United States Patent

Jacobson

[15] **3,657,930**

[45] **Apr. 25, 1972**

[54] **PIEZOELECTRIC CRYSTAL OPERATED PUMP TO SUPPLY FLUID PRESSURE TO HYDROSTATICALLY SUPPORT INNER BEARINGS OF A GYROSCOPE**

[72] Inventor: **Oscar D. Jacobson**, New York, N.Y.

[73] Assignee: **The Bendix Corporation**

[22] Filed: **June 24, 1969**

[21] Appl. No.: **836,056**

[52] **U.S. Cl.** **74/5**, 417/322

[51] **Int. Cl.** **G01c 19/20**

[58] **Field of Search** 340/10; 310/9.6; 103/1; 74/5, 74/5.5; 417/322

[56] **References Cited**

UNITED STATES PATENTS

3,029,743	4/1962	Johns	103/1 UX
3,150,592	9/1964	Stec	103/1
3,361,067	1/1968	Webb	103/1
3,362,231	1/1968	Baldwin	74/5

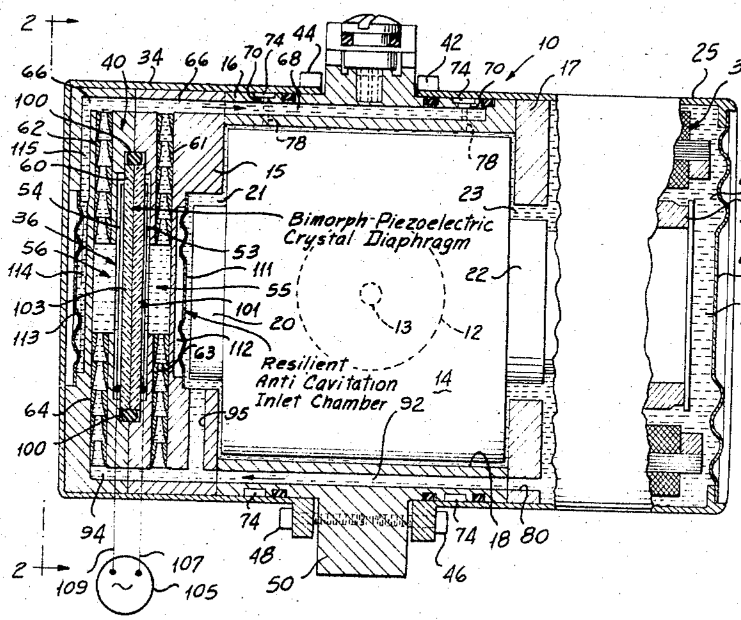
Primary Examiner—Manuel A. Antonakas

Attorney—Herbert L. Davis and Plante, Hartz, Smith & Thompson

[57] **ABSTRACT**

A piezoelectric crystal operated pump including a bimorph (bender type) piezoelectric crystal diaphragm, volumetrically expanding piezoelectric crystal stack, or such a crystal stack operated diaphragm pump arranged to flex in a pump cavity to supply a fluid pressure medium to hydrostatically supported inner bearings of gyroscope.

