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

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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 applied to the VAD is of hybrid type, combining permanent magnets with electromagnets and executing active control only in the axial direction of the rotor. The attraction force between the magnets fixed to the rotor end, and the iron cores fixed to the base 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 sensor signal is sent to the controller, processed, amplified and sent to the electromagnic actuators. The current to the actuators is regulated 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. Moreover, the inductive sensor imposes limitations to the bearing downsizing. In order to overcome these problems, a sort of alternatives techniques for position measuring, for example sensorless technique, are studied and the Hall sensor is identified as one interesting solution. The Hall sensor is a small semiconductor element that gives an electric signal with amplitude corresponding to the magnet field intensity. In a previous work authors proposed a simple solution based on the use of the Hall sensor. The strategy consisted on installing two Hall sensors, one at each end of the electromagnet core in a symmetric way and then, summing these two signals, so as to remove the interference of the electromagnet actuator and keeping only the signal that expresses the rotor axial position. This work presents another method to remove the interference of the actuator on the hall sensor reading. The new method consits on using a model that simulates the behaviour of the electromagnetic actuator.

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. 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, forward referred as EPUSP-MB is elected. Figure 1 shows the configuration of the IDPC-VAD with this magnetic bearing. This magnetic bearing is of hybrid type, combining electromagnets and permanent magnets to levitate the rotor. A magnet is fixed at each end of the rotor. Each magnet faces an 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 PD or 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.
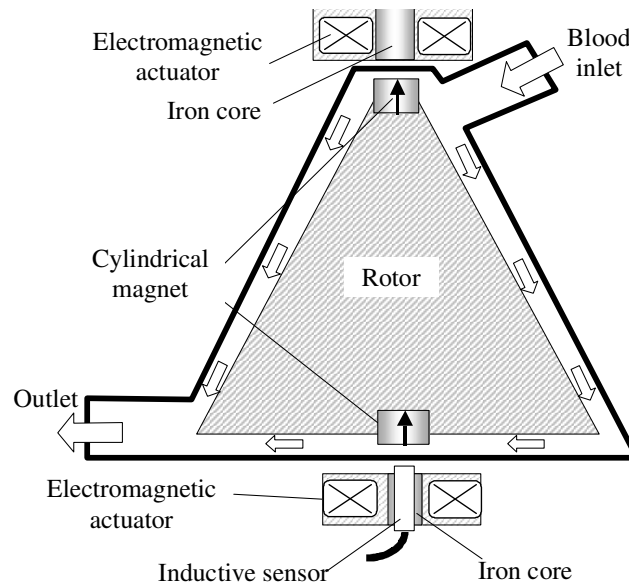
Figure 1. IDPC-VAD with magnetic bearing EPUSP-MB.

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 electromagnetic bearing. Firstly, compared with the upper side actuator, the bottom side actuator 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 the EPUSP-MB, 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.

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. In ultrasound-based techniques, although sound wave propagates even in fluids like blood, requires sound transducer with size comparable to 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 supplied 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 its use 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 assembled to the bearing and its signal processing is described but the work reports problems with interference of the magnetic field generated by the electromagnetic actuators on the hall sensor signal.

2. COMPENSATION BY USING TWO HALL SENSORS

    In a past report (Antunes, 2009), authors presented one possible strategy for using the Hall sensor in the rotor position measurement. The natural solution for applying the Hall sensor is to install it on the top surface of the lower side electromagnetic actuator (see Fig.1), between the magnet of the rotor, the gap and the actuator core, as illustrated in Fig. 2. The magnetic flux density in the Hall sensor varies according to the rotor axial displacement. Although non-linear, this relation is enough linear for small displacements of the rotor, therefore enough for practical uses. However, one important problem arises. The sensor reading is not dependent only of the rotor displacement but also of the magnetic flux created by the coil of the actuator. If the signal induced by the actuator is fed back to the controller, the bearing becomes unstable. To overcome this problem, in the past work, authors proposed the use of one another identical sensor installed at the other extremity of the actuator coil (Fig.2). When a current circulates in the coil, a signal is induced to one sensor. However an identical signal, but with opposite polarity, is induced in the other sensor. By summing the output of two sensors, a signal corresponding to the rotor displacement is obtained and the influence of the coil, cancelled out. This strategy was demonstrated to be efficient by a levitation test (Fig.3).

