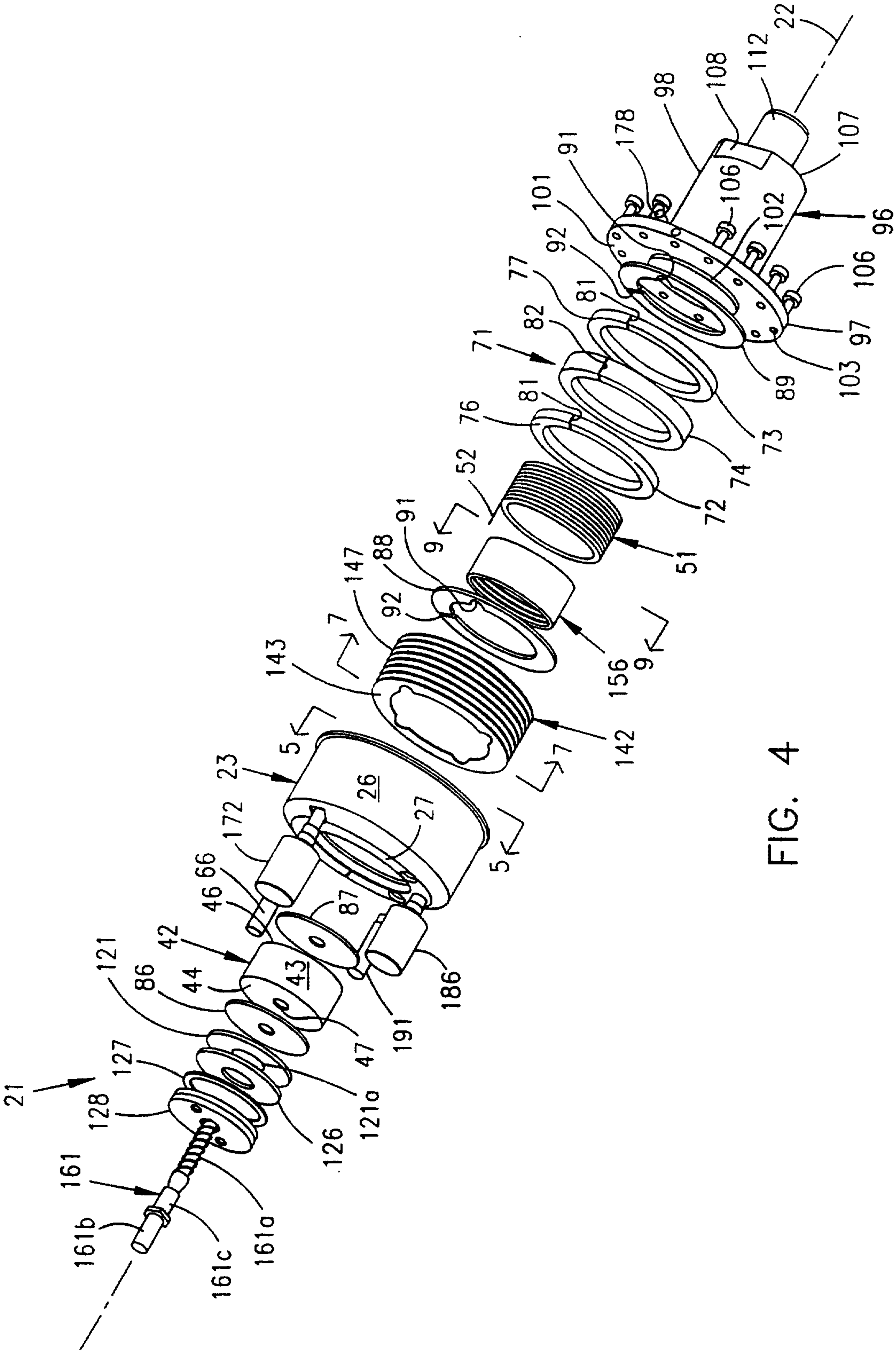
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FIG. 4