18 Claims, 10 Drawing Figures



Patented April 25, 1972 **3,657,930**

5 Sheets-Sheet 1

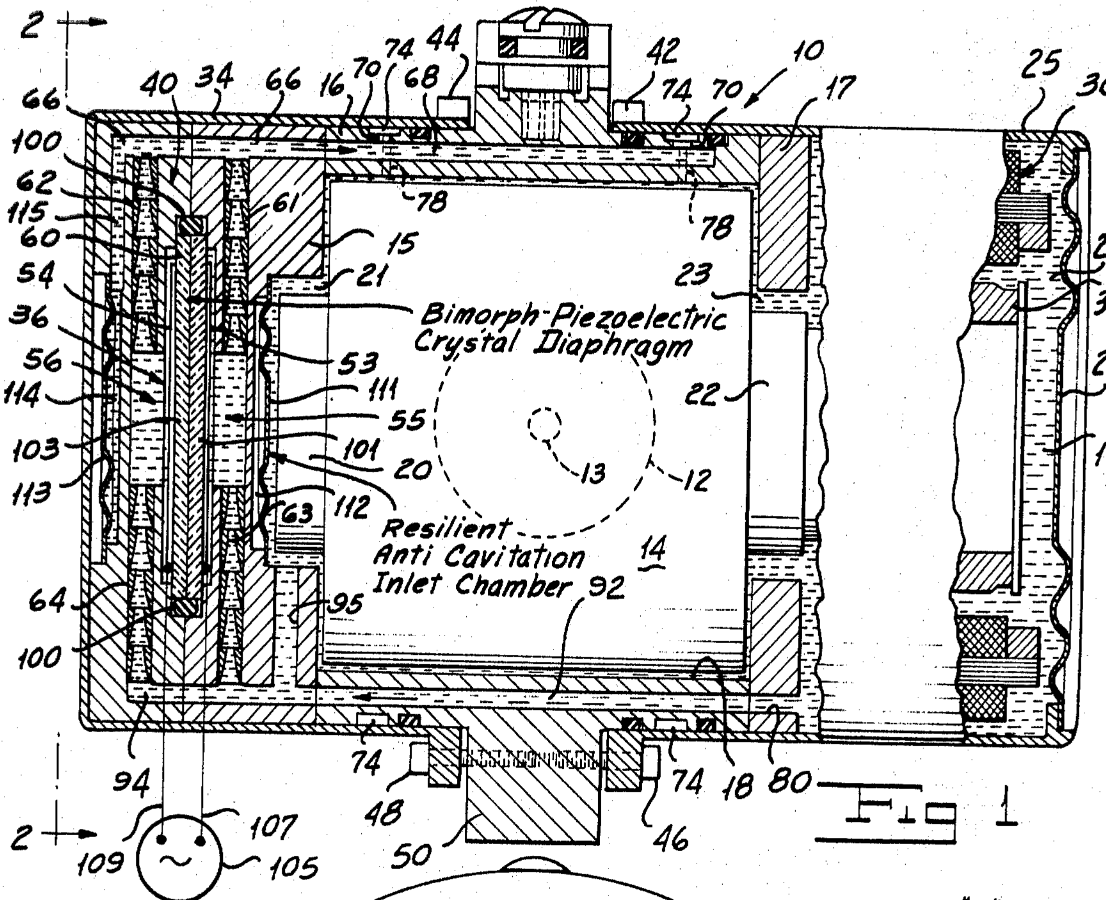


Fig 1

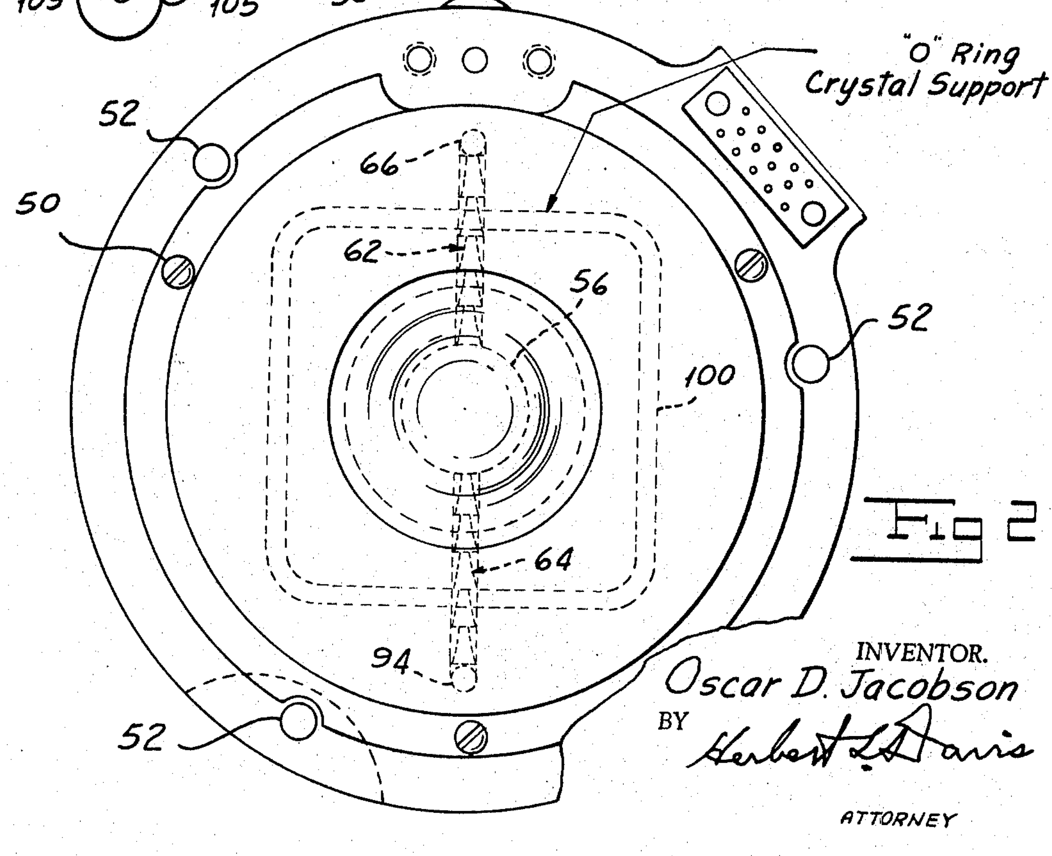


Fig 2

INVENTOR.
Oscar D. Jacobson
BY Herbert L. Davis
ATTORNEY

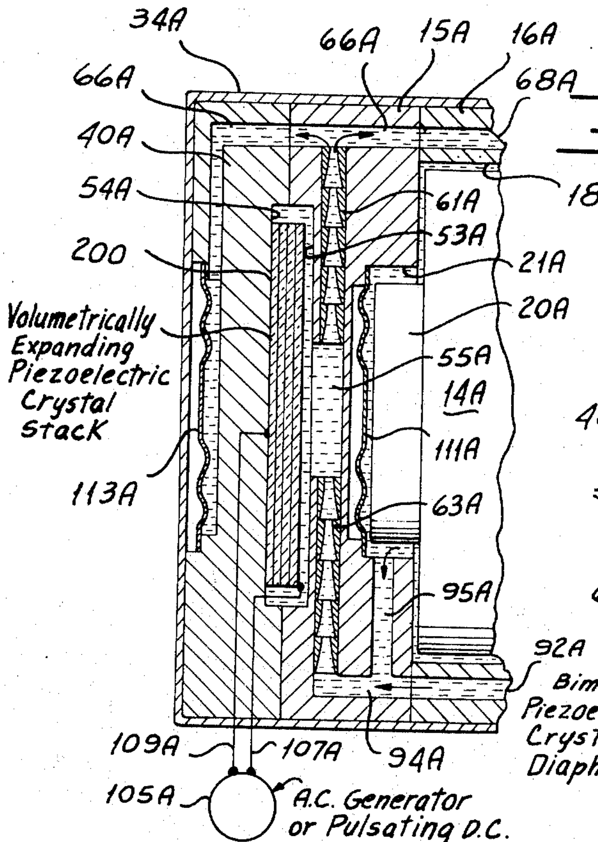


Fig 3

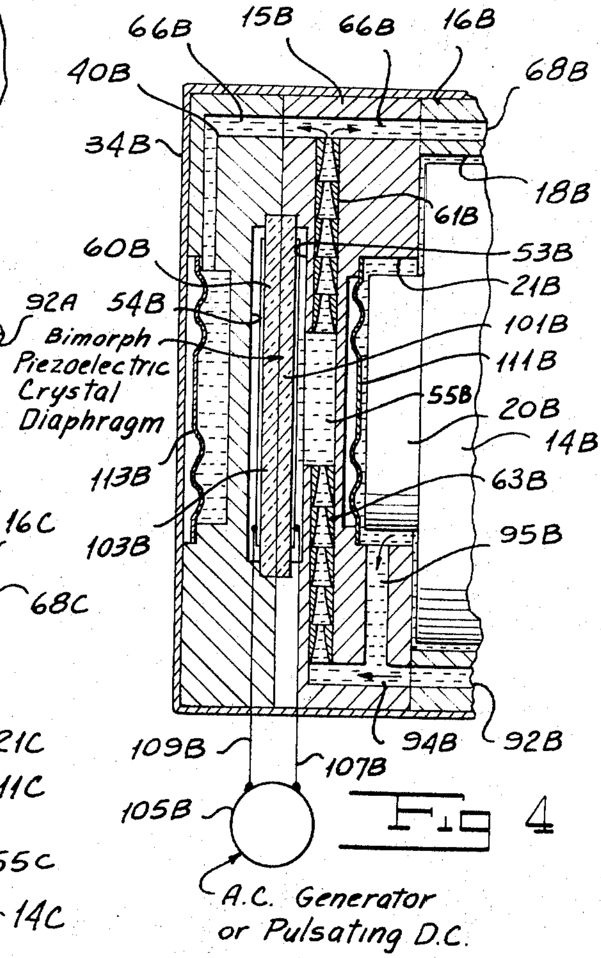


Fig 4

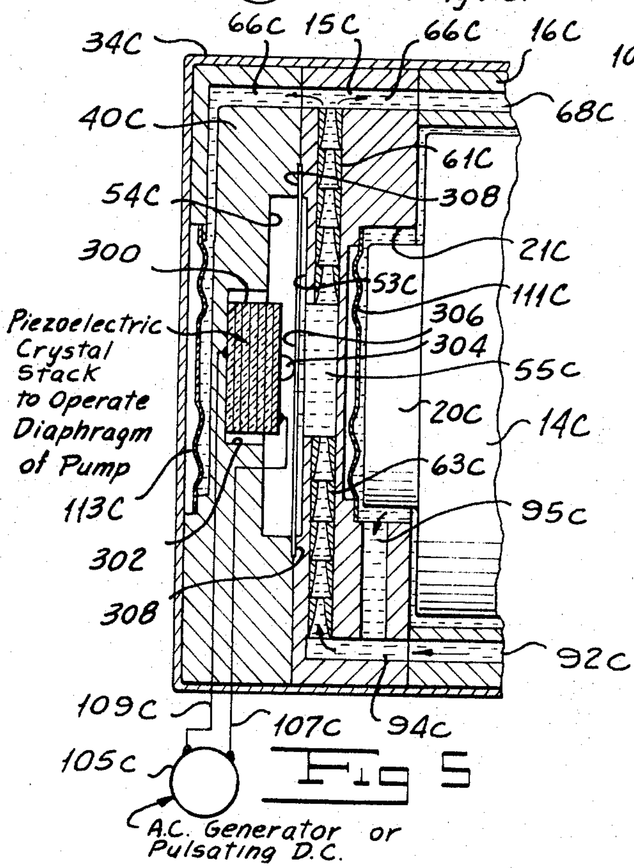


Fig 5

INVENTOR.
Oscar D. Jacobson
BY
Herbert L. Davis
ATTORNEY

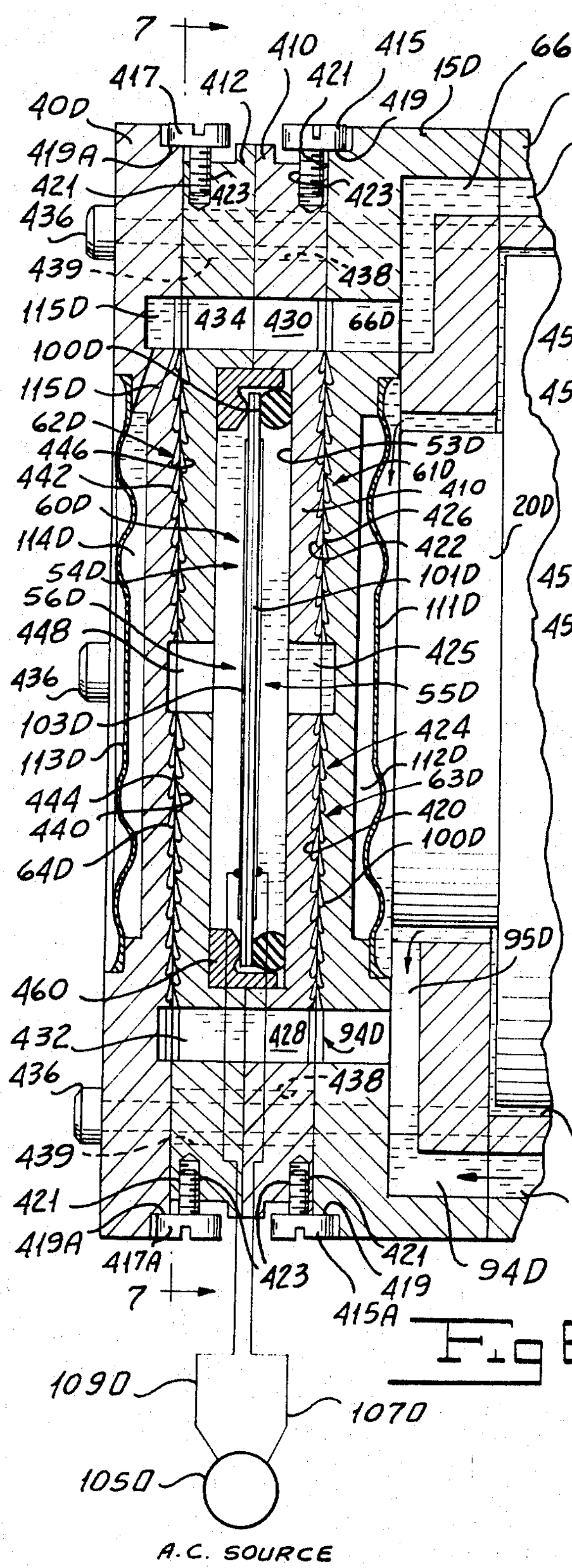
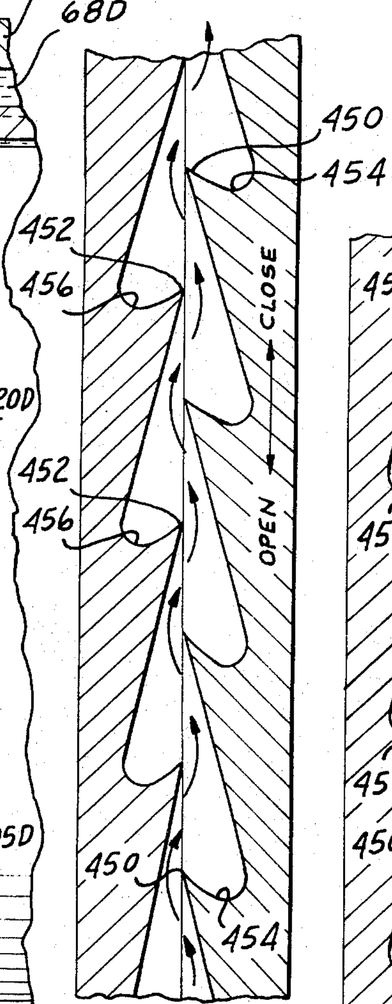