    This work presents another strategy for using Hall sensor to measure the rotor axial position in a magnetic bearing. The strategy is still based on the installation of a Hall sensor on the top surface of the electromagnetic actuator, as shown in Fig.2. However, in the new strategy, only one sensor is used and a compensator corrects the sensor output.
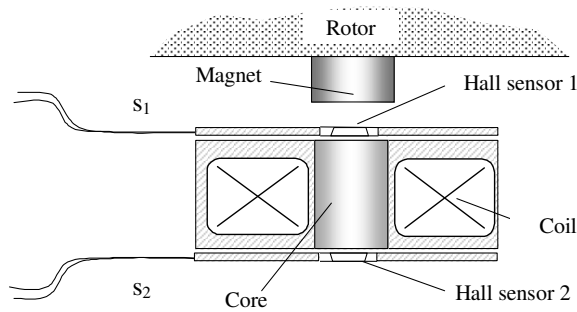

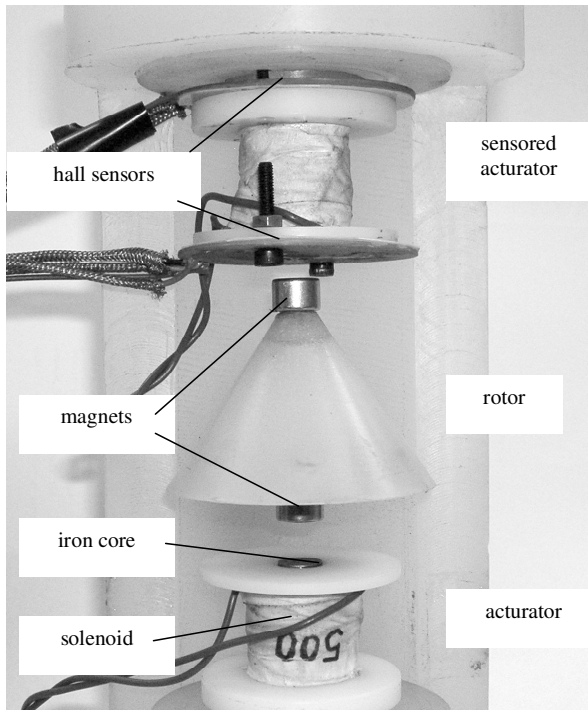Figure 2. Hall sensors with compensation magnet

Figure 3. Rotor being levitated

3. COMPENSATION BASED ON ACTUATOR REFERENCE MODEL

Figure 4 presents the block diagram of the EPUSP-MB as presented in Silva(2000). The block $G_c(s)$ represents the transfer function of the PD controller. $G_1(s)$ represents the dynamics of the magnetic bearing including the power amplifier. Finally, $G_2(s)$ represents the rotor dynamics. Remaining symbols are listed in Tab.1.

