MAGNETIC SUSPENSION OF THE ROTOR OF A VENTRICULAR ASSISTANCE DEVICE OF MIXED FLOW TYPE – HALL SENSOR FOR ROTOR POSITION SENSORING

Pedro Antunes, antunes.pedro@yahoo.com.br
Escola Politécnica of São Paulo University

Orlando de Melo, orlando.hmello@gmail.com
Escola Politécnica of São Paulo University

Eduardo Bock, eduardo_bock@yahoo.com.br
Institute Dante Pazzanese of Cardiology

Aron Andrade, aron@dantepazzanese.org.br
Institute Dante Pazzanese of Cardiology

Oswaldo Horikawa, ohorikaw@usp.br
Escola Politécnica of São Paulo University

Abstract: *The Dante Pazzanese Institute of Cardiology (IDPC, Brazil) and the Escola Politecnica of São Paulo University (EPUSP, Brazil) are jointly developing an implantable Ventricular Assist Device (VAD), i.e, an artificial heart, which is based on a mixed flow pump developed by the IDPC and has its rotor levitated by a magnetic bearing. Since the magnetic levitation approach eliminates the contact betweem the rotor and pump parts, it is possible to minimize the hemolysis and maximize the lifetime of the VAD. The magnetic bearing used is a hybrid type, combining permanent magnets with electromagnets to execute active control only in one direction of motion, the axial direction of the rotor. Permanent magnets are fixed at the both ends of the rotor. Each magnet faces the core of an electromagnet fixed to the pump housing. The attraction force between each magnetic pair compesed of a magnet and iron core, assures a stable retention of the rotor in a central position. In this bearing, an inductive sensor measures the axial position of the rotor. The measurement signal then, is sent to a PID controller and then processed, amplified and sent to the electromagnic actuators. The current supplied to the actuators are controlled in a way to keep the rotor in a fixed axial position. One of the actuators, located at the bottom side of the rotor, is hollow to enable inductive sensor placement. As result, this actuator is less efficient than the electromagnet at the upper side of the rotor. Moreover, the use of an inductive sensor imposes limitations to pump downsizing. In order to overcome these problems, a sort of alternatives techniques for position measuring are studied. One of techniques, commonly applied on magnetic bearings, is the sensorless technique. However, sensorless techniques are complex since they are based on positioning estimative. Therefore, this work proposes a simpler solution, based on the use of the Hall sensor. The Hall sensor is a small semiconductor element that gives an electric signal with amplitude corresponding to the magnet field intensity. The strategy consists on installing two Hall sensors, one at each end of the electromagnet core in a symmetric way. Summing these two signals, the influence of electromagnet actuator on the sensor signal is wiped out. This is necessary since the feeding back signal corresponding to the electromagnet makes the control system unstable. The so obtained signal expresses only the rotor position. This is used to control the rotor axial position in the same way inductive sensor does. This work presents results of preliminary studies concerning this strategy as well as this effectiveness*

Keywords*: Magnetic Bearing; Hall sensor; Position measurement*

1. INTRODUCTION

The Dante Pazzanese Institute of Cardiology (IDPC, Brazil) and the Escola Politécnica of the São Paulo University (EPUSP, Brazil) are jointly developing an implantable Ventricular Assist Device (VAD) i.e., an artificial heart (Horikawa et al, 2008). The pump to be developed is based on mixed flow type blood pump developed by the IDPC (Andrade *et al*, 1996) that uses a conical rotor with spiral impellers. In the original pump, the rotor of the VAD is supported by ball bearings. Even using gaskets and a sort of seals, the blood penetrates in the ball bearings imposing a very short-life time to the VAD. Moreover, the use of ball bearing gives rise to severe damages to the blood components, i.e., hemolysis. For these reasons, the previous model of VAD was suitable only for external use. Therefore, aiming the development of an implantable version of the IDPC-VAD, the replacement of the ball bearings by a magnetic bearing is proposed. Due to the simplicity compared with other now magnetic bearings, the magnetic bearings proposed by Silva *et al*, 2000 is elected. Figure 1 shows the configuration of the IDPC-VAD with this magnetic bearing. This magnetic bearing a hybrid type, combining an electromagnets and permanent magnets to levitate the rotor. A magnet is fixed at each end of the rotor. Each magnet faces a ferromagnetic iron core of an electromagnetic actuator. Due to the attraction force between the magnet and the core, both extremities of the rotor are retained in a central position in a stable way. However, in the axial direction, the rotor is not stable and for this reason, an active control is executed. As inductive type sensor measures the rotor axial position. The measured signal is sent to a PID type controller and then, processed, amplified and sent to the actuators. The current supplied to the actuators is controlled in a way to keep the rotor in a fixed axial position.