Fig 6

Fig 9



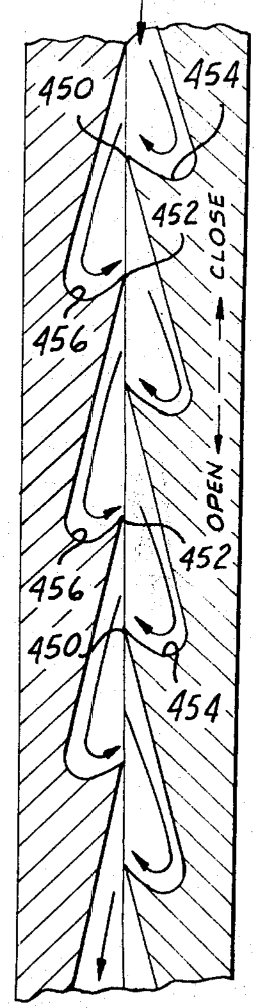


Fig 8

INVENTOR.
Oscar D. Jacobson
BY Hubert L. Davis
ATTORNEY

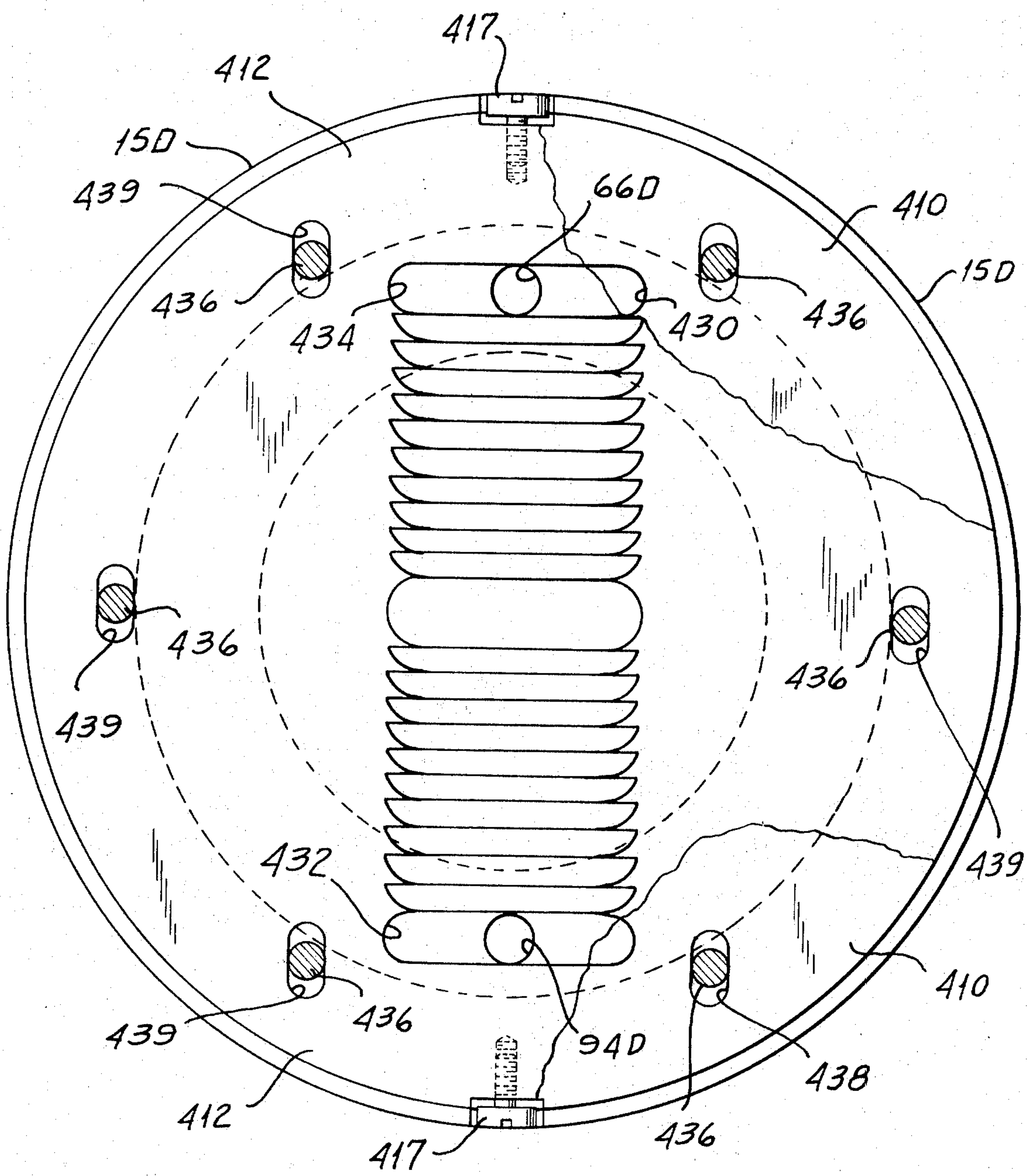


Fig 7

INVENTOR.
Oscar D. Jacobson
BY Herbert L. Davis
ATTORNEY

Patented April 25, 1972

3,657,930

5 Sheets-Sheet 5

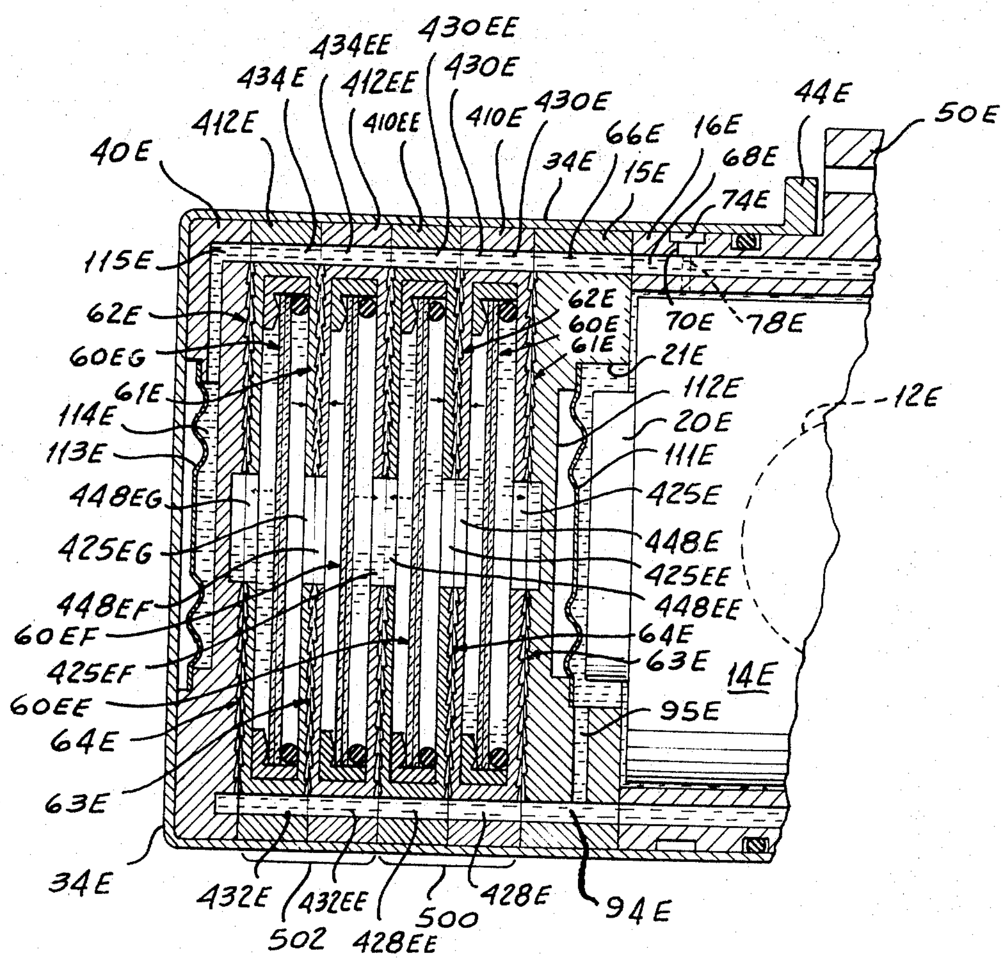


Fig 10

INVENTOR.
Oscar D. Jacobson
BY Herbert L. Davis
ATTORNEY

PIEZOELECTRIC CRYSTAL OPERATED PUMP TO SUPPLY FLUID PRESSURE TO HYDROSTATICALLY SUPPORT INNER BEARINGS OF A GYROSCOPE

CROSS-REFERENCE TO RELATED APPLICATION

The present application relates to an improved compact pump assembly for use in supplying a liquid medium under pressure to hydrostatically supported gimbal elements of a gyroscope of a type such as described in copending U.S. application Ser. No. 807,232 filed Mar. 14, 1969; copending U.S. application Ser. No. 822,524 filed May 7, 1969; and copending U.S. application Ser. No. 838,274, filed July 1, 1969, all of said applications being filed by Oscar D. Jacobson, inventor of the present invention and assigned to The Bendix Corporation, assignee of the present invention.

BACKGROUND OF THE INVENTION

1. Field of the Invention

This invention relates to a field of low power input pumps which may be utilized to supply liquid pressure medium to hydrostatically support bearings of a gyroscope, and an arrangement in which power efficiency is important in order to minimized heating problems.

2. Description of the Prior Art

Heretofore there has been disclosed in a U.S. Pat. No. 3,361,067, granted Jan. 2, 1968, to James E. Webb, administrator of the National Aeronautics and Space Administrator, a piezoelectric pump for a gyroscope fluid suspension system, but in such arrangement there has not been utilized the present improvements in the unidirectional fluid flow inlet and outlet control orifice means for the fluid pressure chamber means in which the piezoelectric element is operatively arranged; intake and outlet fluid reservoirs to prevent cavitation under high operating frequences of the piezoelectric element; slidable plates operatively arranged to vary the orifices of the fluid flow inlet and outlet control means defined by serially arranged teeth in the slidable plates; and the operative arrangement of the Multi Piezoelectric Diaphragm Pump for a gyroscope fluid suspension system, as in the present invention. However piezoelectric pumps generally have been disclosed in a U.S. Pat. No. 3,029,743 granted Apr. 17, 1962 to James F. Johns; as well as in a U.S. Pat. No. 3,107,630 granted Oct. 22, 1963 to Robert R. Johnson et al. and in a U.S. Pat. No. 3,270,672 granted Sept. 6, 1966 to Robert M. Hanes et al. Moreover in an ASME publication by G. M. Benson and Nicholas Kattchee entitled "Application of the Piezoelectric Effect for Energy Converters of the Artificial Heart Program" presented at the ASME Winter Annual Meeting in New York, N. Y. of Dec. 1–5, 1968, crystal diaphragm piezoelectric type pumps have been disclosed as applied for the somewhat different purpose of a blood pump.

Moreover a U.S. Pat. No. 3,215,078 granted Nov. 2, 1965 to Charles L. Stec has been noted of interest in showing a pump in which the vibrating crystals are in cylindrical form, while the U.S. Pat. No. 3,029,743 and a U.S. Pat. No. 3,125,033 granted March 17, 1964 to Jean Henri Albert Mary have been noted as of interest in showing inlet and outlet valves in combination with a diaphragm operated pulsation chamber and cavitation chamber for smoothing out pulsations.

Also the Johnson et al., U.S. Pat. No. 3,107,630 has been noted, as of particular interest, in the arrangement of a piezoelectric bender assembly of diaphragms incorporated in single or double housing arrangements so as to produce particular desired pumping actions, while valving arrangements in the last mentioned patent have been provided whereby oscillation of the pump diaphragm effects cyclic changes in hydraulic resistance.

Furthermore, as disclosed in a U.S. Pat. No. 3,362,231 granted Jan. 9, 1968 to Roland G. Baldwin et al., there has been provided a pump assembly in combination with a gyroscope to provide a fluid medium under pressure for hydrodynamically supporting the rotor and gimbal elements of the gyroscope.

