(54) Title: SYSTEM AND METHOD FOR CONTROLLING THE POSITION OF A LEVITATED ROTOR
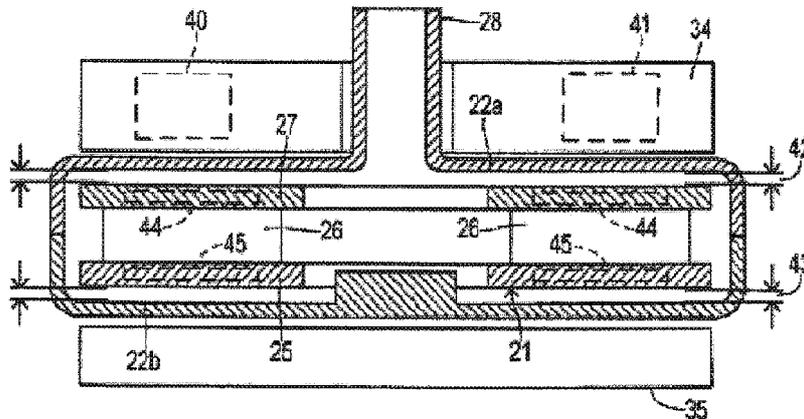
Fig. 3

(57) **Abstract:** A rotary machine is provided which may include a rotor and a stator within a housing. The stator may be for generating a rotating magnetic field for applying a torque to the rotor. A commutator circuit may provide a plurality of phase voltages to the stator, and a controller may adjust the plurality of phase voltages provided by the commutator circuit to modify an attractive force of the stator on the rotor to move the rotor in an axial direction.

SYSTEM AND METHOD FOR CONTROLLING THE POSITION OF A LEVITATED ROTOR

CROSS-REFERENCE TO RELATED APPLICATION

[0001] This application claims priority to U.S. Provisional Application No. 62/1 15,603, filed February 12, 2015, and entitled "SYSTEM AND METHOD FOR CONTROLLING THE POSITION OF A LEVITATED ROTOR," the entire disclosure of which is hereby incorporated by reference, for all purposes, as if fully set forth herein.

[0002] This application also claims priority to U.S. Provisional Application No. 62/1 15,324, filed February 12, 2015, and entitled "SYSTEM AND METHOD FOR CONTROLLING THE POSITION OF A LEVITATED ROTOR," the entire disclosure of which is hereby incorporated by reference, for all purposes, as if fully set forth herein.

BACKGROUND OF THE INVENTION

[0003] The present invention relates in general to rotary devices, and more specifically, to improved pumping devices and methods for their control.

[0004] One exemplary type of rotary machine is a centrifugal pumping device or mechanical circulatory assist device for treating patients with heart failure. Many types of circulatory assist devices are available for either short term or long term support for patients having cardiovascular disease. For example, a heart pump system known as a left ventricular assist device (LVAD) can provide long term patient support with an implantable pump associated with an externally-worn pump control unit and batteries. The LVAD improves circulation throughout the body by assisting the left side of the heart in pumping blood. Examples of LVAD systems are the DuraHeart® LVAS system made by Terumo Heart, Inc. of Ann Arbor, Michigan and the HeartMate II™ and HeartMate III™ systems made by Thoratec Corporation of Pleasanton, California. These systems typically employ a centrifugal pump with a magnetically levitated impeller to

pump blood from the left ventricle to the aorta. The impeller is formed as the rotor of the electric motor and rotated by the rotating magnetic field from a multiphase stator such as a brushless DC motor (BLDC). The impeller is rotated to provide sufficient blood flow through the pump to the patient's systemic circulation.

[0005] Early LVAD systems utilized mechanical bearings such as ball-and-cup bearings. More recent LVADs employ non-contact bearings which levitate the impeller using hydrodynamic and/or magnetic forces. In one example, the impeller is levitated by the combination of hydrodynamic and passive magnetic forces.

[0006] There is a trend for making centrifugal blood pumps used as the mechanical circulatory support devices more miniaturized to treat a broader patient population, more reliable, and with improved outcomes. To follow this trend, contactless impeller suspension technology has been developed in several pump designs. The principle of this technology is to levitate the pump impeller using one or a combination of forces from electromagnets, hydrodynamics, and permanent magnets. In the meanwhile, the pump should be hemocompatible to minimize the blood cell damage and blood clot formation. To that end, the bearing gap between the levitated impeller and the pump housing becomes an important factor. A small gap may lead to the high probability of the thrombus formation in the bearing or to elevated hemolysis due to excessive shear stress. Likewise, a large gap can compromise the hydrodynamic bearing performance and the pump efficiency.

[0007] One pump design utilizing active magnetic bearings achieves the desired bearing gap by levitating the impeller using magnetic fields generated by electromagnetic coils. However, in such a design there is the need for a separate bearing control system that includes the position sensors and electromagnetic coils to control the impeller position. Another pump design levitates the impeller using hydrodynamic thrust bearings combined with passive magnetic bearings. However, such a design usually requires a small bearing gap to provide sufficient hydrodynamic bearing stiffness to maintain impeller levitation and prevent contacts between impeller and the pump housing. Such a

small gap may result in an insufficient washout and vulnerability to blood clotting thus compromising hemocompatibility.

[0008] Therefore, a solution is needed to enhance the bearing gap to achieve adequate washout without increasing the complexity of the pump mechanical design and reducing the pump efficiency.

[0009] There is a need for a pump that includes an integrated control method for controlling the impeller position to enhance the bearing gap without increasing the complexity of the pump mechanical design and reducing the pump efficiency.

[0010] There is the need for a blood pump designed to maintain a centered position of the impeller to limit hemolysis and thrombosis without needing active control of the stationary levitating magnetic field.

[0011] There is a need for pumps which overcomes the above and other disadvantages of known designs.

BRIEF SUMMARY OF THE INVENTION

[0012] In summary, various aspects of the present invention are directed to a rotary machine including a rotor within a housing and having a rotor magnetic structure; a stator on a side of the housing for generating a rotating magnetic field for applying a torque to the rotor magnetic structure; a commutator circuit for providing a plurality of phase voltages to the stator; and a controller for rotating the rotor using the commutator circuit and a vector control algorithm. In one embodiment the controller is configured to adjust the phase voltages to modify an attractive force of the stator on the rotor magnetic structure to translate the rotor.

[0013] In various embodiments, the machine further includes a sensing circuit for determining a position of the rotor. The controller may be configured to calculate successive commanded values for the phase voltages in response to determined phase

3

currents from the sensing circuit and a variable commutation angle. The angle for calculating the commanded values may be determined in response to a phase current characteristic and a rotational speed of the rotor.

[0014] In various embodiments, the rotor is levitated by a substantially constant passive magnetic field.

[0015] In various embodiments, the controller is configured to move the rotor from a first balanced position to a second balanced position.

[0016] Various aspects of the invention are directed to a rotary machine including a rotor within a housing and having a rotor magnetic structure; a bearing mechanism for suspending the rotor in the housing in a balanced, non-contact manner; motor coils on a side of the housing for generating a magnetic field to apply a torque on the rotor magnetic structure; at least a first sensing circuit for determining a rotational and axial position of the rotor; a controller for rotating the rotor using the motor coils; and an impeller position control mechanism for adjusting a position of the impeller in the housing.

[0017] In various embodiments, the bearing mechanism comprises one of a hydrodynamic bearing, magnetic bearing, or combination of the same. In various embodiments, the modification of the attractive force on the rotor magnetic structure by the controller causes the rotor to move from a first balanced position to a second balanced position. The sensing circuit may include a plurality of position sensors for detecting the axial and rotational position of the rotor. The plurality of position sensors may include Hall-effect sensors. The plurality of position sensors may include optical sensors. In various embodiments, the rotor magnetic structure includes a plurality of magnetic members.

[0018] In various embodiments, the rotary machine is a pump. In various embodiments, the rotary machine is a blood pump. In various embodiments, the rotor is formed as an impeller.

4

[0019] Various aspects of the invention are directed to a method of operating the rotary machine described in any of the paragraphs above.

[0020] Various aspects of the invention are directed to a method of operating a centrifugal pump including a stator having windings and an impeller rotating in a non-contact manner within a pump housing, the impeller including a magnetic structure, the method includes applying a first levitating force on the impeller during rotation; and using electromagnetic windings, controlling the position of the impeller in the pump housing axially and rotationally.

[0021] In various embodiments, the first levitating force comprises a passive magnetic attractive force. The at least second levitating force may include an active magnetic force created by electromagnetic coils. The coils may be driven by vector control.

[0022] Various aspects of the invention are directed to a method of operating a centrifugal pump including a stator having windings and an impeller rotating in a non-contact manner within a pump housing, the impeller including a magnetic structure, the method including applying a first levitating force on the impeller during rotation; and using electromagnetic windings, controlling the position of the impeller in the pump housing axially and rotationally.

[0023] In various embodiments, the stator windings form the electromagnetic windings for controlling the impeller position. In various embodiments, the rotation of the impeller is controlled by interaction between the magnetic structure in the impeller and AC currents in the motor stator windings. In various embodiments, the axial position of the impeller is controlled by interaction between the magnetic structure in the impeller and DC currents in the motor stator windings. In various embodiments, the method includes using the electromagnetic windings to move the impeller axially from a first predetermined position to a second predetermined within the pump housing.

[0024] Various aspects of the invention are directed to a system, method, or computer-program product as described herein and/or shown in any of the drawings.

[0025] The systems and methods of the present invention have other features and advantages which will be apparent from or are set forth in more detail in the accompanying drawings, which are incorporated in and form a part of this specification, and the following Detailed Description of the Invention, which together serve to explain the principles of the present invention.

