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# STUDY ON A MAGNETIC SUSPENSION OF THE ROTOR OF AN ARTIFICIAL HEART

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***Abstract.*** *This work presents studies about application of magnetic bearing in a Ventricular Assistance Device (VAD), a variety of artificial heart, being developed by "Dante Pazzanese" Institute of Cardiology – IDPC (São Paulo, Brazil). The VAD-IDPC has a novel architecture that distinguishes it from other known VADs. In this, the rotor that impels and pressurizes the blood has a conical geometry with spiral impellers, showing characteristics that are intermediate between a centrifugal VAD and an axial VAD. That is, it requires a rotor speed lower than an axial VAD and shows dimensions smaller than a centrifugal VAD. The effectiveness of this new type of blood pumping principle was showed by tests and by using it in heart surgery for external blood circulation. However, the support system of the rotor of this VAD is based on a combination of ball bearings and mechanical seals, limiting the life for some ten hours, making impossible its long-term use or its use as an implantable VAD. As a part of development of an implantable VAD, this work aims the replacement of the combination of ball bearing plus mechanical seals by a magnetic bearing. Suspending totally the rotor by magnetic forces, the contact of the rotor with any part of the VAD body is eliminated. Therefore, the problem of hemolysis is minimized and the lifetime of the bearing is optimized. Most important magnetic bearing principles are studied and the magnetic bearing developed by Escola Politécnica of São Paulo University (EPUSP bearing) is elected because of its very simple architecture. Besides presenting the principle of the EPUSP bearing, this work presents possible alternative for applying the EPUSP bearing in the IDPC-VAD. This work also shows the first protoype of the EPUSP bearing applied to the VAD. The protoype is developed, costructed and the obtained results shown here.*

***Keywords*** *artificial heart, ventricular assistance device, magnetic bearing, implantable VAD.*

## 1. INTRODUCTION

This work presents a study concerning a Ventricular Assistance Device (VAD) developed by "Dante Pazzanese" Institute of Cardiology - IDPC, VAD-IDPC (Andrade *et al*, 1996). This VAD, whose scheme is presented in Fig.1, has a novel architecture that distinguishes it from other known VADs. Fig. 2 presents a photograph of the VAD-IDPC. In this, the rotor that impels and pressurizes the blood has a conical geometry with spirals impellers. Other known VADs can be classified in two main categories, those that use centrifugal pumps principle and the others based on axial pumps principle. Examples of radial VADs are VentrAssist (Esmore *et al*, 2005), Duraheart (Nojiri, 2002), CorAide (Fukumachi *et al*, 2002) among others. On the other hand, examples of axial VADs are Hemopump (Don, 2000), Jarvik2000 (Westby *et al*, 1998) and Micromed DeBakey (Wieselthaler *et al*, 2000) among others.

Results show that radial pumps give larger loads, when compared to the axial ones, e.g. larger liquid pressure difference between pump input and output. On the other hand, axial pumps give larger flows rate contributing to reduce pumps size. Thereby, using these pumps as VADs and assuming same flow rate and load for both models and comparing axial VADs with centrifugal VADs, the first operates with low rotation in the rotor, but they have larger dimensions. This is equivalent to say that axial VADs make possible a more compact VAD but they demand a high speed in the rotor. Thus, both types of VADs present potential advantages and disadvantages. The reduced size is very interesting for the development of implantable VADs. On the other hand, low rotor speed is interesting to minimize the risk of the hemolysis, i.e. the damage of blood cells by collisions with the rotor at high speed. Besides, low rotor speed contributes to simplify the control and the driving of the rotor. In this scenery, VAD-IDPC presents an intermediate solution between a centrifugal VAD and an axial VAD, i.e. a VAD based on the mixed flow pump principle. So, VAD-IDPC offers possibility for a VAD whose size and speed of the rotor is intermediate between a centrifugal VAD and an axial one.

A prototype of VAD-IDPC was developed for use in cardiac surgery for extra-corporal blood circulation (Andrade *et al*, 1996). Its efficiency was already demonstrated through *in vitro* tests. It was first implanted in bulls and lately in patients, thus its effectiveness was demonstrated. Currently, IDPC is developing the second phase of the project, i.e. the development of an implantable VAD-IDPC. As part of this new project phase, it was started a study to replace the supporting system of the rotor, at the moment based on an conventional ball bearing and gaskets, by a magnetic bearing.

In this scenario, authors already presented a work (Horikawa *et al*, 2006), a strategy to apply the magnetic bearing to the VAD-IDPC and main consideration concerning the design of the bearing. Besides presenting the bearing, this work reports the prototype developed and results of experiments.