However, in the operation of the device disclosed in the U.S. Pat. No. 3,362,231, the pump assembly effects an inward pumping action to a hydrodynamic journal bearing of a rotor member of the gyroscope through the provision of inwardly diminishing or converging grooves in the stator of the pumping assembly.

There is inherent in the arrangement disclosed in the last mentioned patent, a high viscous drag on the rotor element of the gyroscope in that the rotor element drives an element of the pump assembly. This arrangement of the patent requires a delicate balance between the speed of rotation of the rotor of the gyroscope and the pumping action required by the pumping assembly which is not separately operable in the reference patent from the rotor of the gyroscope, as in the case of the present invention.

Moreover, the aforenoted references fail to suggest either the specific structural arrangement of the present invention of a compact piezoelectric crystal diaphragm pump in a gyroscope or the basic feature of a bimorph piezoelectric crystal diaphragm actuated pump in such a gyroscopic arrangement utilizing stationary orifice valves and resilient intake and outlet anticavitation chambers for high frequency operation of the diaphragm pump to supply the required fluid pressure medium to hydrostatically support bearings of the gryoscope; nor do the cited references suggest such a compact piezoelectric crystal diaphragm pump in combination with adjustable flat plate orifice valves arranged in the inlet and outlet to the diaphragm pump so as to provide a greater resistance to fluid flow in one direction than the other and which resistance may be readily adjusted by the operator effecting a convenient adjustment of the flat plate orifices relative one to the other.

SUMMARY OF THE INVENTION

The present invention relates to a compact flexible piezoelectric crystal diaphragm pump assembly mounted in an end plate of a housing of a gyroscope so arranged as to provide a low power input pump which may be utilized to circulate fluid pressure medium to and from hydrostatically supported bearings of a gyroscope.

An object of the invention is to provide in such an end plate of a gyroscope a compact pump assembly including a bimorph (bender type) piezoelectric crystal held in a cavity of the end plate by an O ring, and in which arrangement the crystal unit includes laminate of two piezoelectric crystals with electrical connections made on inner and outer surfaces of each crystal laminate to an alternating current voltage supply applied to the crystal surfaces so as to cause a contraction in one laminate and an expansion in the other laminate along its long axis resulting in a bending action which effects a push-pull pumping action on both of its sides.

Another object of the invention is to provide such an arrangement in which the mechanical resonance of the crystal matches the electrical input frequency of the energizing alternating current voltage.

Another object of the invention is to provide in such an arrangement a resonant crystal which acts as a diaphragm piston causing a push-pull pumping action on both of its sides and in which the oscillating fluid flow to and from the piezoelectric pump is partially rectified by means of series connected stationary orifice valves providing greater resistance to fluid flow in one direction than the other.

Another object of the invention is to provide such a pumping arrangement in which cavitation at high operating frequency is overcome by pressurizing the entire system and providing resilient intake and outlet reservoirs.

Another object of the invention is to provide a piezoelectric diaphragm pump including a double acting piezoelectric diaphragm operatively connected to an alternating current voltage applied to the crystal surfaces so as to cause a contraction of one laminate of the diaphragm and an expansion of the other laminate of the crystal diaphragm along its long axis so that the crystal diaphragm acts as a diaphragm piston causing a push-pull pumping action on both of its sides.

Another object of the invention is to provide a modified form of the invention including a volumetrically expanding crystal operatively connected across a source of alternating current voltage applied to the crystal surfaces so as to cause a contraction and expansion of the crystal corresponding to the wave form of the alternating current voltage applied thereto to effect the push-pull pumping action as the volumetrically expanding crystal expands and contracts.

Another object of the invention is to provide a modified form of the invention in which a single crystal diaphragm may include two piezoelectric crystals with electrical connections made on its inner and outer surfaces to a source of alternating current voltage so as to cause a contraction of one laminate and an expansion of the other laminate of the diaphragm crystal along its long axis effecting a bimetal or bending action to provide a pumping operation.

Another object of the invention is to provide a further modified form of the invention in which a volumetrically expanding piezoelectric crystal is arranged to operate a diaphragm for effecting the pumping operation in which a crystal may be connected across a source of alternating current voltage to effect an expansion and contraction of the crystal corresponding to the wave form of the energizing alternating current voltage to in turn drive the diaphragm for effecting the pumping operation.

Another object of the invention is to provide in the several forms of the piezoelectric pump aforenoted, stationary orifice valves arranged in the inlet and outlet conduits to the diaphragm pump in which the orifice valves arranged in the inlet conduit to the diaphragm pump provide a greater resistance to fluid flow in an outlet direction than in an inlet direction, while the stationary orifice valves arranged in the outlet conduit from the diaphragm pump provide a greater resistance to fluid flow in an inlet direction that in an outlet direction. The stationary orifice valves in the inlet and outlet conduits to the diaphragm pump are so arranged as to partially rectify the oscillating fluid flow to the inlet and through the outlet of the piezoelectric pump. Cavitation at high operating frequencies is overcome by pressurizing the entire system and providing resilient inlet and outlet reservoirs between the respective inlet and outlet conduits and a hydrostatically supported bearing of the gyroscope and from and to which the diaphragm pump may effectively circulate the fluid pressure medium to hydrostatically support the bearings of the gyroscope.

Another object of the invention is to provide the orifice valves in the form of adjustable flat plate orifices in which the orifices are defined by angular orifice pockets milled into the facing surfaces of the plates, together with novel means for adjusting the orifice openings by slidably positioning one plate in relation to the other.

A further object of the invention is to provide a multi-crystal diaphragm pump, including a series of sets of piezoelectric crystal diaphragms, each set having a pair of the diaphragms operating in opposing senses and connected in parallel with orifice valving so arranged as to amplify a fluid output of the pump while the opposing operation of the pairs of diaphragms of each set serves to balance out vibration in the pump which may have a high flow fluid capacity.

These and other objects and features of the invention are pointed out in the following description in terms of the embodiments thereof which are shown in the accompanying drawings.

DESCRIPTION OF THE DRAWINGS

In which corresponding parts have been indicated by corresponding numerals.

FIG. 1 is a side view, partly in section, of a single degree of freedom gyroscope including a bimorph piezoelectric crystal diaphragm (bender type) pump embodying the present invention.

FIG. 2 is an end view of FIG. 1 taken along the lines 2—2 of FIG. 1 and looking in the direction of the arrows.

FIG. 3 is a fragmentary side sectional view of an end plate for a gyroscope of the type indicated in FIG. 1 in which there is provided a modified form of the invention, including a volumetrically expanding piezoelectric crystal pump for effecting a push-pull pumping action.

FIG. 4 is a fragmentary side sectional view of an end plate for a gyroscope of the type indicated in FIG. 1 in which there is provided a further modified form of the invention including a single bimorph piezoelectric crystal diaphragm pump to effect a push-pull pumping action.

FIG. 5 is a fragmentary side sectional view of an end plate for a gyroscope of the type shown in FIG. 1 and in which end plate there is provided another modified form of the invention including a piezoelectric crystal to operatively drive a diaphragm for effecting the required push-pull pumping action.

FIG. 6 is a fragmentary side sectional view of an end plate for a gyroscope of the type illustrated in FIG. 1 in which there is provided a further modified form of the invention including an adjustable flat plate orifice valve arrangement for use with the piezoelectric crystal diaphragm pump of the type illustrated in FIG. 1, including two sets of adjustable valve plates, each set having angular orifice pockets milled into a surface of a pair of valve plates arranged in cooperative relation one with the other in the assembled unit and in which the valve orifices may be adjusted by sliding one cooperating valve plate with relation to the other so that the orifice openings may be varied from zero to maximum.

FIG. 7 is an end sectional view taken along the lines 7—7 of FIG. 6 and looking in the direction of the arrows so as to better illustrate an operator-operative adjustment means for saw-tooth pockets milled into opposite facing valve plate surfaces each arranged to form with the saw-toothed pockets in the opposite cooperating plate adjustable valve orifice openings.

FIG. 8 is an enlarged fragmentary sectional view illustrating the operative arrangement of the adjustable flat plate orifice valves and the unidirectional fluid flow restriction provided by the resultant fluid flow turbulence effected upon a flow of the fluid in a direction indicated by the solid arrows so as to act in opposition to the direction of the saw-teeth pockets of the restrictive orifice plates.

FIG. 9 is another enlarged fragmentary sectional view illustrating the operative arrangement of the adjustable flat plate orifice valves and the permissible unidirectional fluid flow therethrough in a direction opposite from that indicated in FIG. 8 and shown by the solid arrows of FIG. 9 in that the orifice teeth provide a relatively low restriction due to the minimum turbulence effected upon a fluid flow in the direction of the restricted orifice teeth.

FIG. 10 is a fragmentary side sectional view of a further modified form of the invention and illustrating a multi-crystal diaphragm pump including a series of sets of piezoelectric crystals diaphragms operating in opposing directions and connected in parallel with orifice valving arranged to amplify a fluid output of the pump while the opposing operation of the diaphragm sets serve to balance out vibration in the pump.

DESCRIPTION OF THE INVENTION

Referring now to FIGS. 1 and 2, reference numeral **10** indicates a single degree of freedom gyroscope having a rotor element of conventional type indicated by dash line **12** and rotatably mounted about a first axis **13** in a cylindrical gimbal element **14**. A cylindrical housing **16** is provided with end plates **15** and **17** so as to define a substantially cylindrical chamber **18** in which is mounted the gimbal element **14** of the gyroscope **10**. The gimbal element **14** may be angularly positioned by the gyroscopic action of the single degree of freedom gyroscope **10** about a second axis **19—19** perpendicular to the first axis **13**.

The cylindrical gimbal element **14** is positioned within the cylindrical chamber **18** in a slightly spaced relation to side wall surfaces of the cylindrical housing **16** and the end plates **15** and 17 defining the chamber 18 so as to provide a hydrostatic bearing means for the gimbal element 14, as here in after explained.

