Development of Single Axis Controlled Attraction Type Magnetic Bearing and its Application in Ventricular Assist Device

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Abstract

Aiming the development of an implantable Ventricular Assist Device – VAD, or an artificial heart, a joint project was started in 2007, involving the Escola Politécnica of São Paulo University (EPUSP) and the Dante Pazzanese of Cardiology (IDPC). One of objectives of the project is the development of a VAD with a rotor levitated by a magnetic bearing. Here, a magnetic bearing proposed by authors, called as EPUSP bearing, is elected mainly because of its simplicity. This work presents the entire development work. One of most important work is related with the mitigation of a topology of the EPUSP bearing that enables a robust levitation, enough for supporting the rotor of a VAD. Moreover some complementary studies are developed so as to execute the Zero Power control in the EPUSP bearing, identify the best way of driving the rotor supported by the EPUSP bearing and finally, use the Hall sensor in the measurement of the rotor position in the EPUSP bearing.

1 Introduction

Magnetic bearing is a relatively new machine element that shows an increasingly wide application. One of its important features is the absence of mechanical contact between the table or the rotor and other components of the bearing. Due to this, no wearing or friction takes place. Besides, this modality of bearing enables operation in vacuum environment, therefore especially suitable for space applications.

Many works treated magnetic bearings. However, most of them refer to magnetic bearings with active control in two or more degrees-of-freedom (for example, Schweitzer, 1992). The active control in a degree-of-freedom - dof means the implementation of a control loop including a sensor, an actuator and a controller. Thus the active control of various dofs represents an increasing in the system complexity and consequently, affects negatively the reliability of the system. Also, the increase in the number of dofs to be actively controlled results in a increase in the number of actuators (usually, electromagnets) and an increase in the heat generation, affecting the accuracy of the bearing. On the other hand, although few, there are works treating magnetic bearings with active control in a single dof. However in these works, permanent magnets are mounted so as to work in repulsion mode (Ohji, 1996, Kunbernuss, 2012 and others) presenting therefore the problem of demagnetization (Campbell, 1994). Finally, other group of works focuses on the use of superconducting magnets on constructing a magnetic bearing (Mario-Pera, 1994, Strasik, 2010 and others). However, the requirement for an operation under extremely low temperatures imposes limitation for many practical applications.

Considering the above, authors proposed a new topology of magnetic bearing in which the active control is executed only with respect to the rotor axial position (Figure 1). In the radial directions, the rotor is confined in a central position by the action of permanent magnets operating in attraction mode. This bearing, forward referred as EPUSP bearing, was firstly presented in Silva, 1999 and posteriorly in Silva, 2000. At that occasion, the topology was presented, a prototype was constructed and by experiments, the principle of the EPUSP bearing was demonstrated. After these works, authors also presented in Silva, 2005 and in Silva, 2009a, a linear magnetic bearing in which a sliding table is suspended according to the same principle of the EPUSP bearing.

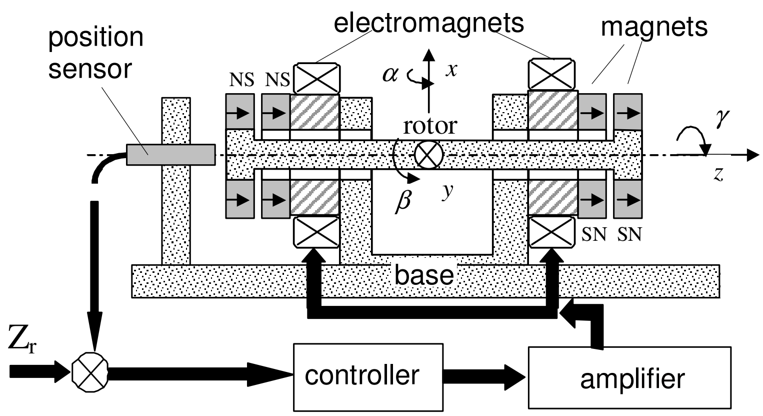


Figure 1 Schematics of the EPUSP bearing

In 2007, a joint project involving the Escola Politécnica of the São Paulo University - EPUSP (São Paulo, Brazil) and the Dante Pazzanese Institute of Cardiology – IDPC (São Paulo, Brazil) was started. The project aimed the development of an intracorporeal Ventricular Assist Device – VAD, or an artificial heart. The development was based on a VAD already developed by the IDPC (Andrade *et al*, 1996) for extracorporeal usage. Many are the challenges for the development of an implantable VAD. One of them is to revise the usage of ball bearings for supporting the VAD rotor. Even a careful design, including the use of gaskets, the blood penetrates the bearing damaging it. Also, no lubricant oil can be used in the bearing to avoid a risk of contamination of the blood. Thus, the lifetime of such VAD was limited to less than 50 hours. This is acceptable for an external usage but not for an implant.

