MAGNETICALLY SUSPENDED PUMP

Applicants: Jeffrey A. LaRose, Parkland, FL (US); Charles R. Shambaugh, JR., Coral Gables, FL (US)

Inventors: Jeffrey A. LaRose, Parkland, FL (US); Charles R. Shambaugh, JR., Coral Gables, FL (US)

Assignee: HEARTWARE, INC., Miami Lakes, FL (US)

Filed: May 17, 2013

Abstract

An axial flow blood pump includes a pump housing and first and second stator permanent magnets fixed to the pump housing. A rotor assembly is disposed within the pump housing and includes first and second rotor permanent magnets. The first fixed permanent magnet may be axially offset from the first rotor permanent magnet and the second fixed permanent magnet may be axially offset from the second rotor permanent magnet. The permanent magnets act as passive radial bearings with maintain the rotor coaxial with the housing, and also exert axial forces on the first and second rotor permanent magnets to urge the rotor towards an equilibrium axial position relative to the housing. The rotor may be suspended and positioned within the housing solely by operation of the permanent magnets.
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CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] The present application claims the benefit of the filing date of U.S. Provisional Patent Application No. 61/648,289 filed May 17, 2012, the disclosure of which is hereby incorporated herein by reference.

BACKGROUND OF THE INVENTION

[0002] Clinical applications of ventricular assist devices to support patients with end-stage heart disease, as a bridge to cardiac transplantation, or as an end stage therapeutic modality have become an accepted clinical practice in cardiovascular medicine. It is estimated that greater than 35,000 persons suffering from end stage cardiac failure are candidates for cardiac support therapy.

[0003] Ventricular assist devices may utilize a blood pump for imparting momentum to a patients blood thereby driving the blood to a higher pressure. One example of a ventricular assist device is the Left Ventricular Assist Device (LVAD). The blood inlet of the LVAD is connected to the left ventricle of the patient’s heart, whereas the blood outlet of the LVAD is connected to the patients aorta. Oxygenated blood from the ventricle enters the LVAD and is pumped by the LVAD into the patient’s aorta.

[0004] Certain LVADs use rotary pumps. A rotary pump includes a rotor that spins about an axis within the housing of the pump and imparts momentum to the blood. Rotary blood pumps may be either centrifugal or axial. In a radial flow or centrifugal blood pump, blood enters the pump along its axis of rotation and exits the pump remote from the axis of rotation. In an axial flow blood pump, blood enters the pump along its axis of rotation and exits the pump along the axis of rotation.

[0005] Certain rotary blood pumps use mechanical bearings to support and position in the axial and radial directions. Mechanical bearings in contact with the blood can cause of thrombosis. Moreover, mechanical bearings that have contact between a part fixed to the housing and a part fixed to the rotor are subject to wear. This can pose a considerable problem, particularly in a blood pump that must remain implanted within the patient for many years.

[0006] To avoid these problems, non-contact bearings have been employed. These bearings utilize magnetic or hydrodynamic forces to suspend the rotor within the housing. For example, certain embodiments in U.S. Pat. No. 5,695,471 to Wampoler, the disclosure of which is hereby incorporated by reference herein, utilize a magnetic bearing including a multipole, rod-like permanent magnet, such as an assemblage of magnetic discs, on the rotor. The rotor permanent magnet is disposed within a multi-pole generally tubular permanent magnet, such as an assemblage of magnetic rings, on the housing. Repulsion forces between like poles of these magnets help to maintain the rotor coaxial with the housing. Stated another way, these permanent magnets act as a radial bearing with constrains the rotor in radial directions. These permanent magnets also produce an axial thrust on the rotor.

The axial position of the rotor relative to the housing is maintained by magnetic or hydrodynamic thrust bearings separate from the radial bearing. Because bearings that rely only on permanent magnets do not require an external source of power and do not require any control circuitry, they are commonly referred to as “passive” magnetic bearings.

[0007] U.S. Pat. No. 6,234,772, to Wampoler et al. (the ’772 Patent), hereby incorporated by reference herein, discloses certain embodiments using a passive magnetic radial bearing incorporating a permanent magnet on a spindle fixed to the pump housing. The spindle is received within a bore in the rotor. The rotor has a tubular permanent magnet surrounding the spindle. In certain preferred embodiments, the ’772 Patent uses hydrodynamic thrust bearings to control axial position of the rotor.

