DIGITAL CONTROL OF ACTIVE MAGNETIC BEARINGS FOR PRECISE ECCENTRIC ROTOR POSITIONING

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ABSTRACT :

Active Magnetic Bearing (AMB) control has been a challenging task for the control engineers since its invention. Various types of control techniques - both analogue and digital - have been tried over the past years. In the application area of rotating machines, the whole concept of AMB control means stabilising the rotor of the machine in the exact centre of the radial AMBs and maintaining that position by counteracting the disturbances exerted on it under running condition. Noise reduction in electrical machines is becoming an increasingly important requirement for the design engineers and rotor eccentricities have been identified as the main source of noise generation. AMB with its relatively large air gap, allows the rotor to move away from the exact centre, provided the controller used is capable of maintaining an eccentric position under running condition. The ability of running the machine with known eccentricities makes the AMB a good actuator to study the noise characteristics of electrical machines. The ultimate objective of the project aims at investigating the magnetic noise from a standard induction machine. This calls for a flexible design of the control that enables the user to move the rotor to an arbitrary position in the air gap. This demand is achieved by using a digital controller based on a DSP.

INTRODUCTION :

The experimental set-up is based on a standard 4-pole induction motor (rated power 15 kW, rated speed 1453 rpm, rated voltage 380/660 V). Its construction is modified with 2 radial AMBs and one axial AMB (air gap of radial AMB 0.4 mm, air gap of axial AMB 0.3 mm. Configuration of AMBs are shown in Fig. 01).

A Digital Signal Processing (DSP) system based on TIM320C40 processor with 5 channels, which was selected giving special considerations to the requirements demanded by closed loop controls [1, 2, 3, 4, 5] has been successfully commissioned. All control techniques are designed and tested in the simulation level using the MATLAB/SIMULINK platform before trying on the real system. Initial approach is to design controllers based on the linearised model of the AMB system and see whether they can achieve the required goals. The DSP system which has the interface to MATLAB/SIMULINK environment makes it easier to generate the necessary C code for the processor and thereby it is possible to focus more attention to various control techniques.

Necessary modifications have been made to the existing hardware electronics so that the analogue controller can be isolated and the digital controller can be introduced to the system. This gives a lot of flexibility in operating the system on both analog or digital controller when ever it is necessary.

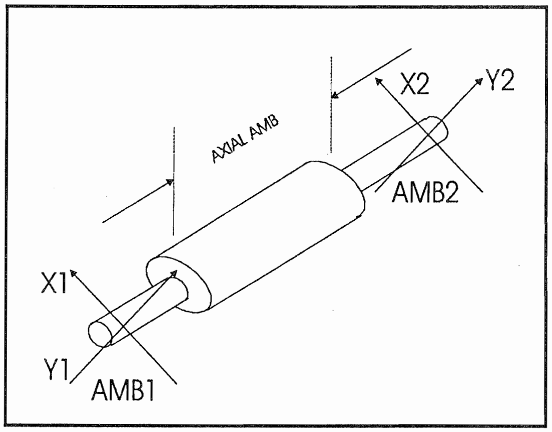

Figure 1 Configuration of AMBs in the set-up

One interesting and in fact vital practical problem that has to be dealt with is determining the exact position of the rotor inside the stator core (Central axes of the two radial AMBs and the stator core may not be co-located due to mechanical problems like inaccurate machining.) This causes serious problems in the noise analysis. Therefore a rotor positioning technique has to be developed to bring the rotor to the exact magnetic centre of the stator core of the induction machine.

MODIFICATIONS TO THE SYSTEM :

Since the work was started off with a ready made AMB system, working on an analog PID controller, some modifications had to be made in order to make it possible for the I/O channels of the DSP system to be connected to the existing hardware. The goal here was to isolate the analog controller and use the rest of the hardware (Namely, position sensing system and low-pass filtering, power amplifiers with the current feed back and bias setting circuits.) with the least introduction of new circuitry (The basic block diagram of the hardware and the isolation points are shown if Fig. 02).