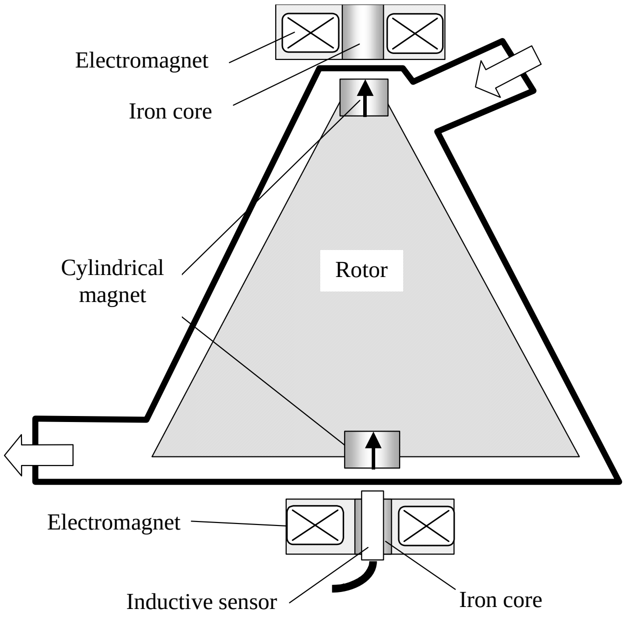

Figure 1. IDPC-VAD with magnetic bearing.

As shown in Fig.1, the core of the electromagnet at the bottom side of the rotor is hollow to enable the sensor installation. This imposes a sort of problems in the design of the bearing. Firstly, compared with the upper side electromagnet, the bottom side electromagnet is less efficient as actuator. Supplying the same current to the both actuator, the bottom one applies a smaller force to the rotor. Secondly, as mentioned, in this bearing, the attraction force between the magnets fixed to the rotor and the core of the actuators, assures the retention of the rotor in a radial fixed position. This retention force is lower in the bottom side magnetic pair, compared with the upper side one. Finally, the use of the inductive sensor imposes limitation to pump downsizing because the probe has significant size compared with dimensions of other parts of the VAD. In order to overcome these problems, this wok discusses a sort of alternatives techniques for position measurement and then, proposes the use of the Hall sensor as one promising solution. It is important that the alternative technique attends following requirements: non-contact type, able to measure in the presence of blood and dimensions smaller than the inductive sensor.

Some of these techniques use specific sensors. According Boehm (1993) and Popovic (1996) there are many techniques for position measuring in magnetic bearings. Besides the use of inductive sensors, techniques, based on the light or the ultrasound are presented. Although light based techniques are fast in response and accurate, considering that this work aims the application of the magnetic bearing in a blood pump, optical methods are immediately eliminated since the blood does not enable light to propagate. On the other hand, ultrasound based techniques, although propagates even in fluids like blood, requires sound transducer which size is comparable with the inductive sensors.

In contrast with these sort of techniques based on the use of a specific sensor, there are other class of techniques called as “sensorless”, in which, no physical sensor is used. Sensorless techniques are presented on Mukhopadhyay, (2005), Vischer, (1993), Mizuno, (1996), Fleming, (2005), and others. These are based on position estimative based on mathematical static or dynamic models of the magnetic bearing and some parameters of the control system, like the current to the electromagnets. Besides complex, the position estimative process is susceptible to errors. For example, if the position estimative is based on the integration of the current value along the time, the estimative givers rises to a cumulative error, and the estimated position deviates more and more from the real position, making the magnetic bearing lost its functionality.

Thus, this study indicated the of Hall sensor as one promising solution. The Hall sensor is a small semiconductor element available in the market that gives an electric signal with amplitude corresponding to the magnet field intensity and attends the necessary sensor features for this work.

Concerning hall sensor, Komori (2005) focuses on the use of Hall sensors for position measurement, however in this approach, the Hall sensor is used to measure the current supplied to the electromagnetic actuators resulting in an approach similar to the sensorless technique. Other work reports similar approaches but not using the hall sensor directly for measuring the object position. The only report in this sense is presented in Lilienkamp (2004). A magnetic bearing for didactic end is developed and the Hall sensor used to measure the target position. No detail about how the sensor is installed and its signal processed is described but the work reports problems with interference of the magnetic field generated by the electromagnetic actuators on the hall sensor signal.

2. HALL SENSOR FOR MEASURING THE AXIAL POSITION

In a first approach to replace the inductive sensor, shown in Fig.1, the Hall sensor is positioned on the superior side of the iron core of the inferior electromagnetic actuator. By this, the Hall sensor detects the magnetic field variation caused by the variation of the axial position of the rotor. However, some problems must be considered.

