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(54) Abstract Title
Pumps using an electro-active device

(57) A pump comprising a pump chamber 42 and an electro-active device 44 arranged, on actuation, to cause pressurisation of the pump chamber 42. The electro-active device comprising an electro-active structure extending along a curved minor axis 13 and arranged on actuation for the structure to twist around the minor axis so that relative displacement of the ends 15 and 16 of the structure occurs. The electro-active structure may curve in a helix around the minor axis and the minor axis may extend in a curve which is a helix. The electro-active structure may comprise electro-active portions disposed successively along the minor axis and have a bender construction of a plurality of layers, including at least one layer of electro-active material.. The electro-active structure may include a piezoelectric material.

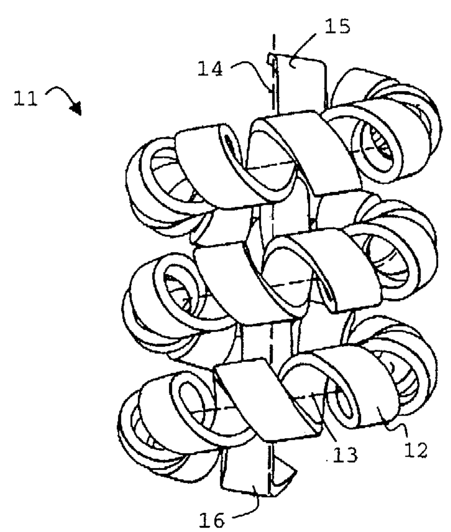

FIG. 2

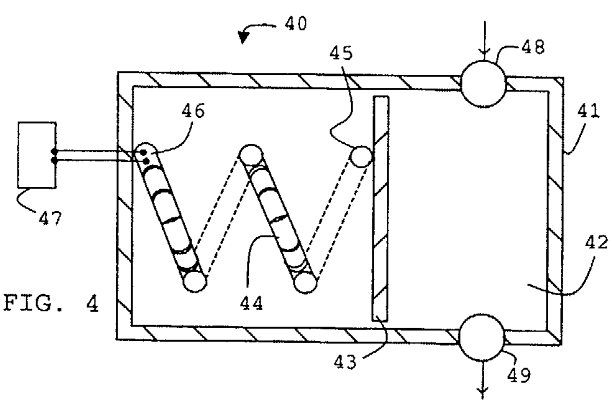

FIG. 4

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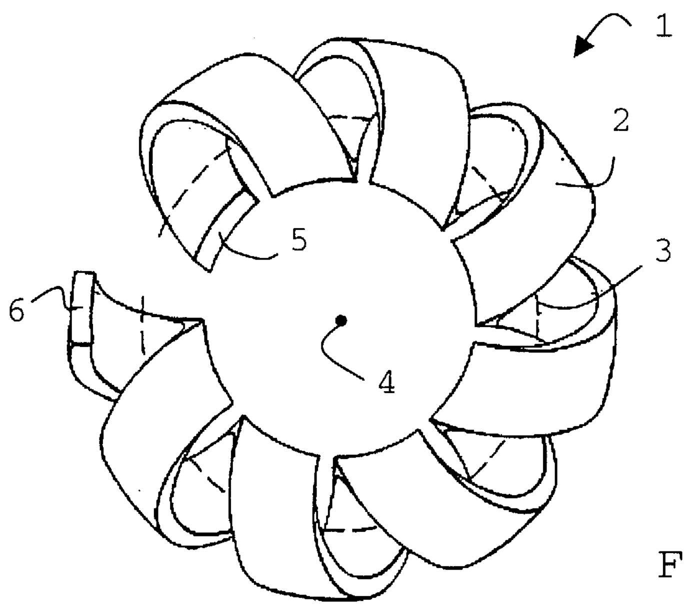