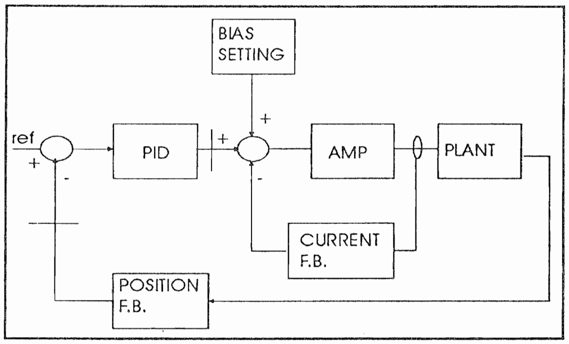

Figure 2 Block diagram of one control loop

All component values of the control loop were traced and mathematical models of each block were obtained. This was necessary to build up the system model in the MATLAB/SIMULINK environment.

The signal levels at the isolation points were checked to see whether they lie within the allowable limits of the I/O channels. The other most important thing was the power spectrum of the signal at ADC input (see Fig. 03). It was discovered that there exists a stray pick-up of the order of 6 MHz and a simple RC filter had to be introduced at ADC input to damp it. With these tests it was confirmed that the Nyquist Criterion is not violated for a sampling frequency of 10 kHz.

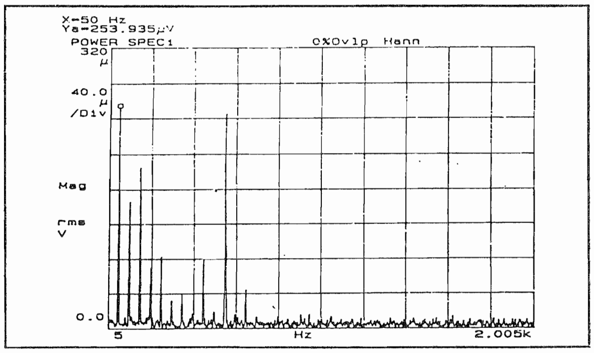

Figure 3 Power spectrum at the ADC input

MODEL OF THE ORIGINAL SYSTEM :

To be able to design the digital controllers, it was essential to obtain the mathematical model of each control loop of the original system. Linearised plant model in state space form was described as below and the parameters were calculated by using the mechanical dimensions of the system and electrical parameters of the AMB system [6]. The basic arrangement of each suspension system is shown in Fig. 04.

$$\begin{bmatrix}\dot{y}\\ \ddot{y}\\ \dot{i}_v\end{bmatrix} = \begin{bmatrix}0 & 1 & 0\\ \dfrac{C}{M_1} & 0 & \dfrac{h_1}{M_1}\\ 0 & -\dfrac{\beta h_1}{L_1} & -\dfrac{r+C_AC_i}{L_1}\end{bmatrix}\begin{bmatrix}y\\ \dot{y}\\ i_v\end{bmatrix} + \begin{bmatrix}0\\ 0\\ \dfrac{C_A}{L_1}\end{bmatrix}U_c'(t)$$

$$y(t) = \begin{bmatrix}C_T & 0 & 0\end{bmatrix}\begin{bmatrix}y\\ \dot{y}\\ i_v\end{bmatrix}$$

where,

y = distance from the centre point along the axis concerned
C = negative stiffness of the suspension system
M_1 = equivalent mass of the rotor
h_1 = current stiffness of the top magnet
β = bias current ratio factor
L_1 = actual inductance
r = resistance of the winding of each electromagnet
C_A = power amplifier gain
C_i = current feed back gain

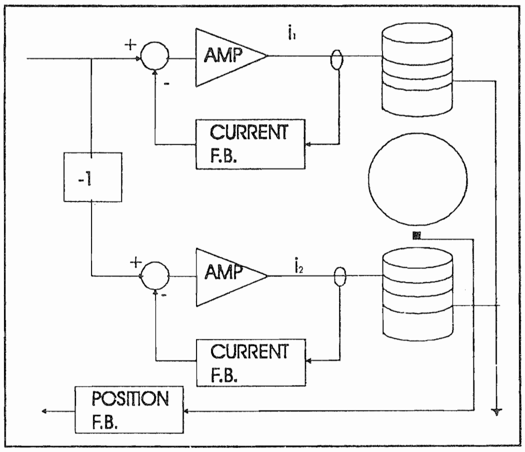

Figure 4 Basic arrangement of suspension system

With the plant model described earlier and the other mathematical models of the remaining hardware modules, complete simulation models of all control loops were built up in SIMULINK. The next step was to see how accurate the built up model is with respect to the real system. This was done by comparing the variation of the feed back voltage during start up. This variation obtained by simulation and from an oscilloscope trace of the real time system are shown in Fig. 05.