The cylindrical gimbal element 14 further includes at opposite end portions thereof axially projecting cylindrical shaft portions 20 and 22 having surfaces positioned in spaced relation to surfaces defining recesses 21 and 23 formed in the end plates 15 and 17 of the housing 16. These surfaces are so arranged in spaced relation as to cooperate in providing a hydrostatic bearing means upon which the gimbal element 14 may be angularly positioned about the longitudinal axis indicated by the reference numeral 19—19. Thus the surfaces of the shaft portions 20 and 22 cooperate with the surfaces defining the recesses 21 and 23 spaced apart therefrom so that a liquid medium supplied to the spaces between these surfaces form hydrodynamic bearings which support the gimbal element 14 for angular movement about the axis 19—19.

Positioned on one end portion of the housing 16 is a cylindrical casing 25 providing a chamber 27 having a fluid expansion diaphragm 28 mounted in an end of the casing 25 opposite from the housing 16. Mounted in the casing 25 and in spaced relation to the diaphragm 28 is a suitable electronic pick-off device indicated generally by the numeral 30 and which may be of a type well known in the art such as a synchro or other suitable electronic signal device having a rotor element 31 operably connected to the shaft portion 22 of the gimbal 14. The electronic pick-off device 30 is electrically connected so as to provide electrical signals in a conventional manner indicative of the angular position of the gimbal 14 effected by the gyroscope 10.

The electronic pick-off device 30 and the expansion diaphragm 28 are mounted in the cylindrical casing 25 which is in turn mounted on the one end portion of the housing 16. At an opposite end portion of the housing 16 there is mounted another cylindrical casing 34 in which there is in turn mounted a compact piezoelectric crystal operated pump 36 embodying the subject matter of the present invention.

The fluid pump 36 includes the end plate 15 so arranged as to provide a pump block sandwiched between an end of the housing 16 and an end plate 40 provided between an inner end portion of the cylindrical casing 34 and the end plate 15 of the housing 16. The casings 25 and 34 have annular flanges 42 and 44, respectively, projecting radially from the inner ends thereof and secured in position, as shown by FIG. 1, by bolts 46 and 48 screw threadedly engaged in an annular flange 50 projecting radially from the housing 16 and intermediate the opposite ends of the housing 16. As shown by FIG. 2, fastening holes 52 are provided in the flange 50 whereby the gyroscope 10 may be suitably affixed to an aircraft for operation.

The end plate 15 provides a pump block in which there is formed an internal recess 53 cooperatively arranged in relation to an internal recess 54 provided in the plate 40. There is positioned in recesses 53 and 54 the piezoelectric crystal operated pump 36 alternately applying pressure to a fluid medium in chambers 55 and 56 from which lead inlet and outlet fluid pressure conduits for the piezoelectric crystal diaphragm pump 36, as hereinafter explained.

An outlet port 66 provided in the end plates 15 and 40 leads alternately through outlet orifice valves 61 and 62 from the fluid pressure applied at chambers 55 and 56 of the pump 36 to a longitudinally extending fluid pressure channel 68 provided in the housing 16. The fluid pressure channel 68 in turn opens at ports 70 into annular fluid pressure channels 74, respectively, which in turn feed through a plurality of ports 78 passing through the wall of the housing 16 and into the cylindrical chamber 18 so as to provide a fluid pressure medium about the cylindrical surface of the gimbal element 14 to provide the required pressure and flow to effect a hydrostatic bearing means between the inner surface of the housing 16 and the cylindrical surface of the gimbal element 14 positioned in spaced relation thereto so as to support the cylindrical gimbal element 14 relative to the cylindrical surface of the chamber 18 for angular movement about the axis 19—19.

The recess 21 formed in the pumping block of the end plate 15 opens through a passage 95 into a fluid pressure return passage 94 leading through inlet orifice valves 63 and 64 to the opposite chambers 55 and 56 of the pump 36 so as to provide a fluid return passage, while the recess 23 formed in the end plate 17 at the opposite end of the housing 16 provides an outlet for the fluid pressure medium from the cylindrical chamber 18 providing a hydrostatic bearing means for the shaft portion 22 of the gimbal element 14. The recess 23 in turn leads into the chamber 27 in the casing 25 carrying the electronic pick-off device 30 and the fluid expansion diaphragm 28.

There is thus provided a fluid pressure chamber 27 in the casing 25, while there is provided in the end plate 17 a fluid pressure return port 80 which opens from the chamber 27 into a longitudinally extending channel 92 formed in the housing 16. The channel 92, as shown by FIG. 1, in turn opens into the return channel 94 formed in the pumping block of the end plates 15 and 40, while the channel 94 is connected by the passage 95 to the recess 21 formed in the pumping block of the end plate 15. Surfaces of shaft portion 20 of the cylindrical gimbal element 14 are, as heretofore explained, positioned in spaced relation to surfaces of the recess 21 in the pumping block of the end plate 15. The recess 21 in turn conducts the returning fluid medium to the channel 94. The fluid pressure medium in the channel 94 is in turn applied alternately through the inlet orifice valves 63 and 64 to the chambers 55 and 56 of the pump 36 providing a fluid pressure return to the pump 36 from the hydrostatic bearing means for the shaft portion 20 of the gimbal element 14.

PIEZOELECTRIC CRYSTAL DIAPHRAGM PUMP

Referring to the form of the invention illustrated by FIGS. 1 and 2, the pump 36 includes a bimorph piezoelectric crystal diaphragm (bender type) indicated by the numeral 60 and mounted between the chambers 55 and 56 formed in the pumping block of the end plates 15 and 40. The crystal diaphragm 60 is supported between the recesses 53 and 54 of the end plates 15 and 40 by a suitable soft O-ring support 100 of a conventional type and in an arrangement in which the piezoelectric crystal diaphragm is effectively unloaded.

The crystal diaphragm 60 is a cemented laminate of two piezoelectric crystals 101 and 103 which may be formed of a material, such as quartz or thin discs of a piezoelectric material or piezoelectric ceramic material, such as discussed in the aforenoted ASME Publication entitled "Application of the Piezoelectric Effect for Energy Converters of the Artificial Heart Program" by G. M. Benson and Nicholas Kattchee.

The piezoelectric effect is attributed to the behavior of aligned, electric dipole domains within certain materials. Aligned domains exist naturally in some materials, such as quartz, or are induced by high dc fields applied to other materials, such as certain ceramics. Subsequent application of voltage to these materials deforms the domains causing the material to exhibit a voltage induced strain.

Piezoelectric ceramics are very stiff (comparable to metals) and produce small deflections and large stresses in response to high electric fields and small currents. As a result piezoelectric ceramics may be characterized as strongly dielectrically coupled, direct electromechanical converters having high electrical and mechanical impedances. These high impedances require novel electrical and electromechanical designs which markedly reduce these impedances and effectively couple the piezoelectric effect to particular mechanical load requirements.

The reduction of the electrical impedance has been achieved by employing a large number of thin disks of piezoelectric material which are assembled into a column and connected electrically in parallel by continuous electrodes. This assembly is referred to as the piezoelectric (PZ) stack.

In the arrangement of FIG. 1, an alternating voltage may be applied from a suitable source 105 through conductors 107 and 109 to inner and outer piezoelectric crystal surfaces causing a contraction in one laminate 101 or 103 and an expansion in the other laminate along its long axis effecting a bimetal or bending action of the piezoelectric crystal diaphragm 60.

The mechanical resonance of the crystal diaphragm 60 is made to match the electrical input frequency of the alternating current supplied by the source 105 so that in operation, the resonating crystal 60 acts as a diaphragm piston causing a push-pull pumping action on both of its sides applying positive pressure to a fluid medium in one of the chambers 55 and a negative pressure to a fluid medium in the output chamber 56 during one phase of energization by the alternating current source 105 and an opposite positive pressure to the fluid medium in the chamber 56 and a negative pressure to the fluid medium in the chamber 55 during the other or opposite phase of energization from the alternating current source 105.

The oscillating fluid pressures thus effected in the pumping chambers 55 and 56 by the energization of the piezoelectric diaphragm 60 in turn effects an oscillating fluid flow. The oscillating fluid flow is partially rectified by the action of the series connected stationary orifice valves 61 and 63 leading respectively from and into the pressure chamber 55 and by the action of the similarly series connected stationary orifice valves 62 and 64 leading from and into the pressure chamber 56.

The orifice valves 61 and 62 are provided so as to effect a greater resistance to fluid flow in an inlet direction than in an outlet direction relative to the pump chambers 55 and 56, while the opposite inlet orifice valves 63 and 64 are arranged to provide a greater resistance to fluid flow in an outlet direction than in an inlet direction relative to the pump chambers 55 and 56.

Cavitation at high operating frequency is overcome by pressurizing the entire system and providing a resilient diaphragm 111 extending across an anti-cavitation inlet chamber 112 adjacent the recess 21 and also through the provision of a resilient diaphragm 113 extending across an outlet chamber 114 to which the outlet pressure conduit 66 is connected through a passage 115, as shown in FIG. 1.

There is thus provided a bimorph piezoelectric crystal diaphragm (bender type) for effecting a pumping action through the provision of the stationary orifice valves 61, 62, 63 and 64 and resilient intake and outlet anti-cavitation chambers including the resilient diaphragms 111 and 113 for high frequency operation.

Moreover it has been found that such a pump is not sensitive to foreign particles in the fluid medium and is free of starting and stopping problems which have been heretofore found to be inherent in rotary type pumps. The piezoelectric diaphragm pump of the present invention also has certain advantages in providing no wear points, having a wide temperature range of operation and further having a very high gravitational capability.

VOLUMETRICALLY EXPANDING PIEZOELECTRIC CRYSTAL PUMP

Referring now to form of the invention illustrated in FIG. 3 corresponding numerals bearing the suffix A indicate corresponding parts those heretofore described with reference to the arrangement of FIG. 1. However in the form of the invention of FIG. 3, there is provided a volumetrically expanding piezoelectric crystal stack indicated by the numeral 200 in place of the crystal diaphragm 60, shown in FIG. 1.

The stack 200 may comprise a large number of thin discs of piezoelectric material which are assembled into a column, as indicated in FIG. 3, bottomed upon an inner surface of the recess 54A formed in the end plate 40A. An opposite surface of the stack 200 extends into the inner recess 53A formed in the end plate 15A. Stack 200 is so arranged that upon a suitable source 105A of alternating current or pulsating direct current being connected by electrical conductors 107A and 109A in parallel across the piezoelectric crystal stack 200, the stack 200 in response to the electrical pulses or alternating current applied thereto will expand and contract in relation to the recess 53A into which the stack 200 extends so as to apply pulsating alternatively negative or positive pressures to the fluid medium in the chamber 55A.

