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(54) **METHOD AND APPARATUS FOR SENSING OF LEVITATED ROTOR POSITION**

(71) Applicant: **WORLD HEART CORPORATION**, Salt Lake City, UT (US)

(72) Inventors: **Carl C. Ketcham**, Murray, UT (US); **Gill Beamson**, Salt Lake City, UT (US)

(73) Assignee: **World Heart Corporation**, Salt Lake City, UT (US)

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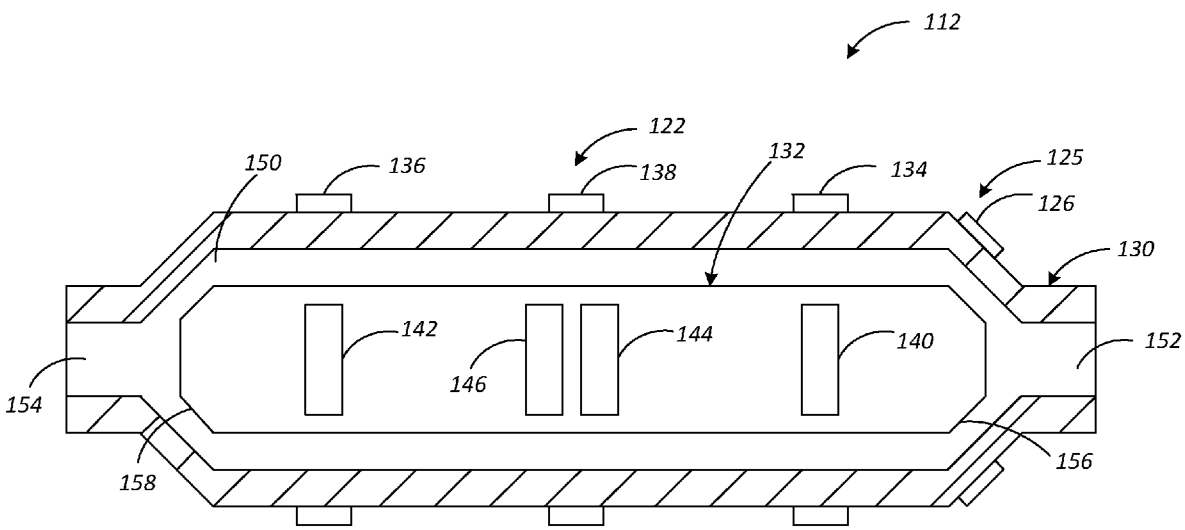
(57) **ABSTRACT**

A pump with magnetically-levitated rotor includes a position sensor having an eddy-current sensor coil that operates as a resonating element in a low frequency oscillator located within the pump housing. The oscillator is operably interconnected with additional electronics that shift the frequency of the oscillator output signal to a lower frequency. The lower frequency signal is directed to a frequency measurement circuit that provides a value representing a position of the rotor.



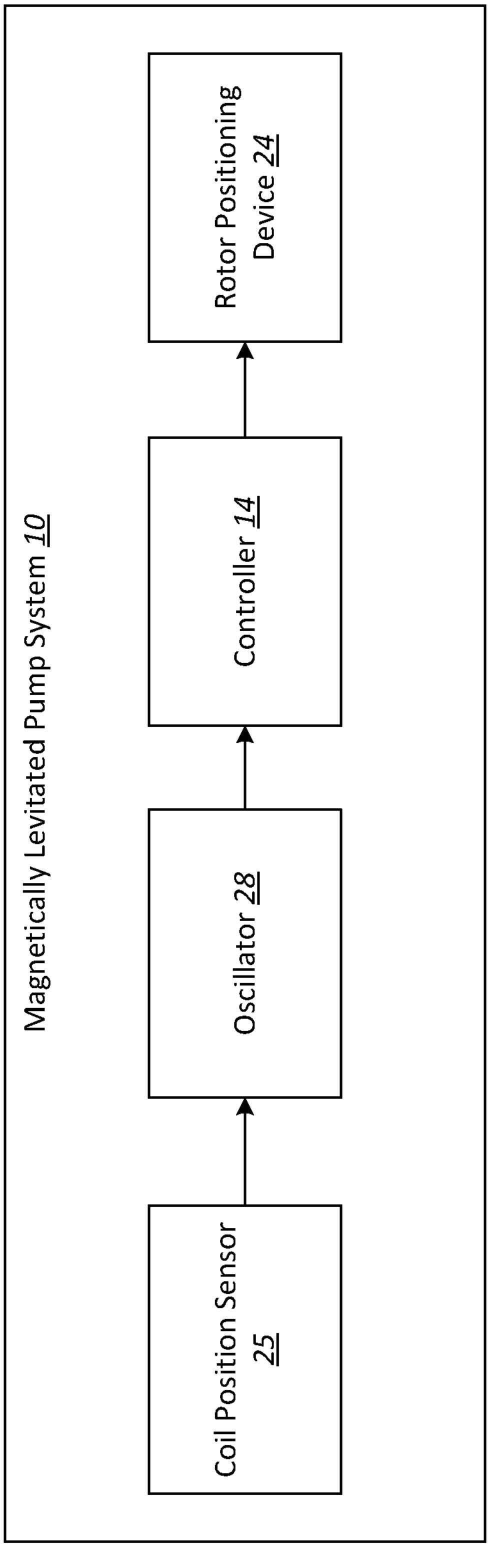

Magnetically Levitated Pump System 10
Coil Position Sensor 25
Oscillator 28
Controller 14
Rotor Positioning Device 24