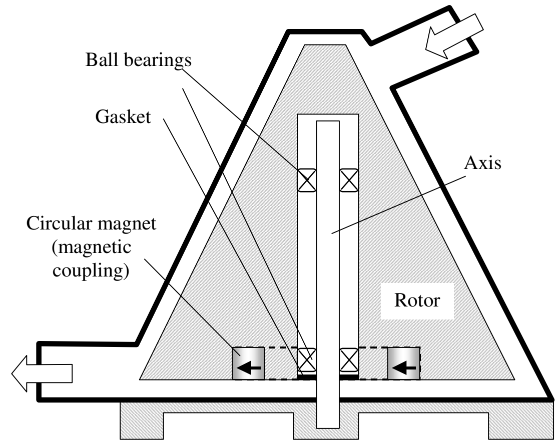



Figure 1. VAD-IDPC scheme.

Figure 2. Photograph of the VAD-IDPC.

## 2. EPUSP MAGNETIC BEARING

There are many researches about magnetic bearings, but most of them are concerned about magnetic bearing with control in 5-d.o.f. (five degrees of freedom) of a rotor or a table. Since the control of each d.o.f. requires a sensor, an actuator and a controller, the entire system becomes very complex in terms of mechanical, electric and control parts project. Thereby, a new architecture of magnetic bearing was proposed at Silva and Horikawa, 2000. This new bearing, here denominated EPUSP magnetic bearing, uses active control in only 1-d.o.f. of a rotor, i.e. the rotor translation in the axial direction. In this bearing, motions of the rotor in other directions are restricted only by the action of permanent magnets that operate in attraction mode, thus minimizing permanent magnets demagnetization (Ohji, 1992 and Campbell, 1994). The majority of known VADs, equipped with magnetic bearing, has control in more than 2 directions (see for example Hoshi *et al*, 2006). The EPUSP magnetic bearing is elected to be used in the VAD-IDPC, because of its simplicity. Fig. 3 shows the schematics of the EPUSP magnetic bearing. A permanent magnet is fixed to each extremity of a rotating axis that passes through two stationary actuators. Each actuator is a combination of an electromagnet and a permanent magnet. The polarity of each magnet is as described in Fig. 3. An attraction force acts between each pair of magnets. As described later, assuring a minimum distance to the length of the axis, the two pairs of magnets assure rotor stable equilibrium along radial direction. The stability in axial direction is assured by a control loop, which is composed of a non-contact-type gap sensor, a controller and an electromagnetic actuator. This control is necessary, since it is impossible to reach the stability only by permanents magnets. This is a consequence of Earnshaw's principle (Earnshaw, 1939).

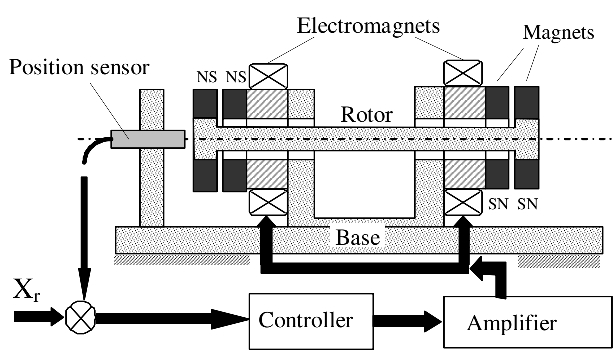



Figure 3. EPUSP magnetic bearing configuration.

## 3. MINIMUM SHAFT LENGTH

Figure 4 illustrates one of the two pairs of magnets attached at each end of the rotor. Fig. 4(a) depicts the case in which one of the magnets is shifted in the radial direction. In this situation, the axial force $f_a$, radial force $f_r$, radial stiffness $k_r$, and axial stiffness

$k_a$ can be expressed by Eqs. (1)–(4) (Yonnet, 1981). On the other hand, if one magnet is inclined in relation to the other, as shown in Fig. 4(b), a stiffness $k_\gamma$ that can be expressed by Eq. (5), is observed (Delamare, 1994).

$$f_a \cong 2B\sin(3\theta)/\sigma^3 \quad (1)$$

$$f_r \cong 2B\cos(3\theta)/\sigma^3 \quad (2)$$

$$k_r = 6B\cos(4\theta)/\sigma^4 \quad (3)$$

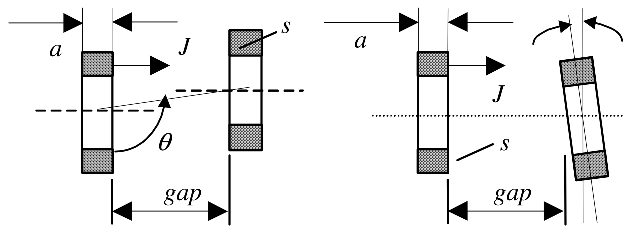
$$k_a \cong 2k_r \quad (4)$$

$$k_\gamma = k_a \frac{R^2}{2} \quad (5)$$

In (1) ~ (4)

$$B = J^2 S^2 p / 2\pi\mu_0 \quad (6)$$

$$\sigma = gap + a \quad (7)$$




(a) radial displacement (b) relative tilt

Figure 4. Permanent magnets.