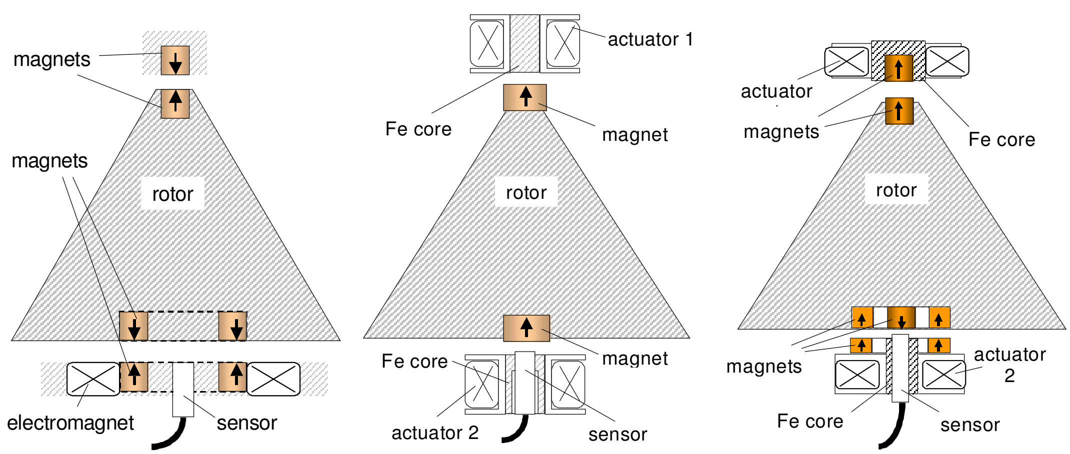
Therefore, concerning the bearing, this project involves study aiming two solutions: the first one focuses on the use of ceramic bearings that can operate without lubrication and presents extended lifetime and, the second one, focuses on the use of magnetic bearing. The use of magnetic bearing is a world wide trend in terms of VAD (see for example, Asama, 2006), firstly, since it minimizes any problem related to wearing in the bearing, and secondly, since it minimizes the hemolysis, that is, the damage to the blood components. Thus, the study for the development of a VAD with the rotor levitated by the EPUSP bearing was started. The EPUSP bearing was elected for this application because of its simplicity and the use of magnets working in repulsion mode.

2 Improvements in the EPUSP bearing stiffness

However, at that moment, when the project was started, only the principle of the EPUSP bearing was available. No directives for obtaining mechanical characteristics for a practical application, specially concerning supporting stiffness, were determined. Therefore, studies were conducted so as to obtain as higher stiffness and robustness in the levitation.

The first attempt is shown in Fig.2(a), the Topology 1 (Horikawa, 2007, Horikawa, 2008). A conical shape rotor is used in order to simulate the rotor of the extracorporeal VAD previously developed by the IDPC. Although it was possible to levitate the rotor, a poor radial stiffness is obtained. Here it was already possible to identify the problem to be solved. Here, the EPUSP bearing contains following fundamental elements: (a) the magnet that, by interacting with the magnet fixed to the rotor, assures the radial stiffness, (b) the actuator, i.e. an electromagnet coil that, by interacting with the magnet fixed to the rotor, exerts a variable force to the rotor so as to keep it in an fixed axial position and (c) the sensor (an inductive type non-contact sensor) that measures the axial position of the rotor. The difficulty arises from the fact that all of above three elements occupy a same position in the bearing. Naturally, the magnet fixed to the base is placed near the rotor magnet. As consequence, the actuator is placed in a more distant position so that only poor efficiency is obtained in the actuator. Thus, in order to improve the actuator efficiency, one possibility is to replace magnet with an iron core: Topology 2 (Yoshida, 2009, Silva, 2009b). Indeed, this improved the actuator efficiency but decreased the radial stiffness. When two axially polarized magnets are faced, the modulus of the radial stiffness is approximately the half of the axial stiffness. However, if one of magnets is faced with an iron piece, the obtained radial stiffness is significantly smaller than the half of the axial stiffness. This explains why in Topology 2, the radial stiffness has dropped.

The solution that tries conciliation between above described aspects is the Topology 3 (Silva, 2009c, Silva, 2010, Silva, 2011a, Silva, 2011b, Silva, 2011c) depicted in Fig.2(c). Here, the core of the actuator is composed by iron and magnet. The iron concatenates the magnetic flux generated by the actuator and the magnet assures the radial stiffness. The Topology 3 was the first effective way of improving the radial stiffness of the EPUSP bearing. Using the Topology 3, a first prototype of VAD was constructed. Immersed in water, the rotor could be driven by a brushless dc motor at 2000rpm in a stable way.