- Although the sensor output is linear with respect to the magnetic flux intensity, the relationship between the rotor axial position and the sensor output is not linear.
- The sensor is sensitive not only to axial motions of the rotor, but also to radial motions of the rotor.
- The sensor is sensitive also to the variation in the magnetic field generated by the electromagnetic actuator. When the bearing control system is activated, the bearing becomes unstable.

The problem concerning the linearity does not constitute a serious problem since only small displacements are considered during the operation of the bearing. Moreover, once the non-linearity is verified to be a serious problem, the signal is easily corrected, by calibrating the sensor and compensating the sensor readings by computer.

The fact of the sensor is sensitive also against radial motions of the rotor will not represent problem. Since displacements to be considered in the axial direction is very small compared to diameters of the magnet and the electromagnet core, it is expected that the variation in the magnetic field due to radial motions of the rotor is smaller that caused by axial motions of the rotor. Moreover, since the rotor is retained in a central radial position due to the effects of the attraction force between the magnet and the electromagnet core, it is expected that motions of the rotor in radial direction is small enough to not affect the sensor readings.

The most important problem is the third problem listed above. The influence of the magnetic field generated by the electromagnetic actuator should be eliminated from the sensor signal. Otherwise, the magnetic bearing becomes unstable. To overcome this problem, this work proposes a strategy that consists on installing two identical Hall sensors, one at each end of the electromagnetic actuator core, in a symmetric way, as illustrated in Fig.2. For a given variation in the current sent to the electromagnet, an identical magnetic field variation is caused in each sensor, but with opposite signal. However, axial motions of the rotor, i.e., motions of the permanent magnet, induce output of different amplitude in the both sensors, but with same signal. Therefore, by simply summing the signals from both sensors, the influence of the electromagnet on the sensor signals can be removed. The signal so obtained expresses only the rotor position and used to control the rotor axial position in a same fashion as it is done using the inductive sensor.

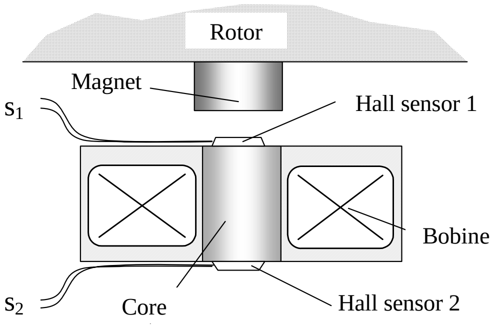

Figure 2. Electromagnet with hall sensors

3. EXPERIMENTAL MEASUREMENT OF BASIC CHARACTERISTICS OF THE SENSOR

In order to verify the possibility of using Hall sensor as a position sensor in magnetic bearing, some experiments are conducted to determinate some basic characteristics of the sensor: a) sensor response for axial displacements of a magnet; b) sensor response for radial displacements of a magnet; c) sensor measurement range; d) output of the sensor when installed in the both ends of as electromagnet.

a) Sensor response for axial movement

Keeping the permanent magnet (rare earth NiFeB, 9mm diameter, 6mm height) concentric with the sensor, the magnet is displaced from the sensor at 2mm intervals until 24mm, as shown on Fig. 3. The measurement is repeated 12 times. Results are shown in Fig.4. The axial displacement represents the gap between the magnet and the sensor upper surface. Sensor responds until a displacement of 25mm, however an acceptable linearity is verified until displacement of 10mm. This is enough for application in magnetic bearing in which, the typical gap between the magnet and the core is up to 5mm.