[0008] It has been suggested in the past that passive magnetic radial bearings alone cannot keep an impeller suspended in both the axial and radial directions. For example, U.S. Patent Publication No. 2011/0237863 (the ’863 Publication), the entire contents of which are hereby incorporated by reference herein, discloses an axial flow blood pump with passive magnetic bearings to radially support the pump impeller. This pump uses an electromagnetic coil, referred to as a “voice coil” energized by an electrical drive circuit, to axially support the pump impeller. The pump also includes sensors that monitor the axial position of the rotor relative to the housing, and the drive circuit is arranged to vary the current supplied to the voice coil responsive to the detected axial position. The use of a voice coil, drive circuit, and sensors makes the design of the pump more complex and more difficult to miniaturize. Such an arrangement is commonly referred to as an “active” magnetic bearing.

[0009] Despite these efforts in the art, further improvement would be desirable.

BRIEF SUMMARY OF THE INVENTION

[0010] One aspect of the invention provides a blood pump which includes a housing having an axis and first and second stator permanent magnets fixed relative to the housing at axially-spaced locations. The pump according to this aspect of the invention desirably also includes a rotor having an axis disposed within the pump housing including a first rotor permanent magnet associated with and magnetically interacting with the first stator permanent magnet and a second rotor permanent magnet associated with and magnetically interacting with the second stator permanent magnet, so that the interacting magnets urge the rotor into an alignment coaxial with the housing.

[0011] Most preferably, the magnets are constructed and arranged so that first stator permanent magnet exerts a first axial force on the first rotor permanent magnet in a first axial direction and the second stator permanent magnet exerts a second axial force on the second rotor permanent magnet in a second axial direction opposite to the first axial direction. The rotor and stator permanent magnets desirably are arranged so that, over an operating range of axial positions of the rotor relative to housing, the first axial force decreases upon movement of the rotor relative to the housing in the first axial direction, whereas the second axial force decreases upon movement of the rotor relative to the housing in the second axial direction. Thus, the first and second axial forces urge the rotor towards an equilibrium position within the operating range.

[0012] In particularly preferred embodiments, the rotor can be suspended and positioned within the housing entirely by interactions between the aforementioned rotor and stator permanent magnets. Preferred embodiments of the present invention can provide simple and compact pumps.
BRIEF DESCRIPTION OF THE DRAWINGS

[0013] FIG. 1 is a cross-sectional view of an axial flow blood pump according to the prior art.

[0014] FIG. 2A is a schematic view of an axial flow blood pump according to one embodiment of the invention.

[0015] FIG. 2B is a schematic view of the interaction of magnetic bearings in the axial flow blood pump of FIG. 2A.

[0016] FIG. 3 is a schematic view of an alternate embodiment of an axial flow blood pump according to a further embodiment of the invention.

DETAILED DESCRIPTION

[0017] FIG. 1 illustrates a cross-sectional view of a portion of the axial blood pump disclosed in the '863 Publication. Although incorporated by reference, certain portions of the '863 Publication are reproduced below to more fully explain that disclosure.

[0018] As shown, blood flow is designed to flow in the direction from inflow lumen 37 to outflow lumen 38 and thereby respectively guide the blood flow into and out of pump. The rotor assembly 60 spins and pumps blood via attached impeller blades 62. Stationary stator blades 102 direct the flow at the outlet end 22 of the blood pump 20. The rotor assembly 60 is rotated via a 4-pole motor assembly 124 forming stator components including motor iron 125, motor windings 126, and potting material 127 and rotor components including motor magnets 70.

[0019] FIG. 1 also shows radial support to the rotor assembly provided by fore and aft PM magnetic bearings. The fore PM magnetic bearing includes rotor PM rings 68a and 68b, and corresponding stator PM rings 121a and 121b. Similarly, the aft PM magnetic bearing includes rotor PM rings 68c and 68d and corresponding stator PM rings 121c and 121d. The magnetization directions of the various PM components are indicated with arrows.

[0020] While the fore and aft PM magnetic bearings provide a radial magnetic spring force that stabilizes and centers the rotor assembly 60 with a positive spring characteristic, the PM magnetic bearings also create a negative spring characteristic in the axial direction which makes the rotor axially unstable. To compensate for the axial negative spring characteristic, a feedback-controlled voice-coil actuator acts on the rotor assembly 60 in the axial direction.

[0021] The voice-coil actuator is comprised of voice coils 129a and 129b wired such that current flows in opposite directions in the two coils 129a, 129b and thus interacts with magnets 71, 72, and 73 to produce an axial force in response to an electronically-controlled current in the coils 129a, 129b. Magnet 68b also contributes to the function of the voice-coil actuator, as it is proximal to voice coil 129a and contributes to the radial magnetic field in voice coil 129a.