FIG. 1

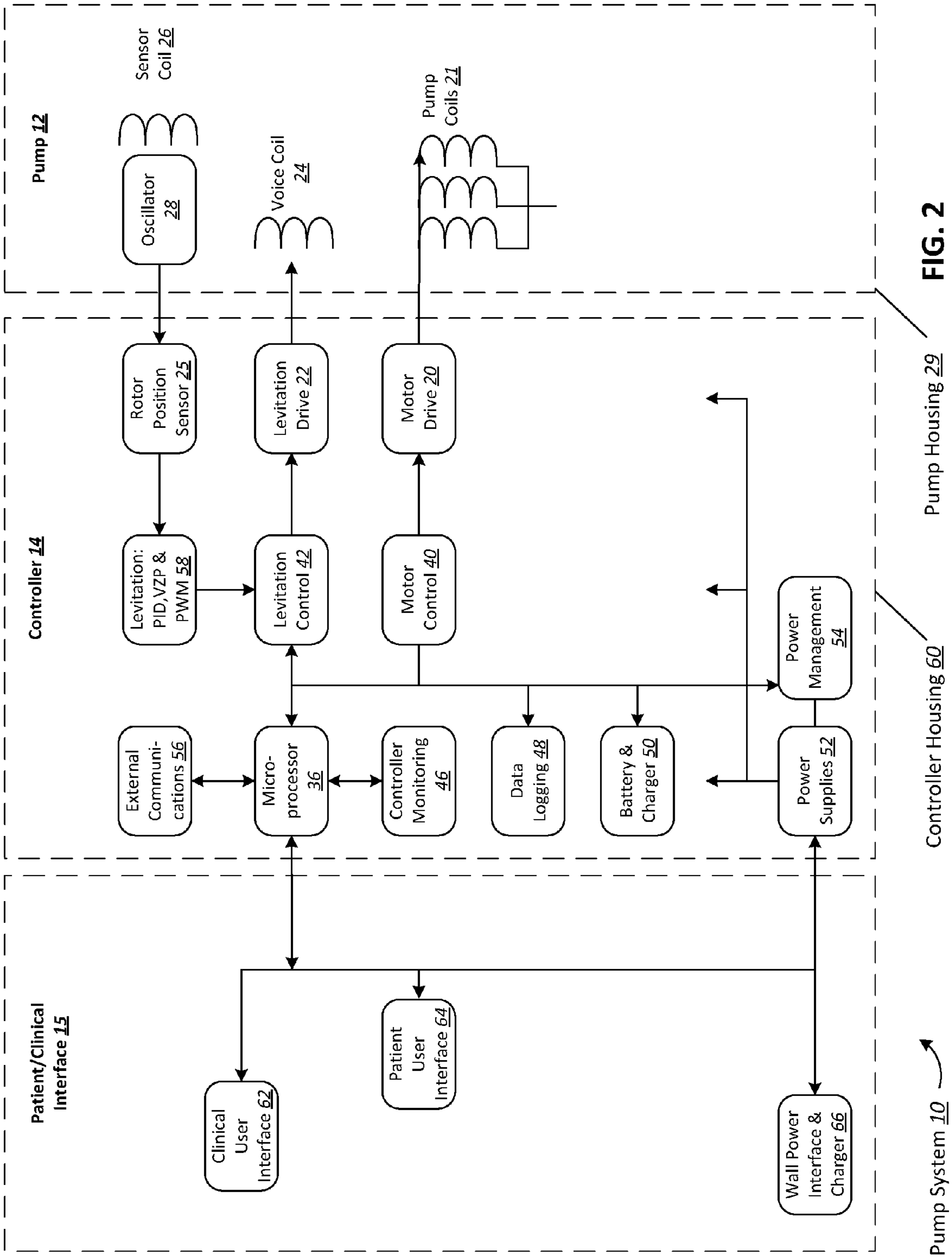

Pump 12
Sensor Coil 26
Oscillator 28
Voice Coil 24
Pump Coils 21
Controller 14
Rotor Position Sensor 25
Levitation Drive 22
Motor Drive 20
Levitation: PID,VZP & PWM 58
Levitation Control 42
Motor Control 40
Power Management 54
External Communications 56
Micro-processor 36
Controller Monitoring 46
Data Logging 48
Battery & Charger 50
Power Supplies 52
Patient/Clinical Interface 15
Clinical User Interface 62
Patient User Interface 64
Wall Power Interface & Charger 66
Pump Housing 29
Controller Housing 60
Pump System 10

FIG. 2

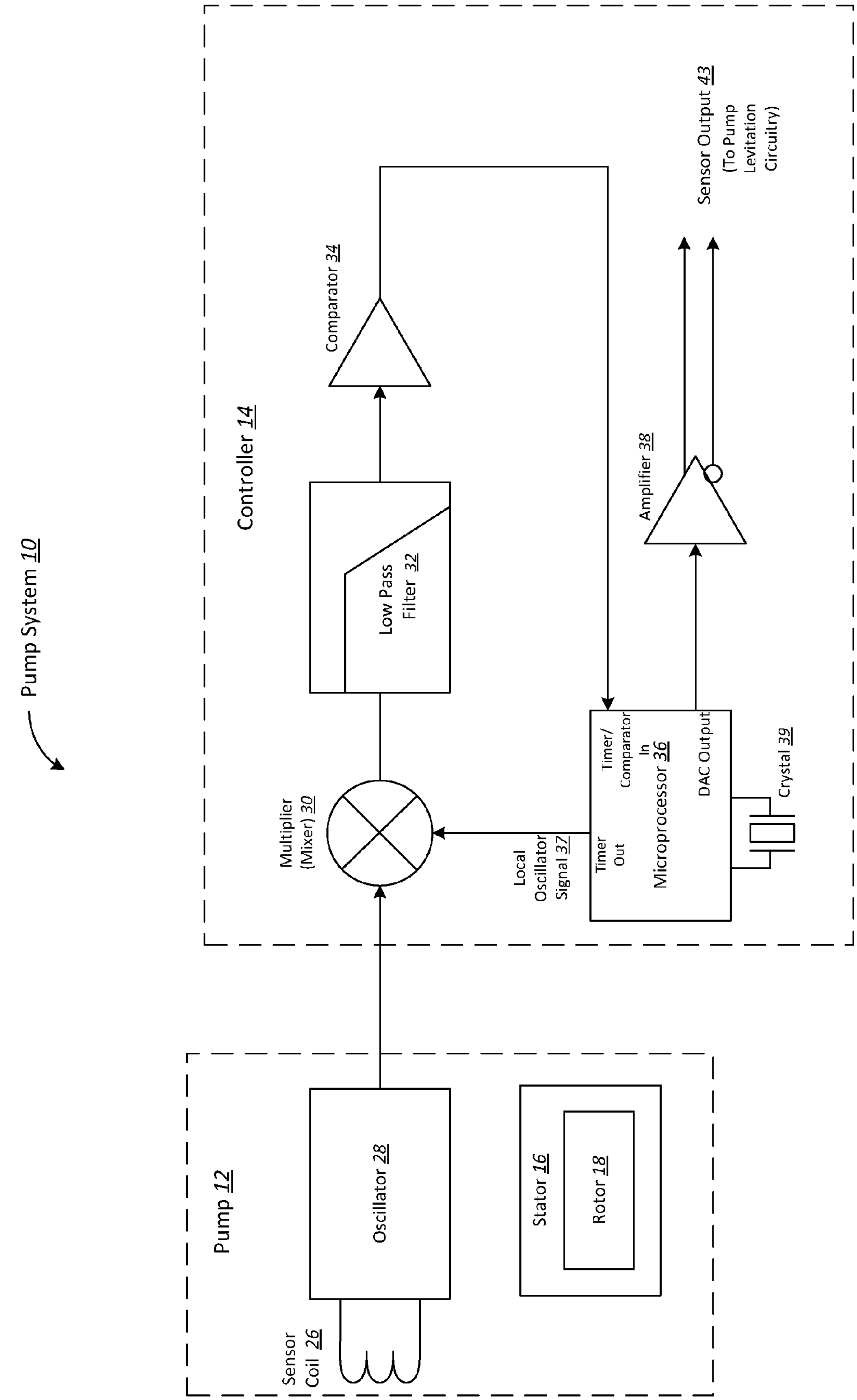

Pump System 10
Controller 14
Comparator 34
Low Pass Filter 32
Multiplier (Mixer) 30
Local Oscillator Signal 37
Timer Out
Timer/ Comparator In
Microprocessor 36
DAC Output
Crystal 39
Amplifier 38
Sensor Output 43
(To Pump Levitation Circuitry)
Pump 12
Oscillator 28
Stator 16
Rotor 18
Sensor Coil 26