BRIEF DESCRIPTION OF THE DRAWINGS

[0026] FIG. 1 is a diagram of an implantable pump as one example of a rotary machine employing the present invention.

[0027] FIG. 2 is an exploded, perspective view of the exemplary centrifugal pump of FIG. 1.

[0028] FIG. 3 is a cross-sectional view of the exemplary pump of FIG. 1, illustrating the impeller levitated at a first balanced position generally centered within the pumping chamber in accordance with aspects of the invention.

[0029] FIG. 4 is a schematic view of the exemplary pump of FIG. 1, illustrating the impeller levitated eccentrically in the pump chamber by the main bearing components.

[0030] FIG. 5 is a block diagram of a pump control system in accordance with the invention.

[0031] FIG. 6 is a line chart depicting the method of controlling the impeller position in accordance with the invention.

[0032] FIG. 7a is a schematic view of the pump of FIG. 1, illustrating the impeller moved to another eccentric position at the bottom of the pump chamber.

[0033] FIG. 7b is a schematic view of the pump of FIG. 1, illustrating the impeller moved to yet another eccentric position at the top of the pump chamber.

[0034] **FIG. 8** is a flowchart showing a method of controlling impeller position in accordance with the invention.

[0035] **FIG. 9a** is a flowchart showing a method of controlling impeller position in accordance with the invention.

[0036] **FIG. 9b** is a line chart depicting a method for moving the impeller between two balanced positions in accordance with aspects of the invention.

[0037] **FIG. 10** is a flowchart showing a method of controlling impeller position during start-up of the pump in accordance with the invention.

[0038] **FIG. 11** is a cross-sectional view of an exemplary centrifugal flow pump in accordance with aspects of the invention, illustrating electromagnetic bearings to supplement the stator assembly positioning control.

[0039] **FIG. 12** is a cross-sectional view of an axial flow pump in accordance with aspects of the invention, the axial flow pump including mechanical bearings.

[0040] **FIG. 13** is a perspective view of the impeller of FIG. 12, with arrows depicting the direction of translation in accordance with the invention.

[0041] **FIG. 14** is a cross-sectional view of another axial flow pump in accordance with aspects of the invention, the axial flow pump including mechanical bearings.

[0042] **FIG. 15** is a cross-sectional view of another axial flow pump in accordance with aspects of the invention, the axial flow pump including passive magnetic and hydrodynamic bearings.

DETAILED DESCRIPTION OF THE INVENTION

[0043] Reference will now be made in detail to the preferred embodiments of the invention, examples of which are illustrated in the accompanying drawings. While the

invention will be described in conjunction with the preferred embodiments, it will be understood that they are not intended to limit the invention to those embodiments. On the contrary, the invention is intended to cover alternatives, modifications and equivalents, which may be included within the spirit and scope of the invention as defined by the appended claims.

[0044] For convenience in explanation and accurate definition in the appended claims, the terms "up" or "upper", "down" or "lower", "inside" and "outside" are used to describe features of the present invention with reference to the positions of such features as displayed in the figures.

[0045] In many respects the modifications of the various figures resemble those of preceding modifications and the same reference numerals followed by subscripts "a", "b", "c", and "d" designate corresponding parts.

[0046] As used herein, "gap" generally refers to the secondary flow gaps around the impeller as would be understood by one of skill in the art. The primary flow is through the impeller blade regions. The secondary flow gaps are the other areas of fluid, generally around the impeller. In some respects, the secondary flow gaps are between the impeller and the housing wall and define the hydrodynamic bearing.

[0047] The term "machine-readable medium" includes, but is not limited to portable or fixed storage devices, optical storage devices, wireless channels and various other mediums capable of storing, containing or carrying instructions and/or data. A code segment or machine-executable instructions may represent a procedure, a function, a subprogram, a program, a routine, a subroutine, a module, a software package, a class, or any combination of instructions, data structures, or program statements. A code segment may be coupled to another code segment or a hardware circuit by passing and/or receiving information, data, arguments, parameters, or memory contents. Information, arguments, parameters, data, etc. may be passed, forwarded, or transmitted via any suitable means including memory sharing, message passing, token passing, network transmission, etc.

[0048] Furthermore, embodiments of the invention may be implemented, at least in part, either manually or automatically. Manual or automatic implementations may be executed, or at least assisted, through the use of machines, hardware, software, firmware, middleware, microcode, hardware description languages, or any combination thereof. When implemented in software, firmware, middleware or microcode, the program code or code segments to perform the necessary tasks may be stored in a machine readable medium. One or more processors may perform the necessary tasks.

[0049] Although aspects of the invention will be described with reference to a blood pump, one will appreciate that the invention can be applied to various rotary machines and other types of pumps. The mechanisms and methods of the invention will be described in relation to blood pumps and in particular the ability to adjust the impeller operating position to address performance, such as the attendant risks for thrombus and hemolysis when pumping blood. One will appreciate from the description herein that the invention can be applied broadly to other pumps, rotary machines, and induction motors.

[0050] Aspects of the invention enable to the ability to enhance or control the bearing gap. One might wish to increase the bearing gap to adjust the washout rate, lubricate the bearing surfaces, or remove materials (particulates, thrombus, etc.) from the bearing gap. Another use of the invention may be to increase pump efficiency. As is known in the art, the motor efficiency increases as the impeller magnet moves closer to the motor drive coils. Another use of the invention may be to correct impeller malpositioning due to bulk forces or external forces (e.g. bumps or movements of the patient's body). These and other advantages can be achieved without the need for complex control systems in accordance with the invention.

[0051] In one embodiment, an electromagnetic force control method is used to change the impeller position and enhance the effective gap between the impeller and the blood chamber. The technique uses the same pump motor stator coils adjust the impeller position as is used to apply a torque to the impeller. No additional control subsystems and components are necessary.

[0052] Turning now to the drawings, wherein like components are designated by like reference numerals throughout the various figures, attention is directed to FIG. 1 which depicts an exemplary pump implanted in a heart failure patient.

[0053] A typical cardiac assist system includes a pumping unit, drive electronics, microprocessor control unit, and an energy source such as rechargeable batteries and/or an AC power conditioning circuit. The system is implanted during a surgical procedure in which a centrifugal pump is placed in the patient's chest. An inflow conduit is pierced into the left ventricle to supply blood to the pump. One end of an outflow conduit is mechanically fitted to the pump outlet and the other end is surgically attached to the patient's aorta by anastomosis. A percutaneous cable connects to the pump, exits the patient through an incision, and connects to the external control unit.

[0054] Various aspects of the implantable pump are similar to those shown and described in U.S. Patent Nos. 4,528,485; 4,857,781; 5,229,693; 5,588,812; 5,708,346; 5,917,297; 6,100,618; 6,222,290; 6,249,067; 6,268,675; 6,355,998; 6,351,048; 6,365,996; 6,522,093; 7,972,122; 8,686,674; 8,770,945; U.S. Pub. No. 2014/0205467; 2012/0095281; and U.S. Pat. App. No. 15/041,987, the entire contents of which patents and publications are incorporated herein by this reference for all purposes.

[0055] The exemplary system utilizes an implantable pump with contactless bearings for supporting the impeller. Contactless bearings (i.e., levitation) provide a number of potential benefits. Because they reduce rotational friction, theoretically they improve motor efficiency and reduce the risk of introducing particulates into the fluid. In one example, the impeller employs upper and lower plates having magnetic materials (the terminology of upper and lower being arbitrary since the pump can be operated in any orientation). A stationary magnetic field from the upper side of the pump housing attracts the upper plate and a rotating magnetic field from the lower side of the pump housing attracts the lower plate. The forces cooperate so that the impeller rotates at a levitated position within the pumping chamber. Features (not shown) may also be formed in the walls of the pumping chamber to produce a hydrodynamic bearing wherein forces from the circulating fluid also tend to center the impeller. Hydrodynamic pressure

grooves adapted to provide such a hydrodynamic bearing are shown in U.S. patent 7,470,246, issued December 30, 2008, titled "Centrifugal Blood Pump Apparatus," which is incorporated herein for all purposes by reference.

[0056] The exemplary impeller has an optimal location within the pumping chamber with a predetermined spacing from the chamber walls on each side. Maintaining a proper spacing limits the shear stress and the flow stasis of the pump. A high shear stress can cause hemolysis of the blood (i.e., damage to cells). Flow stasis can cause thrombosis (i.e., blood clotting).

[0057] With continued reference to FIG. 1, a patient is shown in fragmentary front elevational view. Surgically implanted either into the patient's abdominal cavity or pericardium 11 is the pumping unit 12 of a ventricular assist device. An inflow conduit (on the hidden side of unit 12) pierces the apex of the heart to convey blood from the patient's left ventricle into pumping unit 12. An outflow conduit 13 conveys blood from pumping unit 12 to the patient's ascending aorta. A percutaneous power cable 14 extends from pumping unit 12 outwardly of the patient's body via an incision to a compact control unit 15 worn by patient 10. Control unit 15 is powered by a main battery pack 16 and/or an external AC power supply, and an internal backup battery. Control unit 15 includes a commutator circuit for driving a motor within pumping unit 12.

[0058] In various embodiments, the commutator circuit and/or various electronics may be on the implanted side of the system. For example, various electronics may be positioned on-board the pump or in a separate hermetically sealed housing. Among the potential advantages of implanting electronics is the ability to control the pump even when communication is lost with the control unit 15 outside the body.