The volumetrically expanding piezoelectric crystal stack 200 will effect a flow of fluid medium from the chamber 55A through the outlet orifice valves 61A into the outlet fluid pressure conduits 66A in response to the positive pressure applied upon the stack expanding in relation to the recess chamber 53A, while upon an alternate contraction of the piezoelectric crystal stack 200 the resulting negative pressure applied to the fluid medium in the chamber 55A will cause a fluid medium to flow through the inlet orifice valves 63A from the conduit 94A into the chamber 55A so as to replenish the previously discharged fluid medium effected through the outlet orifice valves 61A in response to the opposite expansion of the piezoelectric crystal stack 200.

SINGLE CYCLE BIMORPHED BY PIEZOELECTRIC CRYSTAL DIAPHRAGM

Referring now to the form of the invention illustrated in FIG. 4, corresponding numerals bearing the suffix B indicate corresponding parts to those heretofore described with reference to FIG. 1.

In the form of the invention illustrated in FIG. 4 a single cycle pumping operation is effected instead of the two cycle operation of FIG. 1 and the operation thereof will be readily apparent from the description of the piezoelectric pump of FIG. 1 in which the corresponding parts of FIG. 4 have been heretofore described with reference to FIG. 1.

DIAPHRAGM PUMP OPERATED BY A PIEZOELECTRIC CRYSTAL STACK

Referring now to the form of the invention illustrated in FIG. 5, corresponding numerals bearing the suffix C indicate corresponding parts to those heretofore described with reference to FIG. 1.

In the form of the invention of FIG. 5, there is provided a piezoelectric crystal stack indicated by the numeral 300 and formed of a large number of thin discs of piezoelectric material. The stack 300 is bottomed on an inner surface of a recess 302 formed in the recess 54C provided in the end plate 40C. A free end surface of the stack 300 has mounted thereon a suitable actuating button 304 operatively contacting a surface of a resilient diaphragm 306 having outer edge surfaces 308 clamped between the plates 15C and 40C, as best shown in FIG. 5.

The piezoelectric crystal stack 300, has applied thereto by a suitable source 105C of alternating current or pulsating dc current a voltage applied through conductor lines 107C and 109C at opposite surfaces thereof so as to cause the piezoelectric crystal stack to expand in a conventional manner to effect deflection of the diaphragm 306 so to provide a push-pull pumping action on the fluid medium of the chamber 55C, so that positive and negative pressures are alternately applied to the fluid medium in chamber 55C. Thus upon the negative pressure being applied a fluid medium is drawn in through the inlet orifice valves 63C from the conduit 94C to the chamber 55C in one cycle of operation while during the positive pressure cycle the fluid medium is expelled through the outlet orifice valves 61C to the outlet passage 66C in much the same manner as heretofore described with reference to FIGS. 1, 2, 3 and 4, and in view of which a further detailed explanation of the operation of the form of the invention of FIG. 5 is not deemed necessary.

ADJUSTABLE INLET AND OUTLET ORIFICE VALVE PLATES

A further modified form of the invention is illustrated in FIG. 6 in which corresponding parts of those heretofore described with reference to FIG. 1 have been indicated by like numerals bearing the suffix D, and in view of which a further detailed explanation of the operation of such corresponding parts is not deemed necessary with reference to FIG. 6.

A novel feature of the form of the invention of FIGS. 6 and 7 resides in the arrangement between the end plates **15D** and **40D** of slidably positioned valve plates **410** and **412** which may be adjustably positioned in relation to the respective end plate **15D** and **40D** by an operator-operative adjustment of two pairs of setting screws **415** and **415A** and **417** and **417A**. Adjustment screws **415** and **415A** each have head portions bearing upon a surface **419** of a recess provided in a circumferencial surface of the plate **15D**, while a screw threaded stem portion **421** of each adjustment screw **415** and **415A** is screw threadedly engaged in a screw threaded hole **423**. Holes **423** are formed at opposite points in the adjustable valve plate **410**, as shown by FIG. 6. The head portions of each of the adjustable setting screws **415** and **415A** may be conveniently positioned in opposite senses so as to effect a radial positioning of the valve plate **410** in relation to the adjacent surface of the end plate **15D**.

Adjustment screws **417** and **417A** also each have head portions bearing upon a surface **419A** of a recess provided in a circumferencial surface of the plate **40D**, while a screw threaded stem portion **421A** of each adjustment screw **417** and **417A** is screw threadedly engaged in a screw threaded hole **423A**. Holes **423A** are formed at opposite points in the adjustable valve plate **412** as shown by FIG. 6. The head portions of each of the adjustable setting screws **417** and **417A** may be conveniently positioned in opposite senses so as to effect a radial positioning of the valve plate **412** in relation to the adjacent surface of the end plate **40D**.

The angular orifice pockets **420** and **424** cooperate to form a series of orifice openings extending between a pump chamber **425** and a fluid inlet passage **428** in plate **410**, while the angular orifice pockets **422** and **426** cooperate to provide a series of orifice openings which extend from the pump chamber **425** to a fluid outlet passage **430** formed in the plate **410**. Further, as shown in FIGS. 6 and 7, the inlet passage **428** opens at one end from the inlet passage **94D** formed in the plate **15D** while an opposite end of the passage **428** opens into a corresponding inlet passage **432** in the plate **412**. Similarly the outlet passage **430** opens at one end into the outlet passage **66D** formed in the plate **15D** while the opposite end of the outlet passage **430** opens from a corresponding outlet passage **434** formed in the plate **412**.

The end plates **40D** and **15D** are securely mounted on the end of the housing member **16D** by mounting bolts **436** which extend through the end plates **40D** and **15D** and are in turn screw threadedly engaged in the housing member **16D**, while the adjustable valve plates **410** and **412** have longitudinal slots **438** and **439** formed therein respectively for receiving the fastening bolts **436** in slidable relation, as shown by FIG. 7, so as to permit the slidable adjustment of the valve plates **410** and **412** in relation to the end plates **15D** and **40D** respectively upon adjustment of the setting screws **415–415A** and **417–417A**.

Angular orifice pockets **430** and **432** are also milled into a surface of the plate **412** extending adjacent a surface of the end plate **40D** in which angular orifice pockets **434** and **436** are milled as shown by FIG. 6.

The angular orifice pockets **430** and **434** cooperate to form a series of orifice openings extending between a pump chamber **438** and a fluid inlet passage **432** formed in the plate **412**, one of the orifice pockets **442** and **446** cooperate to provide a series of orifice openings which extend from the pump chamber **448** to a fluid outlet passage **434** formed in the plate **412**.

The angular orifice pockets milled into the several plate surfaces and indicated generally in FIG. 6 by the numerals **420**, **422**, **424**, **426**, **440**, **442**, **444** and **446** are as best shown by the enlarged sectional views of FIGS. 8 and 9 formed as staggered saw-teeth **450** in the surface of one plate and **452** in the adjacent surface of the other plate with pockets **454** and **456** respectively. The staggered saw-teeth **450** and **452** face one another in the assembled unit so that upon an adjustment of the plate **410** or **412** in relation to the other adjacent surface of the plate **15D** or **40D**, respectively, the orifice opening between the respective saw-teeth **450** and **452** may be changed from zero to maximum. Thus the angular valve orifice may be adjusted for varying operating frequencies and for different fluid viscosities.

Moreover the staggered saw-tooth orifice arrangement of the saw-teeth **450** and **452** together with the pockets **454** and **456** causes a high turbulent effect upon fluid medium attempting to flow through the valve orifices in a direction opposite to that of the staggered saw-teeth **450** and **452** and which high turbulent effects may be attributed to the fluid backing up on itself resulting in a high restriction to the fluid flow in such reverse direction as indicated by the solid arrows of FIG. 8.

However upon the fluid flow being directed through the valve orifices defined by the teeth **450** and **452** and in the same direction as that in which the teeth **450** and **452** extend it will seem that there will result a minimum turbulent effect so that the fluid medium may more readily flow through the valve orifices defined by the staggered saw-teeth **450** and **452**, as indicated by the solid arrows of FIG. 9.

However it will be readily seen that the orifice openings between the saw-teeth **450** and **452** may be readily adjusted by sliding the orifice plates **410** and **412** relative to the other orifice plates **15D** and **40D**, respectively, by appropriate operator-operative adjustment of the respective setting screws **415–415A** and **417–417A**.

As shown by FIG. 6, the piezoelectric diaphragm **60D** is mounted in an annular ring **460** positioned in the recesses **53D** and **54D** formed in the adjustable valve plates **410** and **412** respectively, while an outer edge portion of the piezoelectric diaphragm **60D** is secured in an operative position between the mounting ring **460** and a resilient O-ring support **100D** of a conventional type.

In view of the arrangement of the mounting ring **460** in the recesses **53D** and **54D** formed in the valve plates **410** and **412**, both of the valve plates **410** and **412** may be adjusted to vary the respective valve openings between the staggered saw teeth by the simultaneous adjustment of the setting screws **415–415A** and **417–417A** by the operator to effect the appropriate operative adjustment of the valve openings controlled thereby.

In this connection, it will be noted that the seat of the head of each of the adjustment screws **415** and **415A** is higher on the end plate **15D** than on the slidable valve plate **410**, while the seat of the head of each of the adjustment screws **417** and **417A** is higher on the end plate **40D** than on the slidable vale plate **412**. Upon the operator simultaneously turning the respective adjustment screws in an appropriate sense, there will be effected a slidable positioning of the valve plates **410** and **412** relative to the adjacent surfaces of the end plates **15D** and **40D**, respectively, so that the respective saw-teeth of the valve plates **410** and **412** may be slidably positioned in relation to the saw-teeth milled in the adjacent surfaces of the end plates **15D** and **40D**.

The two adjustment setting screws **415** and **415A** as well as the two adjustment setting screws **417** and **417A** are arranged in a diametrically opposite relation one to the other so as to effectively lock the respective valve plates **410** and **412** in an adjusted position. The head portions of the respective adjustable setting screws **415–415A** and **417–417A** serve as dowels to line up the orifice pockets of the respective valve plates.

MULTI-PIEZOELECTRIC DIAPHRAGM PUMP

Referring now to a further modified form of the invention illustrated in FIG. 10 in which corresponding numerals bearing the suffix E indicate corresponding parts of those heretofore described with reference to FIG. 1.