Figure 5 is the same block diagram shown in Fig.4, but this one shows in detail the portion where the Hall sensor measures the rotor position. The Hall sensor measures the magnetic flux density at the top portion of the electromagnetic actuator. So, the sensor measures the magnetic flux, $B(s)$, due to the electromagnetic actuator and that due to the magnet fixed to the rotor. Both magnetic fluxes generate the force on the rotor. As mentioned before, if the sensor output is directly sent to the controller, the output of the controller is sent directly to itself resulting in instability. It is mandatory removing the direct influence of the controller output from the sensor signal.
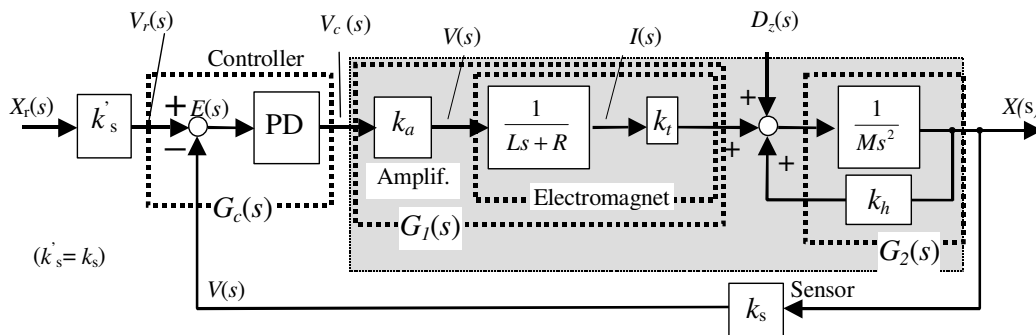

Figura 4. Diagrama de blocos do sistema de controle do AMB EPUSP

Table 1 List of symbols used in Fig.5

| Symbol	Meaning	Unit	Symbol	Meaning	Unit
X	Axial position of the rotor	Meter	D	Disturbance force	Newton
X_r	Reference position	Meter	M	Mass of the rotor	Kilogram
V_r	Reference voltage	Volt	V_c	Controller output	Volt
E	error	Volt	V_s	Sensor output	Volt
V	Amplifier output	Volt	k_t	Electromagnetic constant	Newton / Gauss
L	Coil inductance	Henry	k_h	Magnetic constant	Newton / Gauss
R	Coil resistance	Ohm	k_a	Power amplifier gain	Volt / Volt
I	Current in the coil	Ampere	k_s	Sensor gain	Volt / Meter
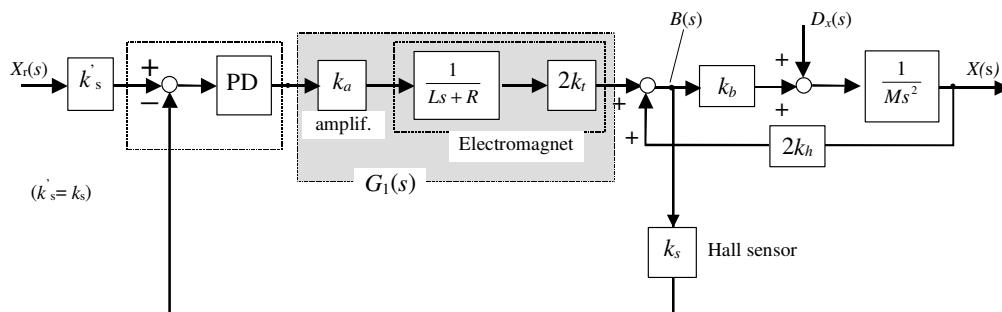
Figure 5 Block diagram of the EPUSP bearing considering the use of a Hall sensor.

As can be seen above, the dynamics of the actuator is well known. Therefore, if the entrance voltage to the power amplifier (V_c) is known, it is possible to calculate the magnetic flux density at the portion corresponding to the gap between the rotor and the actuator. This is the basic strategy for compensating the readings of the hall sensor.
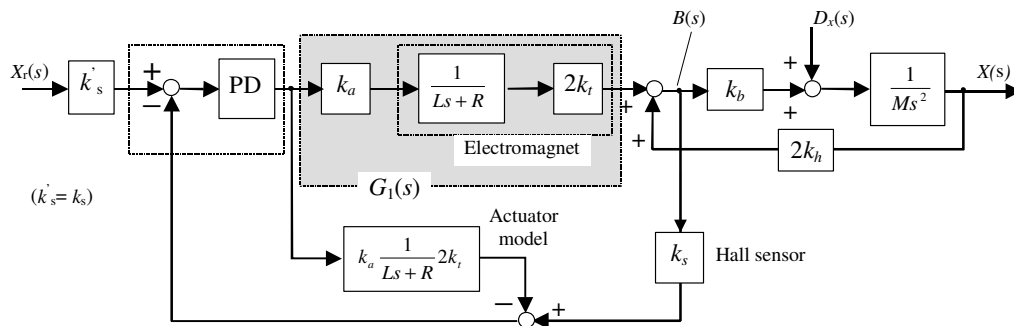
Figure 6 Compensation of the sensor signal