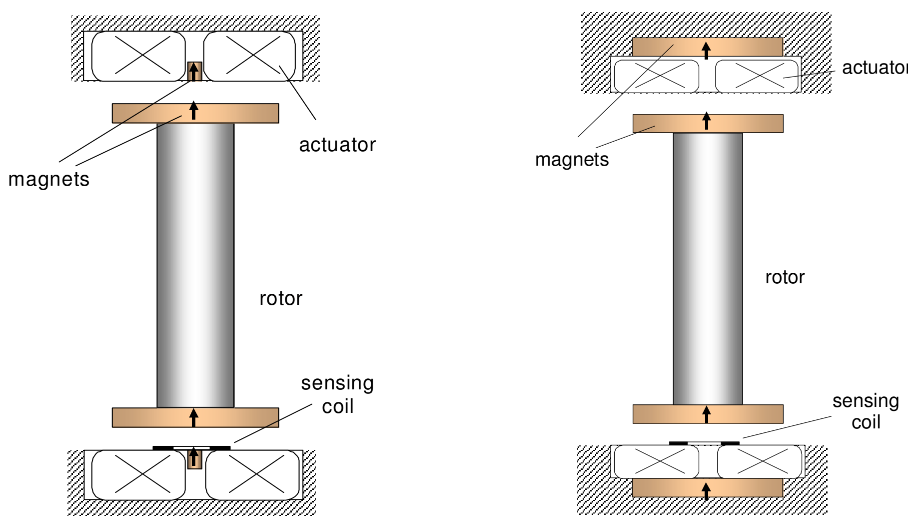


(a) Topology 1 (b) Topology 2 (c) Topology 3

Figure 2 Evolution of the EPUSP bearing and increasing in the radial stiffness

All topologies presented above, employed open magnetic circuit architecture. In order to improve, especially the efficiency of the actuator on converting current to force, also a topology with closed magnetic circuit was developed (Silva, 2010). As expected, a more efficient actuator was obtained and large magnets could be used, resulting in expressively higher value for radial stiffness. However, closing the magnetic circuit imposes difficulties on obtaining bearings, and consequently, VADs of small size. For this reason, the majority of topologies studied along the project have open magnetic circuit. Evidently, if one of these topologies is applied effectively in a VAD, a magnetic shield becomes necessary.

After the Topology 3, a new one is identified, the Topology 4 (Fig.3(a)). Here, a large diameter magnet is placed in front of a set composed by a electromagnet and a magnet of small diameter. This topology resulted in a significantly more robust levitation compared to other previous topologies. The large area of the magnet improved the efficiency of the electromagnetic actuator and the presence of the magnet in the center of the actuator assured the radial stiffness. Moreover, the intensity of the interaction between magnets can be adjusted by changing the position in axial direction, of the magnet fixed to the base. However, the Topology 4 presented a problem of an extremely low stiffness when the rotor is near the concentric position: an effect very similar to the dead zone or the backlash, which are observed in mechanical couplings. Thus, the Topology 5 (Fig.3(b)) is presented. The Topology 5 preserves features of the Topology 4 and minimizes the problem of dead zone. For this, Topology 5 uses two magnets of same diameter and a thin actuator between the magnets. Fig.4 shows picture of the prototype of the EPUSP bearing according to the Topology 5.



(a) Topology 4

(b) Topology 5

Figure 3 Most recent topologies for EPUSP bearing

As an illustration, Figs.5 to 7 show some characteristics measured in the prototype. Fig.5 shows the attraction force between the rotor magnet and the element containing the actuator and the magnet. This force varies from 8.1N to 5.4N while the gap varies from 0 to 2mm, giving an axial stiffness of −1.35N/mm. Fig.6 shows the restoring force versus misalignment between the rotor magnet and the actuator when a gap of 1mm is used. This gives a radial stiffness of 0.57N/mm. And Fig.7 shows the force on the rotor magnet versus current in the actuator. This gives a gain of 0.83N/A in the actuator. These values are for one pair of rotor magnet and actuator. Therefore, for the entire bearing, these values are the twice.