[0059] FIG. 2 shows exemplary centrifugal pump unit 20 used in the system of FIG. 1. The pump unit 20 includes an impeller 21 and a pump housing having upper and lower halves 22a and 22b. Impeller 21 is disposed within a pumping chamber 23 over a hub 24. Impeller 21 includes a first plate or disc 25 and a second plate or disc 27 sandwiched over a plurality of vanes 26. Second disc 27 includes a plurality of embedded magnet

segments 44 for interacting with a levitating magnetic field created by levitation magnet structure 34 disposed against housing 22a. For achieving a small size, magnet structure 34 may comprise one or more permanent magnet segments providing a symmetrical, static levitation magnetic field around a 3600 circumference. First disc 25 also contains embedded magnet segments 45 for magnetically coupling with a magnetic field from a stator assembly 35 disposed against housing 22b. Housing 22a includes an inlet 28 for receiving blood from a patient's ventricle and distributing it to vanes 26. Impeller 21 is preferably circular and has an outer circumferential edge 30. By rotatably driving impeller 21 in a pumping direction 31, the blood received at an inner edge of impeller 21 is carried to outer circumferential 30 and enters a volute region 32 within pumping chamber 23 at an increased pressure. The pressurized blood flows out from an outlet 33 formed by housing features 33a and 33b. A flow-dividing guide wall 36 may be provided within volute region 32 to help stabilize the overall flow and the forces acting on impeller 21.

[0060] FIG. 3 shows an exemplary pump 10 similar to the pump shown in FIG. 2. FIG. 3 shows impeller 21 located in a balanced position. The balanced position sometimes refers to the position the impeller naturally stabilizes or finds equilibrium during operation. In the exemplary embodiment, the balanced position is at or near the center of the pump chamber. In the balanced position, the forces acting on the impeller are generally balanced to stabilize the impeller. As one will understand from the description above that the hydrodynamic forces on the impeller will change as the rotational speed of the impeller changes. In turn, the magnetic attractive forces on the impeller will change as the impeller moves closer to or away from the magnet structure 34 and stator assembly 35. Accordingly, the impeller generally finds a new balanced position as the rotational speed changes.

[0061] As will be described below, however, aspects of the invention are directed to moving the impeller or changing the balanced position for each given rotational speed. For example, the impeller position control mechanisms to be described facilitate moving the impeller axially (up or down) without changing the rotational speed and all other.

This has the effect of enabling movement of the impeller independent of rotor speed. An advantage of this technique is that rotor speed can be determined in normal course (e.g. by a physician based on the patient's physiological needs) without concern for changing the impeller position. Conversely, the impeller position can be changed without affecting pumping throughput.

[0062] FIG. 3 shows impeller 21 located at or near a centered position wherein disc 27 is spaced from housing 22A by a gap 42 and impeller disc 25 is spaced from housing 22B by a gap 43. In the exemplary embodiment, the center position is chosen as the balanced or balanced position to ensure substantially uniform flow through gaps 42 and 43. During pump operation, the balanced position is maintained by the interaction of (a) attractive magnetic forces between permanent magnets 40 and 41 in levitation magnet structure 34 with imbedded magnetic material 44 within impeller disc 27, (b) attractive magnetic forces between stator assembly 35 and embedded magnet material 45 in impeller disc 25, and (c) hydrodynamic bearing forces exerted by the circulating fluid which may be increased by forming hydrodynamic pressure grooves in housing 22 (not shown). By using permanent magnets in structure 34 a compact shape is realized and potential failures associated with the complexities of implementing active levitation magnet control are avoided. To properly balance impeller 21 at the centered position, however, and because other forces acting on impeller 21 are not constant, an active positioning control may be desired. In particular, the hydrodynamic forces acting on impeller 21 vary according to the rotational speed of impeller 21. Furthermore, the attractive force applied to impeller 21 by stator assembly 35 depends on the magnitude of the magnetic field and the angle by which the magnetic field leads the impellers magnetic field position.

[0063] The structures and methods for controlling the motor will now be described with references to FIGs. 4 to 6.

[0064] FIG. 4 shows the main structure of an exemplary centrifugal pump 50 similar to that shown in FIG. 3. It is understood that other pump configurations may be employed, including various combinations of permanent magnets, motor stator windings, and

hydrodynamic bearings. In the exemplary embodiment, the rotor is formed as an impeller and driven by a motor. The impeller is also levitated by the combined force $F_{a\Sigma}$, which can be expressed as the following equation:

[0065] $$F_{a\Sigma} = F_{hdb} + F_{pm} + F_{em}$$

[0066] Where,

[0067] $F_{a\Sigma}$ is the combined force to levitate the impeller

[0068] F_{hdb} is the combination of hydrodynamic forces from the inlet side bearing, the motor side bearing, or both

[0069] F_{pm} is the combination of permanent magnet attraction forces

[0070] F_{em} is the magnetic attraction force generated from the motor

[0071] When the impeller is stabilized, $F_{a\Sigma}$ should be equal to zero. Usually F_{em} can be controlled through the electronic system to adjust the impeller position since all the others are the fixed configurations as the passive mode. Therefore, the basic design concept of this invention is to apply the motor vector control (FOC) to control the force F_{em} so that the impeller position can be adjusted while rotating only using one set of motor coil and drive system. In such way, there is no additional cost in the pump structure .

[0072] FIGs. 5 to 6 illustrate a method for controlling voltages applied to a stator in order to provide a desired rotation for a permanent magnet rotor (e.g. the impeller) 52 is a field oriented control (FOC) algorithm, which is also known as vector control. It is known in FOC that the stator magnetic field should generally lead the impeller position by 90° for maximum torque efficiency. The magnitude of the attractive force on the impeller is proportional to the magnitude of the phase currents in the stator. Phase current is adjusted by the FOC algorithm according to torque demands for the pump. Since the

14

commutation angle is typically fixed at 90°, the resulting attractive force varies according to torque output from the pump. The exemplary technique varies the ¾ current which creates magnetic flux responsible for attracting the impeller. This provides a convenient and accurate mechanism to create a controlled impeller attractive force.

[0073] At any particular combination of the (1) magnitude of the phase current and (2) the speed of the impeller, modifying the commutation angle for generating the phase voltages can change the attractive force generated by the stator thereby affecting the impeller balance. In turn, the impeller moves until it settles at a new balanced position where the hydrodynamic forces and magnetic forces are balanced.

[0074] FIGs. 5, 6, 7a, and 7b illustrate an exemplary system in accordance with aspects of the invention. Based on the principle of motor vector control, the torque current that is usually called quadrature current (I_q current) and stator coil flux current that is called direct current (I_d current) can be decoupled and controlled independently. The quadrature current I_q current is used to control the impeller rotational speed. The direct ¾ current controls the magnetic flux of electromagnetic coils.

[0075] In accordance with the invention, ¾ current is utilized to control the impeller position by enhancing or weakening the magnetic flux between impeller (rotor) and motor stator coils to adjust the attraction force F_{em}. This in turn changes the impeller position (shown in FIG. 6).

[0076] In one embodiment, the impeller position control technique is implemented as an open loop control without impeller position sensors. In one embodiment, impeller position control technique is implemented as a closed loop control with impeller position sensors.

[0077] In order to ensure proper positioning, active monitoring and control of the impeller position has been employed in the exemplary embodiment by adjusting the stationary magnetic field. However, position sensors and an adjustable magnetic source occupy a significant amount of space and add to the complexity of a system.

15

Accordingly, the use of sensors may depend on the design requirements. Suitable sensors may include, but are not limited to, Hall-effect sensors, variable reluctance sensors, and accelerometers.

[0078] In one embodiment using the open loop control, the impeller is controlled by periodically alternating the position from one side to another (e.g. from inlet side to motor side) by modulating the ¾ current as shown in FIG. 6. In this manner, the side gaps (Gap 1 and Gap 2) as shown in FIGs. 7a and 7b can be increased or decreased.

[0079] The position control technique can be implemented into the hardware and/or software of the system. Referring to FIG. 5, by example, the controller may employ FOC to supply a multiphase voltage signal to the stator assembly 53. The exemplary stator assembly is a three-phase stator. Individual phases a, b, and c and currents I_a, ¾, and I_c may be driven by an H-bridge inverter functioning as a commutation circuit driven by a pulse width modulator (PWM) circuit. An optional current sensing circuit associated with the inverter measure instantaneous phase current in at least two phases providing current signals designated I_a and ¾. A current calculating block receives the two measured currents and calculates a current I_c corresponding to the third phase. The measured currents are input to Vector Control (FOC) block 54 and to a current observer block (not shown) which estimates the position and speed of the impeller. The impeller position and speed are input to the FOC block from speed control block 55 and position control block 56. A target speed or revolutions per minute (rpm) for operating the pump is provided by a conventional physiological monitor to FOC block 54. The target rpm may be set by a medical caregiver or determined according to an algorithm based on various patient parameters such heart beat, physiological needs, suction detection, and the like. FOC block 54 and drive electronics 57 generate commanded voltage output values Va, Vb, and Vc. The Va, Vb, and Vc commands may also be coupled to the observer block for use in detecting speed and position.

[0080] The exemplary system differs from conventional configurations inasmuch as the FOC block and electronics are configured to alter the field oriented control algorithm so

that a direct current (Id) can be varied independently and generate a desired attractive force.

[0081] In one embodiment, the invention proceeds according to a method as shown in FIG. 8 which highlights a portion of the impeller position control with the field oriented control algorithm. Thus, in step 65 the phase currents are measured. Based on the measured phase currents, the current speed and rotor angle of the impeller are estimated in step 66. Based on the measured rotor angle in step 66, the phase currents are transformed into a two-axis coordinate system to generate quadrature current (I_q current) and direct current (I_d) values in a rotating reference frame in step 67. Quadrature current is used to control the torque to rotate the impeller and direct current is used to control the attraction force between rotor and stator to control the impeller position. In step 68, the next quadrature voltage is determined by the quadrature current error between the quadrature current transformed from step 67 and the required current for impeller rotation. In step 69, the next direct voltage is determined by the direct current error between the direct current transformed from step 67 and the required current for the attraction force alternation to control the impeller position. In step 70, the quadrature and direct voltages are transformed back to the stationary reference frame in order to provide the multiphase voltage commands which are output to the **PWM** circuit.