FIG. 3

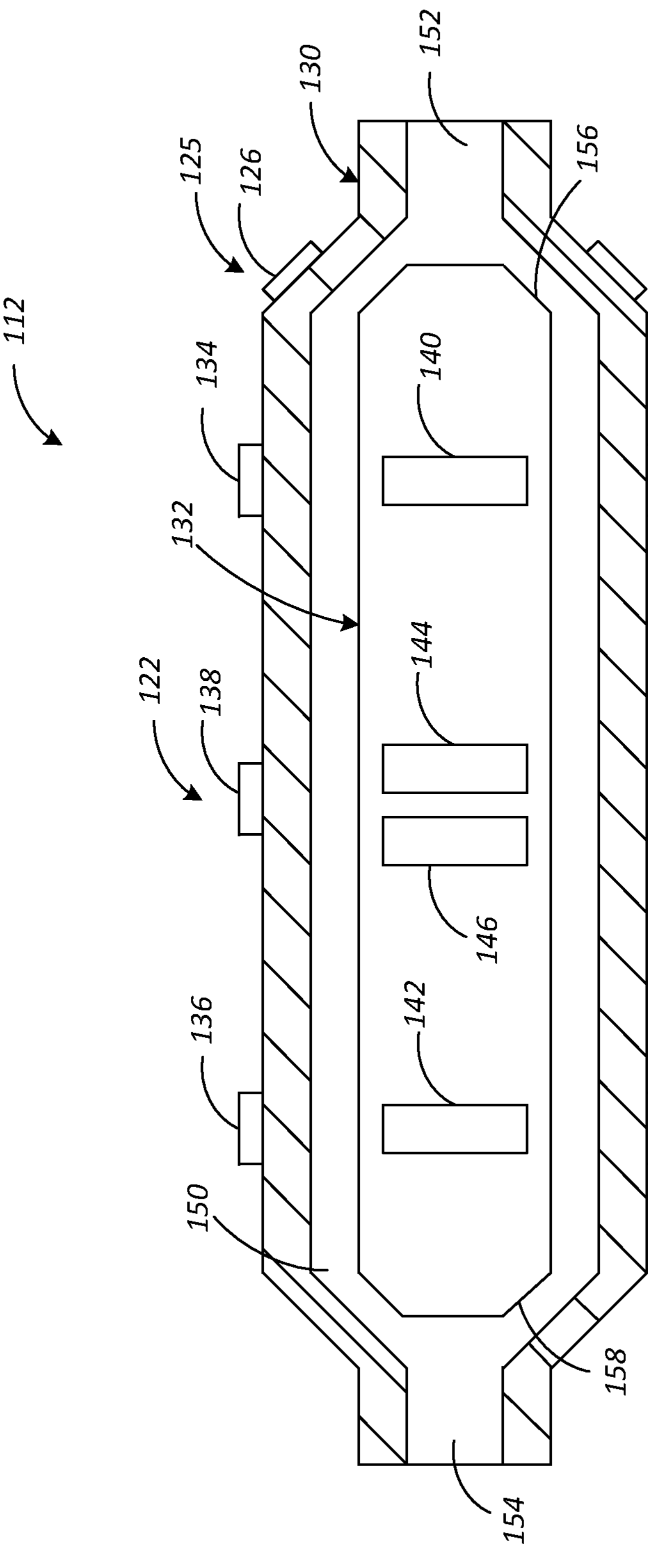

112
125
126
130
152
156
134
140
132
144
122
138
146
136
142
150
158
154

FIG. 4

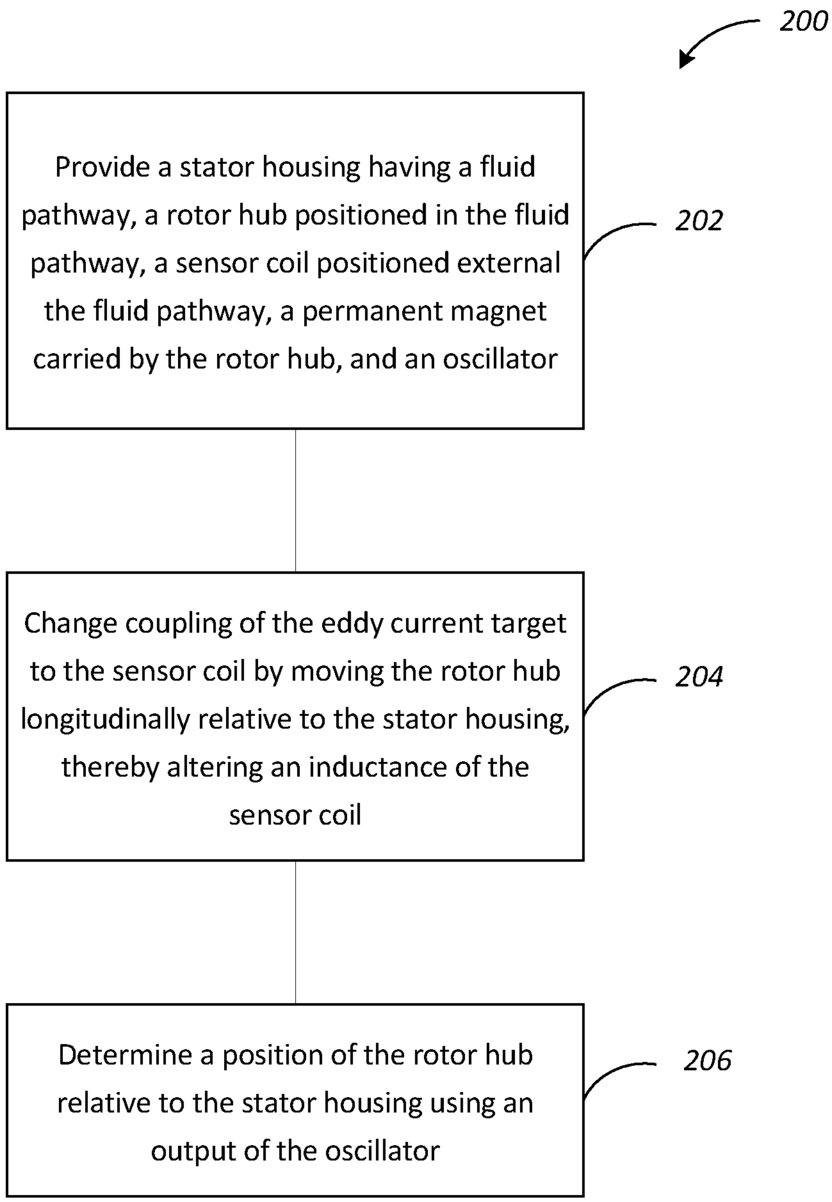

200
Provide a stator housing having a fluid pathway, a rotor hub positioned in the fluid pathway, a sensor coil positioned external the fluid pathway, a permanent magnet carried by the rotor hub, and an oscillator
202
Change coupling of the eddy current target to the sensor coil by moving the rotor hub longitudinally relative to the stator housing, thereby altering an inductance of the sensor coil
204
Determine a position of the rotor hub relative to the stator housing using an output of the oscillator
206