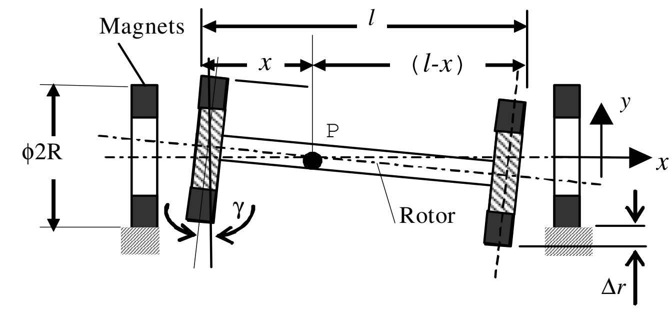



Figure 5. Rotor tilted.

where $J$ is the magnetic flux density of permanent magnet, and $S$, $p$ , and $a$, are the cross-sectional area, the perimeter, and the thickness of the magnet. $\theta$ is the angular deviation.

As shown in Eq. (3), the stiffness in the radial direction is positive. Thus, the rotor will be stable in terms of pure radial motion. In the axial direction, since the corresponding stiffness is negative as Eq. (4) shows, the stability must be assured by the control loop. However, the stability in terms of tilting motions of the rotor must be analyzed as follows.

Consider the configuration of Fig. 5. The distance between the permanent magnets is $l$. In front of each magnet there is another one working in attraction mode, keeping a gap (the position of the fixed magnets differs from that of Fig. 3, but this was made only to simplify the figure). Considering the pair of magnets at the left side of Fig. 5. When the rotor is tilted as shown in the figure, the gap amount increases at the upper side and decreases at the lower side. Thus, the attraction force at the lower side becomes larger than the force at the upper side. The opposite occurs with the pair of magnets at the right side of the rotor. These forces will generate a momentum ($\Sigma M_t$) that tends to increase the tilting amount of the rotor. However, the tilting of the rotor also results in radial displacement of the magnet attached to the rotor, relative to the magnets fixed to the base. These displacements generate a radial force in the opposite direction of the displacements, resulting in a momentum ($\Sigma M_r$) that will force the rotor back to its original position before tilting. Thus, the entire stability of the rotor will be assured if the following is satisfied:

$$\sum M_r > \sum M_t \quad (8)$$

Figure 5 depicts a tilting around a generic point $P$. However, the rotor is stable in terms of translation in the radial direction, as mentioned before. Therefore, to analyze Eq. (8), tilting of the rotor is considered only in the situation in which $P$ coincides with rotor center ($x=l/2$). In such condition and considering a small enough tilting, $\gamma=2\Delta r/l$. Thus, the following are obtained:

$$\sum M_t = k_r \Delta_r \frac{l}{2} + k_r \Delta_r \frac{l}{2} = 2k_r \Delta_r l \quad (9)$$

$$\sum M_r = 2k_\gamma \frac{\Delta_r}{l/2} \quad (10)$$

However, Eqs. (4) and (5) give:

$$k_\gamma = k_r R^2 \quad (11)$$

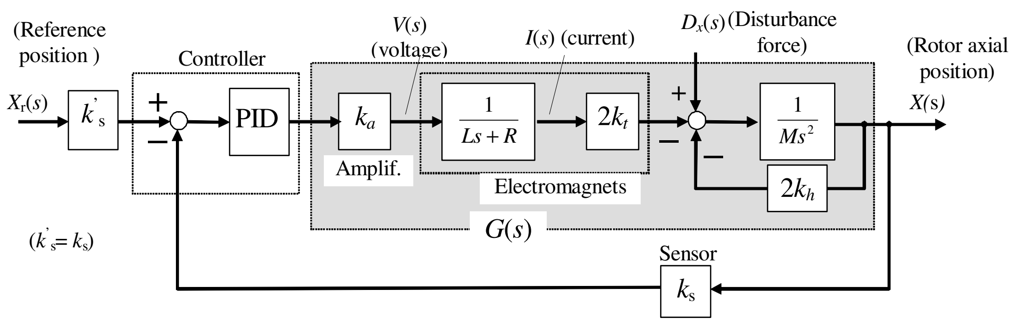
Substituting Eqs. (9) ~ (11) in (8), one can reach the following relation that assures the angular stability of the bearing rotor:

$$l/2r > 1 \qquad (12)$$

With a larger distance between the pairs of magnets, a larger $\Sigma M_t$ is obtained and as consequence, a larger stiffness is achieved for rotor tilting motions.

## 4. EPUSP MAGNETIC BEARING PEFORMANCE

Figure 6 shows the EPUSP magnetic bearing block diagram. The whole system control is assured by an ordinary Proportional – Integral – Derivative (PID) controller.




$M$: Rotor mass — $k_t$: Electromagnetic constant — $L$: Electromagnetic inductance
$k_s$: Sensor gain — $k_h$: Magnetic constant — $R$: Electromagnetic resistance
$k_a$: Amplifier gain

Figure 6. EPUSP magnetic bearing block diagram.