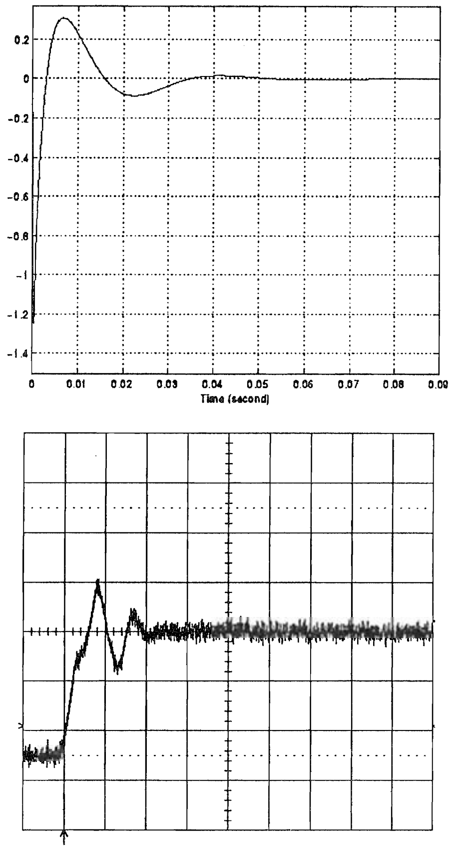

Figure 5 Feed back voltage at start-up
Results from simulation (upper)
Measured results 10 ms/div, 0.5 V/div (lower)

DESIGN OF DIGITAL CONTROLLERS :

Information obtained from tests done on the existing system along with the above mathematical state space model is used to design digital controllers for the AMB system. The aim of the project is to try various digital control techniques and see how they can meet the demands put forward by magnetic noise analysis.

First target was to see whether the AMB system can be successfully controlled by the DSP with the minimum modifications done to the hardware of the existing system. Details of two such designs are described here [7, 8, 9].

1. Lead-lag compensator :

A lead lag network with the following structure (Fig. 06) was successfully implemented and the simulation & real time variations of the feed back voltage during start-up is shown in Fig. 07.

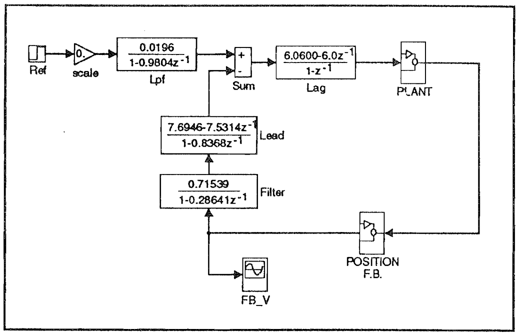

Figure 6 Structure of the controller

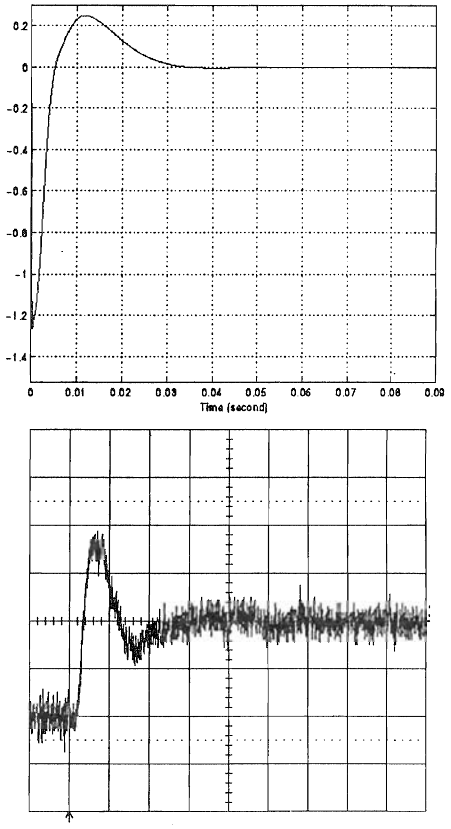

Figure 7 Feed back voltage at start-up
Results from simulation (upper)
Measured results 10 ms/div, 0.5 V/div (lower)

