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# (54) A free piston type fluid pump

(57) A free piston type fluid pump comprising a first piston and a second piston interconnected with a torsion body and elastic bending elements, said first piston and said second piston being driven by a first motor and a second motor by applying force in opposite circumferential directions, so that in use the first piston and second piston displace along a displacement direction, wherein the said motors drive the first piston and the second piston in said opposite circumferential directions transversal to the displacement direction, wherein at least one of the first motor and second motor includes an adjustable stator.

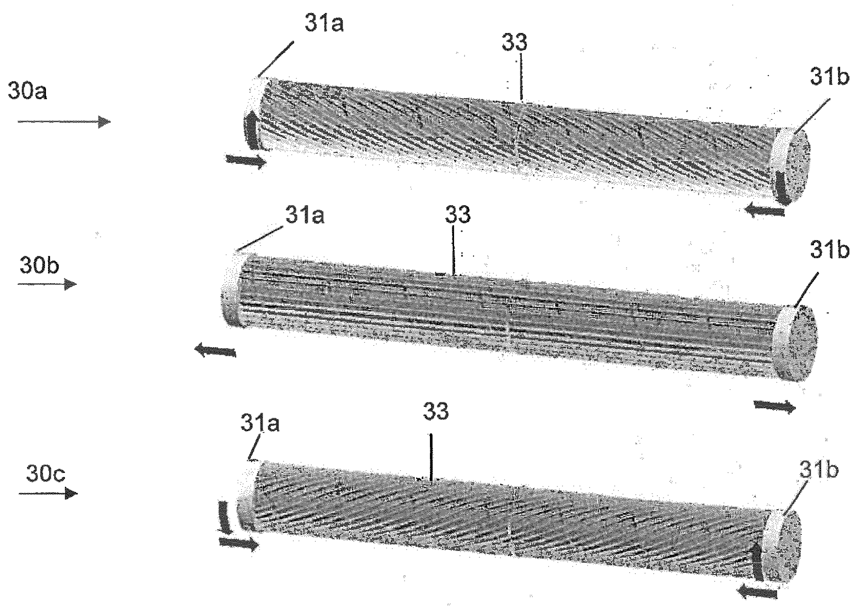



Fig. 3

EP 2 921 704 A1

## Description

[0001] The invention relates to a free piston type fluid pump, e.g. a compressor pump.

[0002] An embodiment of a free piston type compressor is known from US 5, 275, 542. In the known compressor the piston and a driving linear electromotor are connected by a shaft.

[0003] The known free piston type compressor has the following disadvantages: piston movement is not controlled mechanically; speed of the electromotor is limited to the speed of the compression piston. Accordingly, a relative large and thus expensive motor is required to deliver a sufficient force to the piston; motor and compression piston move simultaneously in the same direction which may induce considerable vibration.

[0004] An improved free piston type compressor is described in international patent application WO2012/161575, which discloses a free piston type torsion drive pump/compressor. The pump comprises a first piston and a second piston interconnected with a torsion body and flexible bending elements, said first piston and said second piston being driven by a first motor and a second motor by applying force in opposite circumferential directions, so that in use the first piston and second piston displace along a displacement direction wherein the said motors drive the first piston and the second piston in the circumferential direction transversal to the displacement direction. It is found that when the free piston is driven by a torsion body the resulting construction is substantially vibration-free due to the fact that the pump comprises two opposite moving pistons which are adapted to move with substantially the same speed. More in particular, it is found that when the pistons are connected with flexible elements a large rotational displacement of the pistons is translated into small axial displacement, representing the transmission between the motor and the piston.

[0005] According to WO2012/161575, the capacity of such compressor can be easily adjusted by adjusting the vibration amplitude, by changing driving power of the torsion vibration. The energy delivered by the motor is used to control the amplitude of the torsional vibration. Increasing the amplitude gives an increased displacement capacity.

[0006] The present invention aims to provide an improved (semifree) fluid pump. Particularly, the present invention aims to provide a fluid pump wherein a starting and/or operation of the pump can be carried out in a more economical way.

[0007] To this aim, the invention is defined by the features of claim 1.

[0008] A free piston type fluid pump comprising a first piston and a second piston interconnected with a torsion body and elastic bending elements, said first piston and said second piston being driven by a first motor and a second motor by applying force in opposite circumferential directions, so that in use the first piston and second piston displace along a displacement direction, wherein the said motors drive the first piston and the second piston in said opposite circumferential directions transversal to the displacement direction, characterized in that at least one of the first motor and second motor includes an adjustable stator.

[0009] It has been found that the free piston type fluid pump can be operated relatively economically by application of an adjustable stator.. Each capacity set point, ranging from 0 to 100%, may have its own optimal position of the stator(s). It has also been found that the adjustable stator can improve the starting-up from a stand still position.

[0010] For example, the stator can be adjusted to a first stator position during a starting up of the pump (when the free piston is starting up from a stationary state to a low amplitude vibrational state), wherein the stator position can be changed after starting up to change (e.g. increase) the amplitude of the vibrating piston. For example, the starting up (to reach a first piston amplitude) can be achieved using relatively little power consumption. The same holds for driving the pump when the stator has been adjusted to a second state for increasing the amplitude of the free piston.

[0011] For example, adjusting of the stator can include adjusting a position of the stator with respect to its rotor, for controlling stator-rotor force. When the pump is in an idle (i.e. stationary, initial) state (a stand still position), when the motor is not yet energized, the stator can be adjusted to a starting-up position. In that condition, when the motor is energized, the stator and rotor can cooperate using relatively little energy for bringing the rotor into motion (particularly leading to a first rotor amplitude). Once the rotor is in motion, the stator can e.g. be gradually adjusted to another position (being different from said stating-up position) for gradually increasing the rotor amplitude (the motor still e.g using relatively little energy).

[0012] For example, preferably, an operating position of the adjustable stator of a said motor is adjustable between at least a first and a second operating position, relative to a neutral position of a rotor of the respective motor. Particularly, the neutral position of the rotor can be the rotative position/state of the rotor when the pump is in an idle (non-energized) state. Usually, the neutral position of the rotor coincides with a the top dead centre state of a respective piston.

[0013] For example, the adjustable stator of a said motor can be adjustable enabling setting a location of a respective stator pole (or respective magnetic field orientation) with respect to a pole (or respective magnetic field orientation) of a respective rotor of that motor.

[0014] Also, the adjustable stator of a said motor is preferably configured to provide a magnetic pole, wherein a distance between that magnetic stator pole and a pole of a rotor of the respective motor is adjustable.

[0015] At least one of the motors may includes two stators, at least one of the two stators being an adjustable stator. In that case, according to a further embodiment, each of the two stators may include a core that surrounds a rotor space, the two rotor spaces being axially aligned.

**[0016]** According to a preferred embodiment, the pump is configured to operate at an eigenfrequency of 50 Hz or 60 Hz.

**[0017]** In a further embodiment, the adjustable stator of a said motor includes at least one electromagnet, the magnet providing a north and south pole during operation for magnetic interaction with the rotor of the motor.

**[0018]** In a further embodiment, the adjustable stator is rotatably adjustable, particularly with an axis of rotation that is substantially in parallel with a said piston displacement direction.

**[0019]** Adjusting the stator can enable a maximal electromagnetic connection from the stator relative to the rotor of the electromotor for each workpoint.

**[0020]** In a further embodiment, the pump including a drive or drive means, configured to adjust the adjustable stator.

**[0021]** In a further embodiment, the first motor and the second motor are adapted to rotate with a substantially the same frequency having the opposite phases.