[0022] Feedback control of the voice-coil actuator in FIG. 1 is accomplished by using fore and aft position sensor coils 135 and 136. As the rotor assembly 60 moves fore and aft, the impedance of coils 135 and 136 change and the impedance change is interpreted as positional change by electronics external to the blood pump 20. A feedback control algorithm such as virtually zero power control is applied to the position signal to determine the voltage or current applied to the voice coils 129a and 129b.

[0023] With further regard to FIG. 1, the stator housing 81 extends for a large fraction of the length of the blood pump 20. Stator housing 81 forms the outside wall of annular flow gap 39, which is a large part of the blood flow path through the pump. Additionally, the stator housing 81 supports the stator PM rings 121a, 121b, 121c, 121d, the voice coils 129a, 129b, the motors coils 126, and motor iron 125.

[0024] As pointed out above, the requirement for a voice coil and the associated sensors and circuitry in the pump of FIG. 1 increases the complexity and size of the pump.

[0025] Now referring to FIG. 2A, an embodiment of a blood pump 220 according to an aspect of the invention is shown. Pump 220 includes a hollow housing having an inflow end 237, an outflow end 238, and a housing axis 201 extending between these ends.

[0026] The pump further includes a rotor 260 having a rotor axis 203, the rotor being disposed within the housing. The rotor includes a first set of cylindrical rotor PM rings 268a-c disposed adjacent the inflow end 237 of the pump 220. The first set of rotor PM rings have like magnetic poles of mutually-adjacent rings facing axially toward one another. For example, the north pole of ring 268a faces toward the north pole of ring 268b. The south pole of ring 268b faces toward the south pole of ring 268c. The first set of rotor PM rings thus cooperatively constitute a first rotor permanent magnet 269 that is symmetrical about the rotor axis 203, and which has opposite magnetic poles radially spaced apart from each other in an alternating arrangement. For example, there is a south pole 271a at the end of the magnet defined by ring 268a, a north pole 271b at the juncture between rings 268a and 268b, a south pole 271c at the juncture of rings 268b and 268c, and a south pole 271d at the end of the magnet defined by ring 268c. In this embodiment, the rings are of uniform thickness, so that the axis 271a of magnet 269 is spaced apart from the next adjacent pole of this magnet by a uniform spacing distance DS1. The rotor further includes a second set of rotor PM rings 268d-f, which cooperatively constitute a second rotor permanent magnet 273 disposed adjacent the outflow end 238 of the pump. The second rotor permanent magnet is similar to the first rotor permanent magnet. Thus, magnet 273 is symmetrical about the rotor axis 203 and defines poles 275a-275d in alternating north pole and south pole sequence along axis 203. Here again, the mutually-adjacent poles of magnet 273 are spaced apart by another pole of the uniform spacing distance DS2.

[0027] A first set of cylindrical stator PM rings 321a-c is fixed to the housing 281 of the pump 220 adjacent the inflow end 237 of the housing. The first set of stator rings cooperatively constitutes a first stator permanent magnet 323. This magnet is tubular and symmetrical about the housing axis 201 and has poles 371a-371d in the same alternating sequence of south and north poles as the first rotor permanent magnet 269.

[0028] A first set of stator PM rings 321a-d is fixed to the housing 281 of the pump 220 adjacent outflow end 238. These rings cooperatively define a second stator permanent magnet 325. Magnet 325 is also tubular and symmetrical about the housing axis 201 and has alternating north and south poles 373a-373d in a sequence corresponding to the sequence of poles 275a-275d in the second rotor permanent magnet 273. Adjacent poles of the second stator permanent magnet 325...
are axially spaced from one another at the same spacing distance \(DS2\) as the poles of the second rotor permanent magnet \(273\).

[0029] However, in the illustrated embodiment of pump 220, the axial distance between stator permanent magnets 323 and 325 is slightly greater than the axial distance between the rotor permanent magnets 269 and 273.

[0030] Rotor 260 also has motor permanent magnets schematically depicted at 207. A set of motor coils 209 is mounted to the housing 281. The motor magnets and motor coils may be of conventional construction and are arranged to spin the rotor around its axis when the coils are energized by an appropriate drive circuit. The rotor is also equipped with surfaces such as the vanes schematically depicted at 211, arranged to impel blood in the downstream direction indicated by arrow Q, from the inflow end 237 to the outflow end 238, upon rotation of the rotor about its axis.