Figures 7 to 9 shows step-by-step, reductions of the above block diagram. The final configuration, Fig.9, is corresponding to the original diagram shown in Fig.4, where the feed back signal is gathered directly from the rotor axial position. The element introduced in the block diagram to compensate the sensor signal is a simple 1st order filter. It constitutes an observer that estimates the behavior of the electromagnetic actuator. The compensator block may be implemented by two ways: analogically or digitally.
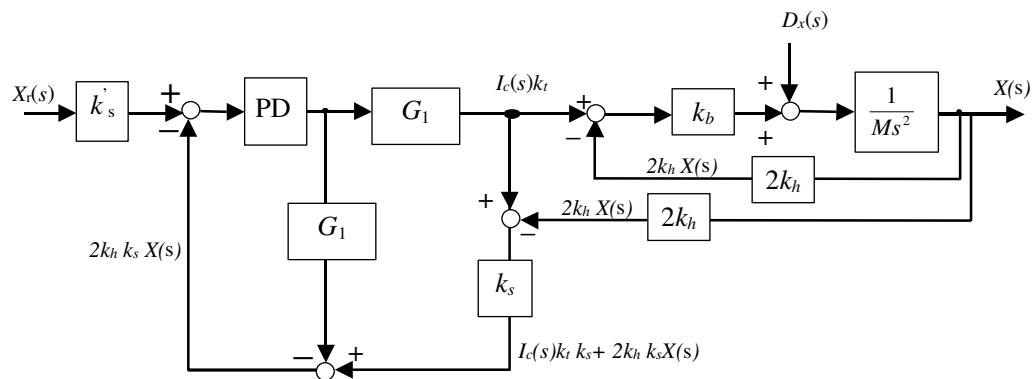
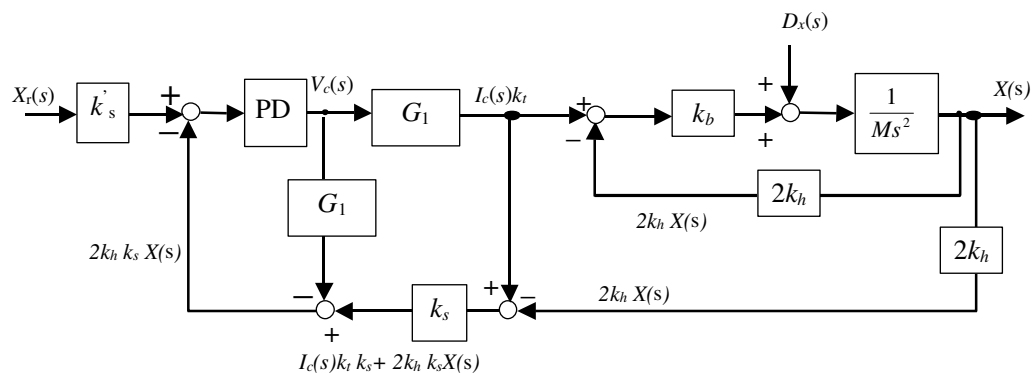Figure 7 Modification of the block diagram shown in Fig.7 –Step 1