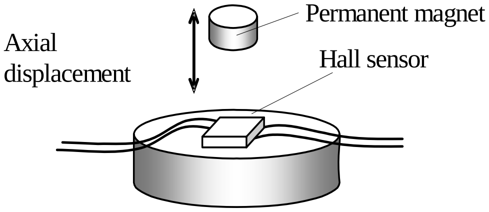

Figure 3. Measurement of the output against axial displacement

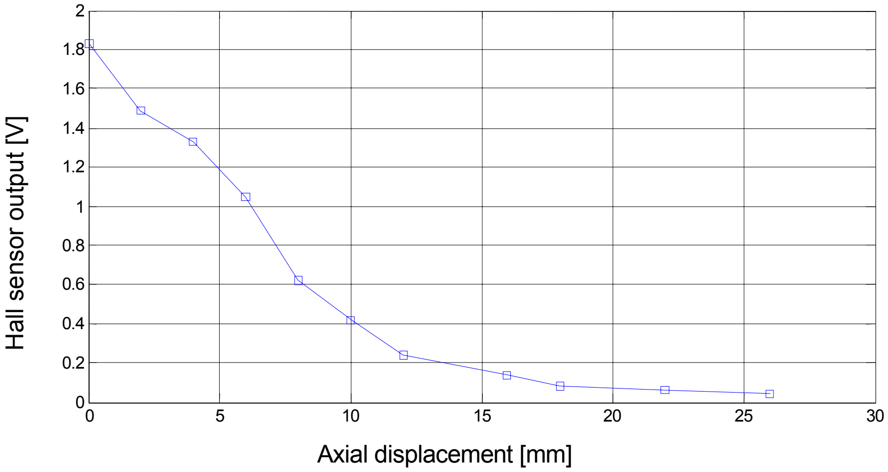

Figure 4 Axial displacement vs sensor output

b) Sensor response for radial movement

Keeping constant the gap between the magnet and the Hall sensor, the magnet is displaced radially in 1mm intervals as shown in Fig.5. The measurement is repeated 17 times. Results are shown in Fig.6. This shows that the sensor, besides responding to axial displacements, also responds to the radial displacements of the magnet. The sensor gain with respect to radial displacements is approximately the half of that in axial direction. Thus, if the sensor is used to measure and control the axial position of the rotor, the influence of the radial displacements of the rotor will be small. Moreover, considering that the magnetic bearing is designed in a way that the radial displacement of the rotor is as small as possible, it is expected that the sensitivity of the sensor to radial displacements will not represent a problem.

c) Hall sensor maximum output voltage

The maximal output of the Hall sensor is measured with the permanent magnet positioned on the sensor. The output is nearly 1.83V. Repeating the same measurement using the opposite pole of the magnet, an output of –1.83V is obtained.

d) Two sensors in the electromagnetic actuator

In this set of measurements, two Hall sensors are placed in the opposite extremities or poles of the electromagnet as shown in Fig.2. Then, the electromagnet is suddenly turner on and the output of both sensors measured. Results are shown in Fig.7.

As it can be noticed in the figure, the output of both sensors is identical in shape and amplitude. These signals are processed using a simple summing amplifier, shown in Fig.8. A residual noise of 1.2mV amplitude, probably caused by the electronics, remains after the processing. This result makes evident the validity of the proposed strategy to eliminate from the sensor signal, the effects of the magnetic field generated by the electromagnetic actuator.