In the form of the invention of FIG. 10, the piezoelectric diaphragm of the type indicated at **60D** of FIG. 6 may be multiplied as shown in the form of the invention of FIG. 2 and indicated by respective numerals 60E, 60EE, 60EF and 60EG. These piezoelectric diaphragms are provided in sets indicated by the numerals 500 and 502 each set including a pair of piezoelectric diaphragms operating in opposing directions. Thus as shown in FIG. 10, the set 500 includes the piezoelectric diaphragms 60E and 60EE which in response to one phase of the alternating current applied by the source 105E are deflected in a sense indicated by the solid arrows in FIG. 10 while in response to an opposite phase of the energizing alternating current the piezoelectric diaphragms 60E and 60EE are deflected in an opposite sense as indicated by the dashed arrows of FIG. 10.

Similarly the set 502 includes the piezoelectric diaphragms 60EF and 60EG which also in response to the energizing alternating current are deflected in response to one phase thereof as indicated by the solid arrows of FIG. 10 and in response to an opposite phase of the energizing alternating current the diaphragms 60EF and 60EG are deflected as indicated by the dashed arrows adjacent thereto in FIG. 10.

Moreover, as heretofore explained, with reference to FIGS. 1 and 6, positive and negative pressures are applied to the fluid medium through the pumping chambers 425E–448E, 425EE–448EE, 425EF–448EF and 425EG–448EG upon the bending of the respective diaphragms.

Such resulting pressures are connected in parallel through the several outlet orifice valving 61E–62E to respective outlet conduits leading to the pressure conduit 66E and through the several inlet orifice valving 63E–64E from the respective return fluid pressure conduits leading from the return conduit 92E.

Any number of sets of the pairs of piezoelectric diaphragms may be used, as may be readily apparent from the drawing in FIG. 10, in which two sets of the pairs of diaphragms have been shown by way of example. The opposing operation of the diaphragms of the sets act to balance out any vibration in the pump while multiple sets of the pairs of piezoelectric diaphragms provide a high fluid flow capacity for the pump and permits high frequency operation thereof without adverse vibration in the pump.

While several embodiments of the invention have been illustrated and described, various changes in the form and relative arrangements of the parts, which will now appear obvious to those skilled in the art, may be made without departing from the scope of the invention.

What is claimed is:

1. In a gyroscope of a type including housing means;
fluid supply means within said housing means;
a gimbal element carrying a gyroscopic motor rotatable about a first axis;
hydrostatic bearing means operable by said fluid supply means to support said gimbal element within said housing for pivotal movement about a second axis perpendicular to the first axis;
the improvement in which said housing means includes a member mounted at one end of the housing means,
the end member includes fluid pressure chamber means therein,
the fluid supply means includes a piezoelectric element having a portion thereof fixedly mounted in the end member,
and another portion of the piezoelectric element being arranged to be movably actuated in relation to fluid medium in the chamber means,
the chamber means of the end member includes a pair of chambers in the end member at opposite sides of the piezoelectric element,
said end member including unidirectional fluid flow inlet control orifice means for permitting an input flow of a fluid medium from the hydrostatic bearing means into one of said pair of chambers in the end member while preventing a reverse output flow of fluid medium to the hydrostatic bearing means from the one chamber,
and other unidirectional fluid flow outlet control orifice means for permitting an output flow of the fluid medium from the other of said pair of chambers to the hydrostatic bearing means while preventing a reverse flow of fluid medium from the hydrostatic bearing means into the other chamber,
the inlet and outlet control orifice means including separate inlet and outlet fluid flow restrictive orifices for each of the chambers of said pair of chambers, said inlet and outlet fluid flow restrictive orifices being selectively operable by the pressure of the fluid medium in the corresponding chamber of said pair of chambers for connecting the fluid medium in said chambers alternately through the fluid inlet and outlet flow restrictive orifices to and from the pair of chambers in the said member dependent upon the sense in which the opposing forces act to movably actuate said other portion of the piezoelectric element for effectively circulating fluid medium in the hydrostatic bearing means under pressure alternately applied to the fluid medium in said pair of chambers;
energizing voltage means for periodically causing the piezoelectric element to bias said other portion thereof in a sense in opposition to an opposing biasing force acting on the piezoelectric element in another sense;
one of said biasing forces to movably actuate said other portion of the piezoelectric element in a first sense to decrease an effective volume of one of said pair of chambers in the end member so as to force fluid medium in the one chamber out through the fluid outlet flow restrictive orifices of said one chamber and to the hydrostatic bearing means from the last mentioned chamber in the end member;
said other portion of the piezoelectric element being movably actuated in said first sense so as to simultaneously increase an effective volume of the other chamber in the end member so as to draw a fluid medium through the fluid inlet flow restrictive orifices of said other chamber and from the hydrostatic bearing means into said other chamber in the end member;
the other of said biasing forces to movably actuate said other portion of the piezoelectric element in an opposite second sense so as to increase the effective volume in the one chamber and decrease the effective volume in the other chamber to simultaneously draw a fluid medium into the one chamber and force a fluid medium out of said outer chamber and through the respective fluid inlet and outlet flow restrictive orifices of said chambers,
and said other portion of the piezoelectric element being movably actuated in said first and second senses to effect an alternate simultaneous push-pull pumping action on the fluid medium in said respective chambers relative to the hydrostatic bearing means.

2. The combination defined by claim 1 in which each of the fluid inlet and outlet flow restrictive orifices includes series connected stationary restrictive orifices providing greater resistance to fluid flow in one direction than in another direction so as to partially rectify the simultaneous oscillating fluid flow to and from the respective chambers in the end member relative to the hydrostatic bearing means,
resilient intake and outlet fluid reservoirs,
and fluid conduct means opening said reservoirs into the hydrostatic bearing means and to the respective inlet and outlet fluid flow restrictive orifices of the chamber means so as to prevent cavitation under high operating frequencies of the piezoelectric element.

3. In a gyroscope of a type including housing means;
fluid supply means within said housing means;
a gimbal element carrying a gyroscopic rotor rotatable about a first axis;
hydrostatic bearing means operable by said fluid supply means to support said gimbal element within said housing for pivotal movement about a second axis perpendicular to the first axis;

a member mounted at one end of the housing means,
the end member including a fluid pressure chamber means therein,
the fluid supply means including a piezoelectric element having a portion thereof fixedly mounted in the end member,
and another portion of the piezoelectric element being arranged to be movably actuated in relation to a fluid medium in the chamber means,
said end member including unidirectional fluid flow inlet control orifice means for permitting flow of a fluid medium into the chamber means in the end member while preventing a reverse flow of fluid medium from the chamber means, and other unidirectional fluid flow outlet control orifice means for permitting flow of the fluid medium out of the chamber means while preventing a reverse flow of fluid medium into the chamber means, the inlet and outlet control orifice means effectively circulating fluid medium in the hydrostatic bearing means under pressure applied to the fluid medium in the chamber means;
energizing voltage means for periodically causing the piezoelectric element to bias said other portion thereof in a sense in opposition to an opposing biasing force acting on the piezoelectric element in another sense;
one of said biasing forces to movably actuate said other portion of the piezoelectric element in a sense to decrease an effective volume of the chamber means in the end member so as to force fluid medium in the chamber means out through the fluid outlet orifice control means from the chamber means in the end member;
and the other of said biasing forces to movably actuate said other portion of the piezoelectric element another sense so as to increase an effective volume of the chamber means in the end member so as to draw the fluid medium through the fluid inlet orifice control means into the chamber means in the end member;
the improvement comprising resilient intake and outlet fluid reservoirs,
and fluid conduit means opening said reservoirs into the hydrostatic bearing means and to the respective fluid inlet and outlet fluid flow control orifice means to the chamber means so as to prevent cavitation under high operating frequencies of the piezoelectric element.

4. In a gyroscope of a type including housing means;
fluid supply means within said housing means;
a gimbal element carrying a gyroscopic rotor rotatable about a first axis;
hydrostatic bearing means operable by said fluid supply means to support said gimbal element within said housing for pivotal movement about a second axis perpendicular to the first axis;
a member mounted at one end of the housing means,
the end member including a fluid pressure chamber means therein,
the fluid supply means including a piezoelectric element having a portion thereof fixedly mounted in the end member,
and another portion of the piezoelectric element being arranged to be movably actuated in relation to a fluid medium in the chamber means,
said end member including unidirectional fluid flow inlet control orifice means for permitting flow of a fluid medium into the chamber means in the end member while preventing a reverse flow of fluid medium from the chamber means, and other unidirectional fluid flow outlet control orifice means for permitting flow of the fluid medium out of the chamber means while preventing a reverse flow of fluid medium into the chamber means, the inlet and outlet control orifice means effectively circulating fluid medium in the hydrostatic bearing means under pressure applied to the fluid medium in the chamber means;

energizing voltage means for periodically causing the piezoelectric element to bias said other portion thereof in a sense in opposition to an opposing biasing force acting on the piezoelectric element in another sense;
one of said biasing forces to movably actuate said other portion of the piezoelectric element in a sense to decrease an effective volume of the chamber means in the end member so as to force fluid medium in the chamber means out through the fluid outlet orifice control means from the chamber means in the end member;
and the other of said biasing forces to movably actuate said other portion of the piezoelectric element in another sense so as to increase an effective volume of the chamber means in the end member so as to draw the fluid medium through the fluid inlet orifice control means into the chamber means in the end member;
the improvement in which the fluid flow inlet and outlet control orifice means includes a pair of plates slidably mounted relative one to the other,
each of the plates having two sets of serially arranged teeth provided in adjacent surfaces of the plates,
one set of the serially arranged teeth defining inlet control orifices opening into the chamber means,
and another set of the serially arranged teeth defining outlet control orifices opening from the chamber means.

5. The combination defined by claim 4 including operator-operative means to adjustably position one of the slidably mounted plates relative to the other plate so as to vary the control orifices defined by the serially arranged teeth.

6. The combination defined by claim 4 in which each of the serially arranged teeth define pockets, the pockets defined by the serially arranged teeth of the one set being so arranged as to permit fluid flow into the chamber means through the inlet control orifices defined by the one set of serially arranged teeth while the pockets defined by the one set of teeth provide a turbulent effect in a reverse flow of fluid causing a restriction of the fluid flow in such reverse direction, the pockets defined by the serially arranged teeth of the other set being so arranged as to permit fluid flow from the chamber means through the outlet orifices defined by the other set of serially arranged teeth while the pockets defined by the other set of teeth provide a turbulent effect in a reverse flow of fluid causing a restriction in the fluid flow in such reverse direction.