[0082] FIG. 9a is a flowchart showing another method of operating a rotary machine in accordance with the invention. The method includes operating the pump to rotate the impeller by applying a rotating magnetic field in step S10. During operation the impeller is levitated and positioned at a balanced position (**Pi**) by a balancing of forces. As described above, in an exemplary embodiment the impeller is levitated by the combination of hydrodynamic forces F_1 and other bearing forces F_2 (e.g. stator attractive force, passive magnetic forces, and/or bulk forces like gravity) in steps SI 1 and S12. Next, at least one of the forces, F_2, is modified to place the impeller out of balance in step S14. The impeller moves to a new position, **P$_2$,** where the forces are once again balanced in step S15.

[0083] As described above, the impeller is moved from the first balanced position (**Pi**) to the second balanced position (**P$_2$)** by applying an attractive force or modifying (increasing or decreasing) an existing attractive force on the impeller. In various embodiments, the attractive force modulation is substantially continuously applied to hold the impeller in the second balanced position. In various embodiments, the attractive force modulation is applied periodically (e.g. as pulses) to hold the impeller in the second balanced position. In various embodiments, the attractive force modulation is applied as a single pulse to move the impeller in the second balanced position. The second balanced position can be configured so the impeller remains in the second balanced position in a stable manner even when the attractive force is removed.

[0084] FIG. 9b illustrates an exemplary method for moving the impeller between two balanced positions in accordance with aspects of the invention. In this example, a permanent magnet arrangement is contemplated whereby the two balanced positions are naturally a product of the permanent magnet arrangement, so that the above-mentioned attractive force modulation may not necessarily be needed or required to hold the impeller in a particular balanced position. Rather, a single (or series) pulse may be applied to "push" the impeller from one stable position to another. For example, as shown in FIG. 9b, the impeller is initially, at a time tl, at a stable balanced position A. At a time t2 a pulse of duration (t3-t2) is applied to push the impeller to a new, stable balanced position B. In practice, the impeller may be pushed between stable balanced position A and stable balanced position B in a manner as needed or desired, such as shown in FIG. 9b. Advantageously, such an implementation may save energy and improve pump efficiency. In one embodiment, one of the two stable positions may be relatively close to the inlet of the above mentioned centrifugal pump unit, and another relatively close to the motor.

[0085] Turning to FIG. 10, in one embodiment, the impeller position control technique is used to facilitate start-up of the pump. In step S20, the exemplary pump is configured so the impeller rests against the inlet side (top of the housing) when the impeller is not rotating. In a typical pump with hydrodynamic forces alone, or in combination with

magnetic forces, the impeller is levitated away from the wall as it rotates. The blood entrained in the gap between the impeller and the house creates hydrodynamic pressure; however, the impeller must be rotating at a sufficient speed to create the hydrodynamic pressure. Until the minimum speed is met, the impeller rubs against the housing wall. In the exemplary pump, by contrast, the impeller is pulled away from the wall prior to, or just after, rotation begins thereby eliminating the deleterious effects of friction. The impeller is pulled away from the wall by applying a force, F, as described above in step S21. For example, the commutation angle may be modified to exert an attractive force. Referring to FIG. 7b, by example, the pump can be configured so the impeller rests at the inlet side. By applying an attractive force to the motor side the impeller moves down from the top wall. In step S22, the regular start-up sequence is initiated after the impeller is removed from the wall.

[0086] FIG. 11 shows a rotary machine in accordance with another embodiment making use of electromagnets. Pump 100 in FIG. 11 is similar in various respects to pump 10 in FIG. 3. In the exemplary embodiment, however, pump 100 includes an active electromagnetic (EM) system 1010. The EM force generated by electromagnets is used primarily or adjunctively to move the impeller. Exemplary electromagnets 101 comprise iron cores and windings. The EM force is modified in a conventional manner by changing the current applied to the windings. The application of the EM force causes the impeller to move to position P_{E2}. One will appreciate that the EM force can overpower hydrodynamic and passive magnetic forces present in the system. Accordingly, the EM structure must be dimensioned and configured to apply a relatively balanced force. An advantage of using electromagnets over the existing stator assembly is that there is relatively greater positional control over the impeller. By contrast, as described above, the phase currents typically cannot be used as the primary variable to adjust the axial attractive force on the impeller. A disadvantage of this embodiment is the need to provide an entirely separate EM system. This may not be an issue with large industrial rotary machines, but many types of motors have restrictive form factors. For example, implanted pumps must be relatively small in order to address a wider patient population.

[0087] FIGs. 12 and 13 illustrate another implantable pump in accordance with the invention. Pump 200 is similar in various respects to pumps 10 and 100 described above except pump 200 is an axial flow pump. Blood flows from in through inlet 201 and out through outlet 202 in a generally linear, axial direction. Pump 200 includes an impeller 210 having blades for moving blood through the pump housing and imparting kinetic energy in the fluid.

[0088] Impeller 210 is fixed within the housing by ball-and-cup bearings 212 and 214. The ball-and-cup bearings are closely toleranced and generally fix the impeller in a specific position. However, the exemplary bearings are lubricated and washed by the blood flow around the impeller. Accordingly, there is some fluid between the ball and cup surfaces.

[0089] Torque is applied to the impeller by a stator assembly 205. The stator assembly 205 includes windings and is driven using a FOC algorithm in a similar manner to the stator assemblies described above. In practice, the impeller position is adjusted proceeding according to the method shown in FIG. 9. Using the FOC technique described above the impeller is rotated in the pump housing. At a desired time the I_d current is modulated to adjust the attractive force on the impeller in the axial direction. As long as the attractive force is sufficient to squeeze blood out from a respective bearing gap, the impeller will move axially towards inlet 201 or outlet 202. The bearing gaps of pump 200 are relatively small compared to Gap 1 and Gap 2 of pump 50 in FIG. 4. However, even relatively small impeller movement may be beneficial to enable control of the bearing gaps.

[0090] FIG. 14 illustrates another pump 300 similar to pump 200. Pump 300 includes an impeller fixed between two mechanical bearings 212 and 214. Pump 300 is slightly different than pump 200 because the outlet extends at an angle from the inlet. Pump 300 is configured in a relatively compact design compared to pump 200 including a relatively smaller stator assembly; however, the same general principles can be applied to control the motor and adjust the impeller position.

[0091] FIG. 15 is a cross-sectional view of another pump 400 similar to pumps 200 and 300, except pump 400 is an axial flow pump with non-contact bearings. Pump 400 includes a pump housing having an inlet 401 and outlet 402. An impeller 411 is positioned within a pump chamber for imparting flow to the blood fluid within the housing. The impeller is entirely formed of a magnetic material which is driven by interaction with a stator assembly 405.

[0092] Impeller 411 is stabilized in the pump chamber by a combination of hydrodynamic and passive magnetic forces. Impeller 411, which is a magnetic material, interacts with the magnetic material in stator assembly 405 to provide an axial centering force. A pump ring 452 with a chamfer surface is positioned at the leading end of the impeller to create hydrodynamic stabilization forces in the axial direction (left to right) and radial direction (up and down on page). A permanent magnet ring 450 is provided at the trailing edge of the impeller is oriented with a north pole facing a north pole of the impeller. This arrangement creates an axial bias force to push the impeller against the pump ring 452. The magnet ring 450 also provides a radially centering force. Finally, the impeller includes deep hydrodynamic grooves to generate a hydrodynamic pressure force against the inner walls of the pump chamber for radial stabilization.

[0093] In operation, the impeller remains stable in the axial and radial directions. There may be some axial movement as the rotational speed of the impeller changes or as a result of other forces (e.g. the native pulse), but generally the impeller remains centered below the stator assembly.

[0094] Using the FOC control technique described above, the attractive force of the stator assembly 405 on impeller 411 can be modified. In one embodiment, pump 400 is configured so impeller is eccentric when centered below the stator assembly 405. In this example, increasing the attractive force amounts to an increase in the axial stiffness to resist axial movement. In one embodiment, the attractive force is modified to actually move impeller 411 axially. For example, the impeller can be moved closer to pump ring 452 to squeeze blood out of the gap between impeller 411 and a surface of ring 452. The impeller may also be moved away from ring 452 to increase the blood gap therebetween.

In this manner, the impeller position control technique adds an element of active position control otherwise not possible with the passive bearing configuration of pump 400.

[0095] Although aspects of the invention have been described in connection with blood pumps, one will appreciate from the description herein that the invention can be applied equally to other types of rotary machines such as washing machines, manufacturing machines, computer drives, and more.

[0096] The foregoing descriptions of specific embodiments of the present invention have been presented for purposes of illustration and description. They are not intended to be exhaustive or to limit the invention to the precise forms disclosed, and obviously many modifications and variations are possible in light of the above teaching. The embodiments were chosen and described in order to best explain the principles of the invention and its practical application, to thereby enable others skilled in the art to best utilize the invention and various embodiments with various modifications as are suited to the particular use contemplated. It is intended that the scope of the invention be defined by the Claims appended hereto and their equivalents.

What is Claimed:

1.   A blood pump, comprising:

a rotor within a housing;

a stator for generating a rotating magnetic field for applying a torque to the rotor;

a commutator circuit for providing a plurality of phase voltages to the stator; and

a controller for adjusting the plurality of phase voltages provided by the

commutator circuit to modify a magnetic force of the stator on the rotor to control a

position of the rotor in an axial direction.