[0031] The magnetic interactions between the first rotor magnet 269 and first stator magnet 323, and between second rotor magnet 273 and second stator magnet 325, levitate the rotor 260 within the housing 281 in the operating position shown. In this operating position, the rotor axis 203 is coaxial with the housing axis 201. First rotor PM magnet 269 is largely received within the tubular first stator PM magnet 323, but the rotor magnet 269 is offset in a first axial direction from the stator magnet by an offset distance \(DO1\), so that pole \(271d\) of the rotor magnet protrudes beyond pole \(371d\) of the stator magnet. In this embodiment, the first axial direction is the downstream direction indicated by arrow Q in FIG. 2A. Preferably, the first offset distance \(DO1\) is less than the spacing distance \(DS1\) between adjacent poles of the first rotor magnet, and typically \(DO1\) is less than one-half \(DS1\). Second rotor magnet 273 is received within second stator magnet 325, but is offset therefrom by a second offset distance \(DO2\) in the second axial direction, opposite to the first axial direction. Thus, the second rotor magnet is offset from the stator rotor magnet in the upstream direction, opposite to arrow Q in FIG. 2A. Preferably, the second offset distance \(DO2\) is less than the spacing distance \(DS2\) between adjacent poles of the first rotor magnet, and typically \(DO2\) is less than one-half \(DS2\).

[0032] FIG. 2B illustrates the interactions between the bearings. The magnetic forces exerted by the poles of the stator magnets on the corresponding poles of the rotor magnets are depicted by the inclined arrows in FIG. 2. Because each pole of the rotor magnet is disposed closer to a like pole of the associated stator magnet, repulsive forces predominate over attractive forces. In the radial direction, the repulsive forces tend to hold each rotor magnet coaxial with the associated stator magnet. Because the poles of the first rotor magnet 269 are offset in the first axial direction (to the right in FIG. 2B) from the like poles of the first stator magnet 323, the first stator magnet imparts a first axial force \(FA1\) on the first rotor magnet 269 and thus on rotor 260. This axial force is in the first axial direction, and thus in the downstream direction indicated by arrow Q. Similarly, the second stator magnet 325 imparts a second axial force \(FA2\) on the second rotor magnet 273, and thus on rotor 260 in the second axial direction.

[0033] In the equilibrium position depicted, these axial forces balance one another. Moreover, within an operating range of rotor axial positions near the equilibrium position, the axial forces will urge the rotor toward the equilibrium position. Within this operating range, displacement of the rotor in the downstream or first axial direction (to the right in FIG. 2B) and toward the outflow end 238 of the housing in FIG. 2A) causes the first axial force to decrease and the second axial force to increase, so that the second axial force \(FA2\) becomes greater than the first axial force \(FA1\). This yields a net force in the second axial direction, which urges the rotor back toward the equilibrium position. The opposite effects occur upon displacement of the rotor from the equilibrium position in the second axial direction. In this case, \(FA1\) decreases and \(FA2\) increases. Stated another way, the interactions between the rotor and stator magnets cause the axial forces exerted on the rotor to vary with axial displacement of the rotor in such a way as to restore the rotor to the equilibrium position.

[0034] Although the axial forces result from interaction of all of the poles of the interacting magnets, the changes in axial forces with displacement of the rotor can be appreciated with reference to the projecting poles \(271d\) and \(275oa\) of the rotor magnets. Movement in the first axial direction increases the first offset distance \(DO1\), and thus moves pole \(271d\) away from the adjacent pole \(371d\) of the first stator magnet and reduces the repulsive force on pole \(271d\). Rotor movement in the first axial direction also reduces the second offset distance \(DO2\) and thus moves pole \(275a\) closer to the adjacent pole and increases the repulsion force exerted on pole \(275oa\) by pole \(373oa\) of the second stator magnet.

[0035] Thus, the rotor permanent magnets 269, 273, and stator permanent magnets 323, 325 tend to keep the rotor 260 not only in radial alignment with the housing 281 of the pump 220, but also in axial alignment.