Figure 7 shows the prototype of the EPUSP magnetic bearing. The bearing uses ferrite permanent magnets ($B$ = 0.25T, axial magnetization, $S$ = 63mm$^2$, $p$=84.8mm and $a$ = 7mm). Fig.8 shows rotor radial displacement curve in function of the applied force in the axial direction. This result shows that the bearing is capable to resist an axial effort of approximately 4N before rotor touch some fixed part of the bearing. High load capacity and a larger stiffness can be reached using magnets of more intense fields, e.g. rare earth magnets.

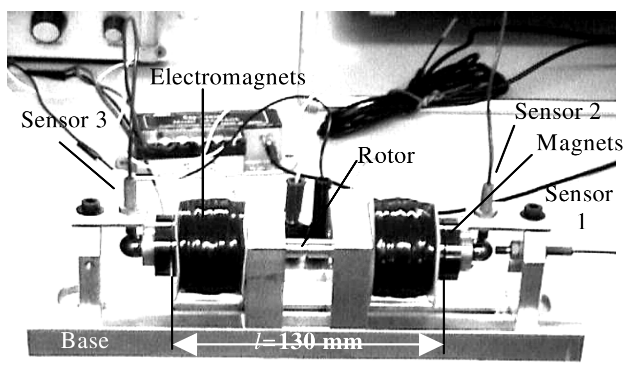



Figure 7. EPUSP magnetic bearing prototype.

Figure 9 shows the readings of the sensor used to control the rotor axial position (sensor 1 in Fig.7) with the rotor rotating at 500rpm. Fig.9 still shows the readings of the additional sensors installed for the measurement of radial displacements of the rotor in the extremities of it (sensor 2 and 3). In the axial direction the rotor presents a vibration of approximately 5µm of amplitude and of approximately 0.4mm in the radial direction. Both vibrations are resulted of an existent unbalance in the rotor. Despite these vibrations the rotor remains stable in a central position without tilting any bearing fixed party.

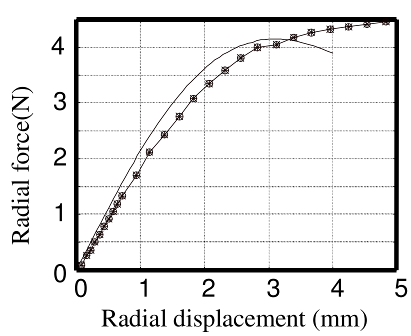



Figure 8. Radial force vs. displacement.

## 5. EPUSP MAGNETIC BEARING APPLICATION

A straight application of the EPUSP magnetic bearing in the VAD-IDPC would be one presented in Fig.10. The rotor shown in Fig. 3 is changed by a rotor that contains permanent magnets in its extremities. In front of each magnet attached to the rotor other magnet is fixed to the VAD frame, maintaining a gap of approximately 2mm. Ring type magnets are located in the lower side of the rotor to allow the installation of the non-contact sensor that measures rotor position. Although using an actuator (electromagnet) in only one side of the bearing, and a pair of cylindrical magnets in one side of the bearing, the principle of the EPUSP magnetic bearing is basically maintained, thus a stable levitation of the VAD is assured.

However, such configuration is not satisfactory since it is necessary to assure moment transmission for the rotor in a non-contact way. Such moment transmission has already been accomplished in VAD-IDPC through a magnetic coupling, Fig.11, i.e. a cylindrical magnet attached to the rotor base and a second magnet, with same geometry and dimensions, attached to the shaft of an electric motor. Both magnets are radially magnetized, so that the magnet fixed to the motor rotor drags the bearing rotor.

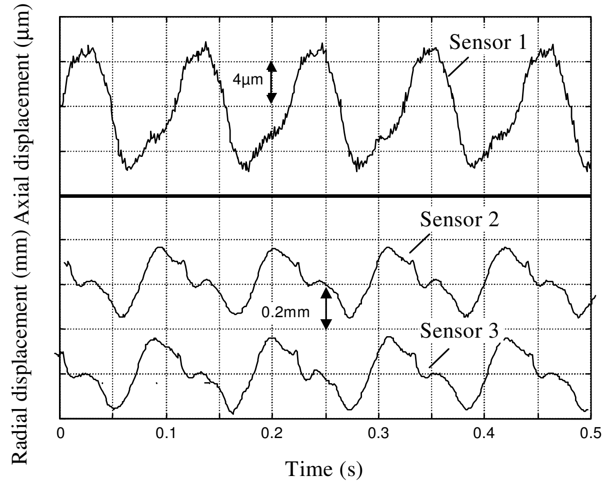



Figure 9. Vibrations of the rotor at 500rpm.

However, aiming an implantable VAD of small dimensions, the coupling shown in Fig. 12 is proposed. Here, various permanent magnets are fixed to the rotor base, alternating their polarity. Facing the magnets, an electromagnet is fixed to the VAD frame. Switching adequately the current to each electromagnet, a moment is induced in the rotor, according to the same principle of a well kwon DC motor. In this coupling, actually, an electric motor, the attraction force between each magnets and the electromagnet core, arranged in ring form, assure a positive radial stiffness, in the same fashion of EPUSP magnetic bearing. This keeps the rotor in a central position.