FIG. 5

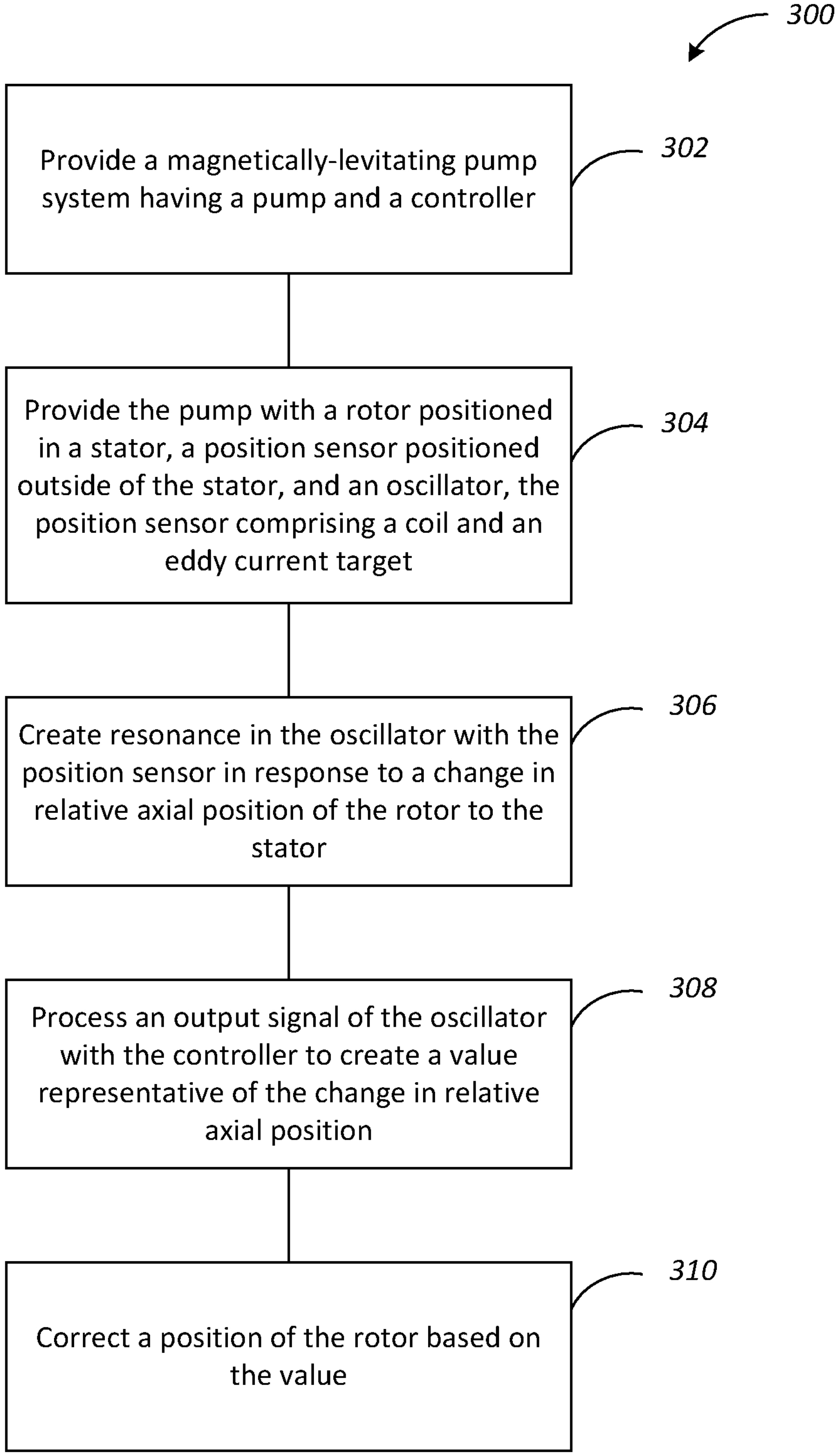

300
Provide a magnetically-levitating pump system having a pump and a controller
302
Provide the pump with a rotor positioned in a stator, a position sensor positioned outside of the stator, and an oscillator, the position sensor comprising a coil and an eddy current target
304
Create resonance in the oscillator with the position sensor in response to a change in relative axial position of the rotor to the stator
306
Process an output signal of the oscillator with the controller to create a value representative of the change in relative axial position
308
Correct a position of the rotor based on the value
310

FIG. 6

METHOD AND APPARATUS FOR SENSING OF LEVITATED ROTOR POSITION

RELATED APPLICATIONS

[0001] This application claims the benefit of U.S. Provisional Application Ser. No. 61/613,307, filed Mar. 20, 2012, entitled "Method and Apparatus for Sensing of Levitated Rotor Position," which is incorporated herein by reference.

TECHNICAL FIELD

[0002] The present disclosure relates generally to position sensors, and more specifically relates to position sensors for magnetically-levitating pumps, such as cardiac assist pumps that may be implanted in a patient.

BACKGROUND OF THE INVENTION

[0003] Rotor dynamic pumps, such as centrifugal, mixed-flow, and axial-flow pumps with mechanical bearings or magnetically suspended systems, have been widely used as a ventricular assist device to support patients with heart diseases. In magnetically-levitated blood pumps, which generally include an impeller or rotor that is both magnetically suspended and rotated without mechanical means, the magnetic bearings may be used to constrain motion in a longitudinal direction and active elements may be used to control a lateral position of the rotor. There is a relatively narrow region of travel along the longitudinal axis over which this constraint applied by the magnetic bearings occurs, and over which there is an adequate force to maintain the concentricity of the rotating element (e.g., rotor) with the longitudinal axis. The magnetic bearing forces tend to push the rotor longitudinally away from this narrow functional region. A control system is used to sense the longitudinal position of the rotor, and based on this position, apply a force to counter the travel away from the intended location and maintain the rotor in the desired longitudinal position.

[0004] For magnetically-levitated pumps, it has historically been a difficult problem to determine the rotor's longitudinal position with suitable precision and with a sufficient bandwidth to maintain a stable position along the longitudinal axis. This difficulty is due, at least in part, to the sealed nature of the fluid flow path through the stator. In particular, in blood pumps, titanium alloys are used for compatibility with the blood. The use of titanium requires that the rotor position sensor be able to sense the position of the rotor through at least one layer of titanium.

[0005] Existing control systems that attempt to address these problems related to magnetically-levitated pumps have suffered from a number of shortcomings. For example, such systems are sensitive to external electrical noise such as radio signals, changing magnetic fields within the pump, temperature changes in the pump, temperature changes in the controller, and temperature changes in the cable that connects the pump to the controller. These systems also have limitations related to minimizing a size of the pump housing because of the large number and size of the electronics that are typically required to be positioned inside the pump housing. The sensitivity to changes in cable impedance is also problematic due to fluid ingress, flexure or other reasons.

SUMMARY OF THE INVENTION

[0006] Various embodiments of position sensors for magnetically-levitated pumps are set forth herein in accordance with the present disclosure.

[0007] In accordance with one embodiment of the present disclosure, a magnetically-levitated pump includes a position sensor having an eddy-current sensor coil that operates as a resonating element in a low frequency oscillator located within the pump housing. The oscillator is operably interconnected with additional electronics that shift the frequency of the oscillator output signal to a lower frequency. The lower frequency signal is directed to a frequency measurement circuit that provides a value representing a position of the rotor along the longitudinal axis of the pump. The value may be in the form of, for example, a binary number, an electrical circuit, an electrical voltage, or other representation.

[0008] An alternative position sensor includes an eddy-current sensor coil that operates as a resonating element in a low frequency oscillator that is positioned within the pump housing. An output from the oscillator may be operably connected with the input to a phase locked loop or frequency locked loop. The output of the phase locked loop or frequency locked loop may be a feedback value that represents a position of the rotor along the longitudinal axis of the pump. The feedback value may be in the form of, for example, a binary number, an electrical current, an electrical voltage, or other representation.

[0009] Either of the example position sensors described above may be associated with at least one memory element that stores calibration, characterization, correction, and other parameters for the pump or the controller. The parameters may permit the pump to be operably interchanged with any similar pump. For example, a common controller positioned remotely of the pump housing may be used with any of a number of different pumps because each pump separately carries a number of the parameters stored in memory that are accessible by the controller. Similarly, any given pump may be used with a plurality of different controllers because of parameters of the controller that are stored by the controller.

[0010] The frequency measurements in the example circuitry described herein may include a high speed counter that is configured to measure an interval of time between cycles of the low frequency signal. The number of cycles of the low frequency signal may be measured over a specified time interval. A microprocessor of the pump system may include such a timer/counter subsystem.

[0011] Another aspect of the present disclosure relates to a pump system configured to provide fluid flow and that includes a stator housing, a rotor hub, and an eddy current sensor coil. The stator housing has an inlet, an outlet and a fluid pathway. The rotor hub is disposed within the fluid pathway between the inlet and the outlet, and includes a body having a leading portion positioned adjacent the inlet and a trailing portion positioned adjacent the outlet. The eddy current sensor coil is positioned external the fluid pathway and operable to determine a position of the rotor hub relative to the stator housing. The sensor coil operates as a resonating element in a low-frequency oscillator.