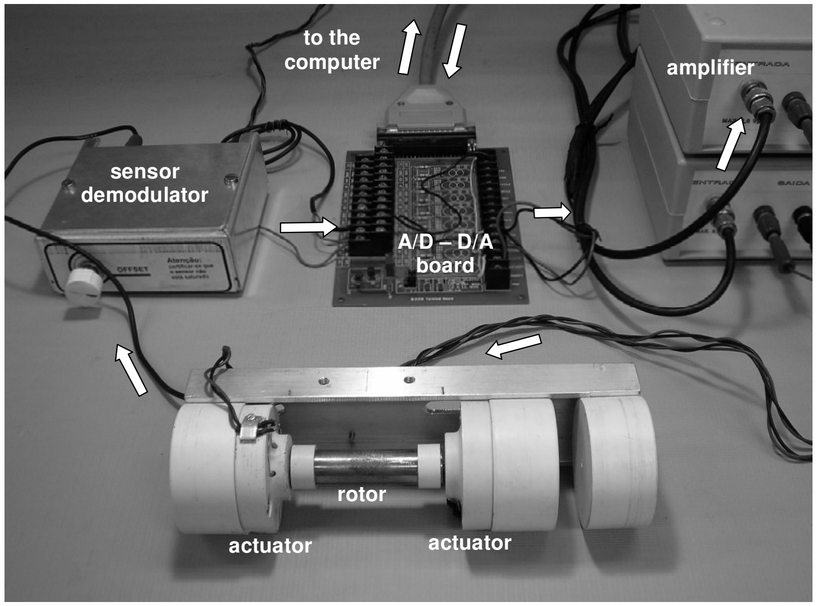


Figure 4 Prototype of Topology 5 of EPUSP bearing

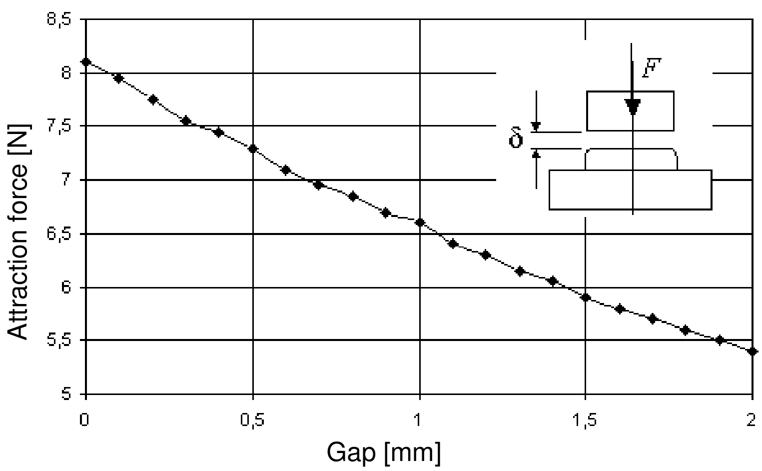


Figure 5 Gap vs attraction force (0~2mm)

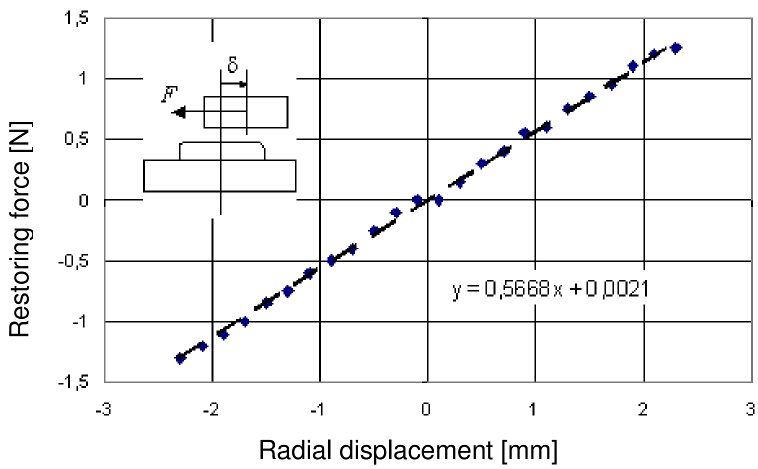


Figure 6 Radial restoring force vs displacement (gap of 1mm)

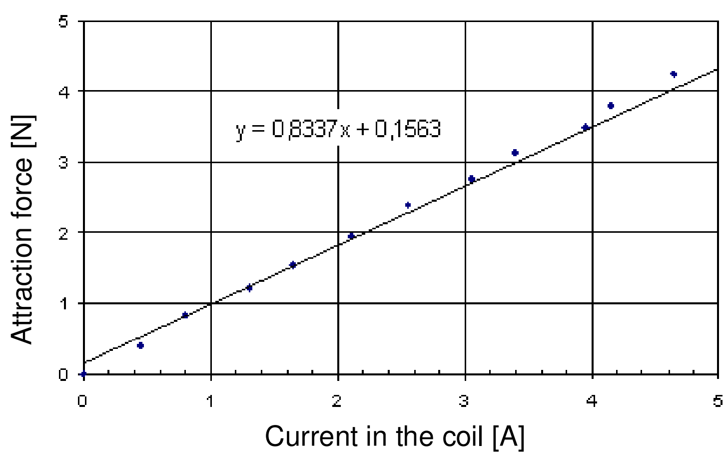


Figure 7 Attraction force vs current in the actuator (gap of 1mm)

A VAD based on the Topology 5 is designed (Fig.8) so as to be incorporated in a new pump (Sverzuti, 2012), as shown in Fig.3(a). Maintaining the essence of the Topology 5 of magnetic bearing, the now prototype uses only one electromagnetic actuator in the lower portion of the pump, i.e., the side opposite to the fluid entrance. At the side of the fluid entrance, a pair of smaller magnets is used. The directive in the design of the prototype, concerning the magnetic bearing, is to use only one pair of magnets of large sizes to resist the load resultant of the action of the electric motor and the fluid pumping. The magnetic pair composed by smaller magnets assures stability against tilting motions of the rotor.