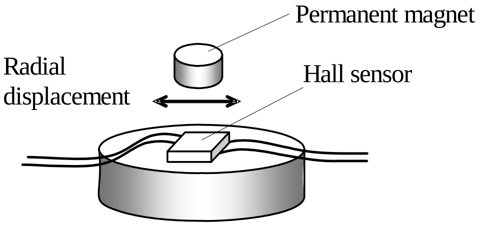

Figure 5. Measurement of the output against radial displacement

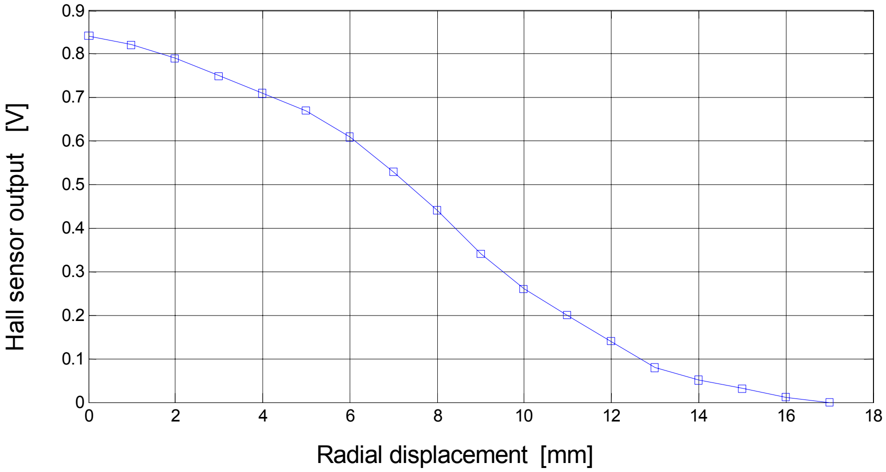

Figure 6 Radial displacement vs sensor output

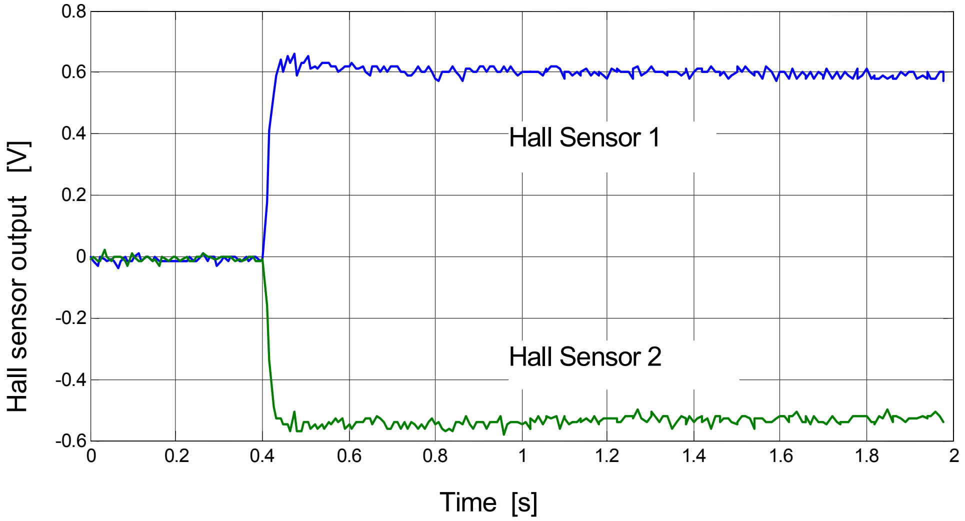

Figure 7 Response of two sensors in opposite poles of an electromagnet

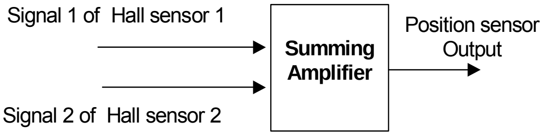

Figure 8. Sensor signal processing

4. EXPERIMENT WITH THE POSITION SENSOR

In the next set of measurement experiments, the position sensor, composed by the pair of Hall sensors installed in the electromagnet (Fig.2) and the processing circuit (Fig.8), is tested. Figs.9 shows one of the Hall sensor installed in a round clinkstone and Fig.10, the two sensors fixed to the actuator. Following characteristics are measured: a) noise level; b) the calibration curve, i.e. the displacement versus sensor output curve; c) measuring range and d) the linearity of the response.

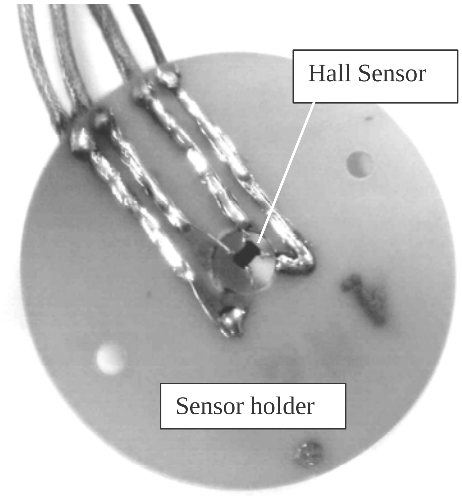

Figure 9 – Sensor hall fixed to the holder

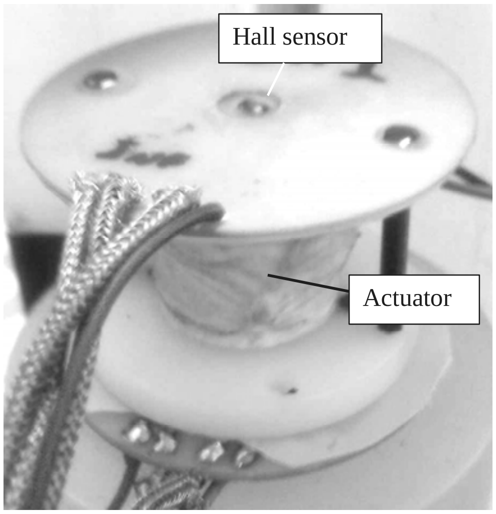

Figure 10 – Sensored actuator

a) Noise level of the position sensor

To measure the noise level in the position sensor output, the sensor is turned on without any magnetic field being applied. The sensor output obtained is shown in Fig.11. The noise, due to the electronics, is approximately 50mV in amplitude. Considering that the sensor gain is 700mV/mm as shown later, this noise is considered acceptable.

b) Calibration

The calibration is executed by applying a known displacement in the magnet and measuring the position sensor output. The result is shown in Fig.12.

c) Measuring range

The measuring range of the sensor is given in Fig.12. The sensor responds in the displacement interval of 0 to 50mm and the output, between 0 and 8.5V. This range is sufficient since in the magnetic bearing, displacements of up to 6mm are considered.

d) Linearity

The calibration curve shown in Fig.12 shows a prominent nonlinearity. However, in the magnetic bearing, only gaps from 0 to 6mm are measured. In this interval, enough linearity is observed in the response curve. In this interval, the sensor gain is of 700mV/mm.