FIG. 1

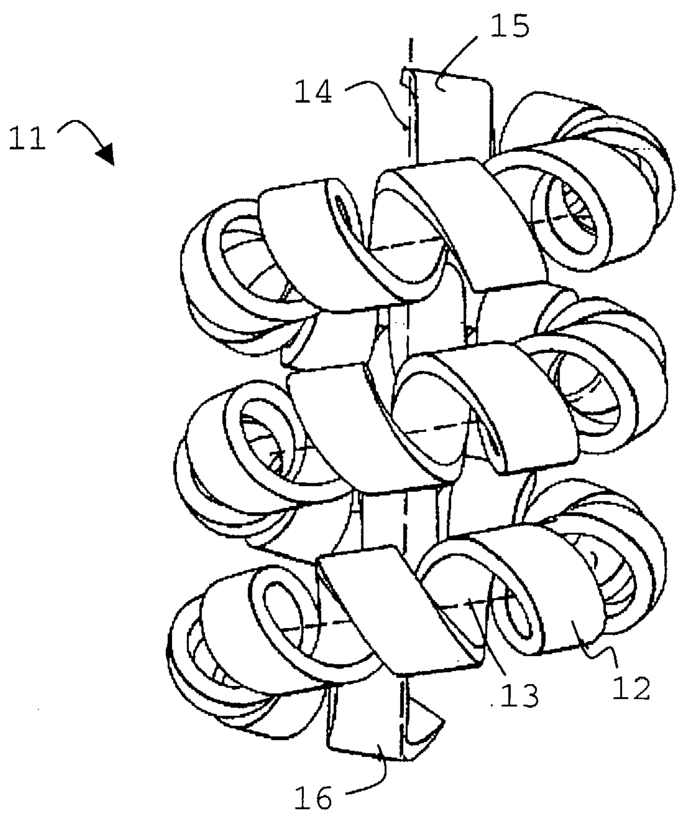


FIG. 2

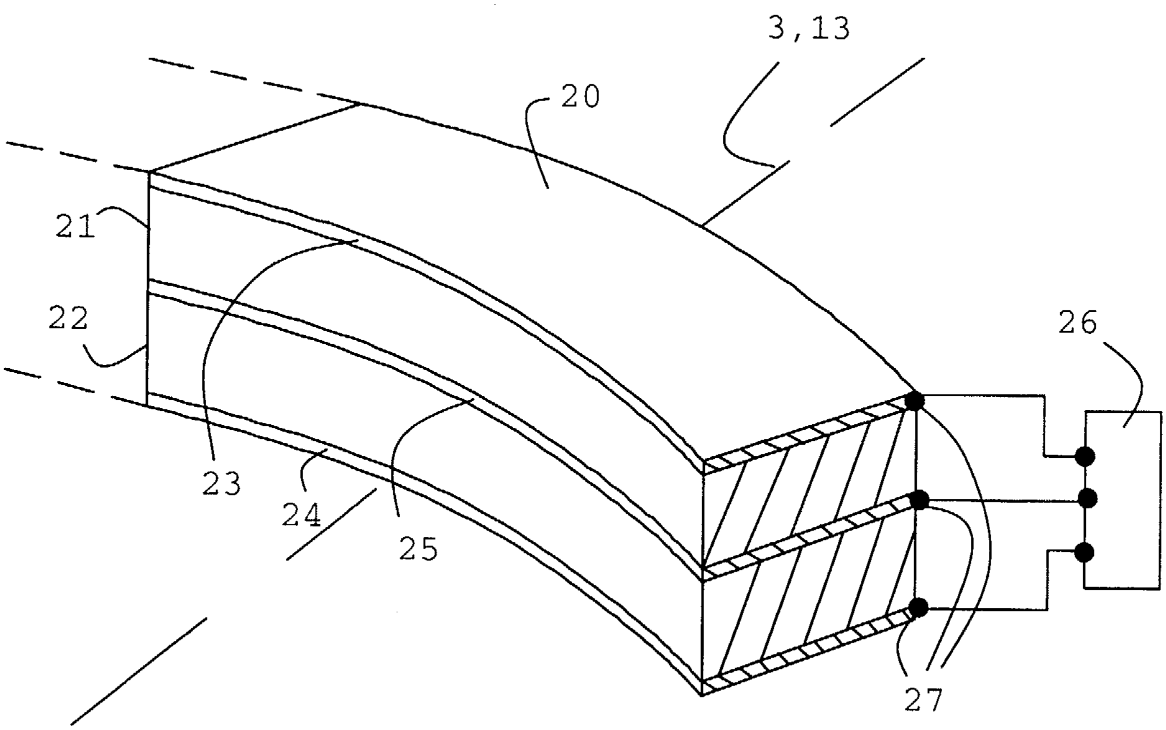


FIG. 3

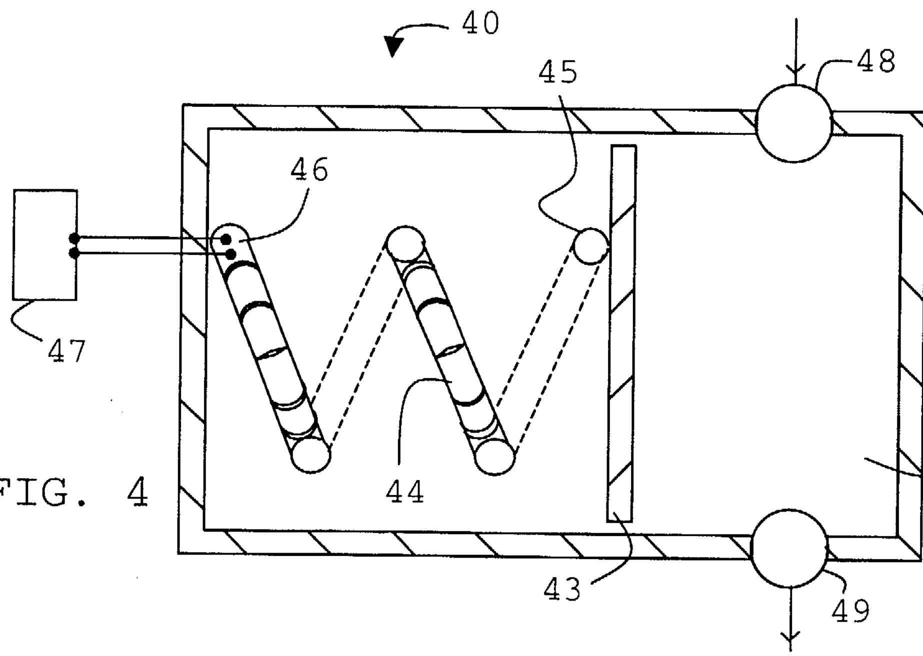


FIG. 4

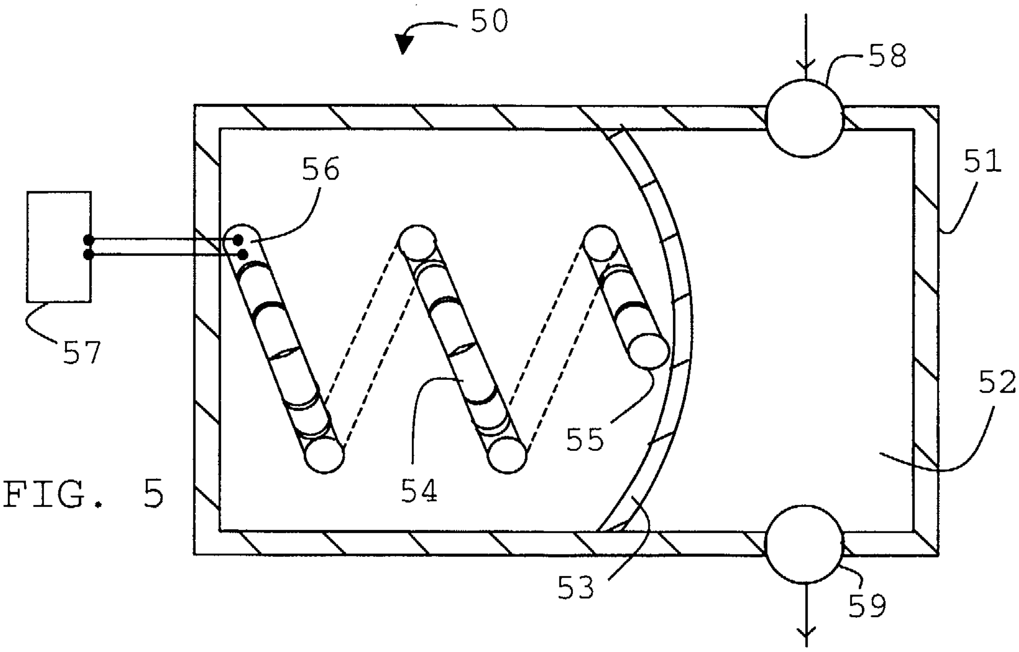


FIG. 5

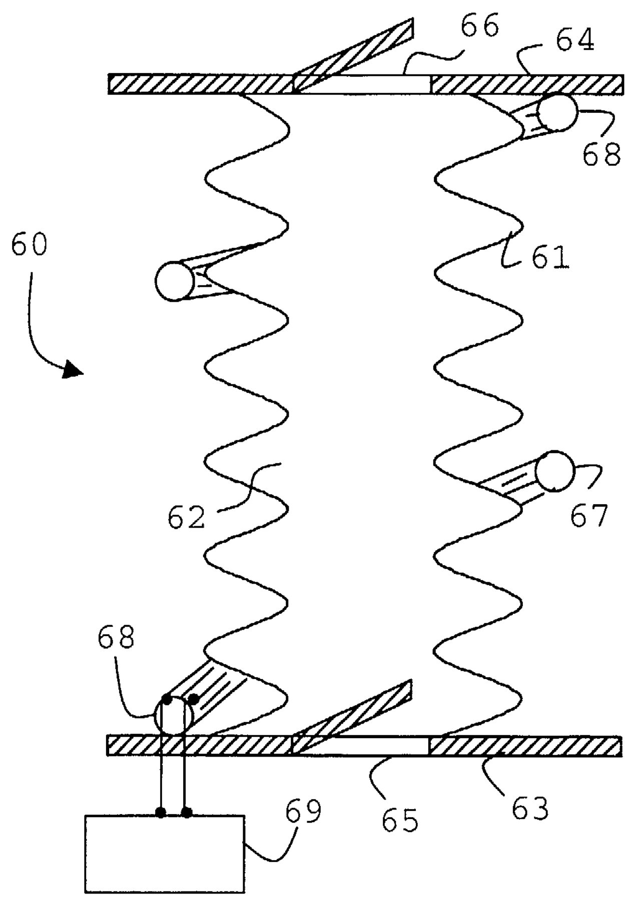


FIG. 6

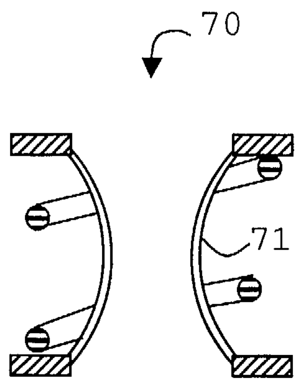


FIG. 7A

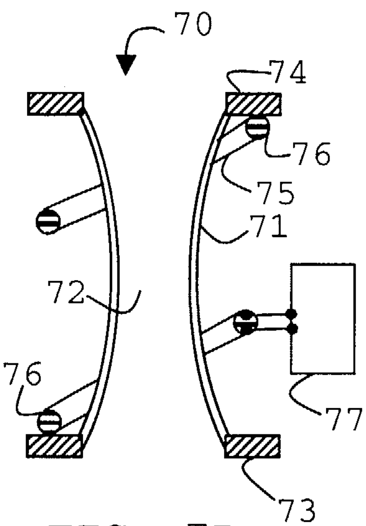


FIG. 7B

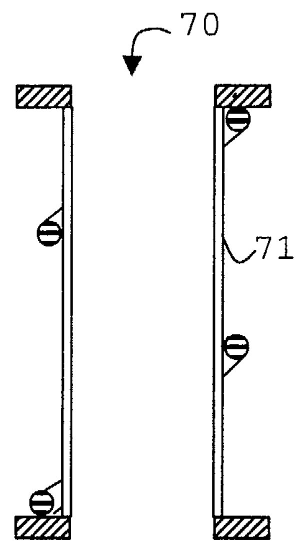


FIG. 7C

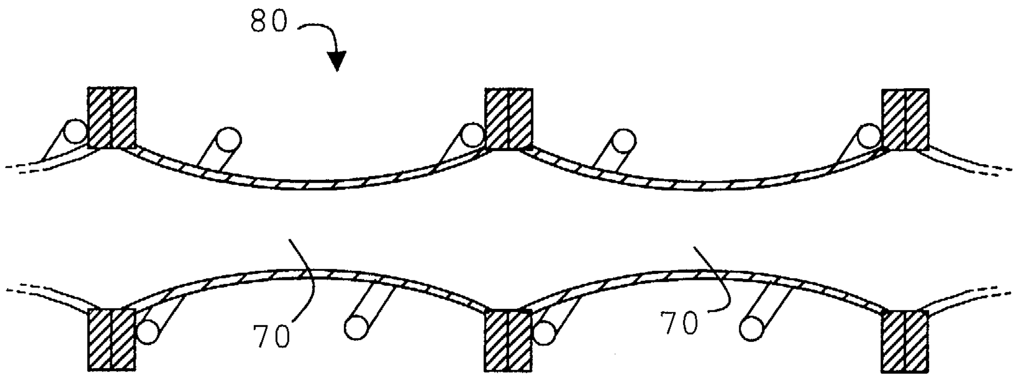
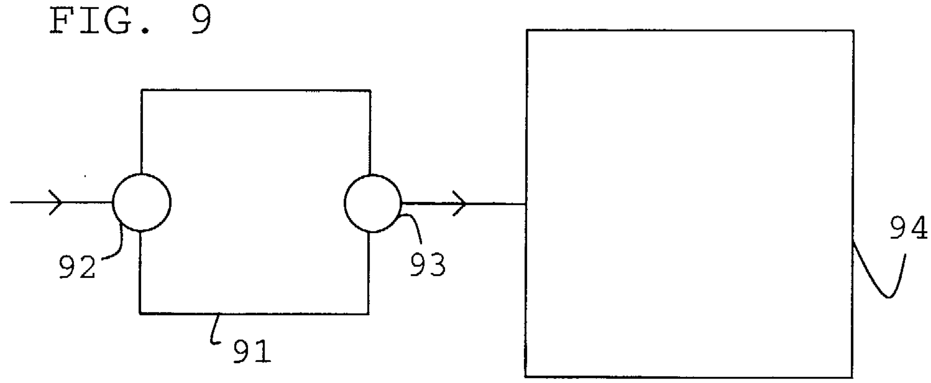


FIG. 8

FIG. 9



Pumps Using An Electro-Active Device

The present invention relates to pumps using an electro-active device to pressurise a pump chamber.

Electro-active materials are materials which deform in response to applied electrical conditions or, vice versa, have electrical properties which change in response to applied deformation. The best known and most developed type of electro-active material is piezoelectric material, but other types of electro-active material include electrostrictive material and piezoresistive material. Many devices which make use of electro-active properties are known.

Piezoelectric devices have been used in pumps for dispensing or moving small volumes of fluid. The most widespread of such known applications of piezoelectric devices in pumps is in inkjet printers, where small volumes typically of the order of picolitres or less are dispensed rapidly and accurately. However such known pumps are incapable of pumping large volumes of fluid due the inherent limitations in the piezoelectric devices used.

Typically, known pumps use the most simple type of piezoelectric device which is a block of piezoelectric material actuated in an expansion-contraction mode by applying an actuation voltage in the direction of poling. However, as the piezoelectric effect is small, of the order 10^{-10} m/V, the change in dimensions is relatively small, typically less than a micron. Hence the limited displacement of the piezoelectric device limits the volume of fluid which can be moved by the pump.

More complicated electro-active structures have been developed to achieve larger displacements but these have not found practical application in pumps.

A known electro-active structure is the bender construction, for example a bimorph bender construction. With a bender construction, the electro-active structure comprises a plurality of layers at least one of which is of electro-active material. On actuation, the layers deform with a differential change in length between the layers for example one layer expanding and another layer contracting. Due to the layers being constrained by being coupled to one another, the differential change in length causes the bender to bend perpendicular to the layers. Accordingly there is a relative displacement of the ends of the structure. However, the relative displacement does not follow a linear path in space. As the structure bends and the degree of curvature increases, the relative displacement of the ends follows a curve in space. Furthermore, to achieve relatively large displacement, it is necessary to increase the length of the structure which therefore becomes inconvenient. For example, to achieve a displacement of the order of 0.1mm with a bimorph bender construction, a structure of length around 5cm is typically needed.

According to the present invention, there is provided a pump comprising a pump chamber and an electro-active device arranged, on actuation, to cause pressurisation of the pump chamber, the electro-active device comprising an electro-active structure extending along a curved minor axis and arranged, on actuation, for the structure to twist around the minor axis and concomitantly for relative displacement of the ends of the structure to occur.

