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Technical note

# New concepts and new design of permanent maglev rotary artificial heart blood pumps

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**Abstract**

According to tradition, permanent maglev cannot achieve stable equilibrium. The authors have developed, to the contrary, two stable permanent maglev impeller blood pumps.

The first pump is an axially driven uni-ventricular assist pump, in which the rotor with impeller is radially supported by two passive magnetic bearings, but has one point contact with the stator axially at standstill. As the pump raises its rotating speed, the increasing hydrodynamic force of fluid acting on the impeller will make the rotor taking off from contacting point and disaffiliate from the stator. Then the rotor becomes fully suspended. The second pump is a radially driven bi-ventricular assist pump, i.e., an impeller total artificial heart. Its rotor with two impellers on both ends is supported by two passive magnetic bearings, which counteract the attractive force between rotor magnets and stator coil iron core. The rotor is affiliated to the stator radially at standstill and becomes levitated during rotation. Therefore, the rotor keeps concentric with stator during rotation but eccentric at standstill, as is confirmed by rotor position detection with Honeywell sensors.

It concludes that the permanent maglev needs action of a non-magnetic force to achieve stability but a rotating magnetic levitator with high speed and large inertia can maintain its stability merely with passive magnetic bearings.


*Keywords:* Permanent maglev; Equilibrium stability; Passive magnetic bearings; Rotary artificial heart blood pumps

## 1. Introduction

The available magnetic levitation technology has been limited to electromagnetic and super-conductive magnetic levitations, because according to Earnshaw's theory (1839) and Braunbeck's Extension (1939), the permanent maglev cannot achieve stable equilibrium [1]. Essentially, permanent maglev has many advantages than current maglev technologies. It needs no position detection and no feedback control, has no electric magnets and thus consumes no additional electric power, as compared with electromagnetic levitation; it needs no bulky cooling system unlike superconductor magnetic levitation; after all, the permanent maglev is simple in construction and low in costs.

In solving the bearing problem of blood pumps, the authors have discovered, however, that a moving (rotating) magnetic body under the combined action of permanent magnetic and non-magnetic forces can achieve a stable levitation; and a permanent magnetic levitator with high rotating speed can maintain the levitation stably. Meanwhile, two permanent maglev impeller blood pumps with different designs have been developed in recent years. This paper presents the new concept and the new design of permanent maglev and its new applications in durable rotary blood pumps.

## 2. Theoretical preparation

### 2.1. Earnshaw's theory (1839)

In 1839, an English scientist proved theoretically that a magnetic body cannot be supported in a stable manner in the field produced by any combination of mere passive magnetic poles [2]. That means, it is impossible for a pure permanent maglev to achieve a stable equilibrium, because the force of attraction (or repulsion) between two magnetized bodies is inversely proportional to the square of their separation

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(distance). In more precise words, there is no point of equilibrium between two magnetic bodies. It follows that any stable suspension system using only magnetic force requires the movement of the suspended body to be mechanically restrained in at least one degree of freedom. In artificial heart rotary blood pumps, this restraint is imposed on the rotor mostly by electromagnetic force; as a result the electric magnet and rotor position measurement as well as feedback control are necessary.

### 2.2. Braunbeck's extension (1939)

In 1939, a German investigator deduced that levitation in electrostatic, magneto-static and stationary field is impossible if the relative dielectric constant ($\xi_r$) and the relative permeability ($\mu_r$) are both greater than or equal to unity everywhere in the system [3]. Since for all materials $\xi_r \geq 1$, levitation is not possible by using electrostatic fields, but with magnetic field and materials with $\mu_r < 1$, stable levitation may be achieved. There are two types of materials with $\mu_r < 1$: diamagnetic material with $\mu_r$ slightly less than 1 and materials in super conductive state with $\mu_r = 0$. It is indicated that superconductive maglev is likely to achieve stable equilibrium.