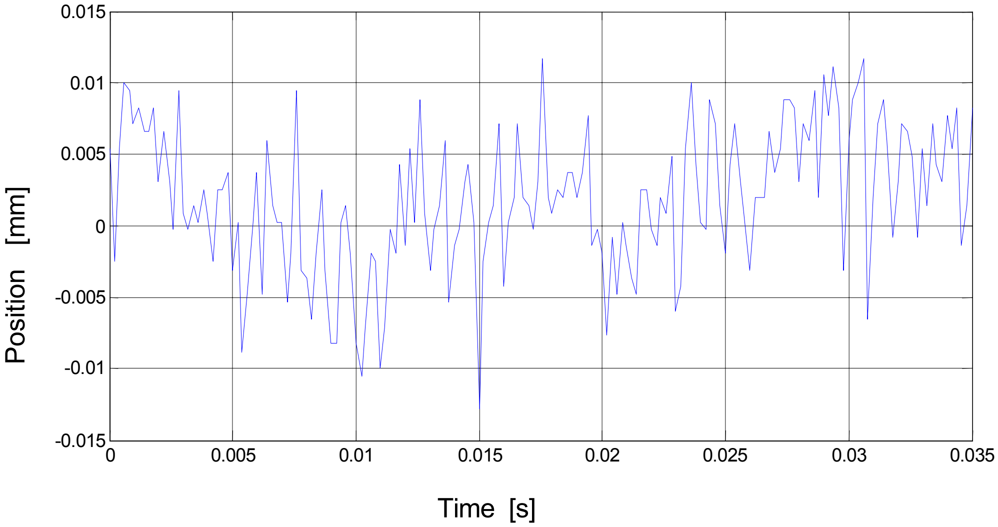

Figure 11. Noise in the position sensor

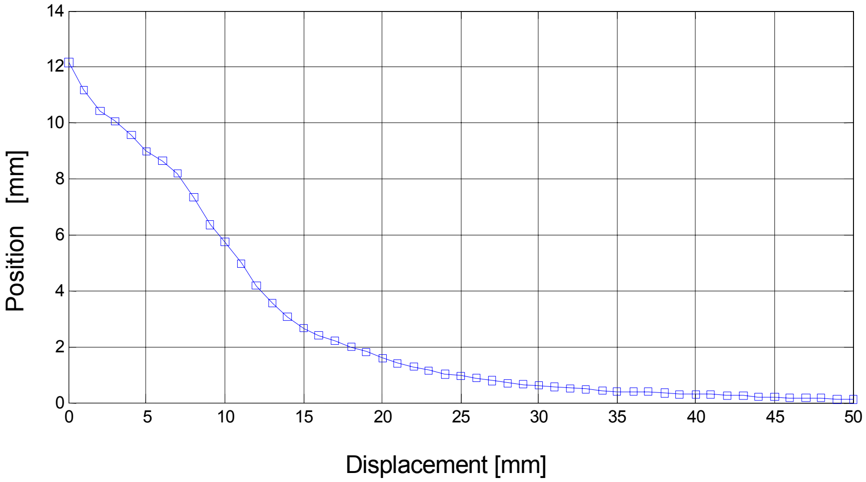

Figure 12. Position sensor calibration curve

5. BALANCING THE GAIN OF SENSORS

Before experiments using the sensor to control the magnetic bearing, one problem has to be considered. When the sensor shown in Fig.10 is installed in the magnetic bearing, the sensor at the upper side (sensor 1) of the actuator will be close to the magnet fixed to the rotor, while the other sensor (sensor 2), at the lower side, will be distant from the same magnet. Fig.13 shows the same graph presented in Fig.4. Due to the difference in distance from the magnet, the sensor 1 operates in a region near the origin of the graph, say region A, while the sensor 2, in another region B, distant from the origin. As can be seen in the figure, the gain of the sensor is clearly different in A and in B. Thus the interference of the actuator on the sensor reading will not be cancelled by simply summing readings of sensors. This is better visualized in results of numerical simulations of the magnetic field around the actuator, assuming a current of 1A in the electromagnet. Figs.14 and 15, show respectively, the magnetic flux around the actuator without and with the magnet close to the core. Fig.14 reproduces the situation in which the sensor is installed in the magnetic bearing. In the graphs, as light the color of the arrow, bigger is the magnetic flux intensity. While in Fig.14, the magnetic field is symmetric at both extremities of the actuator. In Fig.15, the magnetic field at the upper extremity is clearly higher than the field at the lower extremity.

To solve this problem, two solutions are implemented. The first solution consists on placing an identical magnet at the lower side of the actuator (Fig.16) forcing two sensors to operate under similar conditions. The second solution is to modify the processing circuit shown in Fig.8, adding a gain to each entrance of the sensor as shown in Fig.17. These gains are adjusted in order to eliminate interference from the actuator. The first solution assures the gross adjustment and the second one, the fine adjustment for balancing the magnetic field at both sensors.