**[0022]** Also, an aspect of the invention provides a method for controlling a free piston type fluid pump, the pump comprising: a first piston and a second piston interconnected with a torsion body and elastic bending elements, said first piston and said second piston being driven by a first motor and a second motor by applying force in opposite circumferential directions, so that in use the first piston and second piston displace along a displacement direction wherein the said motors drive the first piston and the second piston in the circumferential direction transversal to the displacement direction, wherein the motors include stators and rotors,

**[0023]** the method being characterized by adjusting a position of at least one of the stators from a first stator operating position to a second stator operating position.

**[0024]** For example, the adjustment can take place once the motor has been energized to adjust a piston stroke. In case two independent motors are included, preferably, stators of both motors are adjusted at the same time and by the same amount during operation, for maintaining balanced operation.

**[0025]** In an aspect the method include the use of a pump according to the invention.

**[0026]** According to a further embodiment, for example, at least one of the stators is adjusted to change a torsion amplitude of a respective rotor.

**[0027]** It is found that when the free piston is driven by a torsion body the resulting construction is substantially vibration-free due to the fact that the pump according to the invention comprises two opposite moving pistons which are adapted to move with substantially the same speed. More in particular, it is found that when the pistons are connected with elastic elements a rotational displacement of the pistons is translated into axial displacement accurately.

**[0028]** In an exemplary embodiments of a free piston type compressor/pump it may comprise the first piston and the second piston, positioned in opposite sides and both connected to a torsion body and elastic bending elements. Accordingly, the torsion body may comprise a central torsion rod encircled by a set of elastic bending elements for controlling the axial displacement.

**[0029]** During operation the pistons are driven by the motor(s) which causes them to rotate with alternating direction with a frequency, which is equal to the natural frequency of the mechanical assembly of the pistons and the torsion body. The motor(s) drive the motion by applying driving force in circumference direction. This means the motor(s) takes care for continuous natural torsion vibration. The elastic elements, also connected to the piston convert this alternating rotational displacement in an alternating axial displacement of the piston, which may also be referred to as 'a piston stroke'. Accordingly, movement of the piston has a rotating component (the driving direction) and an axial component (the stroke). The speed of rotation is higher than the axial speed. Pistons move in axially opposite directions during operation. During operation the torsion body and the elastic bending elements undergo an elastic deformation. In Future embodiments the torsion bar and the elastic bending elements may be integrated.

**[0030]** There are various possibilities to drive the system (each embodiment particularly including a motor having at least one adjustable stator). First embodiment is the use of two motors. Each piston is directly driven by its own motor and the piston is an integrated part of the electromotor, called the rotor. In a second embodiment of the drive system is the use of single central positioned motor. The motor is positioned in between the pistons.

**[0031]** In a first embodiment the first motor and the second motor may be adapted to rotate with the same frequency having the opposite phases. This results in an opposite axial movement of the pistons. This technical measure is based on the insight that when the first motor and the second motor are adapted to rotate with the same frequency having the opposite phases for both translation and rotation, the overall vibration of the pump is very small.

**[0032]** In a second embodiment, the motor is positioned centrally between the pistons, whereby each motor side is provided with its own torsion bar and elastic bending elements connected to the piston. The first piston and the second piston are adapted to rotate with the same frequency having synchronous phases. Both pistons move in opposite phase to the central motor. This results in an opposite axial movement of the pistons.

**[0033]** In addition, it is found that the stroke of the pump/compressor is mechanically controlled, which is advantageous. More in particular, it is found that the speed of rotation of the pump is much higher that the speed of translation. Accordingly, a relatively small motor(s) may be used. This may substantially reduce the manufacturing costs of the pump according to the invention.

**[0034]** More in particular, the torsion based pump may have the following additional advantages:

- highly economical, low power, operation at various piston amplitudes;;
- the motor power may be completely independent from the pumping control;
- Stroke of the piston increases, while the top dead centre remains unchanged;
- the rotor of the electromotor may be integrated in the piston.

**[0035]** Accordingly, the motors of the pump according to the invention may be adapted to deliver a substantially limited force or energy for compensating for the energy loss of the pumping process. Accordingly, the efficiency of the pump of the invention is increased.

**[0036]** An embodiment of the a pump with an integrated motor will be discussed in more detail with reference to Figure 2, Figure 3 and Figure 4. In this embodiment the pump comprises two opposite interconnected pistons, where each piston is also part of the electromotor, the rotor. A first connection element is a torsion body provided in the centre to control the torsion stiffness. An exemplar embodiment is given in Figure 2. A second connection element may comprise a set of flexible rods, required to control the axial movement of the pistons. An exemplary embodiment is discussed with reference to Figure 3. Flexible rods may be provided to transform the rotation to a controlled translation in accordance with the invention. Figure 4 shows the torsion drive system positioned in a cylinder liner with the static parts of the motors (windings). Figures 5-9 show further pump embodiments, particularly regarding adjusting a stator and powering the system..

**[0037]** These and other aspects of the invention will be discussed with reference to drawings wherein like reference signs correspond to like elements. It will be appreciated that the drawings are presented for illustrative purposes only and may not be used for limiting the scope of the appended claims.

## BRIEF DESCRIPTION OF THE DRAWINGS

**[0038]**

Figure 1 presents in a schematic way an embodiment of a known pump, having a central positioned motor.

Figure 2 presents in a schematic way an embodiment of the pump with integrated motors, showing the torsion body.

Figure 3 presents in a schematic way an embodiment of the pump with integrated motors, showing the movement of the piston controlled by a set of flexible rods.

Figure 4 presents schematically a complete design of the torsion drive pump according to a further aspect;

Figure 5A schematically a side view of a further embodiment, at a first position of the magnetic poles of the stators;

Figure 5B a similar view as Fig. 5A, at a second position of the magnetic poles of the stators;

Figure 6 schematically a partly opened side view of a further embodiment of part of a fluid pump;

Figure 7 schematically a top view of part of the embodiment shown in Fig. 6; and

Figure 8 a partly opened side view as in Fig. 6, at a second position of the stators; and

Figure 9 power versus time for driving the electromagnets according to an embodiment.

## DETAILED DESCRIPTION OF THE DRAWINGS

**[0039]** Figure 1 presents in a schematic way an embodiment of a known free piston type fluid pump, in this example a compressor 10, with a central positioned motor. The compressor 10 comprises a first free piston 2a and a second free piston 2b interconnected by a torsion body 3a and 3b, and elastic bending element 4a and 4b to the central electromotor 5. The driving force is applied transversely to the direction of the expected displacement D of the first free piston and the second free piston.

**[0040]** It is known to adjust the capacity of such compressor by adjusting the vibration amplitude, by changing driving power of the torsion vibration.

**[0041]** Figures 5-9, described here-below, described an improved way of driving the pump, that is, by using one or more adjustable stators.

**[0042]** Referring to Figure 1, the movement of the pistons 2a, 2b in the direction D is enabled by opposite driving directions of the motor In a particular embodiment, the motor 5 rotates with a substantially the same frequency having the opposite phases of the pistons. The motors thus couple the driving force to the pistons via the torsion body 3a, 3b. The torsion rods are implemented from a material which undergoes elastic deformation when driven by the motor. The opposite phase of the motor with the piston enables a well-balanced design.

**[0043]** For the compressor efficiency it is very important to have an accurate and fixed top dead centre position, to minimize the dead volume losses. Dead volume reduces the volumetric efficiency, especially at high compression ratios.

**[0044]** Due to absence of transmission between the electromotor and the piston, the relative large compression forces of the piston are directly transmitted to the electromotor, so it has a large negative impact on the size of electromotor. Given the required electromotor power, the size can be reduced by increasing its speed.