[0012] The pump system may include a frequency shifting device that shifts a frequency of an output signal from the oscillator to a lower frequency signal. The pump system may include a frequency measurement circuit that measures the frequency of the lower frequency signal and outputs a value representative of a position of the rotor hub relative to the stator housing. The value that is output from the frequency measurement circuit may be in the form of a binary number, an electrical current, or an electrical voltage. The pump system may include a phase-locked loop that locks a phase of an output from the oscillator. The pump system may include a frequency-locked loop that locks a frequency of an output from the oscillator. The pump system may include a memory element containing at least one of calibration, characterization, and correction parameters for the sensor coil.

[0013] The pump system may include a high speed counter configured to measure an interval of time between cycles of the lower frequency signal. The pump system may include a high speed counter configured to measure a number of cycles of the lower frequency signal over a specified time interval. The pump system may include a pump housing, wherein the stator housing, rotor hub, and sensor coil are positioned within the pump housing. The pump system may include a microprocessor positioned remote from the pump housing. The pump system may include a permanent magnet bearing and a magnet motor, wherein the magnet motor includes a motor magnet carried by the rotor hub and a motor coil carried by the stator housing. The at least one permanent magnet bearing levitates the rotor hub within the stator housing, and the magnet motor is operable to rotate the rotor hub within the stator housing.

[0014] Another aspect of the present disclosure relates to a sensor assembly for a pump with a magnetically-levitating rotor. The sensor assembly includes a sensor coil positioned on a stator of the pump, a rotor of the pump that is arranged within the stator and having a conductive surface, and a low frequency oscillator positioned within a housing of the pump. The sensor coil may operate as a resonating element in the low frequency oscillator in response to a change in relative position between the conductive surface and sensor coil. An output signal from the low frequency oscillator is used to adjust a position of the rotor relative to the stator. An output of the low frequency oscillator may be in the range of about 200 kHz to about 350 kHz. An output of the low frequency oscillator may be a sine wave signal.

[0015] Another aspect of the present disclosure relates to an active magnetically levitating pump system configured to provide fluid flow. The pump system includes a stator housing having a fluid pathway, a rotor disposed within the fluid pathway, and an eddy current sensor coil. The eddy current sensor coil is positioned external the fluid pathway and operable to determine a position of the rotor with respect to a defined axis of the stator housing. The sensor coil operates as a resonating element in a low-frequency oscillator.

[0016] The eddy current sensor coil may be operable to determine a position of the rotor with respect to a longitudinal axis of the stator housing. The eddy current sensor coil may be operable to determine a position of the rotor with respect to a lateral axis of the stator housing. The pump system may include a pump housing, wherein the stator housing, rotor and eddy current sensor coil are positioned in the pump housing. The low-frequency oscillator may be positioned in the pump housing.

[0017] A further aspect of the present disclosure relates to a method of determining a rotor position in a stator housing. The method includes providing a stator housing having a fluid pathway, a rotor hub positioned in the fluid pathway, a sensor coil positioned external the fluid pathway, and an oscillator. The method further includes inducing eddy currents in the rotor hub via the magnetic field of the sensor coil, which eddy currents in turn produce magnetic fields that interact with the magnetic fields of the sensor coil as the rotor hub is moved relative to the stator housing, wherein the sensor coil operates as a resonating element in the oscillator. The method also includes determining a position of the rotor hub relative to the stator housing using an output of the oscillator.

[0018] The method may include shifting a frequency of a signal that is output from the oscillator to create a lower frequency signal, measuring the lower frequency signal, and providing a value for the measured lower frequency signal that represents a position of the rotor hub relative to the stator housing. The method may include locking a phase of a signal output from the oscillator to create a phase locked signal, measuring the phase locked signal, and providing a value for the measured phase locked signal that represents a position of the rotor hub relative to the stator housing. The method may include locking a frequency of a signal output from the oscillator to create a frequency locked signal, measuring the frequency locked signal, and providing a value for the measured frequency locked signal that represents a position of the rotor hub relative to the stator housing. The method may include magnetically-levitating the rotor hub in the fluid pathway, and controlling a longitudinal position of the rotor hub relative to the stator housing in response to the determined position of the rotor hub.

[0019] Another example method in accordance with the present disclosure relates to determining a position of a rotor within a housing in a magnetically-levitating pump system. The method includes providing a controller and a pump, wherein the pump includes a rotor, a stator, a position sensor, and an oscillator, the rotor is positioned in the stator, the position sensor is positioned outside of the stator. The position sensor includes a coil. The method includes creating a change in frequency in the oscillator with the position sensor in response to a change in position of the rotor relative to the stator, processing an output signal of the oscillator with the controller to create a correction or error value representative of the change in relative axial position, and correcting a position of the rotor based on the value.

[0020] The method may also include correcting the position of the rotor with a voice coil. The method may include providing a controller that is positioned remote from the oscillator and includes a microprocessor configured to determine the correction or error value using the output signal of the oscillator.

BRIEF DESCRIPTION OF THE DRAWINGS

[0021] The foregoing and other advantages of the invention will become apparent upon reading the following detailed description and upon reference to the drawings in which:

[0022] FIG. **1** is a block diagram showing an example pump rotor levitation system in accordance with the present disclosure.

[0023] FIG. **2** is a block diagram showing additional features of the pump system of FIG. **1**.

[0024] FIG. **3** is a circuit diagram showing circuit components of the pump system of FIG. **1**.

[0025] FIG. **4** is a mechanical diagram showing bearing and positioning components of a pump housing of the pump system of FIG. **2**.

[0026] FIG. **5** is a flow diagram showing an example method in accordance with the present disclosure.

[0027] FIG. **6** is a flow diagram showing another example method in accordance with the present disclosure.

DETAILED DESCRIPTION OF THE INVENTION

[0028] Embodiments are described more fully below in sufficient detail to enable those skilled in the art to practice the system and method. However, embodiments may be implemented in many different forms and the present disclosure should not be construed as being limited to the embodiments set forth herein. The following detailed description is, therefore, not to be taken to be limiting in any sense. For purpose of illustration, discussions of the technology will be made in reference to its utility as a cardiac assist blood pump. However, it is to be understood that the technology may have a variety of wide applications to many types of turbomachinery including, for example, commercial and industrial pumps, compressors, and turbines.

[0029] The present disclosure is directed to a magnetically-levitated pump system that includes a pump and a controller. The pump and controller are typically positioned remote from each other and interconnected with a cable. The pump includes a magnetically-levitated pump and some circuitry. The controller includes a microprocessor and other circuitry. The pump includes a position sensor that senses a position of a rotor that is arranged within a stator of the pump. The position sensor determines a position of the rotor in a longitudinal direction with respect to an inlet or outlet of a flow path through the stator.

[0030] The positioning sensor (also referred to as a resonance sensor) may include a coil that acts as a frequency determining element of a radio frequency oscillator positioned within a housing of the pump. The output of the oscillator is directed to a frequency measuring mechanism, the output of which is directed to an analog or digital converter to obtain a sensor output. Described in another way, the sensor coil acts as a resonant member of an oscillator that varies in accordance with relative axial movement between the rotor and stator. The oscillator, also positioned within the pump housing in proximity to the pump, provides an output signal that is output at a relatively high level (e.g., at about 1 volt peak to peak) through the cable to the controller where the controller operates to measure that frequency. The measured frequency is correlated to an axial position of the rotor relative to the stator. The output from the controller may be used as a position value then used by a position altering device of the pump (e.g., a voice coil) to move the rotor relative to the stator.