First, the operation of the electro-active device will be considered. The relative displacement between the ends of the device occurs concomitantly with the twist of the structure around the minor axis on actuation, because of the fact that the device extends along a curved minor axis. The electro-active device uses the physical principal that twisting of a curved object causes displacement perpendicular to the local curve, and vice versa displacement of the ends of a curved object causes twisting along its length. The displacement is equivalent to a change in the orientation of the minor axis of the structure relative to its original orientation.

The device uses an electro-active structure which twists on actuation. Considering any given small section of the structure along the curved minor axis it is easy to visualise how twist of that given section rotates adjacent sections and hence relatively displaces them in opposite directions perpendicular to the local curve of the given section, because the adjacent sections extend at an angle to the given section as a result of the curve of the minor axis. Therefore twisting of the given section is concomitant with a relative displacement of the adjacent sections perpendicular to the plane of the curve. The degree of relative displacement is proportional to the degree of curvature in the given section and the magnitude of the twisting. The overall displacement of the device is the combination of the displacement of each section. Thus the overall displacement on actuation is a relative displacement of the ends of the structure.

For minor axes which extend along a regular curve around a major axis, such as along an arc of a circle or a helix, on actuation each section produces displacement in the same direction parallel to the major axis. Therefore, the overall relative displacement of the end of the structure is a linear displacement parallel to the major axis. Therefore an electro-active device in accordance to the present invention can produce displacement which is linear in space.

The degree of displacement is proportional to the length of the structure along the minor axis, because each section of the structure contributes to the overall displacement. Therefore any desired degree of displacement may be achieved by suitable design of the device, in particular by selection of the length of the structure along the minor axis and of the type of structure which controls the magnitude of the twisting-field response. This means the electro-active device is capable of displacements of significantly greater magnitude than the piezoelectric devices used in known pumps for inkjet printers. Therefore the use of the electro-active device in accordance with the present invention allows the production of a pump which is capable of pumping a greater volume of fluid.

Furthermore, the displacement of the electro-active device can be accurately controlled, hence allowing accurate control of the volume of fluid pumped by the pump. Some pumps in accordance with the present invention can handle volumes in a range of plural orders of magnitude, for example from picolitres to millilitres.

The electro-active device in accordance with the present invention also provides a number of further advantages, as follows.

As a result of the structure extending along a minor axis which is curved, a relatively compact device may be produced. In general, the curve along which the minor axis extends may be of any shape.

One possibility is for the curve along which the minor axis extends to be planar, for example as the arc of a circle or a spiral. In this case, the displacement on actuation occurs perpendicular to the plane of the curve. The thickness of the device in the direction in which relative displacement occurs is merely the thickness of the electro-active structure so a relatively thin device may be produced.

Another possibility is for the curve along which the minor axis extends to be a helix. In this case, each helical turn of the structure contributes towards displacement in the direction along the geometrical major axis around which the helix is formed. Therefore a large degree of displacement may be achieved proportional to the number of helical turns, therefore producing relatively high displacement for a relatively compact device.

In accordance with the present invention, the pump employs the electro-active device to cause pressurization on the pump chamber of the pump. Typically, the pump chamber has an inlet valve and an outlet valve for generating a fluid flow as the pump chamber is pressurized and depressurised, although the present invention equally applies to pumps which do not employ such valves.

The present invention encompasses many different types of pump to which the electro-active device may be applied, for example as follows.

One type of pump in accordance with the present invention is a piston pump wherein the pump further comprises a piston arranged to pressurize the pump chamber and the electro-active device is arranged to drive the piston to pressurize the pump chamber. This may be a pump wherein the piston is reciprocally moveable to pressurize the pump chamber, or may be a diaphragm pump in which the piston is a diaphragm which is flexible to pressurize the pump chamber. Application of the electro-active device to such a piston pump has a number of advantages. Compared to any known arrangements for driving a piston, the electro-active device is relatively compact, light weight and of higher efficiency. Also, a high degree of control is possible by controlling the actuation voltage applied to the electro-active device thereby allowing control of the flow profile of the pump fluid, for example allowing a slow, continuous delivery such as may be required in a drug dispensing system.

Another type of pump in accordance with the invention is a pump in which the pump chamber is defined by a flexible tubular wall. In this case the electro-active device is arrange to change the axial length of the tubular wall to pressurize the pump chamber. The tubular wall may be corrugated to provide flexibility. Alternatively, the tubular wall may be arranged to flex radially as the actual length is changed. In this manner, the volume of the pump chamber may be reduced not only by reducing the axial length, but also by flexing of the tubular wall radially inwardly. Furthermore, this arrangement allows the pressure pulses created by the pump to be shaped easily by selection of the mechanical properties of the tubular wall to control the degree of flexing.

Such a pump in which the pump chamber is defined by a flexible tubular wall is particularly advantageous because the electro-active device may be attached to the respective ends of the tubular wall without the need for any external frame or additional structure. This simplicity, in combination with the inherent properties of the electro-active device allows the pump to be made with low weight, cost and size.

Preferably the electro-active structure extends along a minor axis which is curved around the tubular wall. This therefore provides a particularly compact arrangement, because the electro-active device does not extend far beyond the tubular wall.

A peristaltic pump arrangement may be formed from a series of such pumps. Known peristaltic pumps have been difficult to produce because of the nature of the pressure and velocity characteristics. Therefore, the ability to shape the pressure pulses from the pump provides a significant advantage in assisting the design and manufacture of the peristaltic pump arrangement.

The present invention is equally applicable to many other types of pump.

A pump in accordance with the present invention may be combined with a compression chamber of larger volume than the pump chamber communicating with the pump chamber of the pump to form a compressor. In this manner, the pump may be used to compress a volume of fluid in the compression chamber.

Preferably, the electro-active structure of the electro-active device comprises electro-active portions disposed successively along the minor axis and arranged to bend, on actuation, around the minor axis.

The electro-active structure is arranged with portions which bend on actuation around the minor axis concomitantly with twisting of the structure around the minor axis. As a result, the electro-active portion may have any construction which bends on actuation. The preferred construction is the known bender construction comprising a plurality of layers including at least one layer of electro-active material, preferably a bimorph bender construction having two layers. Such a construction is well known and understood as applied to a straight bender and particularly easy to manufacture. The same benefits are obtained when the bender construction is applied to the portions of the present invention. However, any other construction which provides bending on actuation may be used.

Preferably, the electro-active structure comprises a continuous electro-active member curving around the minor axis, said electro-active portions being adjacent finite portions of the continuous member.

This structure is particularly easy to manufacture, for example by winding a deformable continuous electro-active member into shape.

Preferably wherein the continuous electro-active member curves in a helix around the minor axis.

By using a continuous electro-active member which curves in a helix around the minor axis a number of advantages are achieved. Firstly, it is easy to provide a structure which is regular along the length of the minor axis and hence provide the same degree of twisting along the entire length of the minor axis. Secondly, the helix is easy to manufacture, for example by winding a deformable continuous member into shape or by making a helical cut in a tubular electro-active member. Thirdly, the device is compact as the helical turns of the member around the minor axis may be packed closely together.