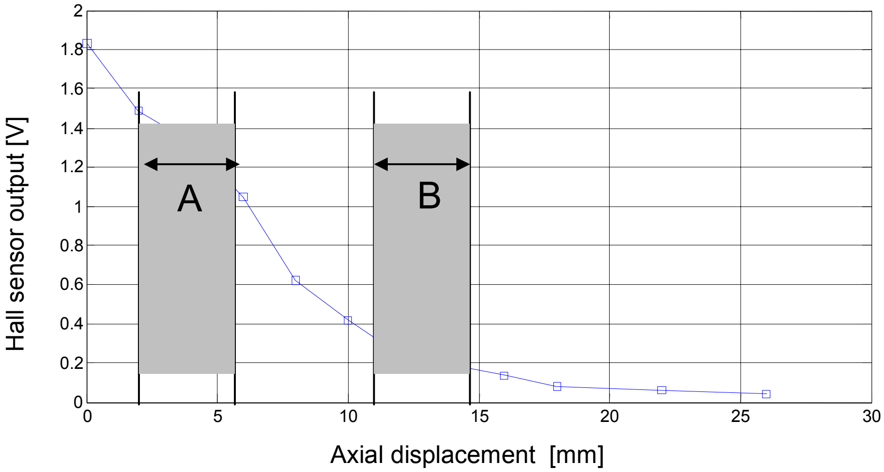

Figure 13 Sensors operating at different regions

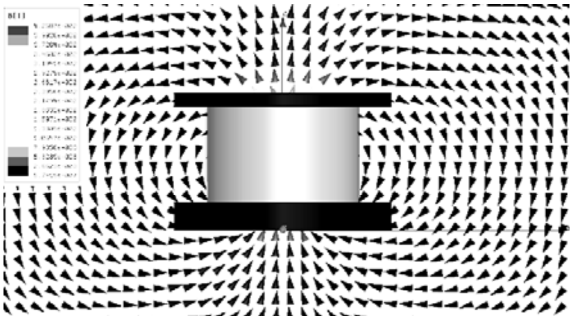

Figure 14 The actuator without the magnet

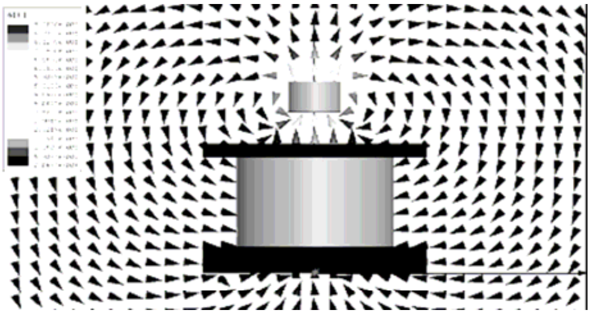

Figure 15 The actuator with the magnet

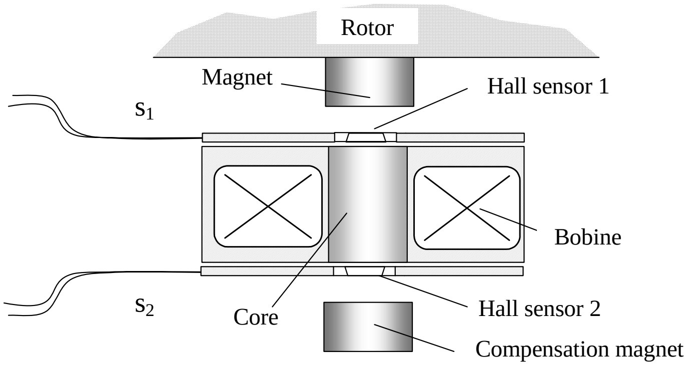

Figure 16. Hall sensors with compensation magnet

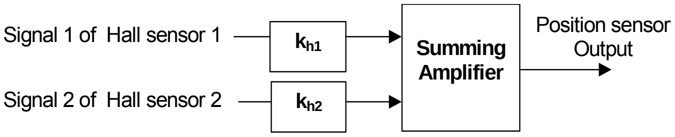

Figure 17. Sensor signal processing

6. EXPERIMENTS WITH THE MAGNETIC BEARING

After concluding the series of measurements and studies about the hall sensor, the actuator with the position sensor, based on hall sensors, is mounted in the magnetic bearing and a levitation test is conducted. Activating the control system, the rotor is levitated in an axial fixed position in a stable way. A gap of approximately 4mm is maintained between the upper actuator (with the position sensor) and the rotor magnet. At the lower actuator, the gap was of around 6mm. Fig.19 shows readings of the developed sensor.