2.   The blood pump of claim 1, further comprising a sensing circuit for determining

at least an axial position of the rotor.

3.   The blood pump according to claim 2, wherein the sensing circuit is further for

determining a rotational position of the rotor.

4.   The blood pump according to claim 2, wherein the controller adjusts the plurality

of phase voltages provided by the commutator circuit by varying a commutation angle in

response to the axial position of the rotor as determined by the sensing circuit.

5.   The blood pump according to claim 1, wherein the rotor is levitated by a

hydrodynamic bearing, a magnetic bearing, or combination thereof.

6.   The blood pump according to claim 1, wherein the rotor is levitated by a

substantially constant passive magnetic field.

7.   The blood pump according to claim 1, wherein the controller is configured to

axially move the rotor from a first balanced position to a second balanced position.

8.   The blood pump according to claim 1, wherein the rotary machine is a blood

pump.

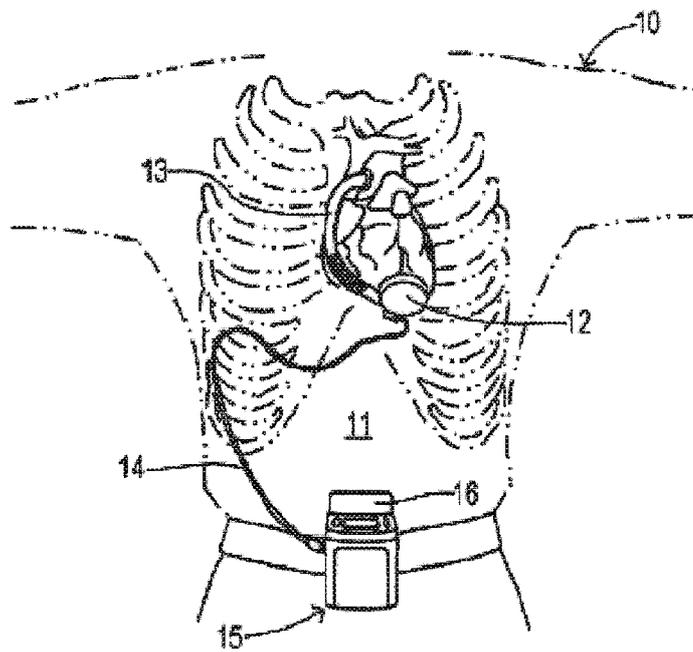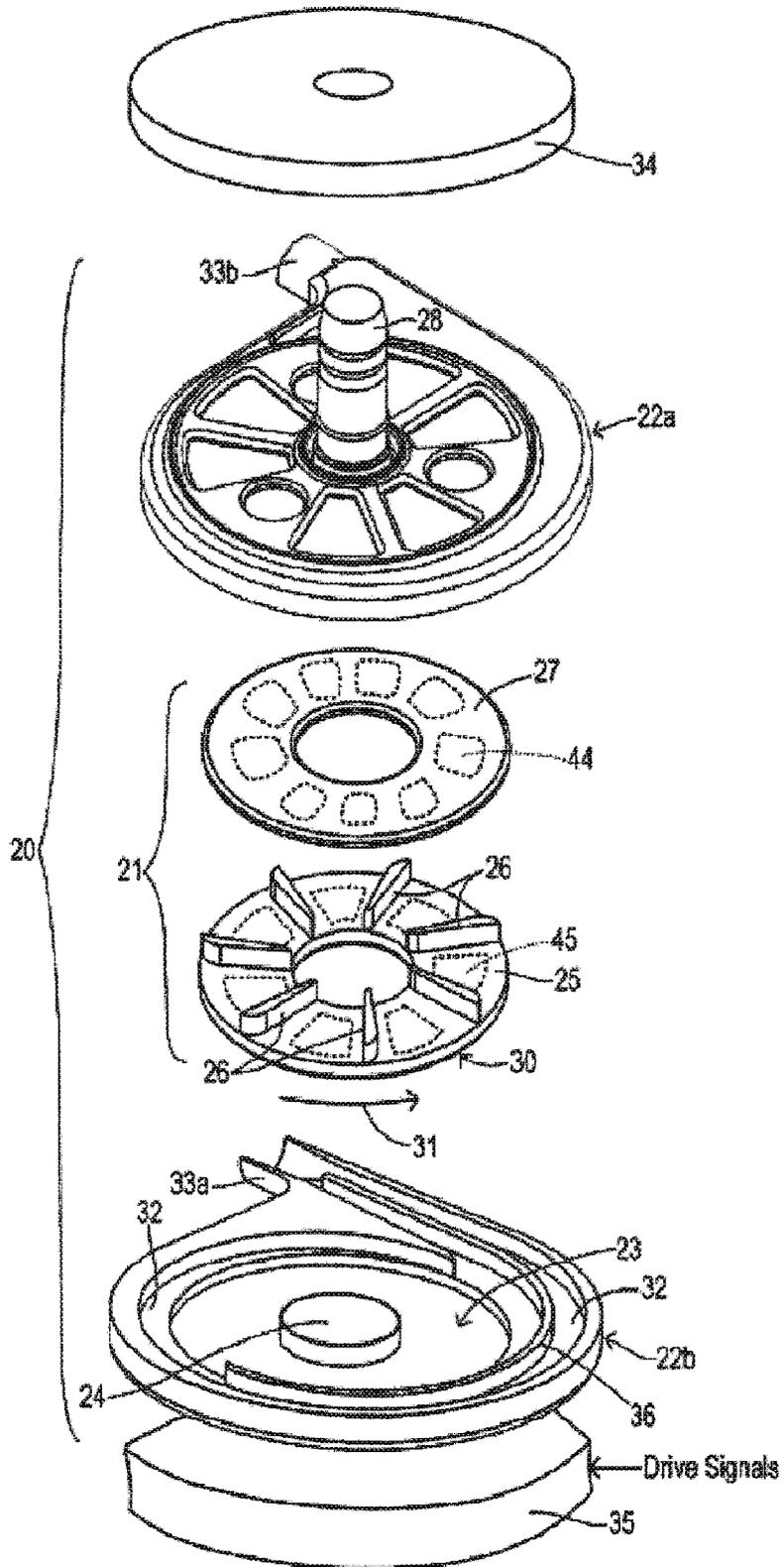9.   The blood pump according to claim 1, wherein the rotor comprises an impeller.

10.   The blood pump according to claim 2, wherein the sensing circuit comprises a

plurality of position sensors.

11.   The blood pump according to claim 10, wherein the plurality of position sensors

comprises Hall-effect sensors and/or optical sensors.

12.   A method of operating a blood pump, wherein the method comprises:

        applying a rotating magnetic field with a stator to rotate a rotor;

        applying a first axial force on the rotor;

        applying at least a second axial force on the rotor, wherein a combination of the

first axial force and at least the second axial force suspends the rotor at a first balanced

position; and

        modifying the at least second axial force such that the impeller is suspended at a

second balance position.

13.   The method according to claim 12, wherein the first axial force comprises a

passive magnetic attractive force.

14.   The method according to claim 12, wherein the at least second axial force comprises an active magnetic force created by electromagnetic coils of the stator.

15.   The method according to claim 14, wherein the electromagnetic coils are controlled by a controller using a vector control algorithm.

16.   The method according to claim 12, wherein the method further comprises sensing at least an axial position of the rotor.

17.   The method according to claim 12, wherein modifying the at least second axial force occurs, at least in part, in response to the axial position of the rotor.

18.   The method according to claim 12, wherein applying at least the second axial force on the rotor comprises adjusting a plurality of phase voltages provided to the stator by varying a commutation angle.

19.   The method according to claim 12, wherein the rotary machine is a blood pump.

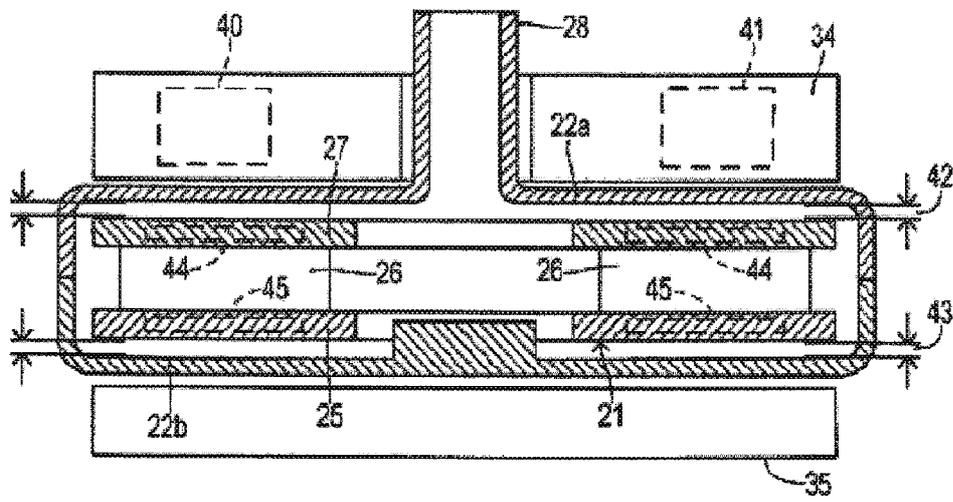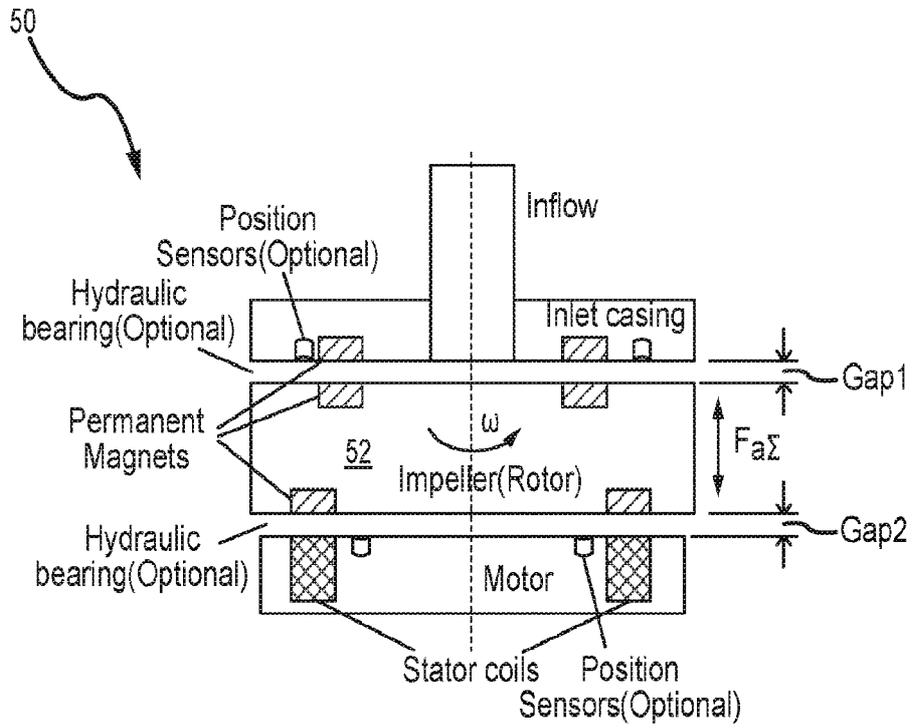20.   The method according to claim 12, wherein the rotor comprises an impeller.