**[0045]** In the embodiment illustrated with reference to Figure 1, a free piston type torsion drive compressor (or pump) is provided, wherein the dead volume is mechanically controlled and wherein the engine speed of the electromotor exceeds the piston speed.

**[0046]** The principle of the torsion drive is based on the reduction of the length of a straight flexible elements in X-direction, when it is loaded. When two pistons are connected by a straight flexible element, the pistons create a sliding guide which allows substantially no rotation. Loading causes bending of the flexible (elastic) element. Loading gives vertical displacement $\Delta y$ and an axial displacement $\Delta x$, which is a second order effect. This has a number of advantageous properties (a high transmission ratio $\Delta y/\Delta x$ may be enabled; the pistons mode symmetrically, therefore they are balanced; there is an accurate mechanical top dead position).

**[0047]** The torsion drive technology uses the elastic properties of dynamically loaded components. At maximum capacity the material stress is found to be well below the fatigue limit. This means that the elastic elements and the torsion bar have substantially unlimited lifetime. The technology can be combined with common valve plates. It is also mentioned that the lifetime of the compressor is not limited by the frequency of the start/stop cycles.

**[0048]** More details on operation of the free piston type torsion drive compressor (or pump) are given in Figures 2 - 4.

**[0049]** Figure 2, 3 and 4 present in a schematic way an embodiment of the free piston type fluid pump having integrated electro motors. The pistons are part of the electromotor, the rotors. The pistons are connected by a torsion bar in the center, see 23, which may be encircled by a set of elastic rods 33 required to control the displacement of both pistons 21, 22 in Figure 2 or 31a, 31b in Figure 3, respectively.

**[0050]** In a particular embodiment of Figure 2 depicting the pump/compressor 20, the first free piston 21 and the second free piston 22 are interconnected by a torsion body 23, which may be implemented as an elastic torsion spring. It will be appreciated that other per se known embodiments of an elastic spring may be used. For the clarity reasons the complete motors driving the torsion body are not depicted.

**[0051]** When the alternating driving force is applied to the torsion body 23 the free pistons 21, 22 will rotate to and fro and translate back and forth along the translation direction D which is substantially parallel to the longitudinal axis L of the compressor 20.

**[0052]** Figure 3 shows the sets of elastic rods controlling the movement of the pistons. In view 30a a shortening of the compressor is illustrated upon the elastic bending of the rods 33 driven by the torsion force by the electromotor on the pistons. The free pistons will rotate and translate in the opposite directions as is depicted by the respective arrows.

**[0053]** In view 30b the compressor returns to its original (rest) state when no driving force is applied. The pistons are now in their top dead centre position, approaching the valve plates 24A and 24B.

**[0054]** In view 30c a second shortened condition of the compressor is shown when the free pistons 31a, 31b are driven by the torsion force of the electro motors in opposite direction with respect to the direction shown in view 30a.

**[0055]** The weight of the piston, or more particularly, the torsion inertia of the pistons, and the stiffness of the torsion bar are selected so that the natural torsion vibrating frequency equals about 50 Hz, or alternatively about 60 Hz (particularly the frequency of an electrical power supply, supplying AC power to the two electro motors during operation). This substantially improves operating parameters of the pump.

**[0056]** By suitably alternating the driving directions for the free pistons 31a, 31b a pulse-like translational movement of the compressor may be obtained.

**[0057]** Figure 4 presents schematically a complete design of a torsion drive compressor 40. The torsion bar 47 is cooperating with the elastic elements 45. Preferably, the compressor has a fully symmetrical design in both the static and the dynamic modes. In the present embodiment, the compressor comprises two integrated oscillating electromotors, wherein the piston is arranged as a rotor with integrated permanent magnets 48. The stator windings are schematically given by 41. The motors may be canned motors. The stator windings are physically separated from the refrigerant/liquid by a cylinder liner. This has an advantage that in the case of application as compressor, it is suitable for operating with different refrigerants, including ammonia. The cylinder liner 43 encloses all moving components, except the valve plates 49.

**[0058]** The cylinder liner is part of the hermetically sealed outer shell of the compressor.

**[0059]** The compressors shown in Figures 1-4 have various advantages. The compressor may operate with a refrigeration capacity of 0.5 to 5 kW. This corresponds to a compressor with an effective length of 500 mm and a piston diameter of 65mm. The compressor can be hermetic, oil free, compatible with all refrigerants and has a step less capacity from 0 to 100%. This combination is very useful for application with natural refrigerants and enables new combinations of technologies, gas compression and sorption cycles. The torsion drive compressor is able to increase the efficiency of the compressor itself and of an overall system using the compressor. The low internal friction, the step less capacity control, the absence of a frequency controller and other part load losses gives a significantly improved energetic efficiency of the compressor. The efficiency of the system will be increased by the used of a natural refrigerant like ammonia and the absence of oil.

**[0060]** According to the present invention, advantageously, the free piston type fluid pump is characterized in that at least one of the first motor and second motor includes an adjustable stator. A non-limiting example of his principle is schematically illustrated in Figures 5A, 5B, 6, 7, 8. Figure 5-8 schematically show a further embodiment of part of the example shown in Figure 4, that is, of one of the electro motor sections.

**[0061]** In the example, an operating position of each adjustable stator 51, 52 of a said motor is adjustable between at least a first and a second operating position, relative to a neutral position of a rotor (i.e. piston) 31 of the respective motor. A said neutral position is shown is each of Figures 5A, 5B, 6, 7, 8. Figures 5A and 6 show first stator positions, and Figures 5B and 8 show second stator positions.

**[0062]** Preferably, each adjustable stator 51, 52 of a said motor is adjustable enabling setting a location of a respective stator pole 51A, 51B, 52A, 52B with respect to a pole of a respective rotor of that motor.

**[0063]** For example, as follows from the drawings, the adjustable stator of a said motor can be configured to provide a magnetic pole 51A, 51B, 52A, 52B, wherein a distance between that magnetic stator pole 51A, 51B, 52A, 52B and a pole ($N_R$, $Z_R$) of the rotor 31 -with the rotor 31 is in the neutral position ($\theta=0^0$)- is adjustable.

**[0064]** Preferably, at least one of the two motors (and preferably each of the motors) includes at least two stators, at least one of the two stators (and preferably each of the stators) being an adjustable stator. For example, each of the stators 51, 52 (of a said motor) can include an electromagnet core 55, 56 that at last partly surrounds or abuts a respective rotor space for receiving part of the rotor, the two rotor spaces being axially aligned (see Figures 6-8). In such a case, the rotor may include one or more fixed magnets in each of these rotor spaces, to magnetically cooperate with respective stators 51, 52.

**[0065]** In particular, an adjustable stator 51, 52 of a said motor includes at least one electromagnet, the magnet providing (in this case alternating) north and south poles during operation for magnetic interaction with the (in this case fixed) poles of the rotor of the motor. The electromagnet can include one or more electrically driven coils 53, 54, surrounding a respective magnet core 55, 56 (see Figures 6-8) to induce magnetic fields in the cores. Each of the cores 55, 56 can be made of magnetic material, i.e. a material having a high magnetic permeability, for example electrical steel or called lamination steel, silicon electrical steel, silicon steel, relay steel or transformer steel, as will be appreciated by the skilled person.

**[0066]** In the present example, there is provided a first stator 51having a first electromagnet that includes a first coil 53 and a first core 55, configured to provide a first magnet pole 51A for interaction with a first rotor pole $N_R$, and an opposite second magnet pole 51B for interaction with a second rotor pole Nz.