Another real time test carried out was applying a step change in reference while the rotor is elevated. To get a visible variation, the step change in reference applied was from +3 V to -1 V. The variation of position feed back voltage is shown below.

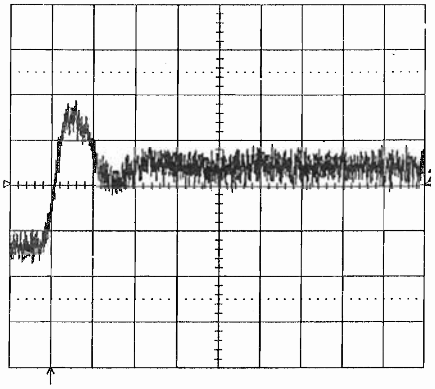

Figure 8 Step response under running condition, 10 ms/div, 0.5 V/div

2. Linear quadratic regulator with integral error feedback :

Another design attempted was a Linear Quadratic Regulator with integral error feed back [7]. The structure of the controller is as in Fig. 09. The variation of feed back voltage from simulation is also shown here (Fig. 10).

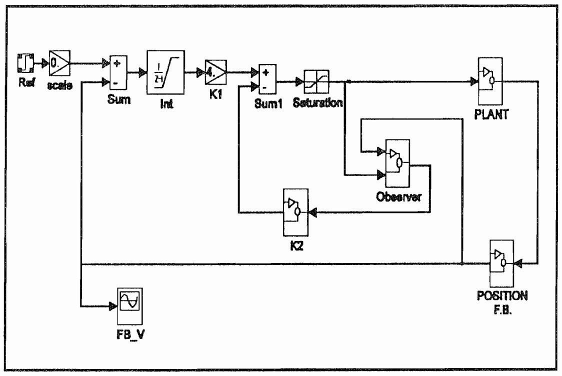

Figure 9 Structure of the controller.

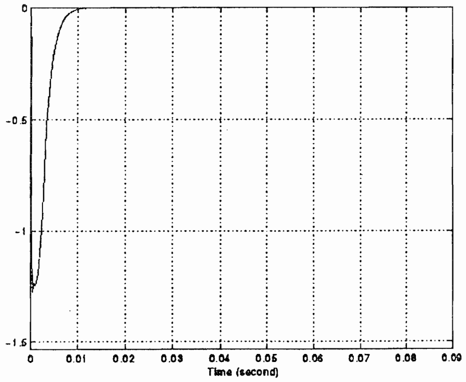

Figure 10 Variation of feed back voltage

Initial tests on this controller have been realised. The tests show that more work has to be done on the filtering problem.

ECCENTRIC CAPABILITY TEST :

The analog controller of the original system was also capable of maintaining eccentric positions. But one limiting factor was the maximum possible reference input that the summing amplifier can with stand. In the case of digital controllers the reference setting is done inside the control algorithm. Therefore the limiting factors on the eccentric positioning in case of digital controllers are the linear characteristics of the position sensors and the effective region of validity of the linearised model (in case of designs based on linearised model). Tests to get the reference voltage vs eccentricity characteristics were done in the case of analog controller and the two digital controllers. The variations are shown in Fig 11.