Fig. 1

Fig. 2
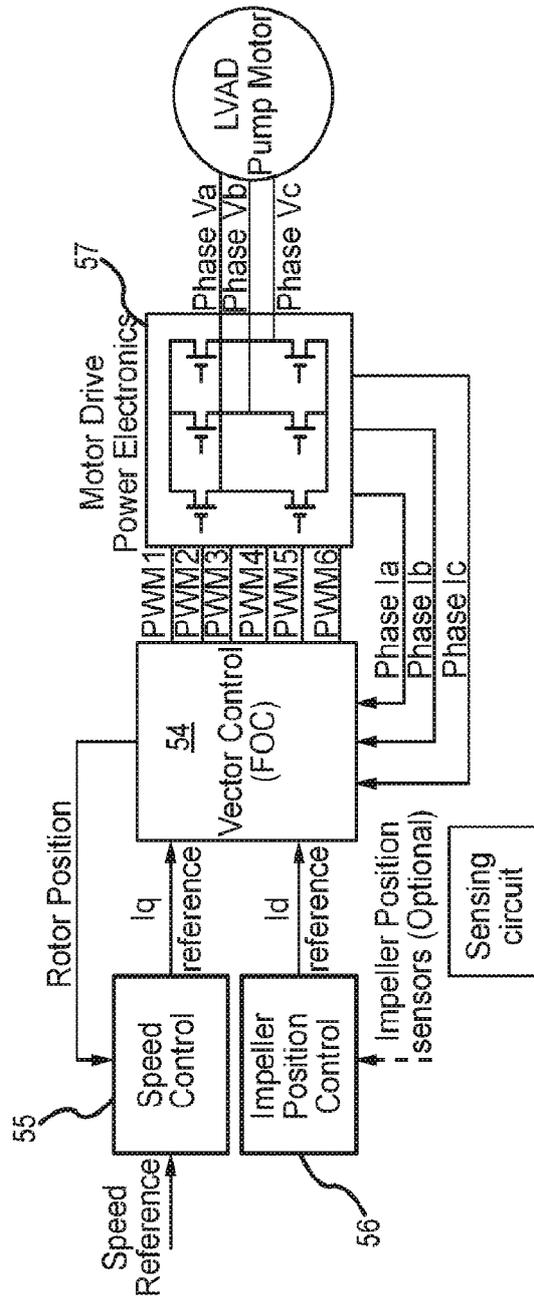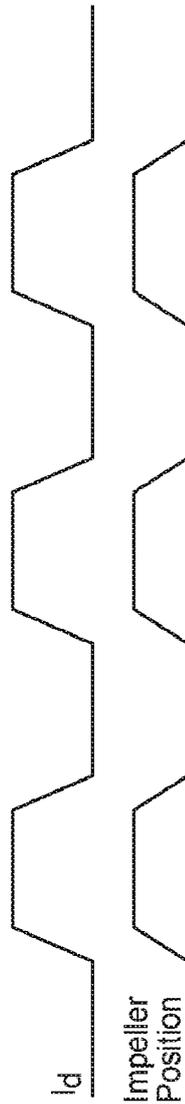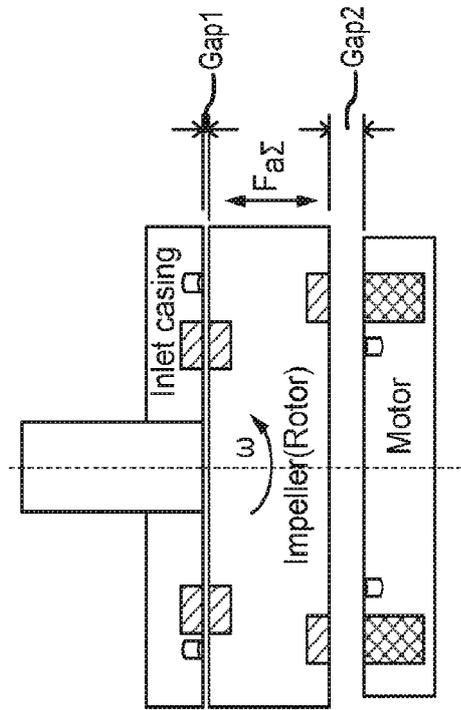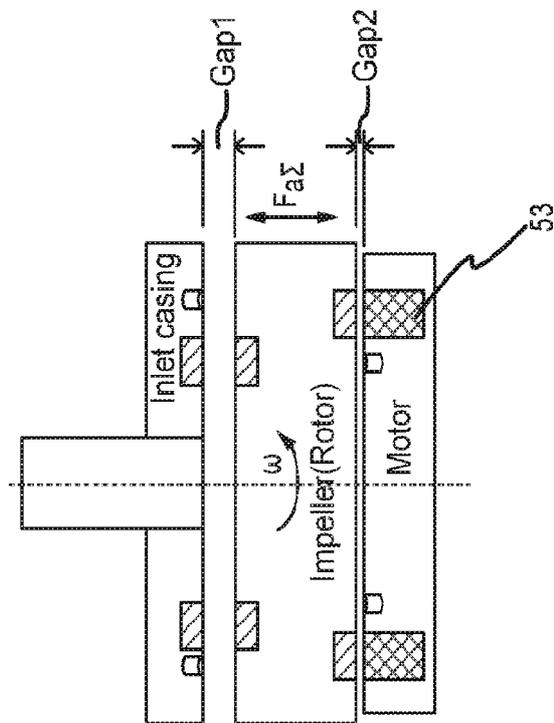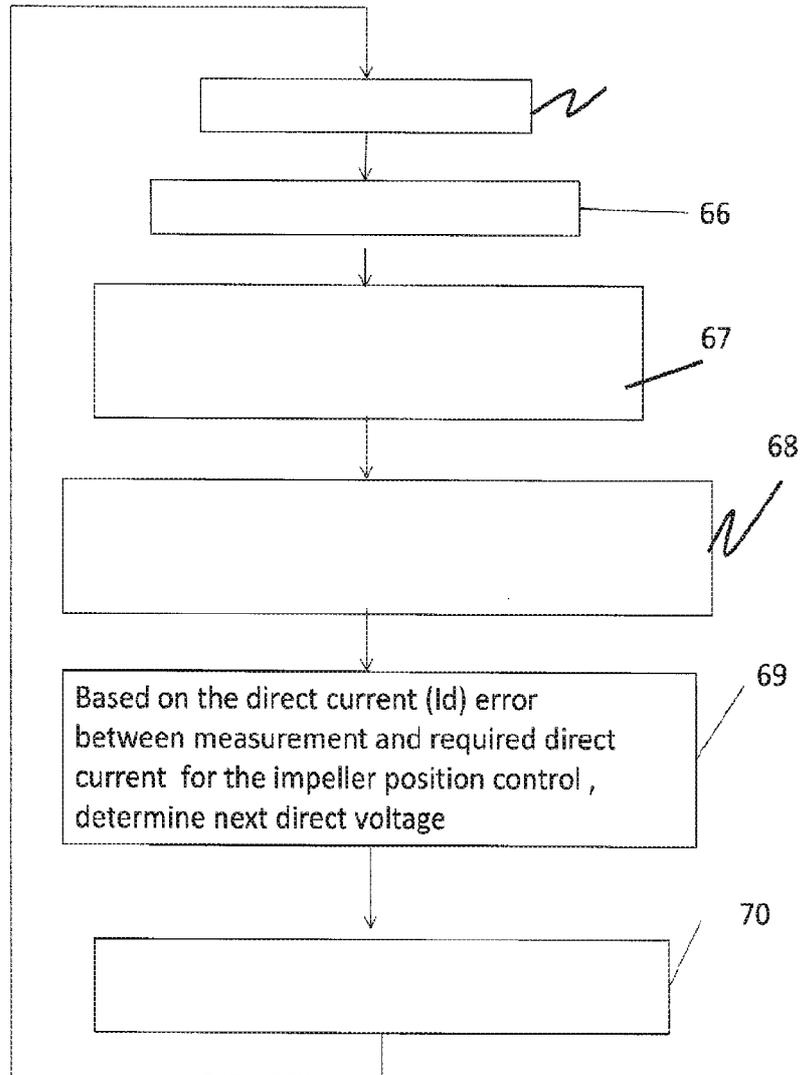