However the electro-active structure may alternatively comprise a continuous electro-active member having a different shape which provides for bending around the minor axis concomitantly with twisting around the minor axis. For example it may comprise a continuous member having the shape of a flat member twisted around the minor axis. Furthermore, instead of comprising a continuous electro-active member, the electro-active structure may comprise a plurality of electro-active portions coupled together.

To allow better understanding, embodiments of the present invention will now be described by way of non-limitative examples with reference to the accompanying drawings in which:

Fig. 1 is a plan view of a first electro-active device;

Fig. 2 is a side view of a second electro-active device;

Fig. 3 is a perspective view of a portion of either the first device of Fig. 1 or the second device of Fig. 2;

Fig. 4 is a cross-sectional view of a piston pump with a reciprocally movable piston;

Fig. 5 is a cross-sectional view of a diaphragm pump;

Fig 6 is a cross-sectional view of a bellows pump having a corrugated tubular wall;

Figs. 7A to 7C are cross-views of a bellows pump having a tubular wall which flexes, each showing a different actuation state of the pump;

Fig. 8 is a cross-sectional view of a peristaltic pump arrangement; and

Fig. 9 is a schematic view of a compressor.

For clarity there will first be described an electro-active device which is used in pumps in accordance with the present invention, followed by a description of the pumps.

In the following description, the electro-active devices are described with reference to minor and major axes which are imaginary, but are nonetheless useful for visualising and defining the devices.

A first electro-active device 1 in accordance with the present invention is illustrated in Fig. 1. The device 1 comprises a structure consisting of a continuous electro-active member 2 curving in a helix around a minor axis 3 so that the structure extends along the minor axis 3. The minor axis 3 is curved, extending in a curve which is an arc of a circle around a geometrical major axis 4 perpendicular to the plane of the minor axis 3, i.e out of the plane of the paper in Fig. 1. As the minor curve 3 is planar, the thickness of the device parallel to the major axis 4 is merely the thickness of the helical structure of the electro-active member 2.

A second electro-active device 11 in accordance with the present invention is illustrated in Fig. 2 . The device 2 comprises a structure consisting of a continuous electro-active member 12 to curving in a helix around a minor axis 13 so that the structure extends along the minor axis 13. The minor axis 13 is curved, extending in a curve which is a helix around a geometrical major axis 14. The electro-active device 11 is illustrated in Fig. 2 with a minor axis which extends along of a helix of three turns merely for illustration, any number of turns being possible.

Fig. 3 illustrates a portion 20 of either the continuous member 2 of the first device 1 of Fig. 1 or the continuous member 12 of the second device 11 of Fig. 2. The construction of the portion 20 being the same for both the first device 1 and the second device 2 the electro-active portion 20 is a finite portion of the continuous member 2 or 12 and hence the electro-active member 2 or 12 may be considered as a plurality of adjacent portions 20 as illustrated in Fig. 3 disposed successively along the minor axis 3 or 13. Hence, the portion 20 extends along part of a helical curve around the minor axis 3 or 13 as shown in Fig. 3.

Fig. 3 illustrates the construction of the electro-active portion 20. This construction is preferably uniform along the entire length of the minor axis 3 or 13 in order to provide uniform properties on actuation. Alternatively, the device 1 or 11 may be designed with some variation along the length of the minor axis 3 or 13, either in the construction of the continuous member 2 or 20 or in the shape of the curve of the continuous member 2 or 20 around the minor axis 3 or 13.

The electro-active portion 20 has a bimorph bender construction comprising two layers 21, 22 of electro-active material extending along the length of the portion 20. The layers 21, 22 of electro-active material both face the minor axis 3 or 13. The electro-active layers 21 or 22 preferably extend, across the width of the portion 20, parallel to the minor axis 3 or 13, although there may be some distortion of the electro-active portion 20 of the continuous member 2 or 12 due to the nature of the curve around the minor axis 3 or 13. Alternatively, the layers 21 or 22 may extend, across the width of the portion 20, at an angle to the minor axis 3 or 13 so that one edge along the electro-active portion 20 is closer to the minor axis 3 or 13 than the opposite edge.

The material of the electro-active layers 21 or 22 is preferably piezoelectric material. The piezoelectric material may be any suitable material, for example a piezoelectric ceramic such as lead zirconate titanate (PZT) or a piezoelectric polymer such as polyvinylidenefluoride (PVDF). However, the material of the electro-active layers 21, 22 may be any other type of electro-active material, for example piezoresistive material, in which the electrical resistance changes as the material is deformed or strained, or electrostrictive material, which constricts on application of an electric field.

The electro-active portion 20 further comprises electrodes 23 to 25 extending parallel to the layers 21, 22 of piezoelectric material. Outer electrodes 23, 24 are provided outside the electro-active layers 21, 22 on opposite sides of the electric-active portion 20. A centre electrode 25 is provided between the electro-active layers 21 and 22. The electrodes 23 to 25 are used to apply poling voltages and to operate electro-active portion 20 in a bending mode. On electrical actuation, actuation voltages are applied to the electrodes 23 to 25. On actuation, the electro-active layers 21 and 22 undergo a differential change in length concomitant with bending of the portion 20 due to the constraint of the layers being coupled together at their interface formed by the centre electrode 25. For maximum displacement, on actuation one of the electro-active layers 21 or 22 expands and the other one of the electro-active layers 21 and 22 contracts The relative direction and magnitude of the actuation and poling voltages may be selected in the same manner as for known linear electro-active devices having a bender construction. For example, poling voltages of sufficient magnitude to pole the electro-active layers 21 and 22 may be applied in opposite directions across the electro-active layers 21 and 22 by grounding the centre electrode 25 and applying poling voltages of the same polarity to both the outer electrodes 23, 24. In this case, the electro-active portion 20 is electrically actuated by applying actuation voltages in the same direction across the electro-active layers 21 and 22 by applying voltages of opposite polarity to the two outer electrodes 23 and 24.

On actuation the electro-active portion 20 bends around the minor axis 3 or 13, either towards or away from the minor axis 3, 13 depending on the polarity of the actuation voltages. On electrical actuation the actuation voltages are applied from a circuit 26 through external terminals 27 electrically connected to the electrodes 23 to 25 in the manner known for known straight piezoelectric devices having a bender construction.

Electrical connection to the electrodes 23 to 25 may be made in the same way as is known for known straight devices having a bender construction, in principle at any point along the length of the device of which the portion 20 forms part but preferably at the end. The preferred technique is to provide the electrodes with fingers (not shown) extending at the end of the device at different lateral positions across the width of the device as known for straight devices having a bender construction.

It will be appreciated that other bender constructions could equally be applied to the portion 20, for example a unimorph bender construction comprising a layer of electro-active material and an inactive layer or a multimorph bender construction comprising a plurality of layers of electro-active material.

Whilst the bender construction illustrated in Fig. 3 is preferred for simplicity and ease of manufacture, it will be appreciated that the continuous numbers 2 or 12 could in fact have any construction which bends around the minor axis 3 or 13 on actuation. For example, the continuous member could be an electro-active element of the type described in the application being filed simultaneously with this application entitled "Electro-Active Elements and Devices" in which the elements have two pairs of electrodes extending along the length of the member for bending across the width on activation.