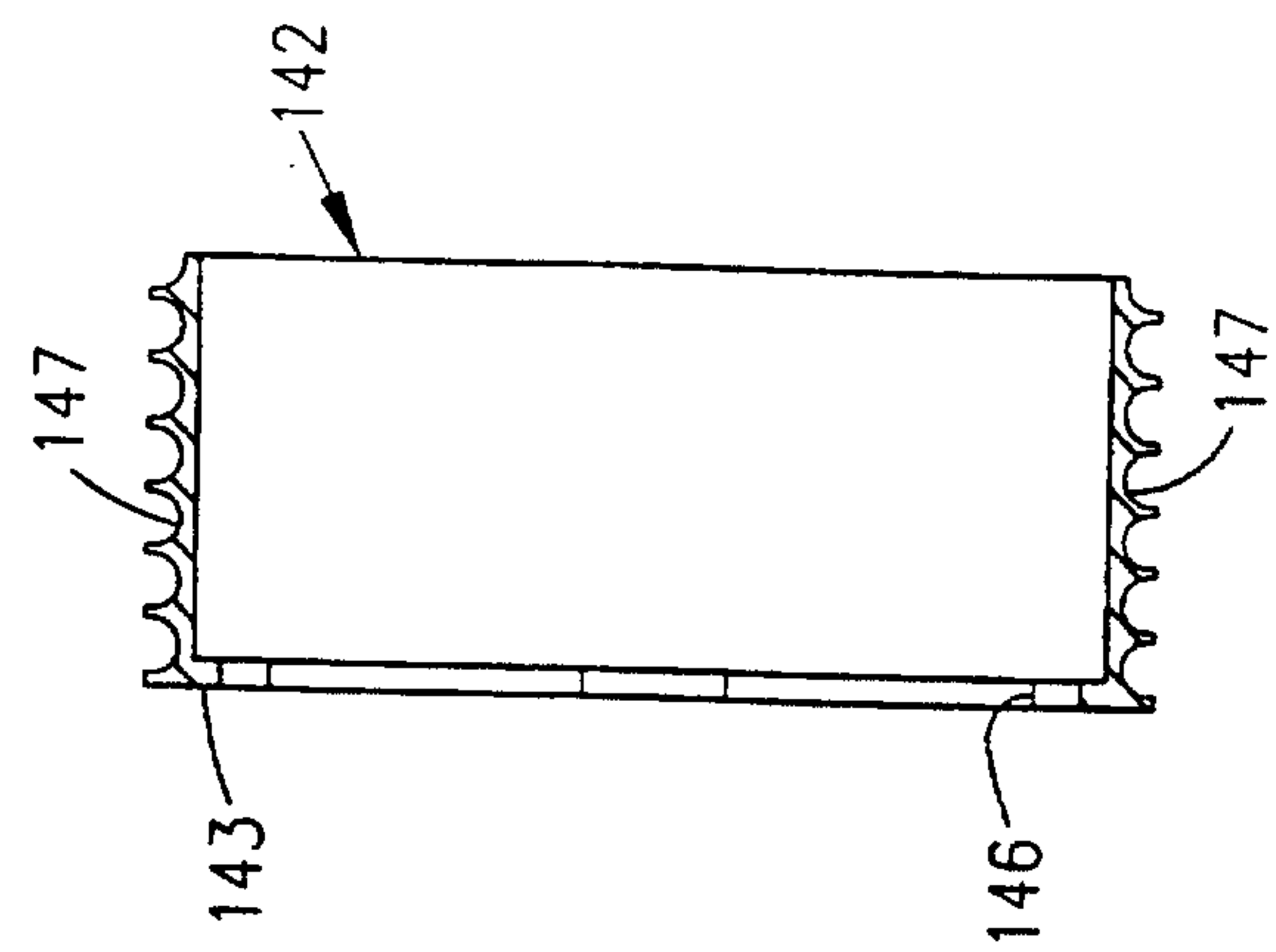

FIG. 8

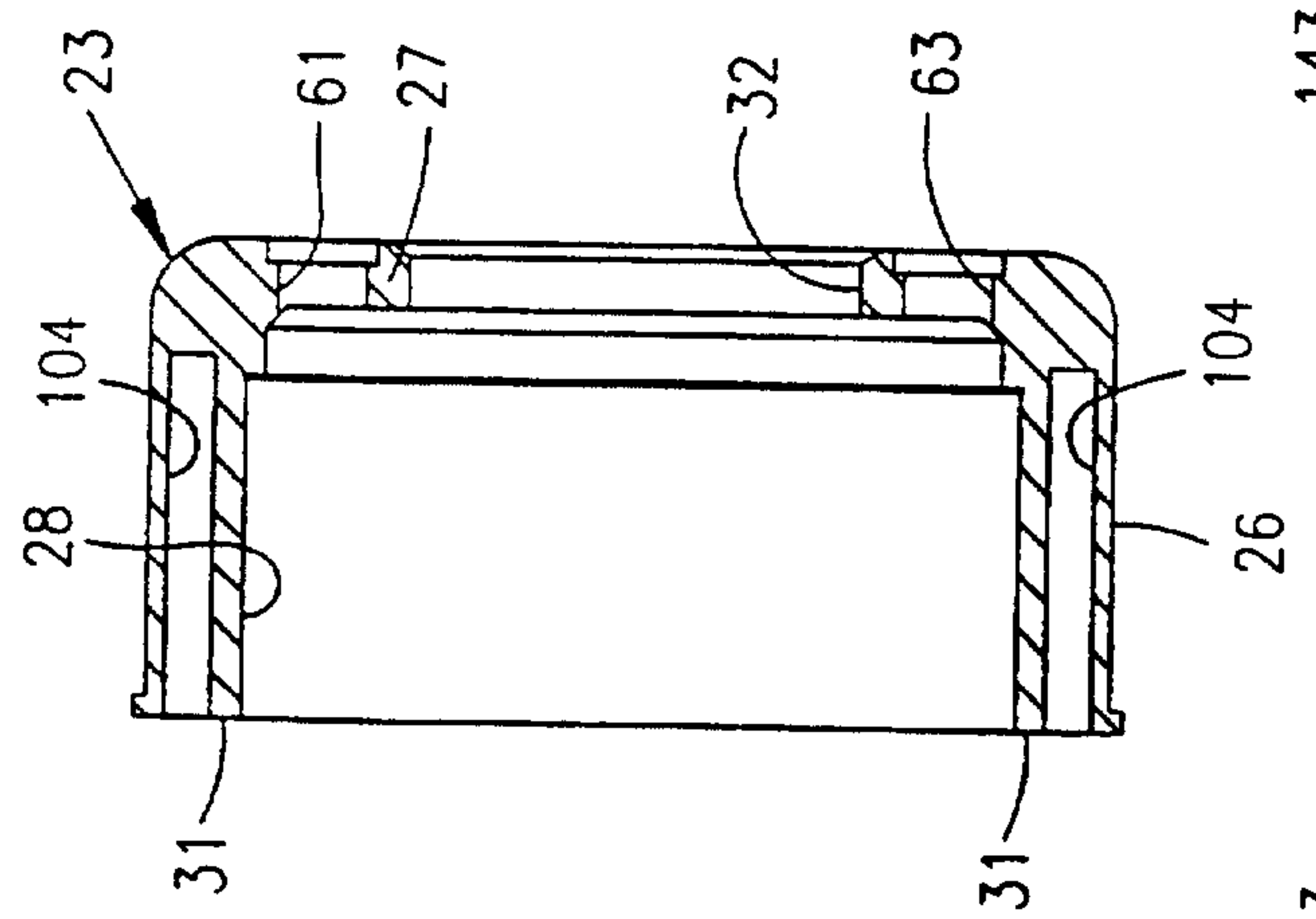