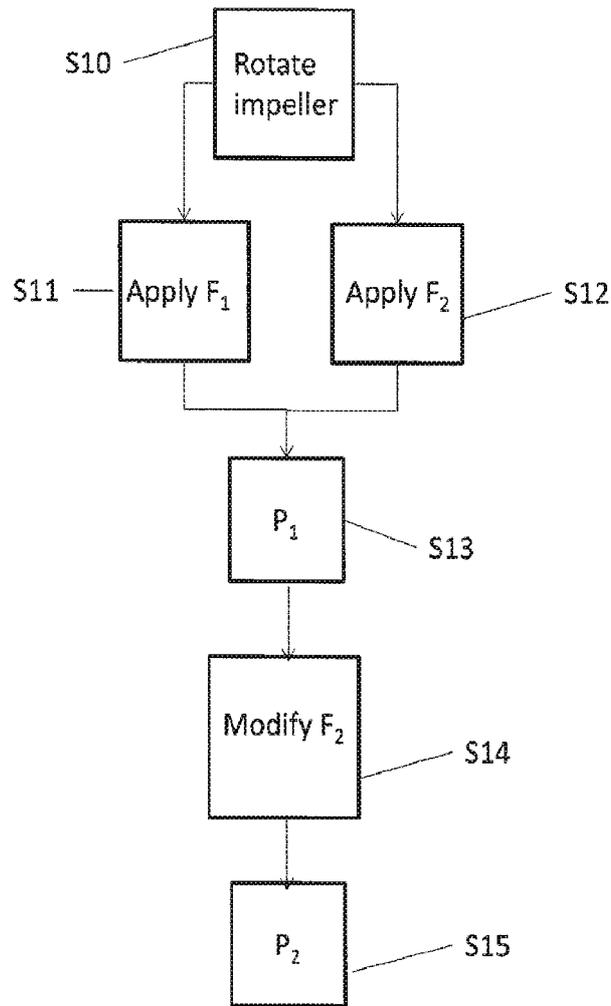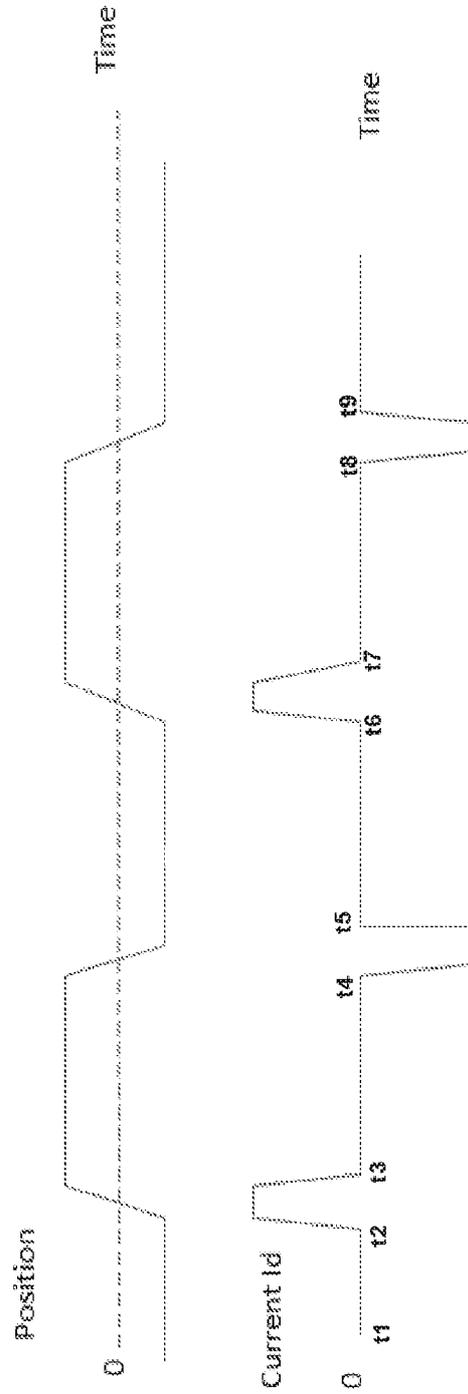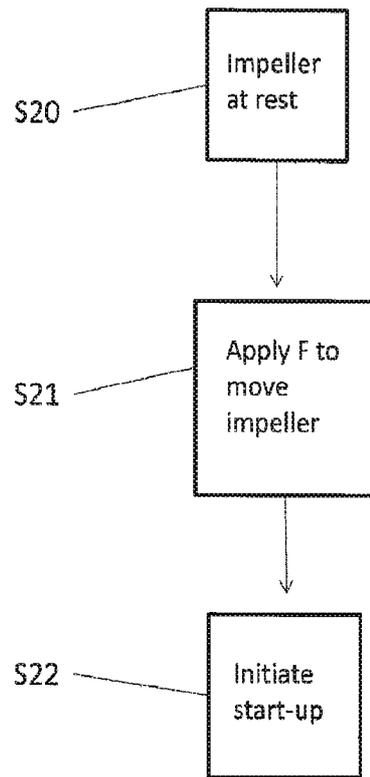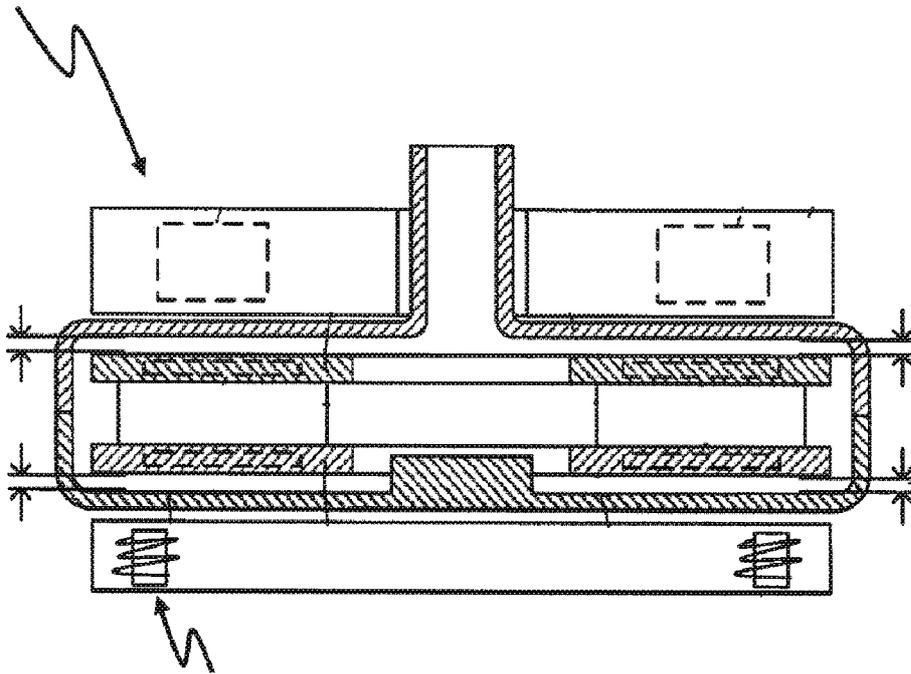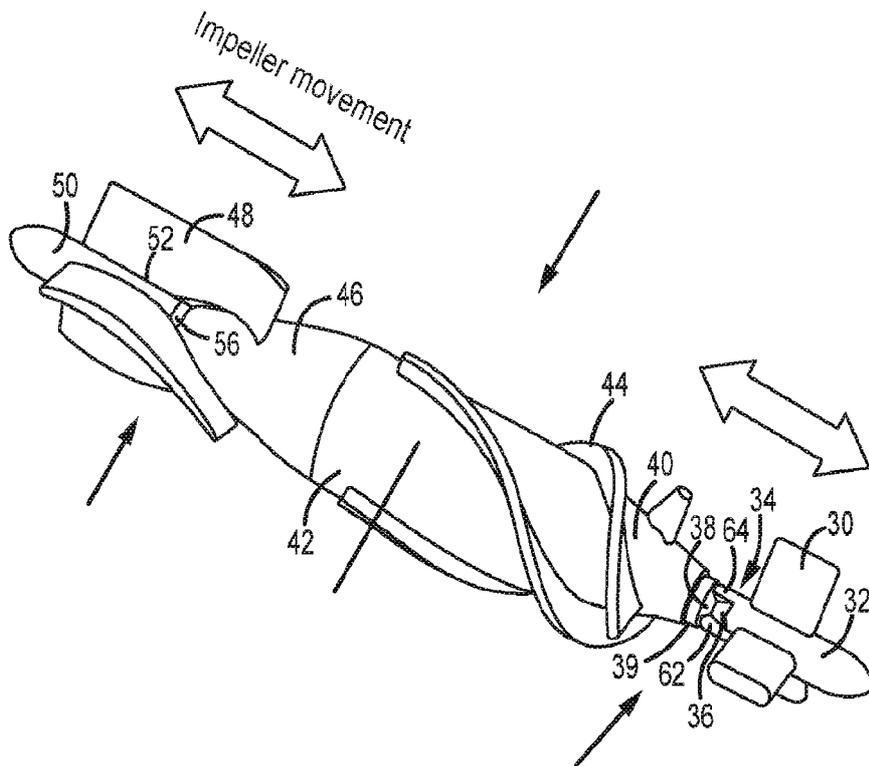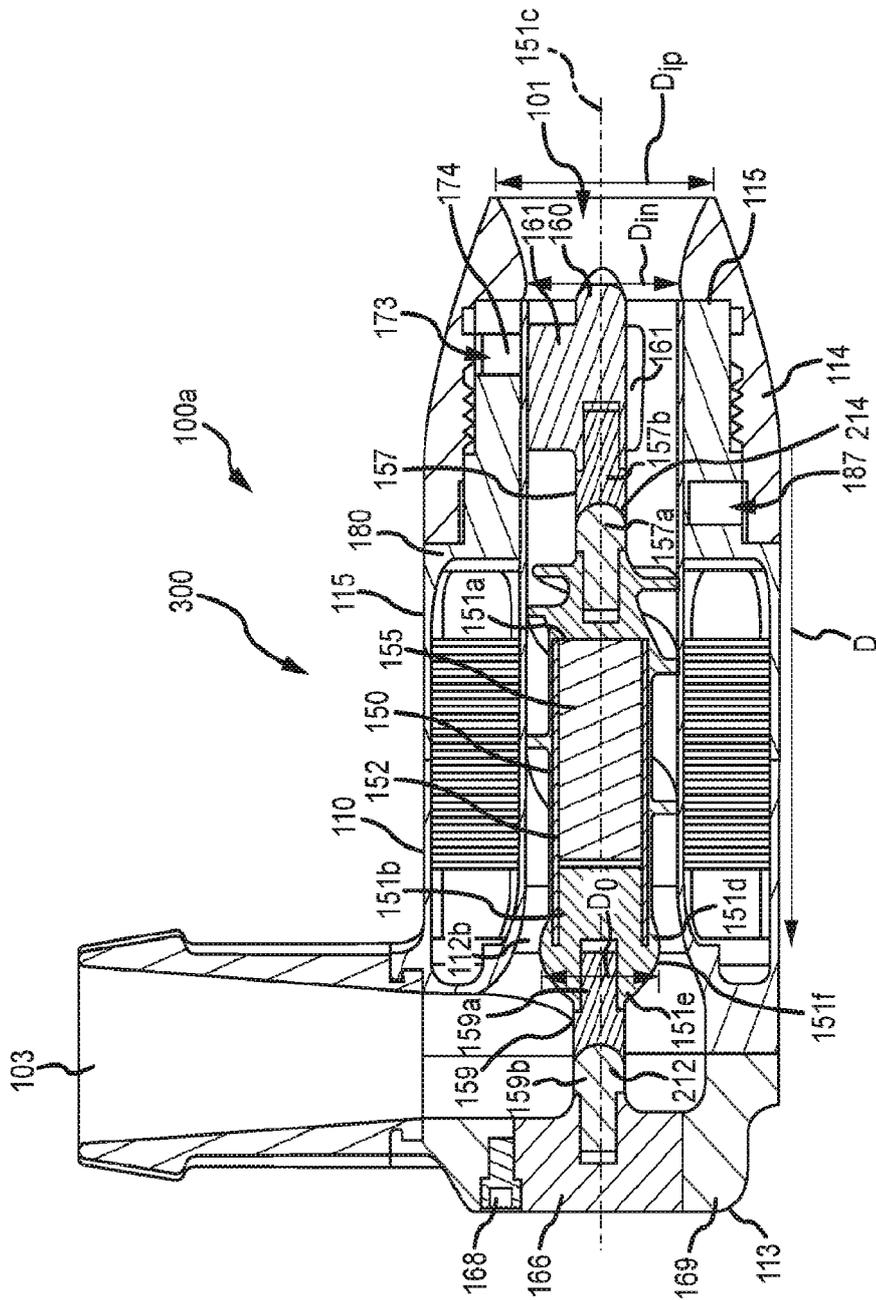
3/16