On actuation, the electro-active portions 20 of the continuous member 2 or 12 bend around the minor axis 3 or 13. As a result of the continuous electro-active member 2 or 12 curving around the minor axis 3 or 13, in particular in a helix, such bending is concomitant with twisting of the continuous member 2 or 12 around the minor axis 3 or 13. This may be visualised as the turns of the continuous member 2 or 12 as the bending tightening or loosening causing a twist of the structure of the member 2 or 12 along the minor axis 3 or 13. The twist of the continuous member 2 or 12 occurs along the entire length of the minor axis 3 or 13 causing a relative rotation of the ends of the structure labelled 5 and 6 in the first device 1 of Fig. 1 and 15 and 16 in the second device 11 of Fig. 2.

It will be appreciated that the continuous member 2 or 12 could curve around the minor axis 3 or 13 in curves other than a helix to produce such twisting, for example by having the shape as though formed by twisting a flat member round the minor axis. It will also be appreciated that other structures other than a continuous member could be applied to produce twisting around the minor axis. For example the electro-active structure could consist of a plurality of electro-active portion disposed successively along the minor axis and coupled together so that the bending of each individual portion twists the adjacent portion around the minor axis causing twisting of the structure as a whole.

Alternatively the electro-active structure could be a device of the type described in the application being filed simultaneously with this application entitled "Piezoelectric Devices" which comprises a plurality of electro-active torsional actuators which may comprise electro-active elements activated in shear mode.

Considering the first device 1 of Fig. 1, the twisting of the continuous member 2 around the minor axis 3 is concomitant with relative displacement of the ends of the device 5 and 6 perpendicular to the curve of the minor axis 3, that is parallel to the major axis 4. The relative displacement of the ends 5 and 6 derives from the twisting of the continuous member 2 around the minor axis 3 in combination with the curve of the minor axis 3. It is an inevitable result that twisting of a curved object causes relative displacement of the ends of that object perpendicular to the local curve of the object.

In a similar manner, on actuation of the second device of Fig. 2, the twisting of the continuous member 12 around the minor axis 13 is concomitant with displacement of the ends of the device 15 and 16 parallel to the major axis 14. Again, this relative displacement derives from the rotation of the continuous member 12 around the minor axis 13 in combination with the curve of the minor axis 13. In this case, the relative displacement caused by any given small section of the structure along the minor axis 13 causes relative displacement of the ends of that section perpendicular to the local curve of the minor axis 13. The overall displacement of the ends 15, 16 of the device 11 is the sum of the displacements of all the sections which results in an overall relative displacement parallel to the major axis 14.

The exact construction and dimensions of the member 2 or 12 and the form of the electro-active structure may be freely varied to produce the desired response. A suitable member 2 or 12 has a 0.5 mm thickness tape wound as a 4 mm diameter minor helix around the minor axis 3 or 13. When this forms the first device 1 in which the minor curve extends around about three quarters of a circle of 30 mm diameter the observed displacement is about ±6mm. Similarly if this structure was used to form the second device 11 in which the minor curve extends along a 20 turn helix of diameter 30mm, this would produce displacement of around ±120mm.

In general, the minor axis, along which the structure of devices in accordance with the present invention extend, may follow any curve and the resultant displacement of the ends of the structure will be the sum of the displacement caused by each section of the structure along the curve. However, curves which are regular such as the curve of the minor axis of the first and second devices 1 and 11 are preferred so that all sections of the device caused relative displacement in a common direction and also because design and manufacture are thereby simplified.

In accordance with the present invention, the first and second devices 1 and 11 are electrically actuated to create mechanical displacement between the ends 5 and 6 or 15 and 16, although the devices 1 and 11 are capable of being mechanically actuated in which case relative displacement of the ends 5 and 6 or 15 and 16 causes an electrical voltage to be developed across the electrodes 23 to 25.

Manufacture of the electro-active devices 1 and 11 will now be described.

The preferred method of manufacture is to initially form the electro-active structure extending along a straight minor axis and subsequently to bend the straight electro-active structure so that the minor axis along which it extends becomes curved.

To form the continuous member 2 or 12 as an electro-active structure along a straight minor axis there are two preferred techniques.

The first preferred technique is to initially form the continuous member 2 or 12 as a straight member and subsequently to deform it to curve around the straight minor axis. The bender construction of the continuous member 2 or 12 is in itself known and the continuous member 2 or 12 may be formed by applying any of the known techniques for manufacturing a device having a bender construction. For example, the continuous member 12 may be initially manufactured by co-extrusion of the layers 21 and 22 of plasticised material or by co-calendering of the layers 21 and 22. Alternatively, the continuous member 2 or 12 may be made through lamination of thin layers 21 and 22. These thinner layers may be made by any suitable route, such as high shear mixing of a ceramic powder, polymer and solvent mixer followed by co-extrusion and calendering. Alternatively, techniques such as tape casting or the process called the Solutech process known in the field of ceramics may be used.

The electrodes may be formed as an integral part of the manufacture of the continuous member 2 or 12, for example by being in co-extruded or co-calendered. Further electrodes, which may be activation layers 23 to 25 or may be terminal electrodes to allow access to the electrodes 23 to 25, may be applied by printing, by electro-less plating, through fired-on silver past or by any other appropriate technique.

The second preferred technique is to initially manufacture the continuous member as a cylinder or other tube with a multi-layered bender construction of electro-active layers 21 and 22 and electrodes 23 to 25 and subsequently to cut the member along the helical line to leave the continuous member 2 or 12 extending in a helix around the axis of the cylinder or tube which then constitutes the minor axis.

Subsequently the straight structure is bent to curve the minor axis along which the structure extends.

To deform the member and structure, there must exist in the initially formed member a sufficient degree of flexibility. Suitably deformable electro-active materials are known, typically including constituent polymers which enhance the deformability. With such materials after shaping, the constituent polymers are burnt out, typically at up to 600°C and the material is then densified through further sintering at higher temperature, typically 1000°C to 1200°C. In this case, the electro-active structure is initially formed with enlarged dimensions to allow for linear shrinkage which occurs during sintering, typically of around 12 to 25%.

The curving of the straight member and the bending of the structure may be performed around formers. The formers are subsequently removed either physically or by destruction of the former for example by melting, burning or dissolving.

Pumps in accordance with the present invention using electro-active devices of the type described above will now be described. The pumps are shown as comprising a structure of the same type as the second device 11 described above extending in a helix. However this is merely for illustration and electro-active devices with any of the types of structure described above may be used.

Fig. 4 illustrates a piston pump 40. The piston pumps 40 has outer walls 41 defining a pump chamber 42 which is tubular. The radial cross-section of the pump chamber 42 is preferably circular, but may be of any shape.

A rigid piston 43 is mounted in the pump chamber 42 and is reciprocally movable axially along the pump chamber 42 to pressurize and depressurize the pump chamber 42. The piston 43 is driven by an electro-active device 44 of the type described above. The electro-active device 44 is coupled at one end 45 to the piston 43 and at the other end 46 to the walls 41 at the opposite end of the pump 40 from the pump chamber 42. Accordingly, relative displacement of the ends 45 and 46 on actuation of the electro-active device 44 drives reciprocal movement of the piston 43. A control circuit 47 is connected to the electrodes of the electro-active device 44 to apply an actuation voltage to actuate the electro-active device 44.