**[0067]** Also, there is provided a second stator 52 having a first electromagnet including a second coil 54 and an opposite second core 56, configured to provide a first magnet pole 52A for interaction with the first rotor pole $N_R$, and a second magnet pole 52B for interaction with the second rotor pole Nz.

**[0068]** In the example, the first and second electromagnet are powered such that the first magnet poles 51A, 52A of the stators 51, 52 are magnetically opposite poles, and the second poles 51B, 52B of the stators 51, 52 are magnetically opposite poles.

**[0069]** Thus, it follows that a said electro motor sections can include a respective rotor (e.g. integrated with a respective piston 31) having one or more permanent magnets 48, one being shown; letter "$N_R$" indicates a magnet first pole and letter "$Z_R$" indicates a magnet second pole in the drawing. The poles of the permanent magnet 48 will not change during operation (the first pole e.g. being the magnet north pole and the second pole being the magnet south pole, respectively).

**[0070]** The rotor 31 is part of a said motor, the rotor vibrating in opposite directions about an axis of rotation R (the axis coinciding with the afore-mentioned longitudinal axis L of the compressor), wherein the vibration leads to the afore-mentioned piston displacement along the displacement direction. In Figure 5A, the rotor is in an initial position, just before vibration has started.; a respective angle $\theta$ of rotation/vibration of the rotor is zero in that rotor state.

**[0071]** As follows from the above, in this example, there are provided two electro motor stators: a first stator 51 and a second stator 52, each of the stators 51, 52 including an electromagnet (e.g. one or more coils 53, 54) providing a respective first pole (51A, 52A) and a generally opposite second pole (51B, 52B). Alternatively, only one stator (with a respective first and second magnetic pole) can be employed, or e.g. more than two stators.

**[0072]** Each of the coils of the electro motors are preferably powered by AC power so that each first pole periodically changes from north to south and vice-versa, and each respective second pole periodically changes from south to north and vice-versa, as will be clear to the skilled person. As is mentioned before, preferably, the pump is configured to operate at an eigenfrequency of 50 Hz or 60 Hz, in which case the motor rotors can be powered with 50 Hz or 60 Hz currents respectively. Electric wiring for powering the coils is indicated at reference signs 58, in Figures 6, 8.

**[0073]** In this example, the first pole ($N_R$) of the rotor magnet 48 is positioned between/near a first pole 51A of the first stator 51 and a first pole 52A of the second stator 52, to be magnetically driven by the two stators 51, 52. Also, in this example, the second pole ($Z_R$) of the rotor magnet 48 is positioned between/near a second pole 51B of the first stator 48A and a second pole 52B of the second stator 52 , to be magnetically driven by the stators 51, 52. Thus, when the electromagnets of the two stators 51, 52 are powered by AC current, the poles $N_R$ ,$Z_R$ of the rotor magnet 48 will experience periodically changing magnetic fields, leading to rotor vibration.

**[0074]** Each adjustable stator can be adjustable in various ways. In a preferred embodiment, the stator 51, 52 is rotatably adjustable, particularly with an axis of rotation that is substantially in parallel with a said piston displacement direction. In the example, both stators 51, 52 are rotatably adjustable (turnable) about an axis of rotation coinciding with the rotor axis of rotation R. For example the angle of rotation can be limited for each of the stators 51, 52. In an embodiment, rotation of each of the stators can be limited to an angle between 1 and 180 degrees, for example 1 and 90 degrees. In an other embodiment, an adjustable stator can be adjusted over an angle of 180 degrees or more (for example in case the pump is configures such that the rotor can vibrate at a said Eigenfrequency at relatively large angular displacements). Figures 5A and 6 show the two stators in an initial state, at a first angle of rotation, and Figures 5B and 8 show the two stators after being rotated to a second state, at second angles of rotation (with respect to the axis R).

**[0075]** The adjustable (e.g. angularly adjustable/rotatable) stators 51, 52 may e.g. be adjustably guided, held by or coupled to a pump housing, support or frame 80 (partly indicated, schematically withdashed lines, in Figures 6, 8) as will be clear to the skilled person.

**[0076]** Also, there pump includes a drive or drive means 61, 62, configured to adjust the adjustable stator. A said drive or drive means 61, 62 can include a servo, a linear actuator, a motor, or another type of drive means. A single drive or drive means can be provided for setting the position of one or more adjustable stators of each motor of the pump.

**[0077]** As an example, referring to Figure 6, there can be provided two drives 61, 62, one for each stator 51, 52, connected or coupled to the stators 51, 52 via respective driven elements 63, 64, for example driven arms, gears, chains or belts, pivotable linkages or thelike, for setting a desired stator position (e.g. adjusting that position to a first, second or other stator position). The drives 61, 62 are particularly configured to set/adjust the positions of the stators with respect to a said pump housing, support or frame 80.

**[0078]** Preferably, the drive or drives 61, 62 are configured, or at least controllable, for simultaneous adjustment of the positions of all the adjustable stators of the pump, but this is not required. Also, preferably, the amount of stator position adjustments (e.g. change of angular position, angular displacements) are the same for all adjustable stators 51, 52 of the pump, but again, that is not essential.

**[0079]** In Fig. 5A, the stators 51, 52 are positioned such that their alternating poles are located at a relatively short (first) distance from the poles (N, Z) of the rotor magnet 48 when the rotor is in an initial idle state. Thus, the pump can be started using relatively low magnetic fields, i.e. little electric power. To start the pump, suitable AC currents are fed to the coils 53, 54 of the stators 51, 52, providing magnetic interaction via the poles of the stators and the rotor and, as a result, eigenfrequency vibration of the rotor 31 at a first, relatively small angle of rotation.

**[0080]** Once the rotor has started vibrating from its idle condition, the stators 51, 52 can be adjusted by respective drive means 61, 62 to respective second positions, an example being shown in Figures 5B and 8. In the second positions, the poles 51A, 51B, 52A, 52B of the stators have been angularly displaced from respective initial positions (shown in Figures 5A, 6), away from the neutral positions of the poles $N_R$, $Z_R$ of the rotor magnet. The change of the stator pole positions will lead to increase of the oscillating movement of the respective rotor 31, particularly without having to increase electric power to drive the respective stator coils. It should be observed that if desired, electric power to the coils can be controlled or adjusted during operation for example in case the pump experiences high pumping loads.

**[0081]** The same operation can be carried out on both rotors of the pump, that is, on each rotor of the two opposite pump motors. Thus, during operation, there can be provided a method for controlling the free piston type fluid pump, the pump comprising: a first piston and a second piston 31 interconnected with a torsion body and elastic bending elements, said first piston and said second piston being driven by a first motor and a second motor by applying force in opposite circumferential directions, so that in use the first piston and second piston displace along a displacement direction wherein the said motors drive the first piston and the second piston in the circumferential direction transversal to the displacement direction, wherein the motors include stators and rotors, the method being characterized by adjusting a position of at least one of the stators 51, 52 from a first stator operating position to a second stator operating position. The adjusting of the stators changes a torsion amplitude of a respective rotor 31.

**[0082]** Figure 9 schematically indicates a graph, of current P versus time t, for driving a coil of a said motor. In this case, particularly, the amplitude of the current P follows a sinus-wave pattern, wherein drive power (being indicated by the dark shaded regions) is simply adjusted using phase control. Such a control can be achieved using e.g. thyristor control as will be appreciated by the skilled person. Particularly, by cutting a phase the drive power can be adjusted to the required level. In Figure 9, t1 indicates a first control phase wherein a relatively large section of a full sinus wave of available alternating operating power is fed to a said electromagnet coil, and t2 a second control phase that will provide less power to the electromagnet coil.