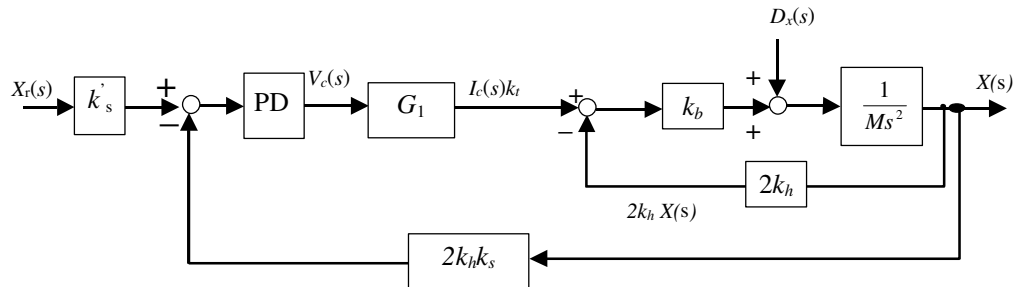Figure 8 Modification of the block diagram shown in Fig.7 –Step 2

Figure 9 Modification of the block diagram shown in Fig.7 –Step 3

Analogical compensation.
The compensator can be implemented by a well-known RC filter, shown in Fig. 10. The relation between the filter output (V_{out}) and input (V_{in}) is given as follows.

$$\frac{V_{out}}{V_{in}} = \frac{1}{1 + RCs} \qquad (1)$$

The value of RC is adjusted so as to be equal to the time constant R/L (Fig.4). Moreover, using an amplifier the gain of the filter (k_f) is adjusted so as to obtain the relation: $k_f = 2k_a k_t L$.
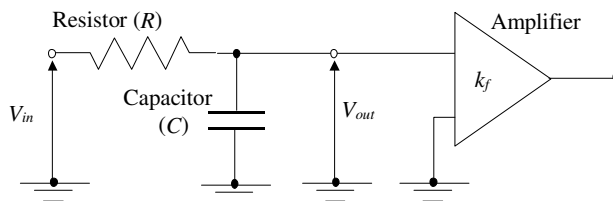

Figure 10 Electronic schematics of a 1st order analogical filter

Digital compensation
Besides the analogical compensation presented above, another possibility is to incorporate a digital numerical model of the 1st order filter in the digital control algorithm. The first order filter can be digitally implemented by using following equation:

$$V_{o,n} = \alpha V_{o,n-1} + \beta V_{in,n} \qquad (2)$$

Here, V_o is the filter output; the index n represents the n-th sampling, α, the filter constant and V_{in}, the sampled input voltage. Filter constants, α and β, are adjusted so as to match the gain and time constant of the original plant shown in Fig.4.

4. RESULTS OF EXPERIMENTS

Prior to levitation tests, the compensator presented in the previous item is tested. The rotor of the magnetic bearing is immobilized so as to keep a constant gap with respect to the actuator. Then, the electromagnetic actuator and the compensator block are fed with a stepwise signal. Finally, the compensator response is compared with the Hall sensor response.

Figure 11 shows step responses of the analogical compensator and of the Hall sensor. In the same figure, the difference between these two signals is also plotted. Despite a small transient error, the compensator reproduces with accuracy the response of electromagnetic actuator response measured by the Hall sensor.

Figure 12 shows the same comparison but here, using a digitally implemented compensator. Also in this case, the compensator reproduces accurately the response of the actuator.

Figure 13 shows results of calibration of the Hall sensor using the analogical compensator presented above. Sensor output is plotted as known displacements are imposed to the rotor. A non-linearity is observed in the graph but this is due to the non-linearity of the relation between the displacement and the magnetic flux density in the sensor. This result is important to show that despite the elimination of the influence of the electromagnetic actuator on the Hall sensor, the Hall sensor responds satisfactorily to the rotor displacement. Although not shown here, similar result is obtained using the digital compensator.