[0036] FIG. 3A shows an alternate embodiment of a blood pump 420. Similar to blood pump 220 of FIG. 2A, pump 420 includes first and second sets of rotor PM rings 468a-c and 468d-f, constituting first and second rotor permanent magnets 402 and 404 on the rotor 460. Corresponding first and second stator permanent magnets 406 and 408 are formed by first and second sets of stator PM rings 521da-c and 521df on the housing 481 of the pump 420. These permanent magnets may have the same configurations as the rotor and stator permanent magnets discussed above. In pump 420, however, the rotor permanent magnets 402 and 404 are disposed farther from one another than the stator permanent magnets 406 and 408. Thus, offsets between rotor and stator permanent magnets are the reverse of those shown in FIG. 2A. In pump 420, the first rotor permanent magnet 402 is largely received within the first stator permanent magnet 406, but is offset therefrom by an offset distance \(DO1\) in a first direction toward the inflow or upstream end 437 of the housing, i.e., to the left as seen in FIG. 3A. The second rotor permanent magnet 404 is largely received within the second stator permanent magnet 408, but magnet 404 is offset from magnet 408 by an offset distance \(DO2\) in a second direction, toward the outflow or downstream end 438 of the housing. Here again, the two offset directions are opposite to one another. Pump 420 also includes motor magnets and coils (not shown) for rotating rotor 460 about its axis 401, as well as surfaces (not shown) on the rotor for impelling blood in a downstream direction toward the outflow end 438 of the housing upon rotation of the rotor.

[0037] In this configuration, the magnetic interactions of first rotor permanent magnet 402 with first stator permanent magnet 406, and of second rotor permanent magnet 404 with second stator permanent magnet 408, levitate the rotor within housing 408 and provide both radial and axial positioning. Repulsion of first rotor magnet 402 by first stator magnet 406 produces an axial force \(FA1\) in the first direction, whereas
second stator magnet 408 and second rotor magnet 404 apply a second axial force \( FA_2 \) in the second, opposite direction on the rotor. In the equilibrium position depicted, these forces balance one another. If the rotor 460 moves in the first direction (toward the inflow end 437 of the pump) from the equilibrium position depicted in FIG. 3A, first axial force \( FA_1 \) decreases and second axial force \( FA_2 \) increases, so that there is a net restoring force in the second axial direction, toward the outflow end 438 of the pump 420. The opposite effects occur upon movement of the rotor in the second axial direction from the equilibrium position.

In the embodiments discussed above, the rotor is levitated within the housing and maintained in radial and axial position without the use of any other bearings or position control elements. For example, active position control elements such as a voice coil and feedback control circuitry are not used in this embodiment. Also, there is no need for separate magnetic or hydrodynamic thrust bearings to maintain rotor position during operation. Thus, the pump can be simple and compact. In other embodiments, the magnetic bearing arrangements discussed above can be used in conjunction with additional magnetic, hydrodynamic, or other bearings, in conjunction with active position control elements, or both.

The number of poles in each of the first and second rotor permanent magnets can be varied. Also, the rotor permanent magnets may be formed from plural discs rather than from plural rings as in the embodiments discussed above. Moreover, each of the rotor permanent magnets and the stator permanent magnets may be formed as a unitary body of magnetic material with magnetization as required to provide the plural poles of each magnet, rather than from separate rings or discs. The stator permanent magnets may be formed integrally with other elements of the rotor and stator.

Patterns of magnetization different from those discussed above can be used in the magnetic bearings as long as the magnets provide radial and axial forces that urge the rotor towards axial and radial equilibrium positions. For example, the arrangement of magnets can be modified so long as one pair of rotor and stator magnets provides an axial force on the rotor in a first direction that decreases upon movement of the rotor in the first direction, whereas another pair of rotor and stator magnets provides an axial force in a second, opposite direction, and that axial force decreases upon movement of the rotor in the second axial direction. The rotor and stator magnets need not be cylindrical, as in the embodiments discussed above. For example, these magnets may be conical or frustoconical. The poles of the rotor and stator permanent magnets need not be disposed at uniform spacing distances, and the spacing distances between a rotor permanent magnet need not be the same as the spacing distances between poles of the associated stator permanent magnet. Still further, the magnetic intensity may vary from magnet type to magnet type and, therefore, the specific shape and size may vary from the specific embodiment shown.

The bearing arrangements can be used in pumps other than the axial flow pumps depicted herein. For example, the bearing arrangements can be used to support the rotor of a blood pump having radial flow or mixed axial and radial flow.

In the embodiments discussed above, the stator permanent magnets are tubular and the rotor permanent magnets are received within the stator permanent magnets. However, the reverse arrangement can be used. For example, where the spindle is fixed to the housing and the rotor surrounds the spindle, the rotor permanent magnets may be tubular, and the stator permanent magnets may be mounted on the spindle and received within the rotor permanent magnets.