**[0083]** Thus, for a torsion drive pump or compressor, there is provided a relatively simple an flexible electric motor to generate the torsion vibration. The electric motor is be able to start the torsion vibration movement from standstill an can to increase the amplitude up to a maximum required value.

**[0084]** As follows from the above, each of the adjustable motors of the pump can be designed to drive a respective rotor 31 in its natural torsion vibration mode. The rotor itself is connected to one or more elastic elements. These elements have a certain torsion stiffness which enable the rotor to vibrate in a natural torsion vibration mode with frequency $f_n$. In the most direct application of the torsion drive motor, the natural frequency $f_n$ equals the frequency of the electrical network (50 or

60Hz).

**[0085]** In an embodiment, each motor includes two separate stator coils and a rotor with integrated permanent magnet(s). Each coil may have its own magnet. Each stator coil can be connected to AC power source and acts as dynamic field generator. The frequency of the field equals the natural frequency of the rotor

**[0086]** Both coils of each motor can be positioned symmetrical to the neutral stand still position of the rotor and can be operated in a opposite phase. This creates a dynamic field where one coil creates an attracting force to the rotor and the other is repulsive force.

**[0087]** Preferably, the position of the coils is variable to optimize the effective motor power with increasing torsion amplitude /capacity. This can be controlled by a motor position actuator 61, 62 . The possibility to adjust the position of the stator coils, results in high effectiveness over the whole amplitude range of the torsion vibration. A thyristor power control can provide an effective and robust way to control the power delivery over the whole capacity range (0 to 100%).

**[0088]** While specific embodiments have been described above, it will be appreciated that the invention may be practiced otherwise than as described. Moreover, specific items discussed with reference to any of the isolated drawings may freely be inter-changed supplementing each outer in any particular way. The descriptions above are intended to be illustrative, not limiting. Thus, it will be apparent to one skilled in the art that modifications may be made to the invention as described in the foregoing without departing from the scope of the claims set out below.

**[0089]** For example, in an alternative embodiment, a said rotor can be provided with alternating magnet poles (i.e. one or more electromagnets), wherein the adjustable stator can include a fixed magnet, for magnetic interaction wit the poles of the rotor.

**[0090]** Also, at least one stator of a or each motor can be adjusted in circumferential position, axial position, or both circumferential and axial position, to maximize the efficiency for the actual work point.

## Claims

**1.** A free piston type fluid pump comprising a first piston and a second piston interconnected with a torsion body and elastic bending elements, said first piston and said second piston being driven by a first motor and a second motor by applying force in opposite circumferential directions, so that in use the first piston and second piston displace along a displacement direction, wherein the said motors drive the first piston and the second piston in said opposite circumferential directions transversal to the displacement direction, **characterized in that**
at least one of the first motor and second motor includes an adjustable stator.

**2.** The fluid pump according to claim 1, wherein an operating position of the adjustable stator of a said motor is adjustable between at least a first and a second operating position, relative to a neutral position of a rotor of the respective motor.

**3.** The fluid pump according to any of the preceding claims, wherein the adjustable stator of a said motor is adjustable enabling setting a location of a respective stator pole with respect to a pole of a respective rotor of that motor.

**4.** The fluid pump according to any of the preceding claims, wherein the adjustable stator of a said motor is configured to provide a magnetic pole, wherein a distance between that magnetic stator pole and a pole of a rotor of the respective motor is adjustable..

**5.** The fluid pump according to any of the preceding claims, wherein at least one of the motors includes two stators, at least one of the two stators being an adjustable stator.

**6.** The fluid pump according to claim 5, wherein each of the stators of a said motor includes a core that at least partly surrounds a respective rotor space, wherein rotor spaces associated with the stators are axially aligned.

**7.** The fluid pump according to any of the preceding claims, wherein the pump is configured to operate at an eigenfrequency of 50 Hz or 60 Hz.

**8.** The fluid pump according to any of the preceding claims, wherein the adjustable stator of a said motor includes at least one electromagnet, the magnet providing a north and south pole during operation for magnetic interaction with the rotor of the motor.

**9.** The fluid pump according to any of the preceding claims, wherein the adjustable stator is rotatably adjustable, particularly with an axis of rotation that is substantially in parallel with a said piston displacement direction.

**10.** The fluid pump according to any of the preceding claims, including a drive or drive means, configured to adjust the adjustable stator.

**11.** The fluid pump according to any one of the preceding claims, wherein the first motor and the second motor are adapted to rotate with a substantially the same frequency having the opposite phases.

**12.** Method for controlling a free piston type fluid pump, the pump comprising: a first piston and a second piston interconnected with a torsion body and elastic bending elements, said first piston and said second

piston being driven by a first motor and a second motor by applying force in opposite circumferential directions, so that in use the first piston and second piston displace along a displacement direction wherein the said motors drive the first piston and the second piston in the circumferential direction transversal to the displacement direction, wherein the motors include stators and rotors,
the method being **characterized by** adjusting a position of at least one of the stators from a first stator operating position to a second stator operating position.

**13.** Method according to claim 12, wherein at least one of the stators is adjusted to change a torsion amplitude of a respective rotor.