As it is commented forward, the use of a coreless radial motor is the most suitable option to drive the rotor levitated by the EPUSP bearing. Fig.9 shows a picture of the prototype, assembled and ready to operate. Fig.10 shows the prototype and its components.

Using the new prototype of VAD, an operation test is conducted using a simple hydraulic circuit. A pressure charge of about 7.5mmHg, under a flow rate of 3 litters per minute, was obtained with the rotor at the speed of 500rpm. Due to motor limitations, this speed was the maximum. During the tests, the EPUSP bearing kept a stable levitation of the rotor and no collision of the rotor against the pump wall was observed.

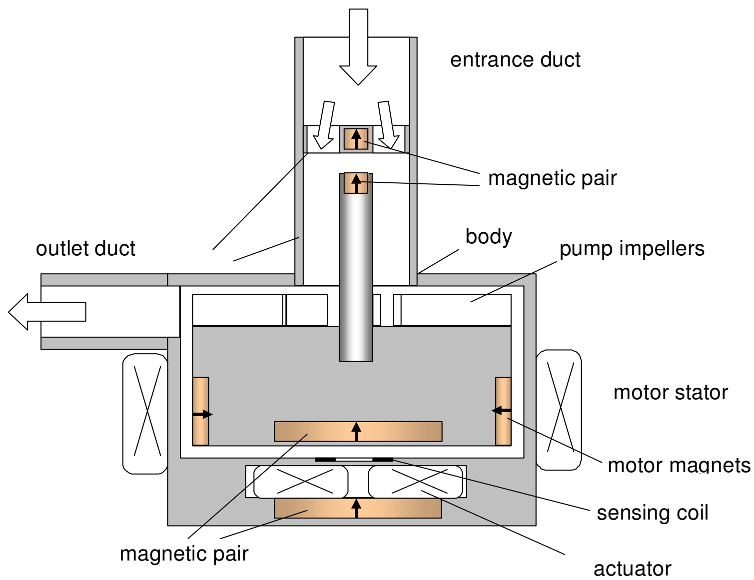


Figure 8 VAD prototype based on Topology 5

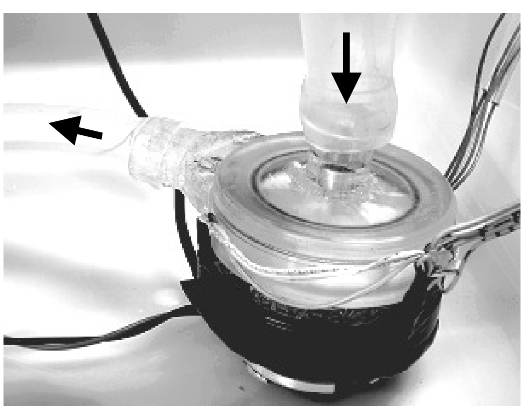


Figure 9 VAD prototype

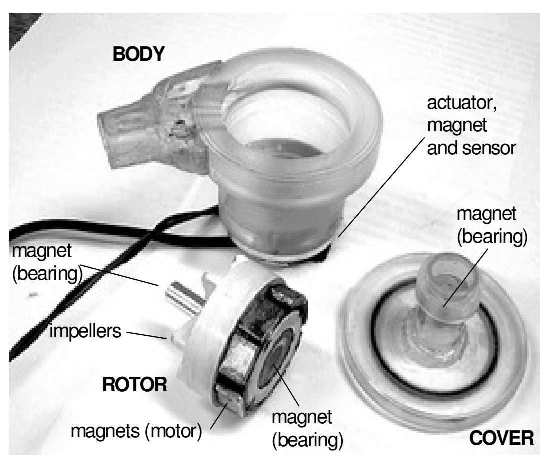


Figure 10 Prototype components

3 Zero power control – ZPC in the EPUSP bearing

When an additional load is applied to the rotor levitated by EPUSP bearing, the effects of the load is compensated increasing the current in the electromagnetic actuators. On the other hand, when operating, the rotor of the VAD is submitted to an axial drag force due to the fluid pumping. This means that, when operating the VAD, an additional current will flow in the actuators permanently resulting in heat generation and temperature rising. This temperature rise is undesirable since it can cause lesion to live tissues around de VAD or even damage in the VAD itself. Besides, the continuous consumption of electric energy is undesirable since the VAD to be developed is implantable, so the energy source is limited. Thus, aiming minimization of the undesirable consequences of the load application on the rotor, the application of a technique known as Zero Power Control – ZPC in the EPUSP bearing is studied (Mello, 2011).