Next to these preliminary tests, the levitation test was tried out. However, this was not possible. In the case of the analogical compensator, the control was not possible probably because of remaining error in the compensator calibration, as it was shown in Fig. 11. In the case of the digital compensator, since the integration of the compensator in the control algorithm is still going on.
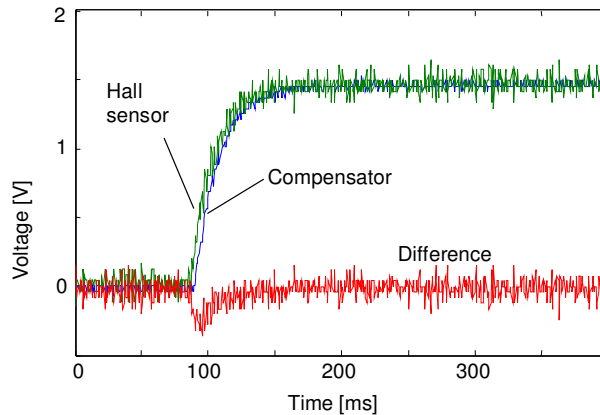
Figure 11 Step responses of the electromagnetic actuator and of the analogical compensator
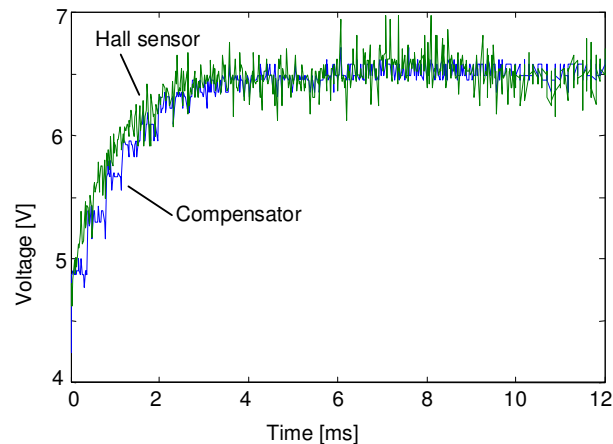
Figure 12 Step responses of the electromagnetic actuator and of the digital compensator

5. CONCLUSIONS

Aiming the development of a technique to use hall sensors to measure position of the rotor in the EPUSP-MB, in past work, authors reported a method that consisted on using two hall sensors, one at each extremity of the electromagnetic actuator core. With respect to this method, its efficiency was proved by levitation tests in a magnetic bearing. In addition to this technique, in this work, authors presented a strategy based on the use of only one hall sensor. The sensor is fixed to the actuator core, between the core and the rotor magnet. The influence of the actuator in the sensor readings is removed by using a reference model of the electromagnetic actuator. Moreover authors presented two methods to implement the reference model: analogically by means a 1st order lag analogical filter or digitally, by incorporating the filter in the digital control algorithm. These two models were compared to the hall sensor response to the rotor displacement and results showed that the both model precisely represents the actuator behavior. Levitation tests in the magnetic bearing were still not executed. Problems of instability occur in the magnetic bearing probably

because of errors that persists in the reference model. The next step of the research is to try fine adjustments in the model parameters and conduct levitation tests in the magnetic bearing using the proposed compensation techniques.
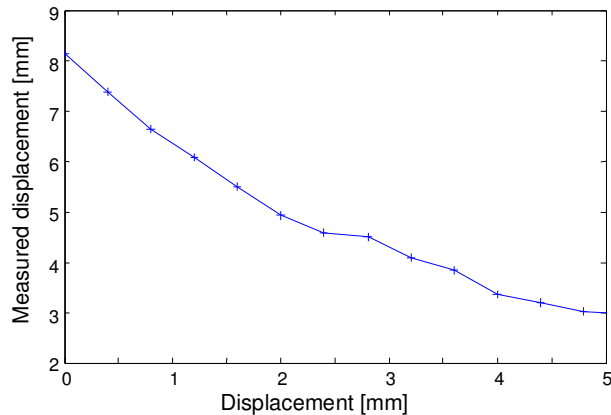

Figure 13 Calibration of the Hall sensor using the analogical compensator

6. ACKNOWLEDGEMENTS

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