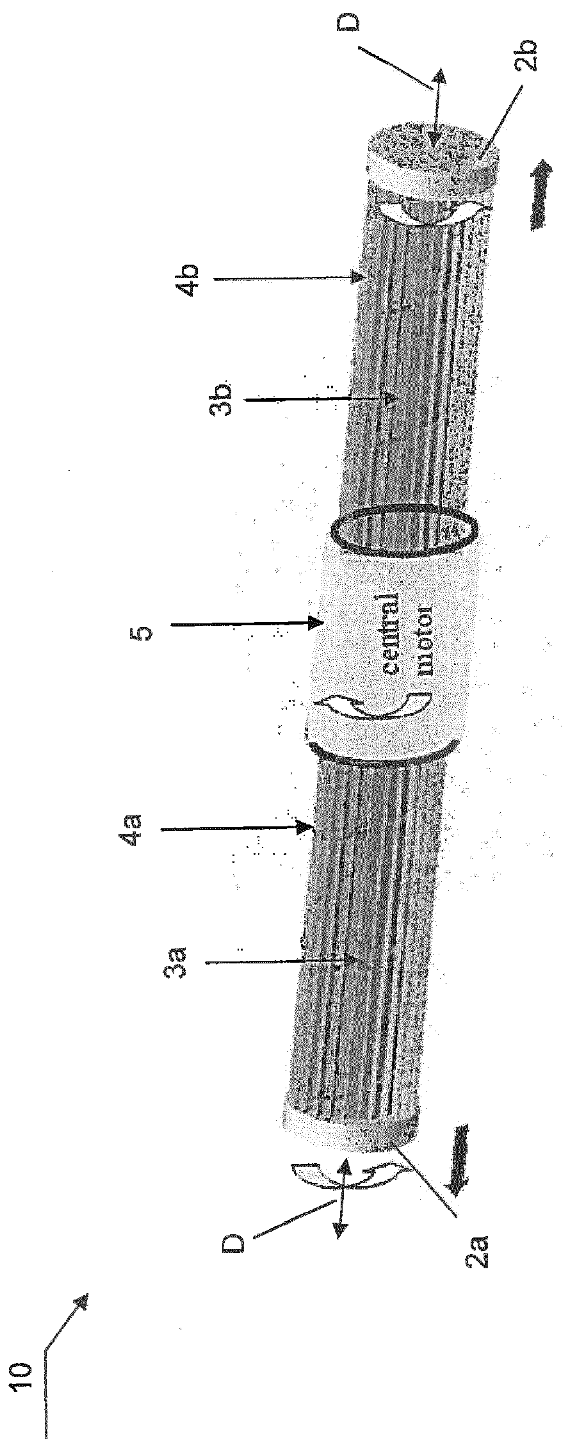



Fig. 1

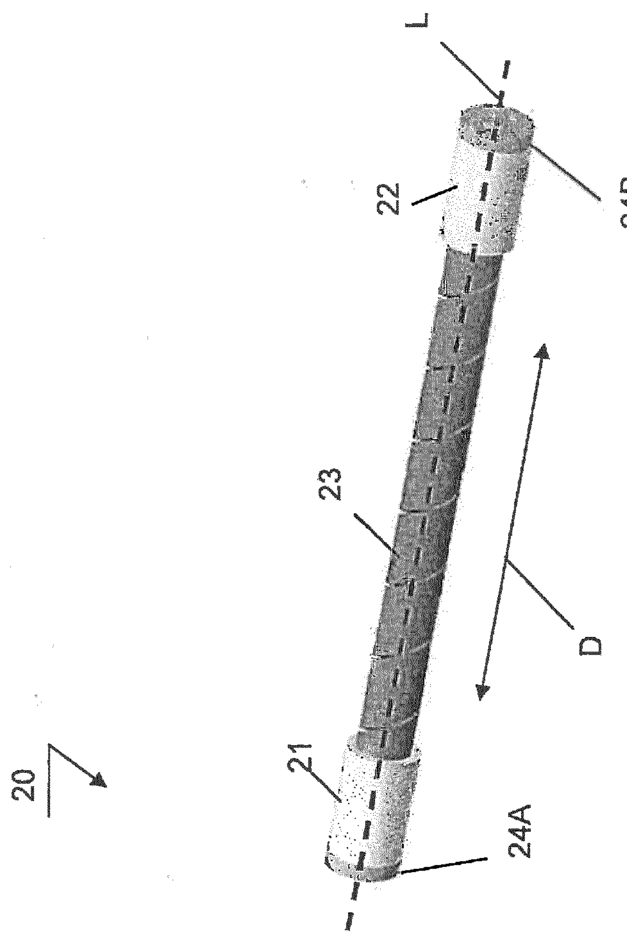



Fig. 2

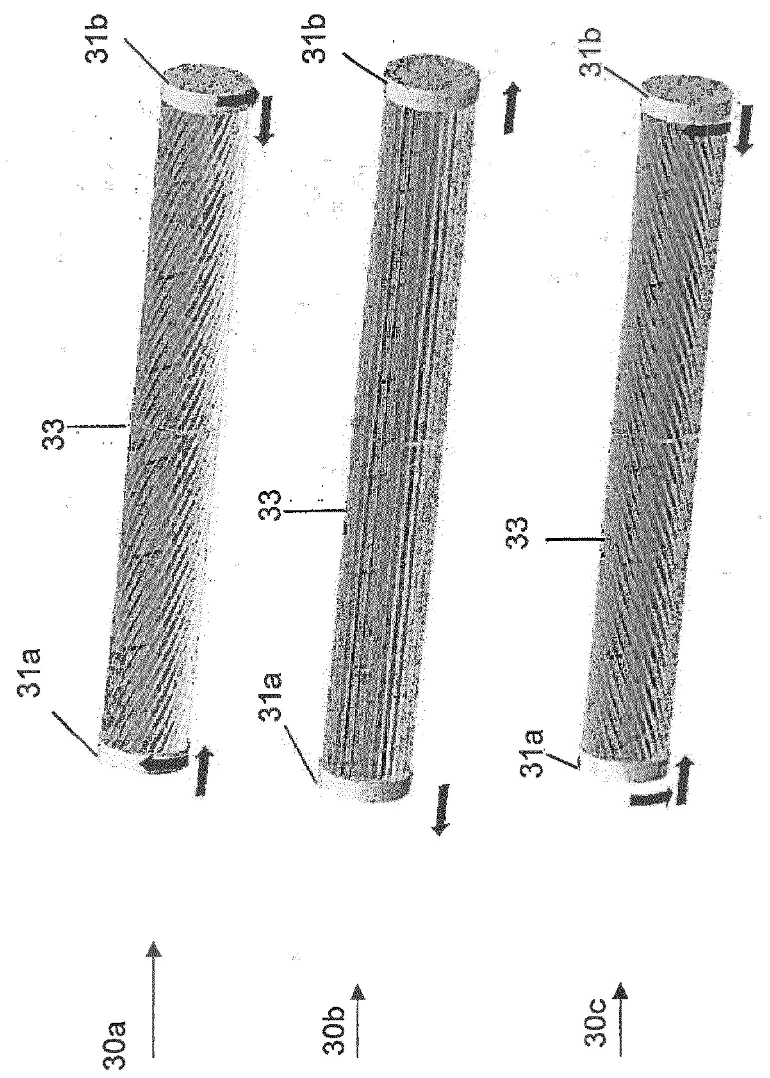



Fig. 3

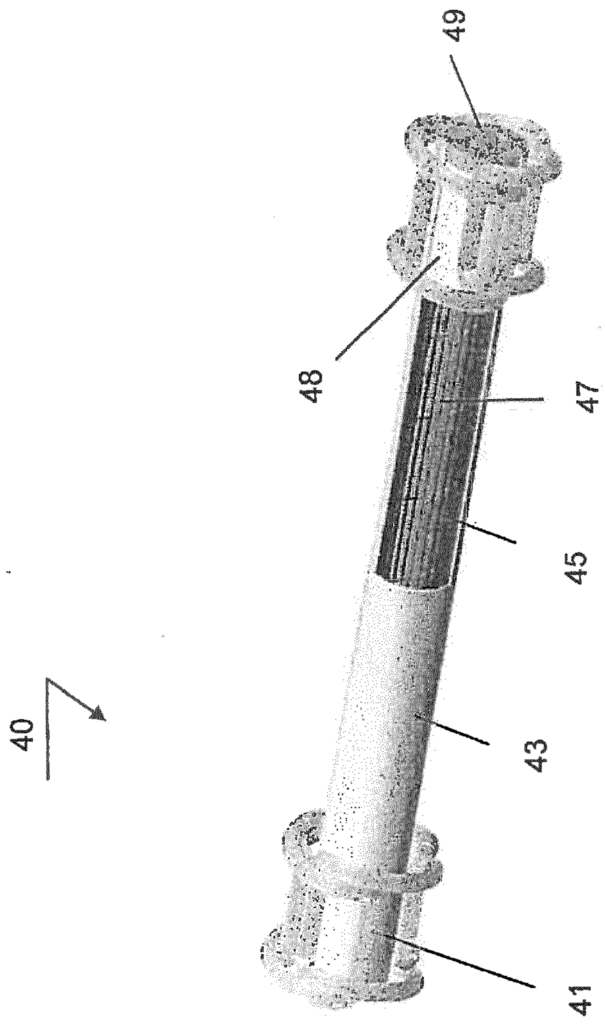