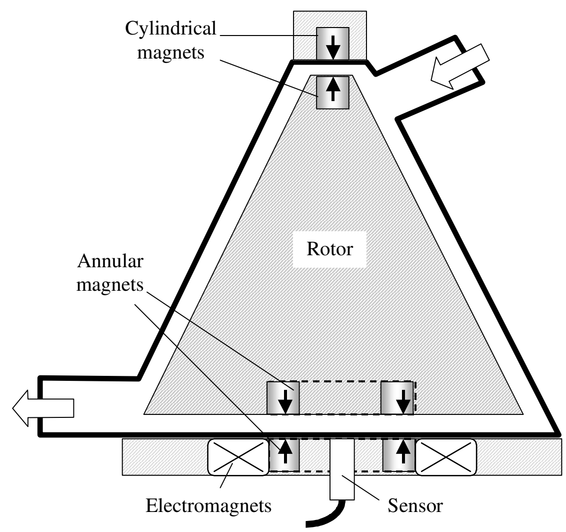



Figure 10. EPUSP magnetic bearing applied to VAD-IDPC.

Now, the electromagnetic actuator that controls rotor axial position is discussed. Aiming a compact VAD, the same electromagnetic mentioned before, for rotary driving of the rotor, would be used to control the axial position. However, since the magnets arranged in the base of the rotor have alternate polarities, this problem is complex. When the rotor is rotating, the current to each electromagnet must be switched permanently and this must be done in a perfect synchronism with the rotor rotation, thus keeping the rotor in a constant axial position in a stable way. In order to simplify the problem, and as a first step in the development, other electromagnet is used in VAD upper side as shown in Fig. 13.

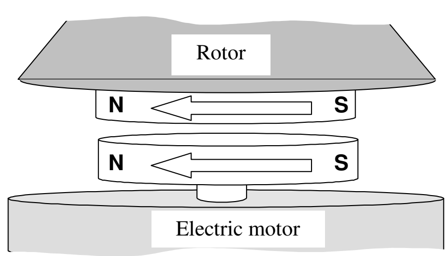



Figure 11. Coupling type 1.

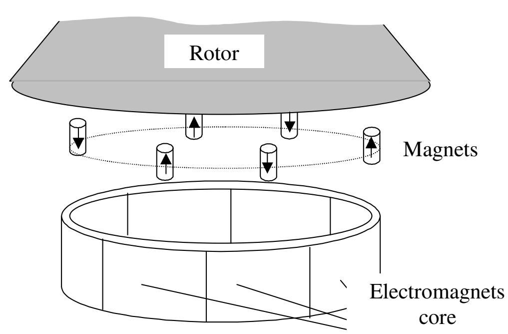



Figure 12. Coupling type 2.

## 6. MAGNETIC BEARING STABILITY ANALISYS

Consider the rotor shown in Figure 13. The magnet pair at both side of the VAD generates two magnetic stiffness: radial and axial, as illustrated in Fig.14. The stable levitation of the rotor depends on the action of each stiffness on the whole bearing.

- **Axial direction stability**. The bearing stiffness in axial direction is result of the sum of all axial stiffnesses at each magnetic pair (magnet-magnet or magnet-core) of the bearing. Since all magnets are working in attraction mode, all axial stiffnesses are negative. Thus, in this direction, the total stiffness is negative and the system stability must be assured by an active control.
- **Radial direction stability**. The radial direction stiffness results from the sum of the stiffness at each magnet pair. Since each radial stiffness is positive (attraction force in all magnet pairs) the total bearing radial stiffness is positive and the rotor is stable in the radial direction.
- **Tilt motion stability**. The stiffness against tilting motions of the rotor, $k_\theta$, is determined by joint effects of stiffness $k_{a1}$, $k_{a2}$ and $k_{r2}$. In order to support the rotor in a stable way, $k_\theta$ must be positive. Using 6 permanent magnets (A ~ F) uniformly arranged along a circle of radius $r$ and assuming that the rotor tilts as shown in Fig. 14, $k_\theta$ is given by:

$$k_\theta = k_{r1}\frac{l}{2} + 2(k_{a2}r + 2k_{a2}\frac{r}{2}) + 2(k_{r2}\frac{l}{2} + 2\frac{k_{r2}}{2}\frac{l}{2}) \quad (13)$$

That is

$$k_\theta = k_{r1}\frac{l}{2} + 4k_{a2}r + 2k_{r2}l \quad (14)$$

Here, it is assumed that the rotor tilts around the point $P$, at the distance $l/2$ from rotor extremities. However, subsequent conclusions do not depend of point $P$ position. It is also assumed, in a simplified way, that the permanent magnets B and C shown in Fig.14 as well permanent magnets E and F (not shown in Fig 14) have radial stiffness of $k_{r2}/2$. When the rotor tilts in the plane of the figure, there is no relative displacement of the magnet in a direction orthogonal to the walls of the cylindrical core.