The ZPC is a control technique for magnetic bearings and it is known since eraly times. One of pioneer work concerning ZPC is the Morishita, 1986. The ZPC is proposed to be applied in a conveyor with magnetic levitation used in fabrication of integrated circuits. The technique consists on changing the set point of the bearing so as to compensate effects due to a static load applied to the conveyor. The compensations is made not by the electromagnets but by the attraction force of permanent magnets.

Following the strategy presented in Morishita, 1986, the control strategy was applied to EPUSP bearing, as shown in the block diagram of the EPUSP bearing, Fig.11. The portion surrounded by dotted lines is that one responsible for the ZPC.

Figures 12 and 13 show the response of the EPUSP bearing when submitted to a stepwise load of about 2.5N. Without ZPC, (Fig.12), after the application of the load, the current reaches 1A intensity. This additional current is applied to the actuator to push the rotor back to its reference position. With the ZPC (Fig.13), 200ms after the load is applied, the reference position shifts by about 0.2mm and the current in the actuator drops to near zero. Numerical and experimental results showed the effectiveness of the ZPC specially for load with frequency inferior to the natural resonance frequency of the mechanical system composed by the rotor mass and the magnetic stiffness.

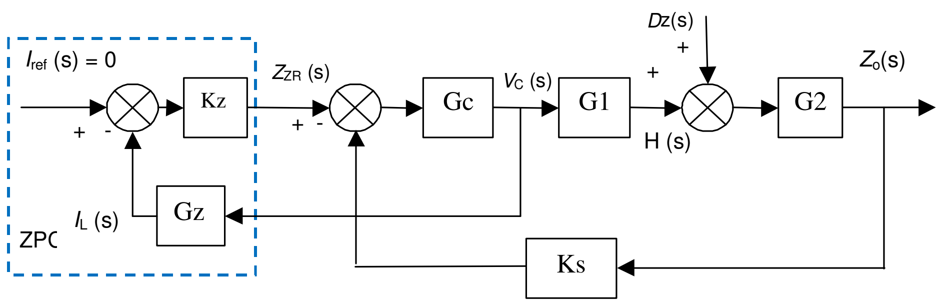


Figure 11 Block diagram of EPUSP bearing including ZPC element

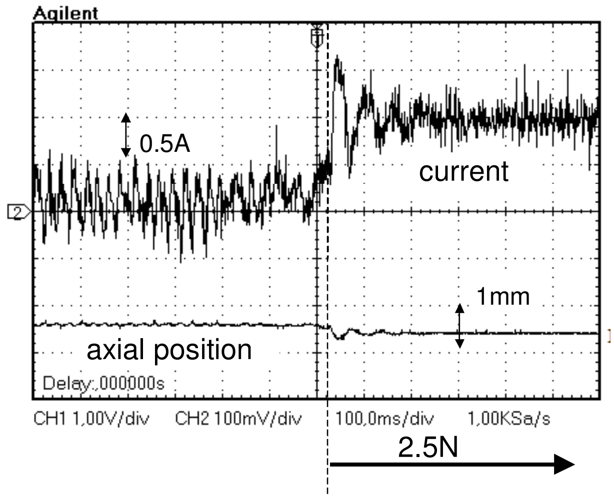


Figure 12 Response to a 2.5N stepwise load without ZPC

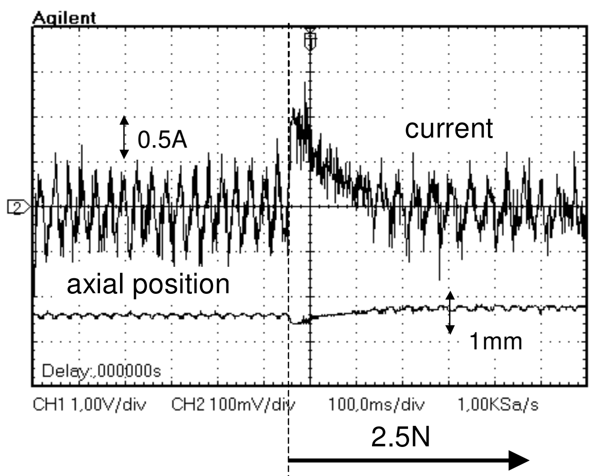


Figure 13 Response to a stepwise load with ZPC

4 Driving method for the rotor levitated by EPUSP bearing

If the rotor levitated by EPUSP bearing is driven by an electric motor, naturally the motor will interfere in the functioning of the magnetic bearing. Such interference is studied for two possible driven strategies: axial magnetic flux drive and radial magnetic flux drive (Camargo, 2011).