FIG. 6

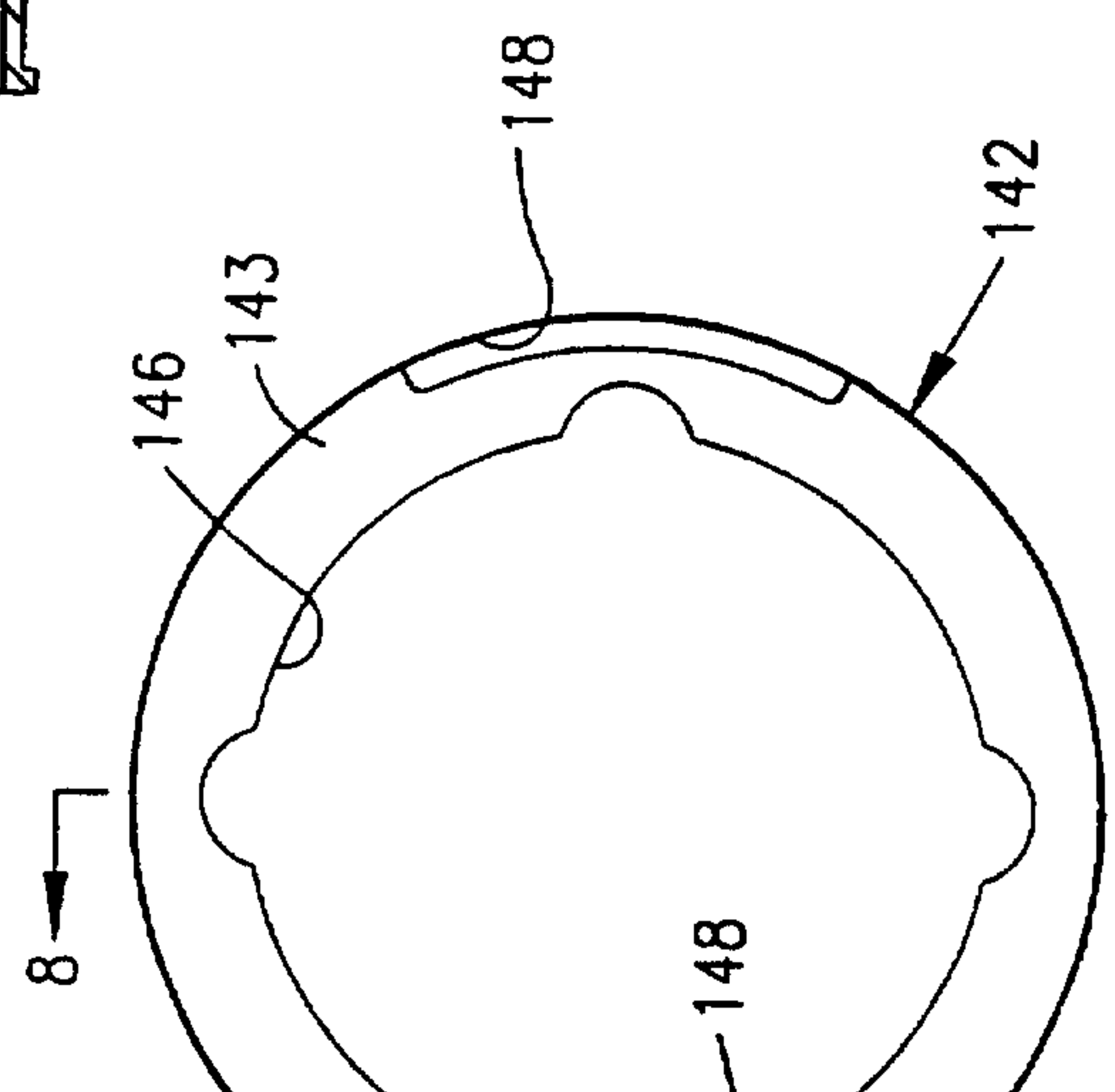

FIG. 7