### 2.3. The author's discovery (2000)

In 2000, the authors discovered that a stable levitation of a moving (rotating) magnetic body is achievable in a field acted by permanent magnetic and non-magnetic forces; the stability of levitation can be maintained when these non-magnetic forces are replaced by other non-magnetic forces; moreover, a passive magnetic levitator with high rotating speed and large rotating inertia can maintain the levitation stably. That means a hybrid permanent magnetic levitator in moving (rotating) state can be achieved stability; with other words, the permanent maglev needs other force to realize stability except passive magnetic force; as a stable maglev is achieved, it can be maintained, even with passive magnetic force alone. The authors would beg attention to the underlined words in this paragraph. Earnshaw proved that a pure maglev is impossible. Braunbeck pointed out that a static maglev is unstable. The author found that a hybrid maglev is achievable, and that a moving (rotating) body with certain high speed and certain large inertia can maintain the passive magnetic levitation stably. There is obviously no theoretical contradiction between traditional and new concepts.

To put it in more detail, here are two things of importance for stable permanent maglev. First, only a hybrid permanent maglev is achievable. For example, theoretically two magnetic bodies on the table will attract or repel each other until they are attached together or separate indefinitely far away from each other. Practically, these two magnetic bodies will keep in still state with a due distance from each other, because they are under the action of magnetic force and friction between table and them. Secondly, only a moving (rotating) magnetic body with high speed and large inertia can maintain stable permanent maglev. It will be shown in following paragraphs of this paper that the rotor of permanent maglev blood pumps is levitated during rotating at certain high speed and certain high flow rate but affiliated to stator during standstill. Here is a so-called gyro-effect, which indicates a function of inertia like some thing following Newton's First Law, as simple as Levitron [4] or riding a bicycle: with certain high speed the rider can avoid to fall over though theoretically a two-wheel bicycle cannot achieve stable equilibrium. People may think a bicyclist can use the steering for control, but nobody can maintain a stable equilibrium of a bike in standstill.

Fortunately, the levitated bodies are scarcely in static state and under mere action of passive magnetic forces, they are always in moving state and under the action of magnetic and non-magnetic forces in applications. For example, the levitated train is moving at high speed and under the action of magnetic force and aerodynamic force except gravity. Therefore, the permanent maglev has not only the theoretical compatibility with Earnshaw's Theory and Braunbeck's Extension, but also the practical feasibility in applications.

## 3. Permanent maglev impeller blood pumps

The research and development of artificial heart blood pumps has a history of over 50 years [5]. The preliminary works had laid particular emphasis on feasibility study. The diaphragm pump based on volume displacement like natural ventricle had been extensively used in experiments and clinics until 1980s. As the advantages of the rotary pump have been recognized, such as small size and weight for better implantation, no diaphragm and no valves for better reliability and anti-thrombogenicity, etc., most attention has been concentrated on developing an implantable, blood compatible, pulsatile and durable impeller pump in the past 20 years [6,7]. Bearing wear and thrombosis along the bearing, which are referred to as bearing problems of the rotary pumps, have led to many designs of electromagnetic bearings all over the world [8–10]. Electromagnetic bearing can solve the bearing problems of the rotary pump, but will cause a series of new problems: complicated measurement and control, additional volume and weight, considerable consumption of electric power for levitation except pumping.

The authors have tried to develop a magnetically levitated impeller pump with a novel patented permanent magnetic bearing [11], which has a double function: radial bearing and axial spring. Two stable permanent maglev impeller pumps have been developed. Their in vitro tests have demonstrated rather positive results.

### 3.1. Axially driven uni-ventricular assist impeller pump

#### 3.1.1. Prototype design

The prototype design of the device is shown in Fig. 1. The rotor is borne by two radial passive magnetic bearings.

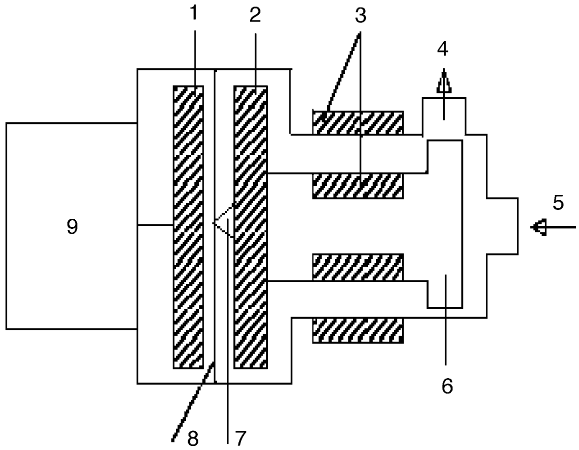


Fig. 1. Prototype design of axially driven uni-ventricular assist blood pump with permanent maglev impeller: (1) driving magnets disc; (2) driven magnets disc; (3) passive magnetic bearings; (4) pump outlet; (5) pump inlet; (6) impeller; (7) one-contacting point; (8) spacer.