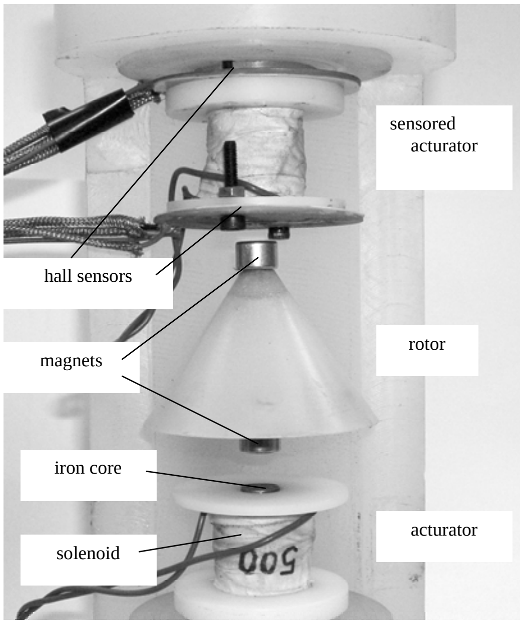

Figure 18 – Rotor being levitated

Smaller values of gap are desirable in the magnetic bearing so as to assure larger values for stiffness in the radial direction. However, the values of gaps mentioned above were the limit. As the gaps were reduced more than the mentioned values, the sensor gain reduced drastically. This problem was caused by the saturation of the sensor. As the gap is reduced, the magnetic flux density in the upper side Hall sensor increased over the sensor saturation limit. Thus, the gain of the upper sensor reduces drastically while the other sensor, at the lower side of the actuator, keeps the original gain. Under this condition, the position sensor detects the magnetic field generated by the actuator. If such signal is sent to the controller, the magnetic bearing becomes unstable. This problem solved by simply using Hall sensors capable of measuring larger values of magnetic flux density. Despite this problem, the levitation experiment demonstrates that the Hall sensor can be used for the measurement and control of the position of the rotor in the magnetic bearing. Moreover, the proposed strategy to eliminate the influence of the electromagnetic actuator from the sensor readings is demonstrated to be efficient.

7. CONCLUSIONS

This study demonstrated the possibility of using Hall sensor, a sensor that measures the magnetic flux density, to measure and control the position of a rotor in a magnetic bearing. Moreover, this study proposed a simple strategy for eliminating from the sensor readings, the influence of the magnetic field generated by the electromagnetic actuator, used to control the magnetic bearing. In the experiments, basic characteristics of the Hall sensor are measured. Then, the position sensor based on Hall sensor is developed, mounted in the magnetic bearing and levitation test conducted. The rotor is successfully levitated in a stable way. In this stage of research, only large gaps are achieved in the magnetic bearing due to the problems related with the saturation of the Hall sensors. Future works includes the use of Hall sensor capable of measuring higher values of magnetic flux density and thus, achieve smaller gaps in the magnetic bearing, resulting in higher stiffness in the radial direction of the bearing. Moreover, some problems are verified in this work due to the nonlinear response of the Hall sensors with respect to the magnet displacements. These problems are contoured in this work by using for example, the compensation magnet. However, in future works, it is expected to linearize the response by acquiring the sensor output by computer and using a calibration table.

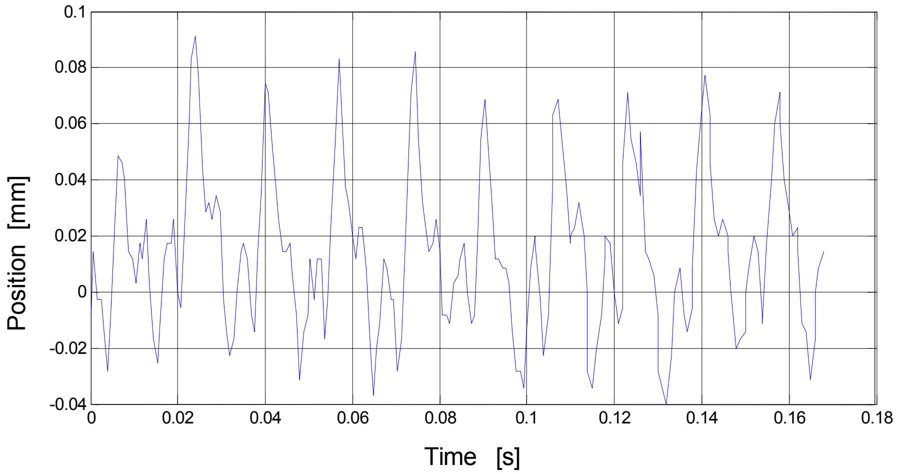

Figure 19. Position sensor output with the rotor being levitated

8. ACKNOWLEDGEMENTS

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