[0031] The circuit components positioned inside the pump housing may be selected such that the circuitry of the pump system is less subject to external electromagnetic fields and radio signals. The circuitry replaces the quadrature sensor and related Wheatstone bridge used for the coil position sensor in prior devices. In one example, the circuitry utilizes a Colpitts oscillator or other oscillators well known in the art that have been updated to use transistors and require a relatively small number and size for the surface mount components.

[0032] Referring now to FIG. **1**, an example magnetically-levitated pump system **10** is shown schematically including a position sensor coil **25** (also referred to as a rotor position sensor or a rotor position sensor coil), an oscillator **28**, a controller **14**, and a rotor positioning device **24** (also referred to as a voice coil **24**). The position sensor coil **25**, oscillator **28** and rotor positioning device **24** are typically positioned within a housing of the pump. The controller **14** is typically positioned remote from the pump. The coil position sensor **25** is typically mounted to an exterior of a stator of the pump and includes a wire coil. A rotor positioned within the stator may carry or comprise a conductive material. The rapidly changing magnetic field induced by oscillator current flowing through the position sensor coil **25** causes currents to be induced in a conductive surface of the rotor. These currents, in turn, produce a magnetic field which interacts with the sense-coil-induced magnetic field, and affect a flow of energy from a current in the position sensor coil **25**, to a magnetic field, and back to a current in the position sensor coil **25**. This change is reflected as a change in inductance of the coil position sensor **25**, which is a measurable parameter. The change in inductance, in turn, changes the frequency of the oscillator **28**.

[0033] An output of the oscillator **28** is delivered to the controller **14** and converted to a value that represents a relative position of the rotor to the stator. This value may be communicated to a rotor positioning device **24** that adjusts the position of the rotor relative to the stator. The rotor positioning device **24** may be a voice coil. The voice coil may comprise a plurality of wire coils positioned on an exterior of the stator and a magnet carried by the rotor that is aligned radially with the wire coils of the voice coil.

[0034] U.S. Published Patent Application No. 2011/0237863 discloses various components of a magnetically-levitated pump such as the rotor, stator, magnetic bearings and voice coil, and is incorporated herein in its entirety by this reference. Many other types of pumps and motors (e.g., a reciprocating pump) having different configurations that utilize various technologies may also be applicable to the present disclosure. FIG. **4** shows schematically an example magnetically-levitated pump **112** having at least some of the same or similar components included in pump **12**. Pump **112** includes levitation components **122**, rotor position components **125**, a stator housing **130**, a rotor **132**, fixed bearing magnets **134**, **136** mounted to the stator housing **130**, and suspended bearing magnets **140**, **142** carried by the rotor **132**. The levitation components **122** include a voice coil **138** mounted to the stator housing **130**, and first and second voice coil magnets **144**,**146** carried by the rotor **132**. The rotor position sensor **125** includes a sensor coil **126** mounted to the stator housing **130**. The stator housing **130** includes a fluid channel **150**, an inlet **152** and an outlet **154**. The rotor **132** includes first and second ends **156**, **158**. The first end **156** may function as a conductive sensor target. The rotor position sensor **125** may operate to determine a position of the rotor **132** with respect to an axis or other feature of the stator housing **130**, such as a longitudinal position or a lateral position with respect to a longitudinal or lateral axis of the stator housing **130**, respectively.

[0035] FIG. **2** illustrates additional components of the pump system **10**. The pump system **10** includes a pump **12**, the controller **14**, and a patient/clinical interface **15**. The pump **12** and controller **14** are typically interconnected with a cable that provides electronic communication between the pump **12** and controller **14**. The patient/clinical interface **15** may be local to either the pump **12** or controller **14** (e.g., included in the housing of the controller **14**) or positioned remotely via an electronic connection. The electronic connection between any of the pump **12**, controller **14**, and patient/clinical interface **15** may be wired or wireless, wherein the wired or wireless connection may be accomplished at least in part using a communications network such as the Internet.

[0036] The pump **12** may include, in addition to the stator housing and the rotor positioned within the stator housing, a rotor position sensor **25**, an oscillator **28**, a sensor coil **26**, a levitation drive **22**, a voice coil **24**, and a motor drive **20** that includes a plurality of pump coils **21**. The rotor position sensor **25**, levitation drive **22**, and motor drive **20** may each include at least one magnet that is carried by the rotor and positioned within the stator. The sensor coil **26**, voice coil **24**, and pump coils **21** are typically all positioned outside of the stator or at least outside of a flow pathway within which the rotor is positioned.

[0037] The controller **14** comprises one or more microprocessors **36**, a motor control **40**, the rotor position sensor **25**, a levitation control **42**, a controller monitoring device **46**, a data logging device **48**, a battery and charger **50**, a power supply **52**, a power management device **54**, an external communication **56**, and a levitation system **58** (e.g., a PID, VZP and PWM). The microprocessors **36** communicate with each of the rotor position sensor **25**, levitation drive **22** and motor drive **20**. The rotor position sensor **25**, levitation drive **22** and motor drive **20** may communicate with the oscillator **28**, voice coil **24**, and pump coils **21**, respectively, via electronic communication provided by a cable interconnecting the pump **12** and controller **14**.

[0038] The patient/clinical interface **15** may include a clinical user interface **62**, a patient user interface **64**, and a wall power interface and charger **66**. The clinical user interface **62** may be provided locally or remotely relative to the controller **14** and pump **12**. Similarly, the patient user interface **64** may be carried by the controller **14** or the pump **12**. The clinical user interface **62** and patient user interface **64** may provide a clinician and patient with the ability to control, modify, and receive feedback from the pump **12** and controller **14**.

[0039] Referring now to FIG. **3**, various circuit components of the pump system **10** are shown. The pump **12** may include the sensor coil **26** connected electronically to the oscillator **28**. As described above, the sensor coil **26** may act as a resonating element for the oscillator **28**. The pump may also include a stator **16** (also referred to as a stator housing) and rotor **18** (also referred to as a rotor hub). The sensor coil **26** may be mounted to the stator **16** and positioned external of a flow pathway of the stator within which the rotor **18** is positioned.

[0040] An output of the oscillator **28** may be directed to a multiplier **30** (also referred to as a mixer **30**) of the controller **14**. Controller **14** also includes a low pass filter **32**, a comparator **34**, at least one microprocessor **36**, and an amplifier **38**. The microprocessor **36** may be an MSP430 processor. The microprocessor **36** may provide a local oscillator signal **37** back to the multiplier **30**. A crystal **39** may be associated with the microprocessor **36** to provide electronic stability. The microprocessor **36** may include a timer/comparator input to receive signals from the comparator **34**, and a DAC output connected to the amplifier **38**. The amplifier **38** may provide a sensor output **43** that is directed back to levitation circuitry of pump **12** (e.g., a voice coil rotor positioning device) to adjust a position of the rotor **18** relative to the stator **16**. Alternatively, the sensor output **43** may be coupled to the levitation circuitry in a digital fashion, without need of a DAC or amplifier.

[0041] In one example, the oscillator **28** typically oscillates at around 250 kHz, and preferably somewhere in the range of about 220 kHz to about 350 kHz. The multiplier **30** may be a diode double balanced mixer. The multiplier **30** may mix the signal received from the oscillator **28** with the local oscillator signal **37** received from the microprocessor **36**. In one example, the microprocessor **36** may be running at about 20 mHz, which frequency may be divided down to whatever frequency is required for the local oscillator signal **37** for use in calibrating.

[0042] A frequency range received in the signal from pump **12** is measured, and from that measured frequency a 20 kHz offset to the local oscillator signal **37** may be used, followed by finding a nearest integer divisor from 20 mHz that will be close to the local oscillator signal **37**. Typically, some correction factors are applied such as a gain or an offset to obtain a signal that accurately represents the rotor position.