Fig. 3

Fig. 4

Fig. 5

Id

Impeller
Position

Fig. 6

Fig. 7b

Fig. 7a

Based on the direct current (Id) error between measurement and required direct current for the impeller position control, determine next direct voltage

Fig. 8

9/16

Fig. 9a

Fig. 9b

S20 —— Impeller at rest

S21 —— Apply F to move impeller

S22 —— Initiate start-up

Fig. 10

Fig. 11

Fig. 12

Fig. 13

Fig. 14

Fig. 15

INTERNATIONAL SEARCH REPORT

A.   CLASSIFICATION OF SUBJECT MATTER

A61M l/12(2006.01)i, A61M l/10(2006.01)i, G01N 21/00(2006.01)i

According to International Patent Classification (IPC) or to both national classification and IPC

B.   FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
A61M 1/12; F04B 17/00; F04B 35/04; F04D 27/00; F04B 49/00; F04D 25/06; F04D 25/02; F04D 17/10; A61M 1/10; G01N 21/00

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
Korean utility models and applications for utility models
Japanese utility models and applications for utility models

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
eKOMPASS(KIPO internal) & Keywords: blood pump, rotor, impeller, stator, commutator circuit, controller, sensing circuit, phase voltages, axial force, levitate

C.   DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2014-0205467 Al (THORATEC CORPORATION) 24 July 2014 See paragraphs [0016]-[0022] ; claims 1-3, 12, 13, 17; and figures 1-4.	1,5-9, 12-15, 18-20
Y		2-4, 10, 11, 16, 17
Y	US 2015-0023803 Al (CIRCULITE, INC.) 22 January 2015 See paragraphs [0022]-[0025] , [0027] , [0029H0032] , [0034] , [0035] , [0046H0049] ; and figures 2-6C, 8.	2-4, 10, 11, 16, 17
A	US 2015-0017030 Al (THORATEC CORPORATION) 15 January 2015 See paragraphs [0068]-[0072] , [0080]-[0085] , [0097H0125] ; and figures 3, 4, 8, 10-12, 14, 15.	1-20
A	US 7128538 B2 (TSUBOUCHI et al.) 31 October 2006 See column 3, lines 10-44; column 4, lines 22-45; column 5, line 25-column 6, line 45; column 7, lines 40-54; column 9, line 29-column 10, line 42; and figures 1, 3, 4.	1-20
A	US 6589030 B2 (OZAKI, TAKAYOSHI) 08 July 2003 See column 4, line 39-column 7, line 30; and figures 1A-8.	1-20

☒ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

*   Special categories of cited documents:
"A" document defining the general state of the art which is not considered to be of particular relevance
"E" earlier application or patent but published on or after the international filing date
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"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents,such combination being obvious to a person skilled in the art
"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
16 May 2016 (16.05.2016)	**16 May 2016 (16.05.2016)**

Name and mailing address of the ISA/KR	Authorized officer
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C (Continuation).	DOCUMENTS CONSIDERED TO BE RELEVANT	
Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 6394769 Bl (BEARNSON et al.) 28 May 2002 See column 4, line 36-column 6, line 34; column 8, lines 6-42; and figures 1-3B, 12.	1-20

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 2014-0205467 Al	24/07/2014	EP 2948202 Al	02/12/2015
		¥0 2014-116676 Al	31/07/2014
US 2015-0023803 Al	22/01/2015	EP 2968714 Al	20/01/2016
		US 2014-275723 Al	18/09/2014
		US 8882477 B2	11/11/2014
		WO 2014-159035 Al	02/10/2014
US 2015-0017030 Al	15/01/2015	CN 102341600 A	01/02/2012
		CN 102341600 B	10/12/2014
		EP 2405140 Al	11/01/2012
		EP 2405140 A4	01/05/2013
		JP 2010-209691 A	24/09/2010
		JP 2010-261394 A	18/11/2010
		JP 5378012 B2	25/12/2013
		JP 5378060 B2	25/12/2013
		US 2011-0318203 Al	29/12/2011
		US 8770945 B2	08/07/2014
		WO 2010-101107 Al	10/09/2010
US 7128538 B2	31/10/2006	AT 422914 T	15/03/2009
		EP 1495773 A2	12/01/2005
		EP 1495773 A3	29/11/2006
		EP 1495773 Bl	18/02/2009
		JP 2005-028137 A	03/02/2005
		JP 4308723 B2	05/08/2009
		US 2005-0008496 Al	13/01/2005
US 6589030 B2	08/07/2003	JP 2002-005073 A	09/01/2002
		JP 2002-005077 A	09/01/2002
		JP 2002-017849 A	22/01/2002
		JP 2002-021763 A	23/01/2002
		JP 4252197 B2	08/04/2009
		JP 4555437 B2	29/09/2010
		JP 4651157 B2	16/03/2011
		US 2001-0053330 Al	20/12/2001
US 6394769 Bl	28/05/2002	AU 1999-38657 Al	08/11/1999
		AU 1999-38657 B2	29/11/2001
		AU 2001-24289 Al	18/06/2001
		CA 2330048 Al	28/10/1999
		CA 2330048 C	20/04/2004
		CA 2393772 Al	14/06/2001
		EP 1073844 A2	07/02/2001
		EP 1073844 Bl	26/12/2012
		EP 1235983 Al	04/09/2002
		JP 2002-512333 A	23/04/2002
		JP 2003-516212 A	13/05/2003
		KR 10-2001-0071171 A	28/07/2001

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
		US 2002-0094281 Al	18/07/2002
		us 2008-0240947 Al	02/10/2008
		us 6074180 A	13/06/2000
		us 6302661 Bl	16/10/2001
		us 6595762 B2	22/07/2003
		us 7462019 Bl	09/12/2008
		¥0 01-42653 Al	14/06/2001
		Wo 99-53974 A2	28/10/1999
		¥0 99-53974 A3	09/03/2000