7. The combination defined by claim 6 including and operator-operative means to adjustably position one of the slidably mounted plates relative to the other plate so as to vary the control orifices defined by the serially arranged teeth.

8. In a gyroscope of a type including housing means;
fluid supply means within said housing means;
a gimbal element carrying a gyroscopic rotor rotatable about a first axis;
hydrostatic bearing means operable by said fluid supply means to support said gimbal element within said housing for pivotal movement about a second axis perpendicular to the first axis;
the improvement in which said housing means includes a member mounted at one end of the housing means,
the end member includes a fluid pressure chamber means therein,
the fluid supply means includes multiple sets of piezoelectric elements,
each of said sets of piezoelectric elements including a pair of piezoelectric elements,
each of the piezoelectric elements having a portion thereof fixedly mounted in the end member,
another portion of each of the piezoelectric elements being arranged to be movably actuated in relation to a fluid medium in the chamber means,
the chamber means of the end member including chambers at opposite sides of each of the piezoelectric elements,
said end member including unidirectional fluid flow inlet control orifice means for permitting flow from the hydrostatic bearing means of a fluid medium alternately into

each of said chambers in the end member at the opposite sides of the piezoelectric elements while preventing a reverse flow of fluid medium from said chambers, and other undirectional fluid flow outlet control orifice means for permitting flow into said hydrostatic bearing means of a fluid medium alternately out of each of said chambers at the opposite sides of said piezoelectric elements while preventing a reverse flow of fluid medium into said chambers,

the fluid flow inlet and outlet control orifice means being selectively operable by an applied pressure of the fluid medium in said chambers for effecting a flow of fluid medium alternatively through the fluid inlet control orifice means to said chambers from the hydrostatic bearing means and through the outlet control orifice means from the chambers to said hydrostatic bearing means depending upon the applied pressure of the fluid medium in said chambers,

energizing voltage means periodically causing each of the piezoelectric elements of each set to be actuated in opposite senses to prevent adverse vibration while acting to increase and decrease the volume of the respective chambers at the opposite sides of the piezoelectric elements,

the actuation of the multiple piezoelectric elements thereby increasing and decreasing the pressures applied to the fluid medium in said chambers in a push-pull pumping action for effectively circulating the fluid medium in the hydrostatic bearing means and through the fluid inlet and outlet control orifice means under the pressures applied to the fluid medium in said chambers by the actuation of the piezoelectric elements.

9. The combination defined by claim **8** in which

the fluid inlet and outlet orifice control means includes series connected stationary restrictive orifices providing greater resistance to fluid flow in one direction than in another direction so as to partially rectify the oscillating fluid flow to and from the chamber means in the end member.

10. The combination defined by claim **8** in which

each of the piezoelectric elements includes a piezoelectric diaphragm having a laminate of piezoelectric crystals at opposite sides thereof so arranged that upon an alternating current voltage being applied to surfaces of the crystals by the energizing voltage means there is effected an alternate expansion and contraction of said laminate causing a bending of the diaphragm to effect a push-pull pumping action on the fluid medium in the chamber means,

the fluid inlet and outlet orifice control means includes series connected stationary restrictive orifices providing greater resistance to fluid flow in one direction than in another direction so as to partially rectify the oscillating fluid flow to and from the chamber means in the end member.

11. In a pump of a type including

a housing member,

a fluid pressure chamber means in said housing member,

a piezoelectric element having a portion thereof fixedly mounted in the housing member,

another portion of the piezoelectric element being arranged to be movably actuated in relation to a fluid medium in the chamber means,

said housing member including unidirectional fluid flow inlet control orifice means for permitting flow of a fluid medium into the chamber means in the housing member while preventing a reverse flow of fluid medium from the chamber means, and other unidirectional fluid flow outlet control orifice means for permitting flow of the fluid medium out of the chamber means while preventing a reverse flow of fluid medium into the chamber means,

energizing voltage means for periodically causing the piezoelectric element to bias said other portion thereof in a sense in opposition to an opposing biasing force acting on the piezoelectric element in another sense;

one of said biasing forces to movably actuate said other portion of the piezoelectric element in a sense to decrease an effective volume of the chamber means in the housing member so as to force fluid medium in the chamber means out through the fluid outlet orifice control means from the chamber means in the housing member;

and the other of said biasing forces to movably actuate said other portion of the piezoelectric element in another sense so as to increase an effective volume of the chamber means in the housing member so as to draw the fluid medium through the fluid inlet orifice control means into the chamber means in the housing member;

the improvement comprising resilient intake and outlet fluid reservoirs,

fluid conduit means opening the resilient intake fluid reservoir into the inlet fluid flow control orifice means to the chamber means, other fluid conduit means opening the outlet fluid flow control orifice means from said chamber means to the resilient outlet fluid reservoir,

and said resilient intake and outlet fluid reservoirs being responsive to oscillating fluid pressures applied at said intake and outlet conduit means so as to prevent cavitation under high operating frequencies of the piezoelectric element.

12. In a pump of a type including

a housing member,

a fluid pressure chamber means in said housing member,

a piezoelectric element having a portion thereof fixedly mounted in the housing member,

another portion of the piezoelectric element being arranged to be movably actuated in relation to a fluid medium in the chamber means,

said housing member including unidirectional fluid flow inlet control orifice means for permitting flow of a fluid medium into the chamber means in the housing member while preventing a reverse flow of fluid medium from the chamber means, and other unidirectional fluid flow outlet control orifice means for permitting flow of the fluid medium out of the chamber means while preventing a reverse flow of fluid medium into the chamber means,

energizing voltage means for periodically causing the piezoelectric element to bias said other portion thereof in a sense in opposition to an opposing biasing force acting on the piezoelectric element in another sense;

one of said biasing forces to movably actuate said other portion of the piezoelectric element in a sense to decrease an effective volume of the chamber means in the housing member so as to force fluid medium in the chamber means out through the fluid outlet orifice control means from the chamber means in the housing member;

and the other of said biasing forces to movably actuate said other portion of the piezoelectric element in another sense so as to increase an effective volume of the chamber means in the housing member so as to draw the fluid medium through the fluid inlet orifice control means into the chamber means in the housing member;

the improvement in which

the fluid flow inlet and outlet control orifice means includes a pair of plates slidably mounted relative one to the other,

each of the plates having two sets of serially arranged teeth provided in adjacent surfaces of the plates,

one set of the serially arranged teeth defining inlet control orifices opening into the chamber means,

and another set of the serially arranged teeth defining outlet control orifices opening from the chamber means.

13. The combination defined by claim **12** including operator-operative means to adjustably position one of the slidably mounted plates relative to the other plate so as to vary the control orifices defined by the serially arranged teeth.

14. The combination defined by claim **12** in which

each of the serially arranged teeth define pockets, the pockets defined by the serially arranged teeth of the one set being so arranged as to permit fluid flow into the chamber means through the inlet control orifices defined by the one set of serially arranged teeth while the pockets defined by the one set of teeth provide a turbulent effect in a reverse flow of fluid causing a restriction of the fluid flow in such reverse direction, the pockets defined by the serially arranged teeth of the other set being so arranged as to permit fluid flow from the chamber means through the outlet orifices defined by the other set of serially arranged teeth while the pockets defined by the other set of teeth provide a turbulent effect in a reverse flow of fluid causing a restriction in the fluid flow in such reverse direction.

15. The combination defined by claim **14** including operator-operative means to adjustably position one of the slidably mounted plates relative to the other plate so as to vary the control orifices defined by the serially arranged teeth.

16. A pump comprising

a housing member

a fluid pressure chamber means within said housing member,

multiple sets of piezoelectric elements,

each of said sets of piezoelectric elements including a pair of piezoelectric elements,

each of the piezoelectric elements having a portion thereof fixedly mounted in the housing member,

another portion of each of the piezoelectric elements being arranged to be movably actuated in relation to a fluid medium in the chamber means,

the chamber means of the housing member including chambers at opposite sides of each of the piezoelectric elements,

said housing member including unidirectional fluid flow inlet control orifice means for permitting flow from a fluid supply means of a fluid medium alternately into each of said chambers in the end member at the opposite sides of the piezoelectric elements while preventing a reverse flow of fluid medium from said chambers, and other unidirectional fluid flow outlet control orifice means for permitting flow of a fluid medium alternately out of each of said chambers at the opposite sides of said piezoelectric elements while preventing a reverse flow of fluid medium into said chambers,

the fluid flow inlet and outlet control orifice means being

selectively operable by an applied pressure of the fluid medium in said chambers for effecting a flow of fluid medium alternately through the fluid inlet control orifice means to said chambers from the fluid supply means and through the outlet control orifice means from said chambers depending upon the applied pressure of the fluid medium in said chambers,

energizing voltage means periodically causing each of the piezoelectric elements of each set to be actuated in opposite senses to prevent adverse vibration while acting to increase and decrease the volume of the respective chambers at the opposite sides of the piezoelectric elements,

the actuation of the multiple piezoelectric elements thereby increasing and decreasing the pressures applied to the fluid medium in said chambers in a push-pull pumping action for effectively directing flow of fluid medium through the fluid inlet and outlet control orifice means under the pressures applied to the fluid medium in said chambers by the actuation of the piezoelectric elements.

17. The combination defined by claim **16** in which

the fluid inlet and outlet orifice control means includes series connected stationary restrictive orifices providing greater resistance to fluid flow in one direction than in another direction so as to partially rectify the oscillating fluid flow to and from the chamber means in the housing member.

18. The combination defined by claim **16** in which

each of the piezoelectric elements includes a piezoelectric diaphragm having a laminate of piezoelectric crystals at opposite sides thereof so arranged that upon an alternating current voltage being applied to surfaces of the crystals by the energizing voltage means there is effected an alternate expansion and contraction of said laminate causing a bending of the diaphragm to effect a push-pull pumping action on the fluid medium in the chamber means,

the fluid inlet and outlet orifice control means includes series connected stationary restrictive orifices providing greater resistance to fluid flow in one direction than in another direction so as to partially rectify the oscillating fluid flow to and from the chamber means in the housing member.

* * * * *