In both driving methods, it is assumed that ferromagnetic core is not used in the motor since this will generates an additional negative stiffness in the radial direction due to the interaction between the magnets of the motor rotor and the ferromagnetic core. In the worst case, the rotor may adhere to the core. These aspects are confirmed, for example, by Asama, 2004. Also, the absence of the ferromagnetic core in the stator does not affect the motor torque (Ooshima, 2007).

Then, a BLDC motor is designed and constructed according to the axial and other, to the radial magnetic flux configuration. Both motors are designed so as to furnish a power enough to pump 5 litters of blood per minute under the pressure of 100mmHg, with the rotor at 2000rpm. These reference values are based in literatures, as for example Asama, 2004. The above values implies in a torque larger than 0.013Nm and a mechanical power of 2.8W. After constructed, the motors are tested and above specifications confirmed in a dynamometer. At the same time, an EPUSP bearing is constructed using the Topology 3.

Both motors are tested driving a rotor supported by an EPUSP bearing. Fig.14 shows simultaneous records of the electrical current in the actuator of the bearing and the axial position of the rotor, when the motor of axial magnetic flux motor is used. It is observed that, as the speed of the rotor increases, the axial load on the rotor increases, requiring more current in the bearing actuator. At some speed, the driver of the bearing actuator no longer furnishes enough power to the actuator and the bearing becomes unstable. When using the motor of radial magnetic flux (Fig.15), despite the increase in the speed, the average current in the actuator remains constant, indicating that the radial motor exert small or no axial effort on the rotor although the motor is furnishing torque to it.

Thus, it is confirmed that, compared to the motor of axial magnetic flux, the motor of axial magnetic flux is the better option to drive the rotor supported by EPUSP bearing.

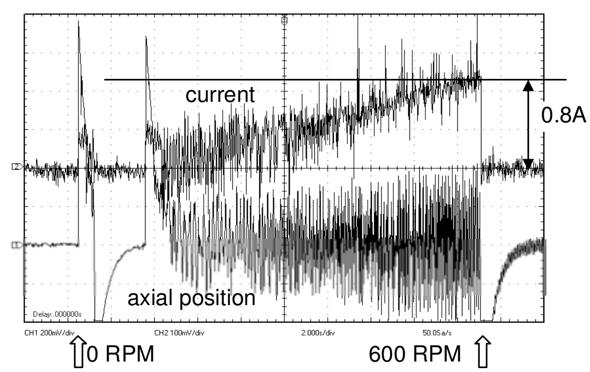


Figure 14 Response when driven by axial motor

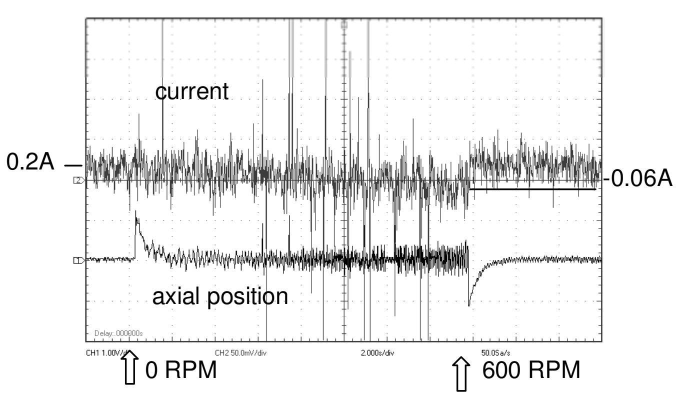


Figure 15 Response when driven by radial motor

5 Sensing strategies of the rotor axial position

On developing an implantable VAD equipped with the EPUSP bearing, one limitation is the sensor used to measure the axial poition of the rotor. Originally, an inductive sensor was used. However, the sensor has a considerable size, imposing limitation on miniaturizing the implantable VAD. Besides, the use of the inductive sensor requires the use of hollow magnet and actuator so as to enable installing the sensor probe.

One posssible alternative for this sensor is the use of the sensorless technique. This sensorless technique for magnetic bearings (Vischer,1993, Mizuno,1996, Fleming,2005 etc) is based on estimatives of the rotor position, calculated from the measurement of varios internal variables of the bearing, such as the current supplied to the electromagnets, and the dynamic model of the bearing. Besides requiring a complex algorithm processing, another limitation of this technique are the errors in the position estimation as consequence of errors in the model used to this end. Here, the study is focused on use of the Hall sensor, i.e. a sensor that furnishes an electric output according to the intesity of the magnetic flux density. There are some works proposing the use of this sensor, such as Lilienkamp, 2004, Komori, 2005, Jayawant,1981 and others. However no work presented an application as of this work.