The impeller is fixed on the right side of the rotor; on the left side, a driven magnets assemblage is mounted. Opposite this assemblage, a driving magnets assemblage is fastened to the motor axis. Therefore, the motor drives the rotor via magnetic coupling. At standstill or when the impeller rotates at a low speed, the driven magnets assemblage has one point in axial contact with a spacer between the driving and driven magnets assemblages. The contacting point is located in the center of the rotor.

As the rotating speed increases gradually, the enlarged hydrodynamic force of the fluid acting on the impeller will make the rotor taking off from the contact point and disaffiliate from the stator. Then the rotor becomes fully suspended (Fig. 2). Because the "taking off" of the rotor is generated by hydrodynamic force, which acts on the impeller because the impeller propels the flow, the rotation of the impeller is very stable during levitation; the things are same during "landing". It is worthy to notice that during landing the rotor is supported axially by magnetic force and mechanical pressure at contact point, and then the rotor is supported axially by both the magnetic and the hydrodynamic forces during suspension. It may follow that a magnetic levitation will keep its stability when a non-magnetic force (mechanical pressure) is replaced by another non-magnetic force (hydrodynamic force). Because in the latter case there is no mechanical contact between the rotor and the stator, the rotor can be considered already levitated.

Fig. 2. Demonstration of permanent maglev of rotating impeller. The rotor magnets disc is levitated axially (lower) at high rotating speed and in contact with spacer (upper) at low rotating speed. The space (black ring) at the right side of the driven magnets disc in the upper image is 0.5 mm bigger than that in lower image, because the spacer is located on the left side the disc.

### 3.1.2. Improved type design

The prototype design of permanent maglev impeller pump has demonstrated the feasibility of stable permanent maglev, but its length is too long to be implanted because of its separated driving motor. In improved type design (Fig. 3), the driving motor is replaced by a motor coil, which produces a rotating magnetic field and drives the rotor magnets disc to rotate. Similar to its prototype, the rotor of the improved type is supported radially by two permanent magnetic bearings, and has one contact point axially with stator during standstill or rotating at low speed. As the rotating speed increases, the rotor will move towards its pump inlet and the levitation of the impeller will be realized (Fig. 4).

In Fig. 4 the driven magnets disc is levitating axially (upper) during rotating at high speed and contacting the spacer (upper) during standstill. The space (black ring)

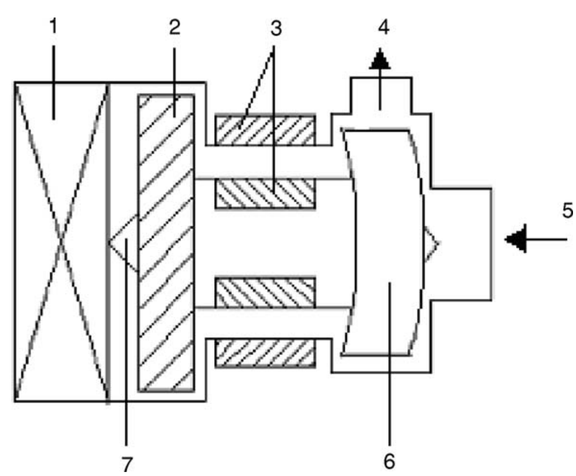


Fig. 3. Schematic drawing of an improved-type design of permanent maglev impeller pump: (1) motor coil; (2) driven magnets disc; (3) passive magnetic bearings; (4) pump outlet; (5) pump inlet; (6) impeller; (7) one-contacting point.

Fig. 4. The driven magnets disc is levitating axially (upper) during rotating at high speed and contacting the spacer (lower) during standstill. The space (black ring) between motor coil and rotor magnets disc at left side of the disc is 0.5 mm bigger in upper than that in lower.

between motor coil and rotor magnets disc at left side of the disc is 0.5 mm smaller in lower than that in upper.

The improved type design demonstrates the reproducibility of permanent maglev impeller pump and indicates that the stability of permanent maglev will not be destroyed when magnetic force of magnetic coupling is replaced by magnetic force of motor coil.