As shown before with respect to the EPUSP magnetic bearing, for a same magnetic pair that operates in attraction mode, the value of the radial stiffness is the half of that of the axial stiffness, although with opposed signals. In other words, in Eq.(14), $k_{r1}=-k_{a1}/2$ and $k_{r2}=-k_{a2}/2$. Thus,

$$k_\theta = -k_{a1}\frac{l}{4} + 4k_{a2}r - k_{a2}l \quad (15)$$

Since the stable suspension of the rotor requires $k_\theta>0$, following relationship is obtained.

$$-k_{a1} > -k_{a2}4(4\frac{r}{l} - 1) \quad (16)$$

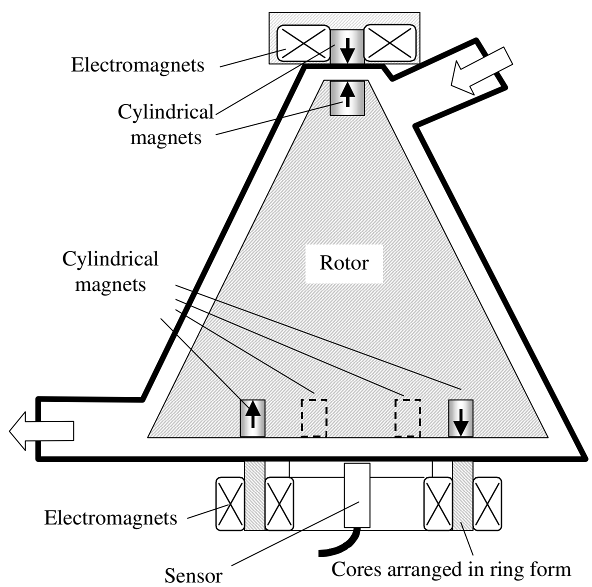



Figure 13. VAD-IDPC with magnetic bearing.

Equation 16 shows that, if $r<l/4$ the table is suspended in a stable way, regarding tilting motions of the rotor. Consequently, the rotor is suspended in a stable way regarding all rotor degrees off freedom, excepting for the motion in the axial direction. However, the torque induced by electromagnets to the rotor, decreases as small is the value of $r$. This can represent difficulties to achieve values of $r$ smaller than $l/4$. In such case, the magnets are arranged on the rotor base so as to assure enough torque transmission. After that, the rotor upper magnets are chosen to assure the stiffness stated in Eq. (16). This can be reached, for instance, through the use of larger traverse section or larger perimeter magnets when compared with those used in the rotor base.

## 7. MAGNETIC PAIRS DEFINITIONS GUIDELINES

Once implanted, the VAD receives blood pumped by the heart and both, blood pressure and blood flow are oscillatory. Such flow and pressure oscillations can submit the rotor to oscillatory efforts. Also, rotor oscillations due to the VAD-IDPC peculiar architecture must de considered. These oscillations occur even the blood flow and pressure remains constant. The magnetic bearing should assures enough radial stiffness so that the resulting vibrations caused by oscillatory efforts, as mentioned, do not induce vibrations with amplitudes larger than the existent gap between the rotor and VAD walls.

It is also expected that VAD-IDPC rotor will be submitted to an axial force of considerable magnitude, due to its characteristics of a mixed flow pump. If in the VAD, the blood flow is descending, the rotor will be submitted to an ascending force. In this aspect, the EPUSP magnetic bearing presents possibility for compensating effects of that force, because the active control acts along axial direction. Fig.15 shows the EPUSP magnetic bearing response when a step signal is applied to the entrance reference $X_r$ (Fig.6). In this case, the rotor axial position was altered of 0.08mm and in less than 0.2s the rotor reaches the new position and maintains this position in a stable and precision way. This result shows the possibilities of EPUSP magnetic bearing to change its operating position to a new one in which, the magnetic attraction force generated by permanent magnets, balances the force applied to the rotor in the axial direction. This procedure reduces the effort generates by the electromagnetic actuators when the axial load is applied to the rotor, minimizing the energy consumption. Fig.16 shows magnetic bearing response to an impulse signal applied along rotor axial direction. Due to this force, the rotor displaces from its original position, but it returns to the original position quickly.