A simple approach to use the Hall sensor to measure the rotor axial position is to place the sensor on the top of the actuator. Thus, as the rotor magnet moves axially, the magnetic flux density in the sensor changes and consequently the sentor output changes accordingly to the rotor displacement. However, the sensor output also changes due to the magnetic flux generated by the actuator. If this component is sent back to the controller, the system becomes unstable.

This problem is solved by two strategies. The first one consists on placing another sensor in the oposite pole and in the simmetric position of the actuator (Fig.16). Thus, any magnetic flux generated by the actuator, gives rise to an symmetric output in the sensors. However, the output of two sensors due to the rotor motion has same polarity. Therefore, a differential amplification of the the output of both sensors furnishes the the rotor axial displacement. The second strategy is based on the model of the electromagnetic actuator (Fig.17). The Hall sensor output is affected by the rotor position and the magnetic field generated by the actuator. Knowing the tension applied to the actuator and the dynamic model of the actuator, the output of the sensor due to the actuator is calculated. The result is subtracted from the senror gross output remaining only the output due to the rotor axial displacement.

Both strategies are tested and by obtaining stable levitation of a rotor by a EPUSP bearing, the effectiveness of the strategies are demonstrated.

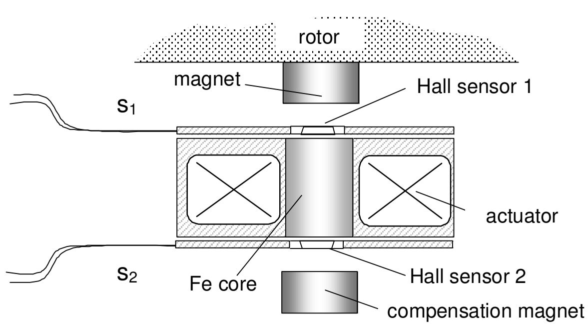


Figure 16 Actuator with Hall sensors

Despite this study, another simpler alternative is identified. The solution is to replace the probe of the commercial inductive sensor by a thin circular coil, matching the impedance to the electronics of the sensor. This solution was adopted in all EPUSP bearing after Topology 3. However, the solution based on Hall sensors has the advantage of requiring a simpler electronics (only operational amplifiers) compared with the inductive one. Therefore, depending on the application, the use of Hall sensor may be interesting.

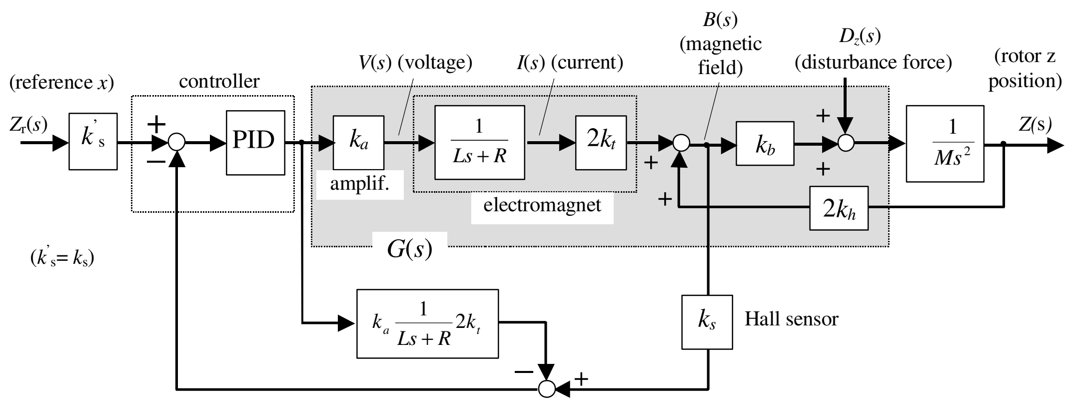


Figure 17 Compensation of the Hall sensor output

6 Conclusions

Aiming the development of an implantable Ventricular Assist Device – VAD, a joint project was started in 2007, involving the Escola Politécnica of São Paulo University (EPUSP) and the Dante Pazzanese of Cardiology (IDPC). One of objectives of the project is the development of a VAD with a rotor levitated by a magnetic bearing. Here, a magnetic bearing proposed by authors, here called as EPUSP bearing, is elected mainly because of its simplicity. This work presented the entire development process that involved identification of a topology of the EPUSP bearing that enables a robust levitation, enough for supporting the rotor of a VAD. Although, not described here, the development includes the study concerning the pump portion. Since it is very important that the VAD has small sizes, the pump and the bearing should not developed independently. The design of the bearing affects the pump and vice versa.

The first phase of the project was concluded in 2012. However it is expected that the second phase starts soon and the development of a VAD with the rotor supported by the EPUSP bearing is continued.

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