Fig. 4

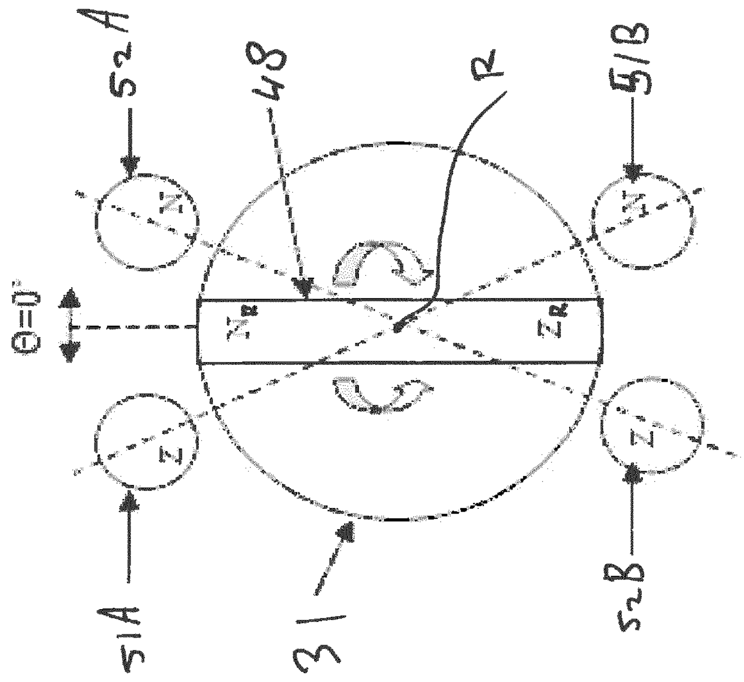



Fig. 5A

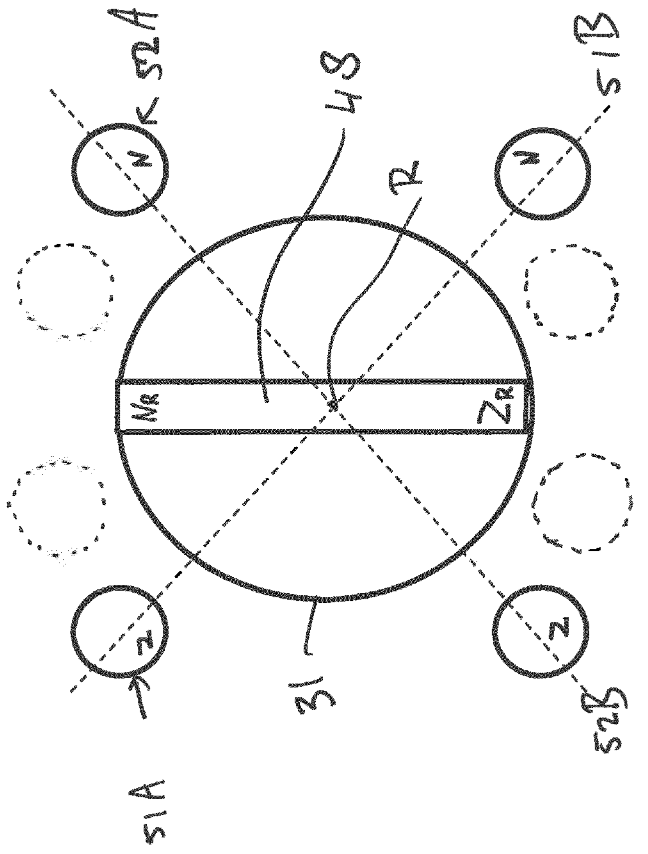



Fig. 5B

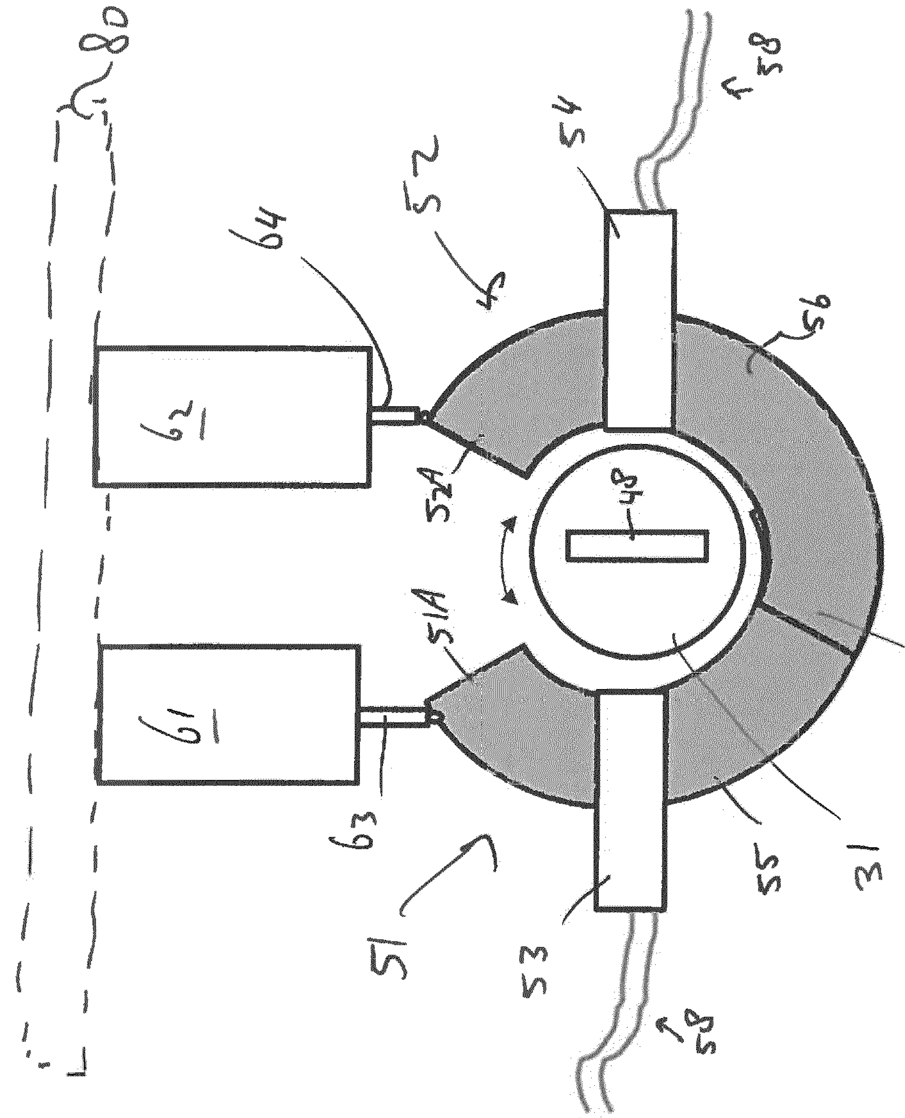
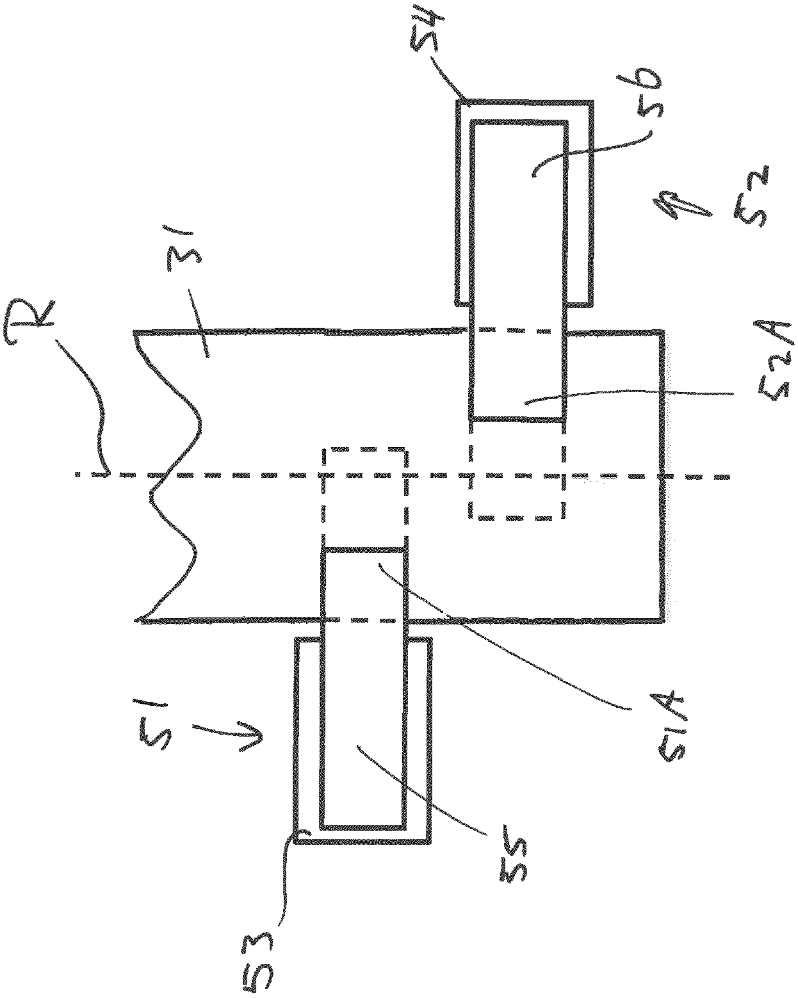