The pump chamber 42 is provided with an inlet valve 48 and an outlet valve

49 so that pressurization of the pump chamber 42 by the piston 43 causes the pump 40 to pump liquid through the pump chamber 42.

Fig. 5 illustrates a diaphragm pump 50 which is a type of piston pump. The diaphragm pump 50 has outer walls 51 defining a pump chamber 52 which is tubular. The radial cross-section of the pump chamber 52 is preferably circular, but may be of any shape.

The pump chamber 52 has a piston in the form of a diaphragm 53. The diaphragm 53 is fixed at its circumference to the walls 51 of the pump 50. The diaphragm 53 is flexible. Flexing of the diaphragm 53 pressurizes and depressurizes the pump chamber 52.

The diaphragm 53 is driven by an electro-active device 54 of the type described above. The electro-active device 54 is coupled at one end 55 to the centre of the diaphragm 53 and at the other end 56 to the wall 51 at the opposite end of the pump 50 from the pump chamber 52. Accordingly, relative displacement of the ends 55 and 56 on actuation of the electro-active device 54 flexing and drive reciprocal movement of the diaphragm 53. A control circuit 57 is connected to the electrodes of the electro-active device 54 to apply an actuation voltage to actuate the electro-active device 54.

The pump chamber 52 is provided with an inlet valve 58 and an outlet valve 59 so that pressurization of the pump chamber 52 by the piston 53 causes the pump 50 to pump liquid through the pump chamber 52.

The piston pump 40 and diaphragm pump 50 may have a wide range of sizes which may be selected according to the fluid to be pumped and the desired flow rate. The required displacement of the piston 43 or diaphragm 53 may be achieved by appropriate design of the electro-active device 44 or 54, because any desired displacement can be achieved simply by increasing the length of the electro-active structure of the electro-active device 44 or 54. The application of the electro-active device to the pump drives a pump which is of relatively lower size and weight and of relatively higher efficiency as compared to the driving arrangement for many known pumps.

Also, the pumps 40 and 50 allow for accurate control of the movement of the piston 43 or diaphragm 53, thereby allowing accurate control of the volume of fluid pumped. This allows any desired flow rate to be achieved simply by control of the actuation voltages applied to the electrodes of the electro-active devices 44 and 54. For example, a slow, continuous delivering may be achieved such as is useful for drug dispensing systems.

Fig. 6 illustrates a bellows pump 60 in accordance with the present invention. The bellows pump 60 comprises a tubular wall 61 which defines a pump chamber 62. The tubular wall 61 is corrugated to provide flexibility which allows axial compression and expansion to change the axial length of the pump chamber 62.

The tubular wall 61 is connected at each axial end to respective end plates 63 and 64 which define the axial ends of the pump chamber 62 and are provided with an inlet valve 65 and an outlet valve 66, respectively.

For driving of the pump 60, an electro-active device 67 of the type described above is provided coupled at each end 68 to a respective one of the end plates 63 and 64. The electro-active device 67 has a structure which extends along a minor axis which is curved in helix around the outside of the tubular wall 61. Although other forms of the electro-active device could be used, this arrangement is desirable because it is compact because the electro-active device 67 does not extend far from the tubular walls 61.

On actuation, the relative displacement of the ends 68 of the electro-active device 67 causes a change in the axial length of the pump chamber 62 because the ends 68 of the electro-active device are coupled to the end plates 63 and 64 and hence indirectly to the ends of the tubular wall 61.

A control circuit 69 is provided to apply appropriate actuation voltages to the electrodes of the electro-active device 67. As the axial length of the pump chamber 62 changes, so the volume of the pump chamber 62 changes, pressurizing and depressurizing the pump chamber 62. This pumps fluid in through the inlet valve 65 and out through the outlet valve 66 creating a flow through the pump 60.

The bellows pumps 60 may be of any size selected to provide a desired flow rate.

As the electro-active device 67 is attached to the end plates 63 and 64, there is no need for any external frame or additional structure which would increase the size, weight and cost of manufacture. This complements the advantages of the electro-active device 67 of providing a relatively large displacement and hence a relatively large pump rate whilst having a relatively low size and weight.

Fig. 7 illustrates a bellows pump 70 in accordance with the present invention. The bellows pump 70 comprises a tubular wall 71 which defines a pump chamber 72. The pump chamber 72 may have any cross-section, preferably circular. The tubular wall 71 is arranged to flex radially as the axial length of the tubular wall 71 is changed. The natural position of the tubular wall 71 is illustrated in Fig. 7B. When the axial length of the tubular wall 71 is decreased, the tubular wall 71 flexes radially inwardly as shown in Fig. 7A. Similarly when the axial length of the pump chamber 72 increased, the tubular wall 71 flexes radially outwardly as shown in Fig. 7C. In this way the change in the volume of the pump chamber 72 is changed not only by the change in the axial length of the pump chamber 72, but also by the change in radial size of the tubular wall 71. This makes it very easy to shape the pressure pulse created by the pressure pump 70 simply by adjusting the flexing of the tubular wall 71.

The tubular wall 71 may be made in any suitable manner, for example from an isotropic polymer, or from an arrangement of flexible strips.

The tubular wall 71 is connected at each axial end to respective end plates 73 and 74 which define the axial ends of the pump chamber 72. The bellows pump 70 has no inlet or outlet valves, although these may alternatively be provided.

For driving of the pump 70, an electro-active device 77 of the type described above is provided coupled at each end 78 to a respective one of the end plates 73 and 74. The electro-active device 77 has a structure which extends along a minor axis which is curved in helix around the outside of the tubular wall 71. Although other forms of the electro-active device could be used, this arrangement is desirable because it is compact because the electro-active device 77 does not extend far from the tubular walls 71.

On actuation, the relative displacement of the ends 78 of the electro-active device 77 causes a change in the axial length of the pump chamber 72 because the end 78 of the electro-active device are coupled to the end plates 73 and 74 and hence indirectly to the ends of the tubular wall 71.

A control circuit 79 is provided to apply appropriate actuation voltages to the electrodes of the electro-active device 77. As the axial length of the pump chamber 72 changes, so the volume of the pump chamber 72 changes pressurizing and depressurizing the pump chamber 72. This pumps fluid through the pump chamber 72.

The bellows pump 70 may be of any size selected to provide a desired flow rate. As the electro-active device 77 is attached to the end plates 73 and 74, there is no need for any external frame or additional structure which would increase the size, weight and cost of manufacture. This compliments the advantages of the electro-active device 77 of providing a relatively large displacement and hence a relatively large pump rate whilst having a relatively low size and weight.