The axially driven permanent maglev impeller pump has proved that: (1) a magnetic body can keep stable levitation in a permanent magnetic field only when it is moving (rotating) with certain speed, but its levitation should be initiated under the action of permanent magnetic force and non-magnetic force; (2) the permanent maglev stability will not be destroyed when non-magnetic force is replaced by other non-magnetic force.

The flow rate ($Q$) and pressure head ($H$) of the pump were measured and their relation is shown in Fig. 5. The pump can

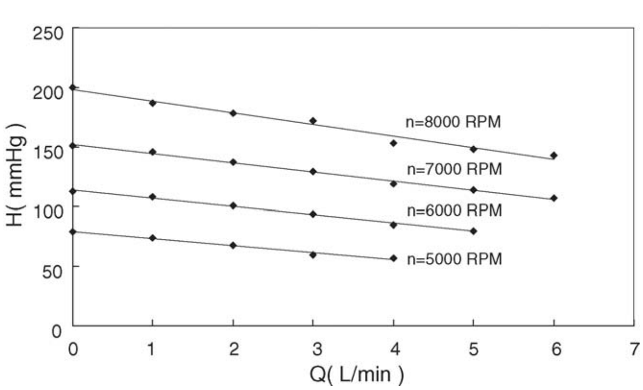


Fig. 5. The $H$–$Q$ curve of the axially driven permanent impeller pump.

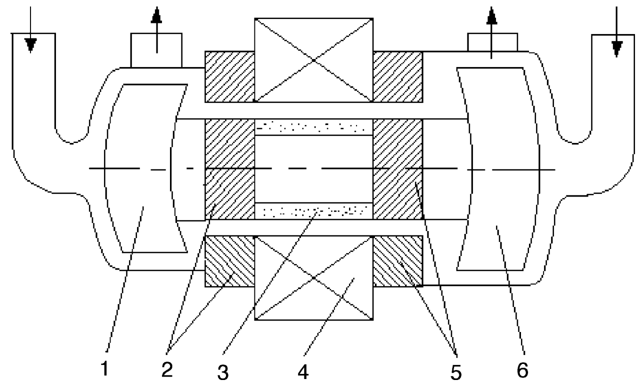


Fig. 6. Schematic drawing of a permanent maglev impeller TAH: (l) right impeller; (2 and 5) passive magnetic bearings; (3) driven magnets; (4) motor coil; (6) left impeller.

produce a flow of 4–6 l/min against 100 mmHg mean pressure at 6000–7000 rpm, meeting with the dynamic requirement of a left ventricular assist pump.

### 3.2. Radially driven bi-ventricular assist impeller pump

The equilibrium stability of permanent maglev can be better demonstrated in a bi-ventricular assist blood pump. A schematic drawing of permanent maglev impeller total artificial heart (TAH) is shown in Fig. 6.

The device consists of a stator and a rotor. The rotor assemblage has motor magnets 3, right impeller 1, and left impeller 6, as well as small rings of magnetic bearings 2 and 5. The motor coil 4 and big rings of magnetic bearing 2 and 5, together with pump housings make up the stator. The stator coil iron core attracts the rotor magnets but the magnetic rings of bearings repel each other to counteract the attractive force. The radial permanent maglev is easier achievable, if the repelling force of the magnetic bearings is larger than the attracting force between motor coil and motor magnets. For this reason, the motor magnets are designed as small as possible. The small rotor magnets will decrease the motor torque value at which the motor achieves its highest efficiency. It can be remedied, however, if the rotating speed increases [12]. For axial suspension of the rotor, a strong enough magnetic spring is prerequisite to overcoming the hemo-dynamic force acting on the rotor.

At standstill, the rotor is affiliated to the stator somewhere occasionally and thus the rotor keeps eccentric with the stator; during rotation the rotor is suspended and therefore keeps concentric with the stator (Fig. 7).