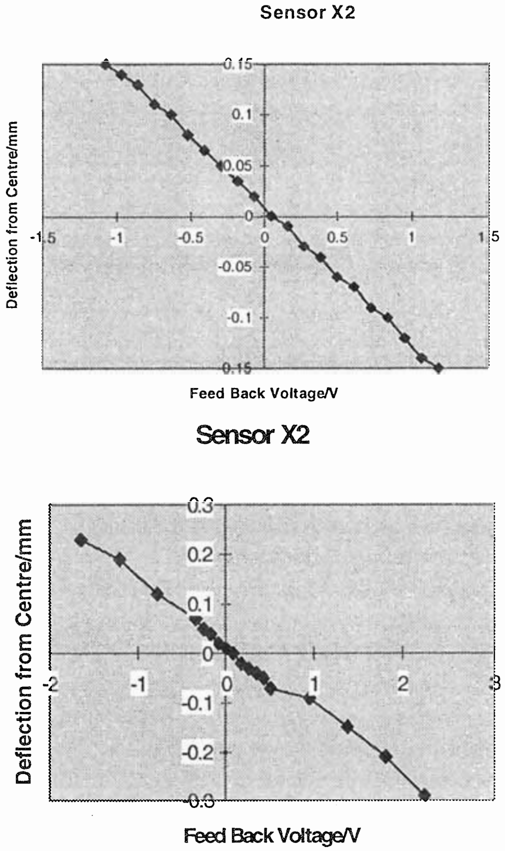

Figure 11 Eccentricity vs feed back voltage
For the analog PID (upper)
For the Lead lag network (lower)

FUTURE WORK :

1. Signal conditioning.

Even if there is some success in controlling the system with the DSP it has to be mentioned here that a lot of improvements have to be done by designing proper filters for the position feed back signals. What is shown in Fig. 12 is the position feed back signal variation for a step voltage of -10 V applied to the power amplifier input. In this case the controller is disabled and therefore this gives an idea about the mechanical rise time of the suspension system (closer to 7 ms). But since a sampling frequency of 10 kHz is used in this case the digital controllers can respond to the high frequency components visible in the feed back signal.

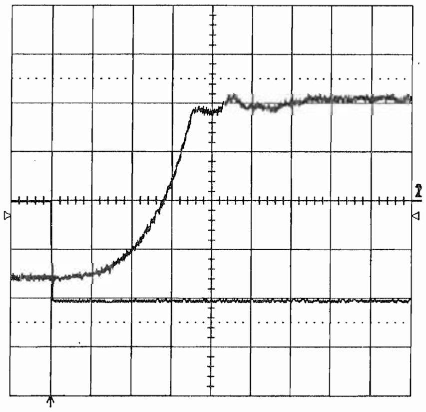

Figure 12 Rise time of the suspension system, 2 ms/div, 2 V/div

2. On modelling of the system.

The modifications done to the system has paved the way to inject a random signal to the power amplifier input and monitor the position feed back signal from the DSP. This means that a lot of work can be done on the area of identification of the mechanical suspension system. This will lead to more accurate models of the system.

3. On controller design aspects.

With the preceding description it is clear that the first major task of modifying the system to work with the DSP has been successfully done. This leads the research to pay more attention on the design of advanced control strategies for the eccentric rotor positioning.

Another interesting thing to investigate will be the region of validity (in side the air gap) of the linearised designs. This will answer the question of whether is it necessary to go for non-linear control design techniques to achieve precision eccentric rotor positioning.

4. Eccentricity tests under running condition.

Before doing the eccentricity tests under running condition (to run the motor while the rotor is being positioned with a certain eccentricity or to apply a step change in reference under running condition) it is very important to settle all kinds of noise problems. Due to this reason all tests that can be done under running condition has been postponed.

5. Rotor positioning technique.

The problem encountered was to derive some method of checking whether the rotor is located exactly at the centre of the stator core. There can be two centres in this case.

1. Geometric centre of the stator core.
2. Magnetic centre of the stator core.

These two need not to be co-located due to small differences in inductance of the three windings and so on. Precision mechanical techniques (using laser beams) can be used to position the rotor at the geometric centre.

But it is known that the noise in induction machines is generated mainly due to eccentric magnetic forces exerted on the rotor by stator windings. Therefore positioning the rotor at the magnetic centre of the stator can be more important in noise reduction.

Rotor can be eccentric from the centre of the stator core due to two reasons in this case.

1. There can be deformations in the rotor (it can be bended).
2. It can be stabilised with an eccentricity due to above mentioned problems in the magnetic bearings.

Deriving a method, which can overcome all these problems and position the rotor at the centre of the stator core, is sighted as a challenging task for the future.

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