The bellows pump 70 is particularly suitable for use in the cardio-vascular system to assist, or potentially even replace, the heart. In this application, the low weight and size of the bellows pump 70 are of particular advantage. The bellows pumps 70 could be provided with inlet and outlet valves or alternatively could be positioned in an artery downstream of the heart so that the heart valve effectively forms the input valve to bellows pump 70. Actuation of the bellows pump 70 may be synchronized with the contractions of the heart using the same techniques as used in known pacemakers, for example by the control circuit 79 including a sensor electrode that detects the atrial impulse. Alternatively, the bellows pump 70 may be controlled based on blood flow by providing the control circuit 69 with a detector which may be ultrasonic or optical. In the case of an optical detector, a flow sensor and a flow receiver may be positioned outside the tubular wall 71 by forming the tubular wall 71 from a transparent material.

Several bellows pumps 70 of the type shown in Fig. 7 may be arranged in series to form a peristaltic pump arrangement 80 as shown in Fig. 8. Fig. 8 illustrates just two of the bellows pumps 70 in the peristaltic pump arrangement 80 for illustration, but any number may in fact be provided. In operation, the individual bellows pumps 70 are operated with a predetermined phase relationship to generate a pressure pulse which transmits along the series of bellows pumps 70, to pressurize adjacent bellows pumps 70 one after the other in the same manner as is known for peristaltic pump arrangements using different types of pump. For example, the activation voltages applied to each bellows pump 70 in the pump arrangement 80 may be sinusoids of the same frequency but with a predetermined phase difference, typically of a quarter cycle, between adjacent bellows pumps 70. Alternatively, the drive frequency signal may be amplitude modulated and then applied to each bellows pump 70 with a different phase.

A major advantage of the peristaltic pump arrangement 80 is that it avoids the need for input and output valves because the sequential operation of each bellows pump 70 in series drives a pressure pulse along the pump arrangement 70.

As an alternative to each bellows pump 70 in the peristaltic pump arrangement 80 having a separate electro-active device, a single electro-active device arranged along the entire length of the pump arrangement 80 may be used. In this case, the electrodes of the single electro-active device are split along its length between each bellows pump 70 to provide independently actuatable portions of the electro-active device to drive each bellows pump 70.

Whilst a number of specific pumps have been exemplified above, it will be appreciated that the electro-active device may be applied to any type of pump. For example, the electro-active device may be applied to other forms of piston pump and bellows pump, and also to other types such as rotary pumps.

A pump in accordance with the present invention may be used to form a compressor. Fig. 9 illustrates such a compressor 90 comprising a pump 91 and having an inlet valve 92 and an outlet valve 93. The pump 91 may be any pump in accordance with the present invention including the examples described above. The compressor 90 further includes a compression chamber 94 of larger volume than the pump chamber of the pump 91 communicating with the outlet of the pump 91 through the outlet valve 93. Accordingly when the pump 91 is operated it pressurizes the volume of fluid in the compression chamber 94. The compression chamber 94 is closed to prevent fluid flow or, for use in a pressurized fluid flow system, allows a limited output fluid flow lower than the pumping capacity of the pump 91.

CLAIMS

1. A pump comprising a pump chamber and an electro-active device arranged, on actuation, to cause pressurisation of the pump chamber, the electro-active device comprising an electro-active structure extending along a curved minor axis and arranged, on actuation, for the structure to twist around the minor axis and concomitantly for relative displacement of the ends of the structure to occur.

2. A pump as claimed in claim 1, wherein the electro-active structure comprises electro-active portions disposed successively along the minor axis and arranged to bend, on actuation, around the minor axis.

3. A pump as claimed in claim 2, wherein the electro-active structure comprises a continuous electro-active member curving around the minor axis, said electro-active portions being adjacent finite portions of the continuous member.

4. A pump as claimed in claim 3, wherein the continuous electro-active member curves in a helix around the minor axis.

5. A pump as claimed in any one of claims 2 to 4, wherein the successive electro-active portions have a bender construction of a plurality of layers including at least one layer of electro-active material.

6. A pump as claimed in claim 5, wherein the electro-active portions have a bimorph bender construction of two layers of electro-active material or a multimorph bender construction of more than two layers of electro-active material.

7. A pump as claimed in any one of the preceding claims, wherein the electro-active structure includes electrodes for application of an electric field to actuate the electro-active structure.

8. A pump as claimed in any one of the preceding claims, wherein the minor axis extends in curve which is a helix.

9. A pump as claimed in any one of the preceding claims, wherein the minor axis extends in curve which is planar.

10. A pump as claimed in any one of the preceding claims, wherein the electro-active structure includes piezoelectric material.

11. A pump as claimed in claim 10, wherein the piezoelectric material is a piezoelectric ceramic or a piezoelectric polymer.

12. A pump as claimed in claim 11, wherein the piezoelectric material is lead zirconate titanate (PZT) or polyvinylidenefluoride (PVDF).

13. A pump as claimed in any one of the preceding claims, wherein the pump chamber has an inlet valve and an outlet valve.

14. A pump as claimed in any one of the preceding claims, wherein the pump further comprises a piston arranged to pressurise the pump chamber and the electro-active device is arranged to drive the piston to pressurise the pump chamber.

15. A pump as claimed in claim 14, wherein the piston is reciprocally movable and the electro-active device is arranged to drive movement of the piston to pressurise the pump chamber.

16. A pump as claimed in claim 14, wherein the piston is a flexible diaphragm and the electro-active device is arranged to drive flexing of the diaphragm to pressurise the pump chamber.

17. A pump as claimed in any one of claims 1 to 13, wherein the pump chamber is defined by a flexible tubular wall, and the electro-active device is arranged to drive change in the axial length of the pump chamber to pressurise the pump chamber.

18. A pump as claimed in any one of claims 16 to 19, wherein the electro-active structure extends along a minor axis which is curved around the tubular wall.

19. A pump as claimed in claim 17 or 18, wherein the tubular wall is corrugated to provide flexibility.

20. A pump as claimed in claim 17 or 18, wherein the tubular wall is arranged to flex radially as the axial length of the tubular wall is changed.

21. A peristaltic pump arrangement comprising a series of pumps each being a pump as claimed in claim 20.

22. A compressor comprising a pump as claimed in any one of claims 1 to 20 and a compression chamber of larger volume than the pump chamber communicating with the outlet of the pump.

23. A pump constructed and arranged to operate substantially as hereinbefore described with reference to the accompanying drawings.

24. A peristaltic pump arrangement constructed and arranged to operate substantially as hereinbefore described with reference to the accompanying drawings.

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Claims searched:	1 - 22	**Date of search:**	8 October 2001

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Databases searched:

UK Patent Office collections, including GB, EP, WO & US patent specifications, in:

UK Cl (Ed.S): F1W (WCK)

Int Cl (Ed.7): F04B (17/00, 43/04, 43/09)

Other: Online: WPI; EPODOC; JAPIO

Documents considered to be relevant:

Category	Identity of document and relevant passage		Relevant to claims
A	US 6071088	(Face Int Corp) Whole document	
A	US 6060811	(NASA) Whole document	
A	WO 9965088	(Oceaneering Int Inc) Whole document	

X	Document indicating lack of novelty or inventive step	A	Document indicating technological background and/or state of the art.
Y	Document indicating lack of inventive step if combined with one or more other documents of same category.	P	Document published on or after the declared priority date but before the filing date of this invention.
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