[0043] In one example, the oscillator signal coming from oscillator **28** is about 250 kHz, which is nominal within about 250-254 kHz moving over the range of the rotor positioning sensor. In one example, the local oscillator signal **37** is preferably set at about 230 kHz. The difference frequency would be about 20 kHz up to about 24 kHz and a sum of the frequencies would be about 480 kHz to about 484 kHz. The signal is then directed through the low pass filter **32** that filters out the summed frequency so that the low frequency component remains.

[0044] The low frequency component is then directed to the comparator **34**. The comparator **34** may be a squaring comparator that provides a square wave output in the range of about 20 kHz. The signal from the comparator **34** may be directed to a timer/comparator input of the microprocessor **36**, which may also be referred to as a clock input, counter input or high speed counter. In at least one example, a time interval measurement between when the signal crosses zero becomes proportionate to a position of the rotor relative to the stator. The microprocessor **36** corrects for calibration errors and converts the signal to a number, possibly represented by a voltage range that is appropriate for use by the rotor positioning member (e.g., the voice coil).

[0045] By putting the oscillator **28** within a housing of the pump **12**, the signal delivered to the microprocessor in the controller **14** and received back from the microprocessor **36** to the rotor positioning member is much less sensitive to minor voltage changes that may be induced with the cable that interconnects the pump **12** and controller **14**. Some arrangements include positioning the oscillator **28** at other locations, such as adjacent to the controller **14** at a location remote from the housing of the pump **12**.

[0046] Another aspect of the present disclosure relates to the interchangeability of the pump **12** and controller **14** with other pumps and controllers. The calibration constants for the pump may be stored in memory (e.g., an ID chip) of the pump, and calibration constants for the controller may be stored in memory of the controller. For example, the pump may have calibration constants A, B, C that are stored in memory of the pump. The controller may have calibration coefficients D and E that are stored in memory of the controller. When the pump is connected to the controller, an ID chip of the pump is connected in electronic communication with the controller. The pump calibration coefficients are downloaded to the controller. The controller uses those pump coefficients to correct the frequency of the signal received from the oscillator of the pump. For example, the pump parameters are used to set the local oscillator signal **37** in FIG. **3** so that the correct local oscillator frequency **37** is used for calibrating the frequency that is being received from the oscillator **28** of the pump.

[0047] In one example, the pump parameters are determined during manufacture of the pump. The pump is tested during manufacturing to receive certain data such as, for example, a frequency measurement from the oscillator when the rotor is moved longitudinally to the inlet and another frequency measurement when the rotor is moved to the outlet of the stator. The various pump parameters may be calculated based on these two frequency measurements. The pump parameters may be used to determine, for example, the local oscillator divisor or signal, a pump gain, and a pump offset. Those parameters are stored in memory of the pump (e.g., on an ID chip of the pump). Similarly, the controller is tested during manufacturing to determine a DAC divisor and DAC offset, which is essentially a first order correction to the sensor output **43** of FIG. **3**.

[0048] In one example, the pump includes about 20 to 25 circuit components as part of the oscillator **28** that are positioned inside the pump housing. Of these components, 4 to 6 may critically affect the accuracy of the oscillator. The controller may include multiple resistors (e.g., preferably about 4 to 5 resistors) that set gains and offsets for the controller output. The parameters of the pump and controller are typically relatively stable in the presence of variations in temperature. Further, a crystal **39**, which is typically stable with changes in temperature, is used in connection with the microprocessor **36** to even further stabilize the pump system **10**.

[0049] Another aspect related to the pump system disclosed herein relates to the number of components and the related complexity of the system corresponding to the number of components. Some types of pump systems include at least 50 components associated with the accuracy of the position sensor circuitry. The numerous amplifier stages and associated gains and offsets for these components all affect the performance of the pump. The pump of the present disclosure uses only a few critical circuit components, which are primarily for the oscillator. The pump circuit components may be thermally stabilized using known techniques, such as negative temperature coefficient capacitors and properties of the sensor coil and the larger capacitors that make up the oscillator. The pump circuitry may be simpler to manufacture, test and maintain because of its few number of critical components.

[0050] Another advantage related to the reduced number of components in the pump system **10** as compared to other pump systems relates to the power usage of the pump system. Other rotor sensor systems use as many as at least 100 to 150 circuit components for the pump and controller, which may consume several watts of power. The rotor position sensor system of the present disclosure may be configured to consume power in the order of 60 to 1,000 milliwatts and more preferably in the range of about 20 to 100 milliwatts. In scenarios where the pump system **10** is battery-operated, the amount of power consumption can be an important design factor. Furthermore, the increased use of power and the number of components affects the amount of heat generated within the pump housing and controller housing. The reduced number of components in the pump system of the present disclosure and the related decreased amount of heat generated may lead to improved consistency in performance, increased component life, and increased battery life.

[0051] Referring now to FIGS. **5** and **6**, several example methods of determining a rotor position in a stator housing are described. FIG. **5** shows an example method **200** that includes a step **202** of providing a stator housing having a fluid pathway, a rotor hub positioned in the fluid pathway, a sensor coil positioned external to the fluid pathway, a conductive target carried by the rotor hub, and an oscillator. A step **204** includes changing coupling of the eddy current target to the sensor coil by moving the rotor hub longitudinally relative to the stator housing, thereby altering an inductance of the sensor coil. The sensor coil operates as a resonating element in the oscillator. A step **206** includes determining a position of the rotor hub relative to the stator housing using an output of the oscillator.

[0052] Other steps of method **200** may include shifting a frequency of a signal output from an oscillator to create a lower frequency signal, measuring the lower frequency signal, and providing a value for the measured lower frequency signal that represents a position of the rotor hub relative to stator housing. Another step for method **200** may include locking a phase of the signal output from the oscillator to create a phase locked signal, measuring the phase locked signal, and providing a value for the measured phase locked signal that represents a position of the rotor hub relative to the stator housing. A further method step may include locking a frequency of the signal output from the oscillator to create a frequency locked signal, measuring the frequency locked signal, and providing a value for the measured frequency locked signal that represents a position of the rotor hub relative to the housing. The method **200** may also include magnetically-levitating the rotor hub in the fluid pathway, and controlling a longitudinal position of the rotor hub relative to the stator housing in response to the determined position of the rotor hub.

[0053] FIG. **6** illustrates a method **300** of determining a position of a rotor within a housing in a magnetically-levitating pump system. The method **300** includes a step **302** of providing a magnetically-levitating pump system having a pump and a controller. A step **304** includes providing the pump with a rotor positioned in a stator, a position sensor positioned outside of the stator, and an oscillator, wherein the position sensor comprises a coil. A step **306** includes creating resonance in the oscillator with the position sensor in response to a change in relative axial position of the rotor to the stator. A step **308** includes processing an output signal of the oscillator with the controller to create a value representative of the change in relative axial position. A step **310** includes correcting a position of the rotor based on the value.

[0054] The position of the rotor may be corrected using a voice coil. The magnetically-levitating pump system may further include a magnetic bearing and a magnetic motor. The controller may include a microprocessor configured to determine the rotor position value using the output signal of the oscillator. The controller may include a multiplier, a low-pass filter, a comparator and an amplifier to create an output signal having the value.

[0055] The term "resonant eddy current sensor" as used herein may generally refer to the class of measuring based on currents induced in a non-magnetic or non-contacting surface. The resonant eddy current sensor as disclosed herein may be used for measuring position based on magnetic or on electrical currents induced by a magnetic field from a coil that is positioned somewhere that is not touching the rotor. The term "frequency shifting" as used herein may relate to shifting the frequency of resonance or the signal that is the resonant frequency down to a frequency where the signal may be more readily measured.