Fig. 6

Fig. 7



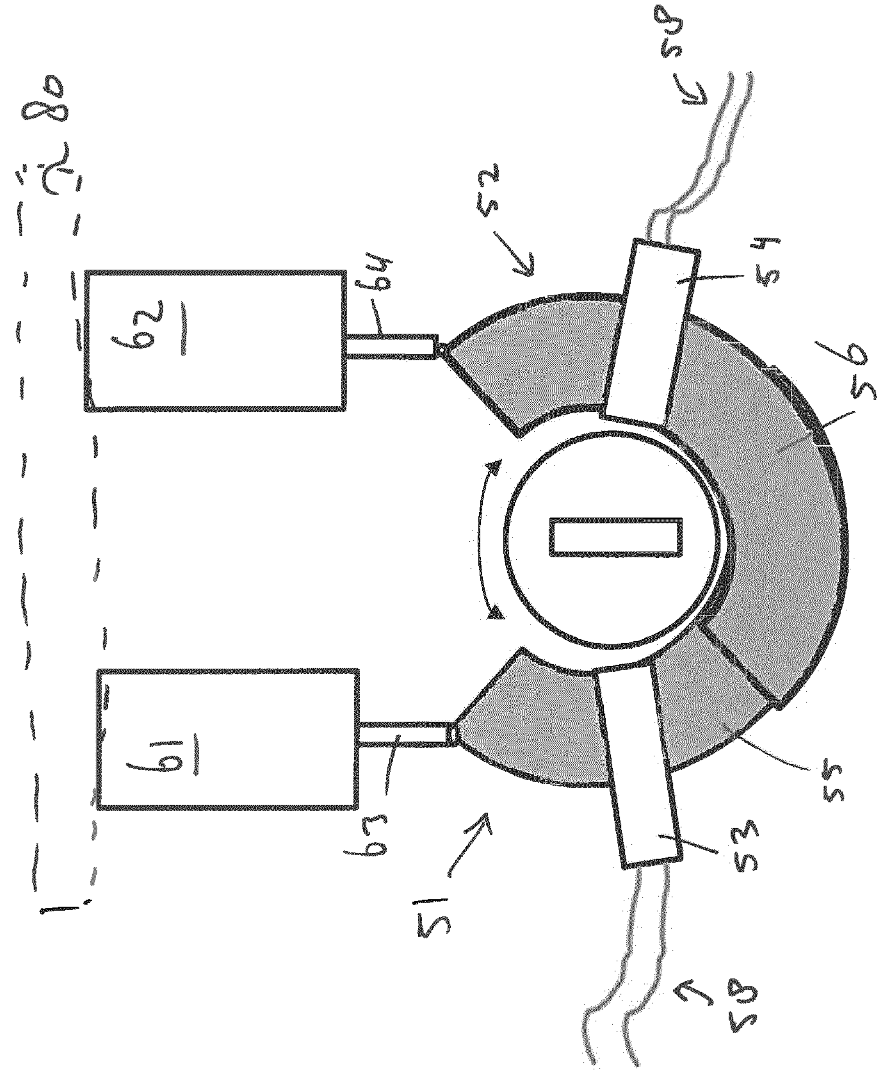



Fig. 8

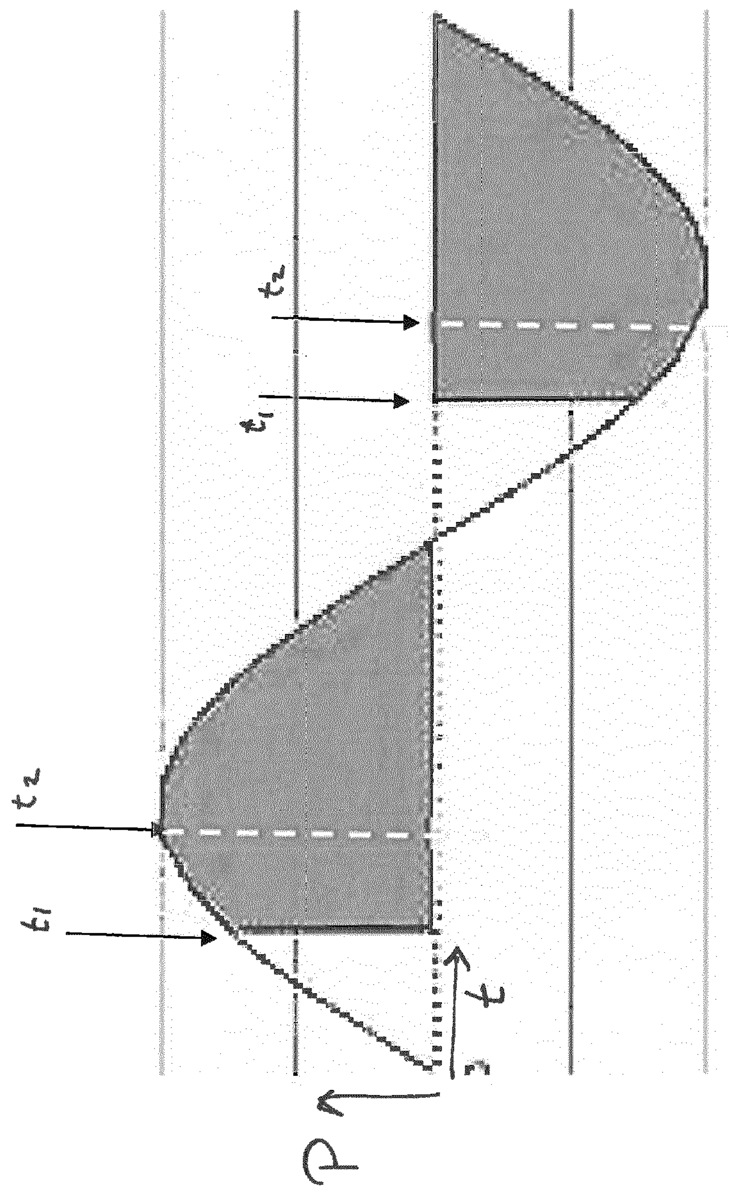



Fig. 9

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# EUROPEAN SEARCH REPORT

Application Number
EP 14 16 0265

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| Category | Citation of document with indication, where appropriate, of relevant passages | Relevant to claim | CLASSIFICATION OF THE APPLICATION (IPC) |
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