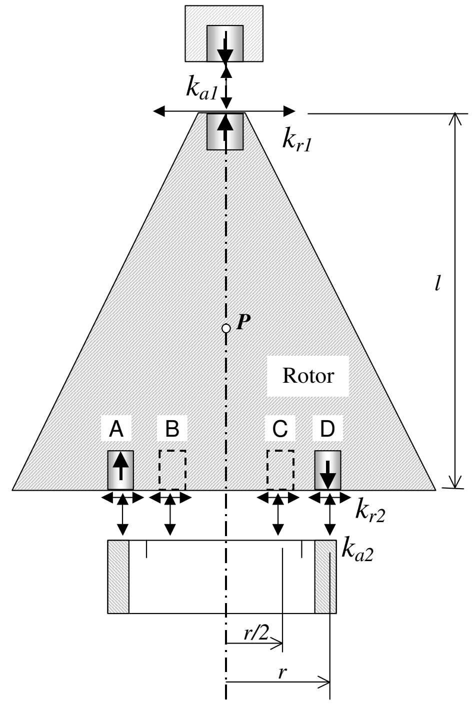


Figure 14. Magnet pairs stiffnesses.

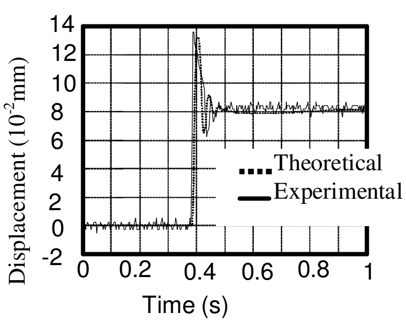


Figure 15. Step response.

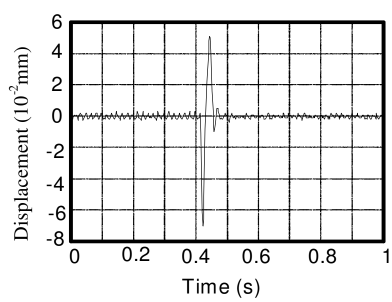


Figure 16. Impulse response.

## 8. THE PROTOTYPE OF THE MAGNETIC BEARING

Based on considerations presented above, a prototype of the bearing was developed and tested. Fig. 17 shows the prototype and the experimental set up used to test it. A polymeric (PVC) cylindrical structure supports, in its top side, the actuator (Fig.18), the combination of a permanent cylindrical magnet (ϕ13mm diameter by 6mm height) and an electromagnet (inner diameter of ϕ13mm by 30mm height, 700 turns). In the lower side of the structure, an annular iron target (ϕ35mm by 20mm height) and a non-contact eddy current sensor are arranged. In the future, this iron target will be replaced by 6 independent targets, that will be cores of an electric motor that will drive the rotor, as shown in Fig.12. A conical rotor (PVC, ϕ53mm radius circular base by 34.5mm height) is set between the actuator and the target. Since the objective here, is to test the magnetic bearing, no blades were machined in the rotor. Fig. 19 shows photographs of the rotor. In the top of the rotor, one cylindrical magnet (ϕ13mm diameter by, 6mm height) is fixed. In the base of the rotor, 6 cylindrical magnets (ϕ6mm diameter by, 6mm height) were arranged uniformly along a circle of 35mm diameter. All magnets are rare earth, Ni-Fe-Bo magnets. A computer is used to control the system according to a PID algorithm. Sensor signal is sampled to the computer through 12bits A/D converter and control signal is sent to the actuator through a 12bits D/A converter and a current amplifier.

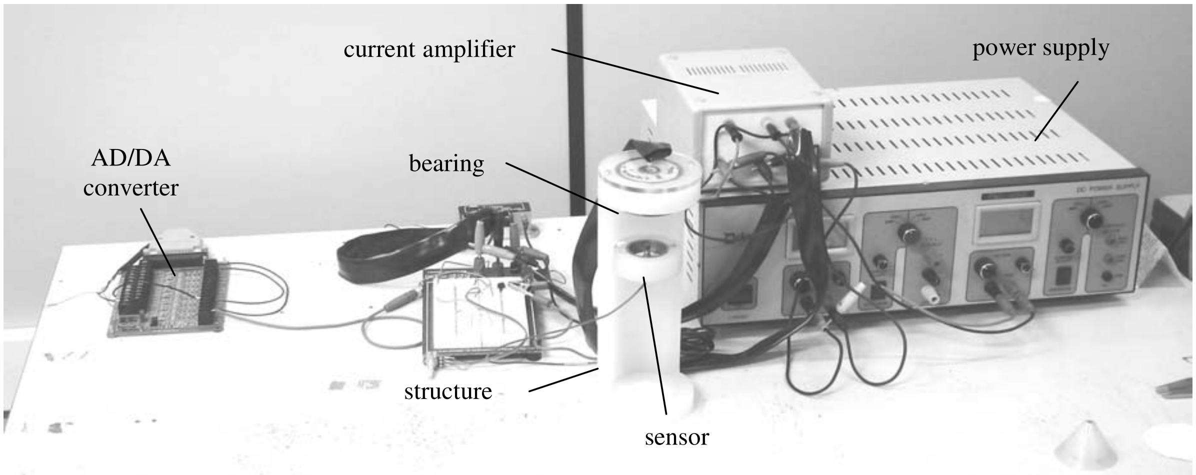



Figure 17. Prototype of the magnetic bearing and the experimental set up.