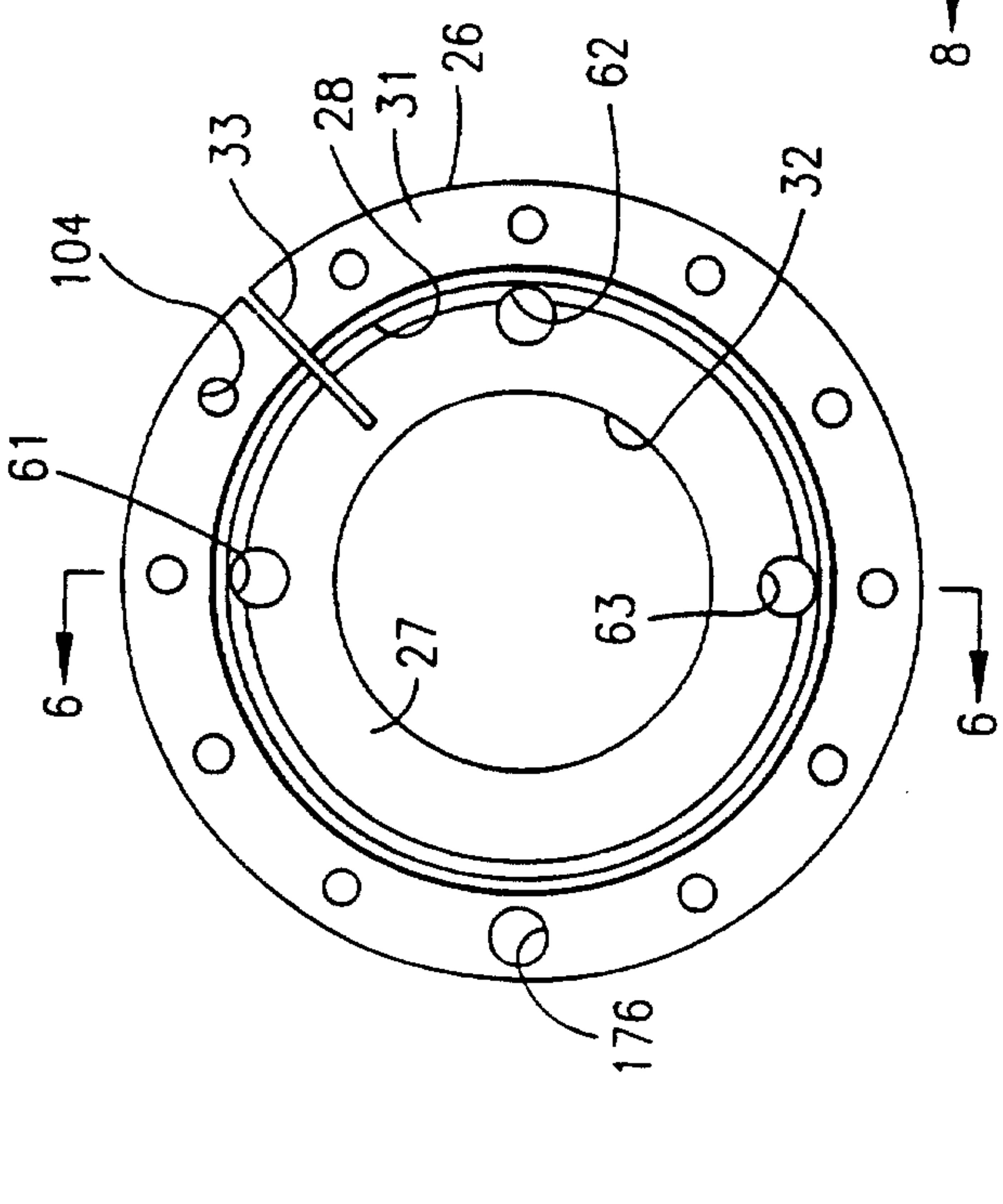

FIG. 5

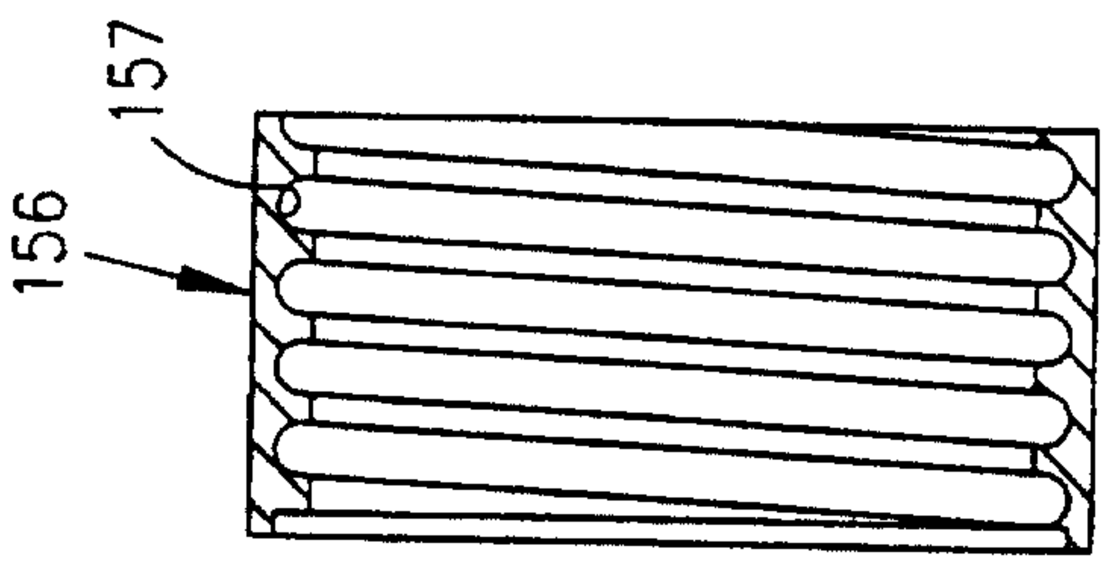