The rotor position detection with Honeywell sensors on the stator, usually used in electromagnetic levitation technology, has confirmed that the rotor has no contact with stator during rotation but does have contact with stator at standstill. Here a so-called gyro-effect plays a very important role in levitator's stability [13–16]. To describe briefly, that is, a rotating body at high speed and with big inertia will rotate along its rotation center (axis) stably. This indicates that only one degree of axial freedom keeps free and other five freedom

Fig. 7. The rotor keeps concentric with stator during rotating (left) and eccentric at standstill (right), indicating the rotor is levitated during rotation and affiliated to the stator at standstill.

degrees need no restraint for stability. It can be concluded that a moving (rotating) magnetic body can be levitated stably in a permanent magnetic field because its motion (rotation) inertia will help to maintain stability in at least one degree of the freedom. The axial stability of the rotor is achieved due to a combined action of hemo-dynamic force and magnetic spring effect of the magnetic bearings [11].

The rotating speed of the rotor is cyclically changed in order to produce a pulsatile flow similar to that of the natural heart, and thus the axial hydrodynamic force of the fluid acting on the impellers will be bigger at higher speed than at lower speed. At the same time, the hydrodynamic force on left impeller is larger than that on the right impeller, because the left pump delivers higher pressure of the blood than the right pump, and the resultant force on the rotor which is different from the forces acting on left impeller (toward left pump inlet) and right impeller (toward right pump inlet) will also be changed cyclically. Then the rotor floats axially back and forth (Fig. 8).

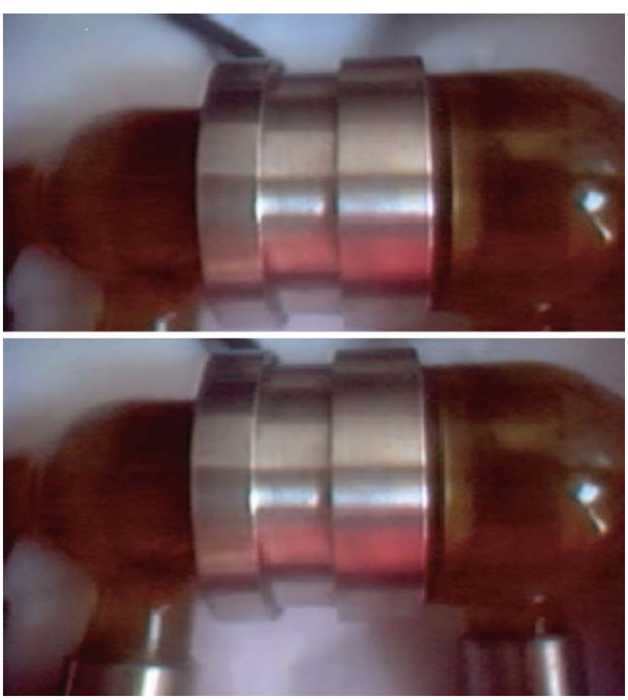

Fig. 8. The hemo-dynamic force acting on left impeller is bigger than that on the right impeller during rotation at higher speed (systole), and this force is theoretically zero during rotation at lower speed (diastole), the rotor will move 1–2 mm towards left pump inlet during systole (upper) compared with in diastole (lower), resulting in 1–2 mm axial reciprocation of the rotor once a cycle.

## 4. Discussion

This paper gives several examples of technical applications of permanent maglev, in order to show that stable permanent maglev is possible. The stability of equilibrium is achieved and maintained either by introducing non-magnetic force together with magnetic force to act on the levitator or by using the inertia of the moving (rotating) levitator to result in gyro-effect. Actually, these two approaches will be combined to ensure a stability of equilibrium in all six degrees of freedom. The mechanism of these two approaches may be explained as follows: Earnshaw's theory was deduced from energy equations, the levitator should have the minimal energy in the point of stable equilibrium, any change from these point needs energy increase; passive magnetic force is inversely proportional to the square of the distance between two magnetic bodies and therefore no position of minimal energy exists; if the levitator is under the action of non-magnetic force, or the levitator is moving (rotating), then the energy of the levitator will be combined both magnetic potential energy and non-magnetic energy or dynamic energy, thus the position of minimal energy may exist which corresponds the stable equilibrium point.

Permanent maglev needs no electromagnet, no rotor position detection and feed-back control, consumes no additional power, compared with electromagnetic levitation; permanent maglev needs no bulk cooling system compared with the super-conduction maglev. Therefore, permanent maglev has a bright prospect for further research and development.

For medical applications, Dr. Wang et al. from University of Texas reported that the maglev pump was used alternatively with the author's another pump having rolling bearing to make the experiments on goats [17,18]. The experiments lasted 7 days and the long-term experiments will be made in near future.

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