[0056] A "phase lock resonant eddy current sensor" may receive the output of the oscillator **28** of the pump **12** and direct the output signal to a phase detector (e.g., delta phase) where the output signal is summed together and integrated. This summed and integrated signal is returned back for comparing to the oscillator output. The voltage (VCO) is adjusted to be analogous of the frequency and is called a control voltage in a phase lock loop. From there, the voltage may be digitized and used in a levitation system.

[0057] A phase locked resonant eddy current sensor may have similarities to a frequency locked resonant eddy current sensor. A phase locked resonant eddy current sensor measures the phase between two signals and controls the voltage based on that comparison. A frequency locked resonant eddy current sensor measures frequency and adjusts the voltage up and down on a DC arc to control the frequency.

[0058] The principles of the coil positioning sensor disclosed herein may be applied to magnetically levitated motor and magnetically levitated pumps, and specifically to magnetically levitated blood pumps. Principles disclosed herein may be useful in other applications outside of blood pumps where accurate measurements of the rotor position relative to the stator and obtaining a position signal relatively free of influence from outside environmental conditions is desired.

[0059] While the invention may be susceptible to various modifications and alternative forms, specific embodiments have been shown by way of example in the drawings and have been described in detail herein. However, it should be understood that the invention is not intended to be limited to the particular forms disclosed. Rather, the invention includes all modifications, equivalents, and alternatives falling within the spirit and scope of the invention as defined by the following appended claims. It is specifically noted that any features or aspects of a given embodiment described above may be combined with any other features or aspects of other described embodiments, without limitation.

What is claimed is:

1. A pump system configured to provide fluid flow, comprising:

a stator housing having an inlet and an outlet and a fluid pathway;

a rotor disposed within the fluid pathway between the inlet and the outlet, the rotor hub comprising a body having a leading portion positioned adjacent the inlet, a trailing portion positioned adjacent the outlet;

an eddy current sensor coil positioned external the fluid pathway and operable to determine a position of the rotor hub relative to the stator housing, the sensor coil operating as a resonating element in a low-frequency oscillator.

2. The pump system of claim **1**, further comprising a frequency shifting device that shifts a frequency of an output signal from the oscillator to a lower frequency signal.

3. The pump system of claim **2**, further comprising a frequency measurement circuit that measures the frequency of the lower frequency signal and outputs a value representative of a position of the rotor hub relative to the stator housing.

4. The pump system of claim **3**, wherein the value output from the frequency measurement circuit is in the form of a binary number, an electrical current, or an electrical voltage.

5. The pump system of claim **1**, further comprising a phase-locked loop that locks a phase of an output from the oscillator.

6. The pump system of claim **1**, further comprising a frequency-locked loop that locks a frequency of an output from the oscillator.

7. The pump system of claim **1**, further comprising a memory element containing at least one of calibration, characterization and correction parameters for the sensor coil.

8. The pump system of claim **2**, further comprising a high speed counter configured to measure an interval of time between cycles of the lower frequency signal.

9. The pump system of claim **2**, further comprising a high speed counter configured to measure a number of cycles of the lower frequency signal over a specified time interval.

10. The pump system of claim **1**, further comprising a pump housing, the stator housing, the rotor hub, and the sensor coil are positioned in the pump housing.

11. The pump system of claim **10**, further comprising a microprocessor positioned remote from the pump housing.

12. The pump system of claim **1**, further comprising at least one permanent magnet bearing and a magnet motor, the magnet motor comprising a motor magnet carried by the rotor hub and a motor coil carried by the stator housing, the at least one permanent magnet bearing levitating the rotor hub within the stator housing, and the magnet motor operable to rotate the rotor hub within the stator housing.

13. A sensor assembly for a pump with magnetically-levitating rotor, the sensor assembly comprising:

a sensor coil positioned on a stator of the pump;

a rotor of the pump arranged within the stator and having a conductive surface;

a low frequency oscillator positioned within a housing of the pump;

wherein the sensor coil operates as a resonating element in the low frequency oscillator in response to a change in relative position between the rotor and sensor coil, and an output signal from the low frequency oscillator is used to adjust a position of the rotor relative to the stator.

14. The sensor assembly of claim **13**, wherein an output of the low frequency oscillator is in the range of about 200 kHz to about 350 kHz.

15. The sensor assembly of claim **14**, wherein an output of the low frequency oscillator is a sine wave signal.

16. An active magnetically levitating pump system configured to provide fluid flow, comprising:

a stator housing having a fluid pathway;

a rotor disposed within the fluid pathway;

an eddy current sensor coil positioned external the fluid pathway and operable to determine a position of the rotor with respect to a defined axis of the stator housing, the sensor coil operating as a resonating element in a low-frequency oscillator.

17. The active magnetically levitating pump system of claim **16**, wherein the eddy current sensor coil is operable to determine a position of the rotor with respect to a longitudinal axis of the stator housing.

18. The active magnetically levitating pump system of claim **16**, wherein the eddy current sensor coil is operable to determine a position of the rotor with respect to a lateral axis of the stator housing.

19. The active magnetically levitating pump system of claim **16**, further comprising a pump housing, the stator housing, rotor and eddy current sensor coil being positioned in the pump housing.

20. The active magnetically levitating pump system of claim **16**, wherein the low-frequency oscillator is positioned in the pump housing.

21. A method of determining a rotor position in a stator housing, the method comprising:

providing a stator housing having a fluid pathway, a rotor hub positioned in the fluid pathway, a sensor coil positioned external the fluid pathway, and an oscillator;

inducing eddy currents in the rotor hub via the magnetic field of the sensor coil, which eddy currents in turn produce magnetic fields that interact with the magnetic fields of the sensor coil as the rotor hub is moved relative to the stator housing;

determining a position of the rotor hub relative to the stator housing using an output of the oscillator.

22. The method of claim **21**, further comprising shifting a frequency of a signal output from the oscillator to create a lower frequency signal, measuring the lower frequency signal, and providing a correction value for the measured lower frequency signal, the correction value representing a position of the rotor hub relative to the stator housing.

23. The method of claim **21**, further comprising locking a phase of a signal output from the oscillator to create a phase locked signal, measuring the phase locked signal, and providing a correction value for the measured phase locked signal, the correction value representing a position of the rotor hub relative to the stator housing.

24. The method of claim **21**, further comprising locking a frequency of a signal output from the oscillator to create a frequency locked signal, measuring the frequency locked signal, and providing a correction value for the measured frequency locked signal, the correction value representing a position of the rotor hub relative to the stator housing.

25. The method of claim **21**, further comprising magnetically-levitating the rotor hub in the fluid pathway, and controlling a longitudinal position of the rotor hub relative to the stator housing in response to the determined position of the rotor hub.

26. A method of determining a position of a rotor within a housing in a pump with magnetically-levitating rotor system, the method comprising:

providing a controller and a pump, the pump having a rotor, a stator, a position sensor, and an oscillator, the rotor being positioned inside the stator, the position sensor being positioned on the stator, and the position sensor comprising a coil;

creating a change in frequency in the oscillator with the position sensor in response to a change in position of the rotor relative to the stator;

processing an output signal of the oscillator with the controller to create a correction value representative of the change in relative axial position;

correcting a position of the rotor based on the value.

27. The method of claim **26**, further comprising correcting the position of the rotor with a voice coil.

28. The method of claim **26**, further comprising providing a controller that is positioned remote from the oscillator, the controller comprising a microprocessor configured to determine the correction value using the output signal of the oscillator.

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