FIG. 10

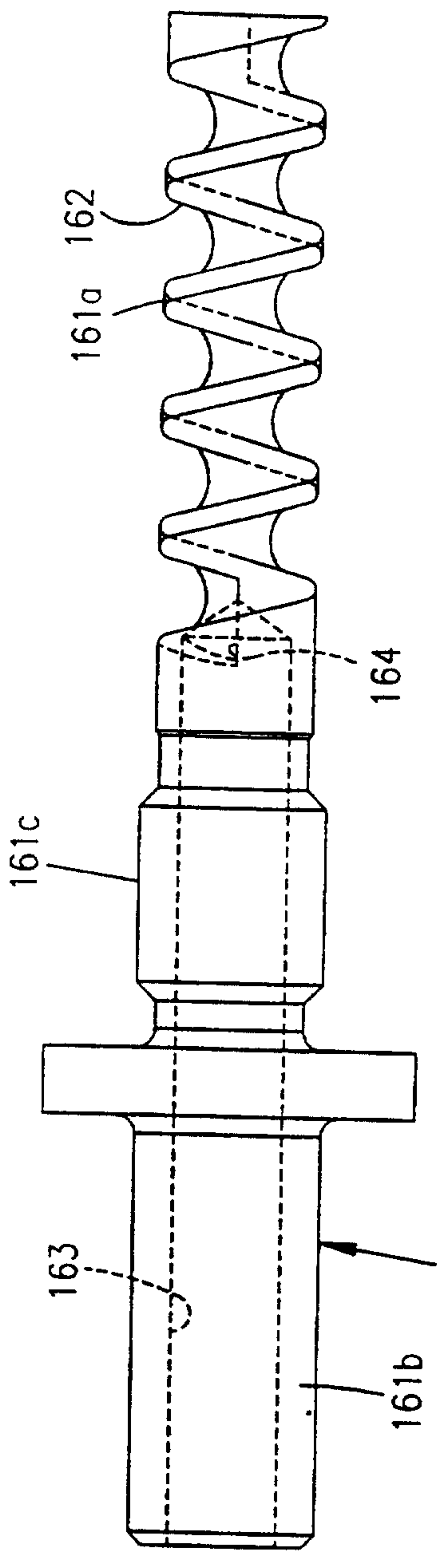

FIG. 11