Although the invention herein has been described with reference to particular embodiments, it is to be understood that these embodiments are merely illustrative of the principles and applications of the present invention. It is therefore to be understood that numerous modifications, including combinations of features illustrated in different embodiments of the disclosure, may be made to the illustrative embodiments and that other arrangements may be devised without departing from the spirit and scope of the present invention as defined by the appended claims.

1. A blood pump comprising:
   a housing having an axis;
   first and second stator permanent magnets fixed relative to the housing at axially-spaced locations;
   a rotor having an axis disposed within the pump housing including a first rotor permanent magnet associated with and magnetically interacting with the first stator permanent magnet and a second rotor permanent magnet associated with and magnetically interacting with the second stator permanent magnet, so that the interacting magnets urge the rotor into an alignment coaxial with the housing,
   wherein the first stator permanent magnet exerts a first axial force on the first rotor permanent magnet in a first axial direction and the second stator permanent magnet exerts a second axial force on the second rotor permanent magnet in a second axial direction opposite to the first axial direction.

2. A blood pump as claimed in claim 1, wherein, over an operating range of axial positions of the rotor relative to housing, the first axial force decreases and the second axial force increases upon movement of the rotor relative to the housing in the first axial direction, whereas the first axial force increases and the second axial force decreases with movement of the rotor relative to the housing in the second axial direction, whereby the first and second axial forces urge the rotor towards an equilibrium position within the operating range.

3. A blood pump as claimed in claim 2, wherein, in operation, the rotor is suspended and positioned within the housing without contact between the rotor and the housing.

4. A blood pump as claimed in claim 3, wherein, in operation, the rotor is suspended and positioned within the housing without feedback control of the axial position of the rotor.

5. A blood pump as claimed in claim 3, wherein, in operation, the rotor is suspended and positioned within the housing solely by the permanent magnets.

6. A blood pump as claimed in claim 2, wherein each stator permanent magnet is generally tubular and symmetrical about the axis of the housing and defines a plurality of opposite magnetic poles axially spaced from one another.

7. A blood pump as claimed in claim 6, wherein each rotor permanent magnet is symmetrical about the axis of the rotor and defines a plurality of opposite magnetic poles axially spaced from one another, and wherein the first rotor permanent magnet is at least partially disposed within the first stator permanent magnet, the second rotor permanent magnet being at least partially disposed within the second stator permanent magnet.
8. A blood pump as claimed in claim 7, wherein the first stator permanent magnet has poles disposed at first axial locations and the first rotor permanent magnet has identical poles disposed at the same first axial locations, plus a first offset distance in the first axial direction, and wherein the second stator permanent magnet has poles disposed at second axial locations and the second rotor permanent magnet has identical poles disposed at the same second axial locations, plus an second offset distance in the second axial direction.

9. A blood pump as claimed in claim 8, wherein the first offset distance is less than an axial spacing distance between any two opposite poles of the first stator permanent magnet and the second offset distance is less than an axial spacing distance between any two opposite poles of the second stator permanent magnet.

10. A blood pump as claimed in claim 2, wherein each stator permanent magnet includes at least one magnetic ring element coaxial with the axis of the housing and each rotor permanent magnet includes at least one magnetic disc or ring element coaxial with the axis of the rotor.

11. A blood pump as claimed in claim 10, wherein each stator permanent magnet includes a plurality of magnetic ring elements having like magnetic poles facing axially toward one another and each rotor permanent magnet includes a plurality of magnetic ring or disc elements having like magnetic poles facing axially toward one another.

12. The blood pump of claim 1, wherein the pump housing has an inflow end and an outflow end, the axis of the housing extends between the inflow and outflow ends, and the rotor includes impeller surfaces arranged to impel blood toward the outflow end upon rotation of the rotor about the axis of the rotor.

13. The blood pump of claim 12, wherein the first rotor permanent magnet is positioned closer to the inflow end than the first stator permanent magnet and the second rotor permanent magnet is positioned closer to the outflow end than second stator permanent magnet, the first stator permanent magnet exerts an axial force on the first rotor permanent magnet toward the inflow end, and the second stator permanent magnet exerts an axial force on the second rotor permanent magnet toward the outflow end.

14. The blood pump of claim 12, wherein the first rotor permanent magnet is positioned further from the inflow end than the first stator permanent magnet, the second rotor permanent magnet is positioned further from the outflow end than the second stator permanent magnet, the first stator permanent magnet exerts a force on the first rotor permanent magnet toward the outflow end, and the second stator permanent magnet exerts a force on the second rotor permanent magnet toward the inflow end.