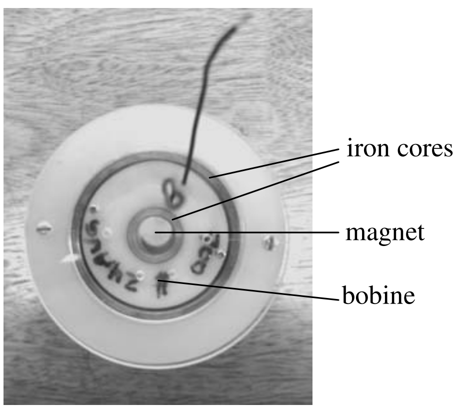
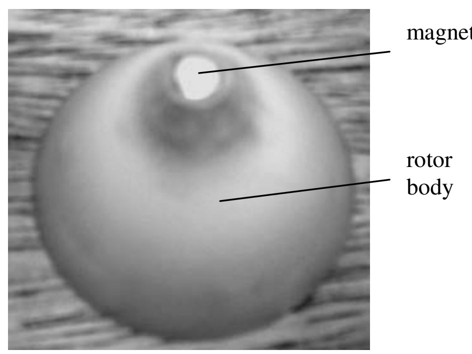
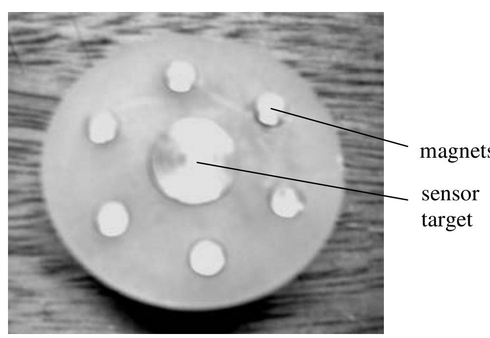



Figure 18. The actuator, combination of an electromagnet and a permanent magnet.




(a) Top view




(b) Lower view

Figure 19. The rotor used in the prototype.

Figure 20 shows the rotor being levitated by the developed magnetic bearing. As it is observed in the photo, a clearance (approximately 5mm) is maintained at the upper and the lower side of the rotor. The clearance between the sensor and the rotor is of approximately 1mm. Thus the rotor is suspended without any mechanical contact in a stable way. In order to achieve this, one additional magnet ($\phi$6mm diameter by, 6mm height) is added to the existing one, at the top of the conical rotor. Thus the length of the rotor is increased, increasing the rigidity of the bearing against the inclination of the rotor (see Eq.(2)). Without the additional magnet, the bearing is unstable in terms of the rotor tilting. The sampling rate of the digital control executed by the computer, as well as the parameters of the PID controller, are adjusted experimentally. The optimization of such parameters will be treated in future works. The objective here is to verify the validity of the suspension strategy.

In the experiments, a problem was detected because of the use of rare earth magnets. Since such magnets generates an intense magnetic force, a slice deviation of the rotor from its reference position, makes the electromagnet and the current amplifier saturating. For this reason, a small force that acts in the rotor makes the bearing unstable.

## 9. CONCLUSIONS

This work presented the strategy regarding application of a magnetic bearing in a centrifugal and implantable ventricular assistance device (VAD) being developed by "Dante Pazzanese" institute of Cardiology - IDPC. The magnetic bearing implantation has as final objective, the development of a VAD-IDPC for intra body use. After analysis of the main known magnetic bearings for application in VAD-IDPC, it was chosen for study a bearing developed by Escola Politécnica of São Paulo University, EPUSP magnetic bearing, which has a very simple architecture. The rotor levitation stiffness problem, as well as the problem of rotor stable levitation through magnetic bearing was analyzed and the main criterion to construct magnetic bearing was delineated. A prototype of the VAD with the magnetic bearing was constructed and tests demonstrate that a stable suspension of the rotor is possible by the presented strategy. Future works will treat the development of more efficient actuators for the magnetic bearing, avoiding problems of saturation of the actuator and of the current amplifier, verified in this work. Moreover, in an advanced stage of the development, the miniaturization of the entire system will be considered.

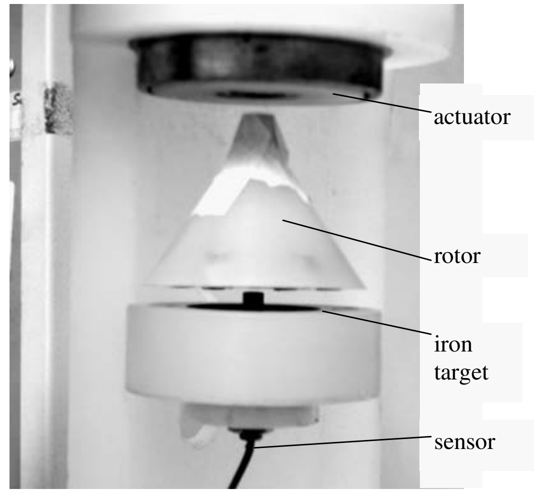



Figure 20. Rotor being suspended.

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