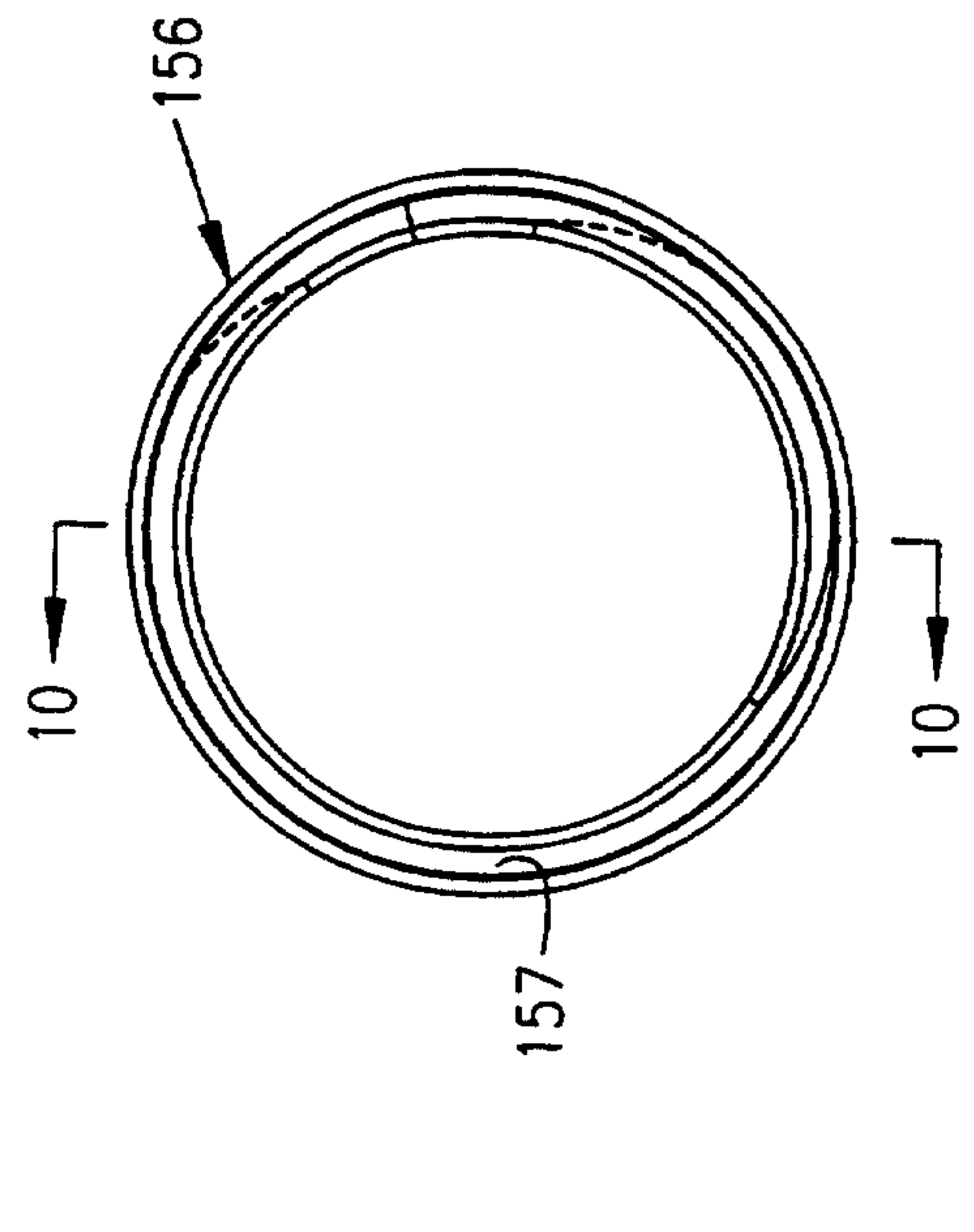

FIG. 9

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141b
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