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# PERFORMANCE OF THE ACTIVE MAGNETIC BEARINGS*

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**Abstract** The digital controllers of active magnetic bearings system (AMB) are designed. The performance of the controllers are measured and analyzed. The stability is an essential feature for a closed loop control system. By adjusting the magnitude and phase characteristics of the controllers, a stable close-loop control systems are obtained. The step disturbance forces are applied to the system and the responses of system in different conditions are measured and the system stability is optimized by modifying the properties of the controllers. The optimal controllers can attenuate the vibration of the rotor effectively and have large stable range. Some problems of the digital controllers are discussed. The structure of the magnetic bearing system is analyzed for improving the stiffness and the damping of the rotor.

## Introduction

The active magnetic bearings system is a closed loop control system. For this system, the stability is an essential feature. By adjusting the magnitude and phase characteristics of the controllers, a stable closed loop control system can be obtained. But it may be difficult to obtain a system with a wide stable range.

For a magnetic bearing, the stiffness and dynamic range are also important features. High stiffness may make AMB system unstable, while low stiffness may make it unable to suspend the rotor. Some tradeoffs should be made to decide these features.

There are two approaches to implement the AMB controller. One is analog approach, the other is digital approach. The later approach is suitable for adaptive or optimal control because its properties can be changed easily by modifying its software. Therefore, it is an approach which makes the design of controller easier.

## Experimental System

Figure 1 shows the axial AMB system. It is independent of the radial AMB system and can be considered as a single degree of freedom system. It is relatively easy to study the performance by changing the control parameters.

The closed loop control system consists of an eddy-current displacement sensors, magnitude and phase controller, power amplifiers, bias coils and control coils. For the digital approach, the controllers are implemented with real-time FIR, IIR filters and other software packages in the digital signal processing (DSP) system, which consists of a personal computer and a TMS320 development system.

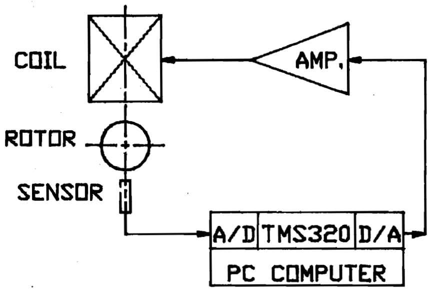


Figure 1: Axial AMB System

The bias coil and control coil are separated and the number of the bias coil turns is more than that of the control coil turns. In this case, the bias coil needs less current to suspend a given weight. In addition, the control coil has less inductance to decrease the phase-lag caused by large coil inductance.

The eddy-current displacement sensor is mounted at the center of the coils, a short axial distance away from the shaft. In the linear range, the output of the sensor, which is produced by a analog circuit, is a DC voltage proportional to the position offset of the shaft. Its reference point (zero-output point) and sensitivity can be changed easily.

The offset signal is sent to the controller which possesses of two parallel paths. These paths allow for the proportional gain and the velocity adjustment, which affect the stiffness and damping of the AMB system, respectively. In our experiments, the controller is implemented both with analog circuits and with a digital

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signal processing system. As shown in Figure 1 DSP system consists of a TMS320 microprocessor, which can perform an addition or multiplication operation in a 200ns instruction cycle. The TMS320 also includes some special instructions for fast implementation of sum-of-products computations encountered in digital filtering calculations.

The filters programs are sent to TMS320 from a PC computer. When a signal is sampled by the AD converter, an interrupt signal make the filter programs execute. The result is sent to DA converter. The output of DSP system has a DC component and noise, whose frequency is proportional to the sample rate of DSP system. In order to filter the high frequency noise, a low pass filter with small time constant is used before the signal is sent to the power amplifier. The effect of the low pass filter to the performance of the system can be ignored, because the small time constant causes a large pole point. The power amplifier is used as control coil driver, which can control the position of the rotor, as well as position adjustment.

## Digital Controller Performance

The design of the analog controllers is relatively familiar to most of designers and have been implemented in many laboratories. In this paper, we focus to the design of digital controllers.

A digital PID controller is used. The proportional path is used to adjust the stiffness, the differentiator is used to adjust the damping of the rotor and the low pass digital filter with certain gain is used to adjust the total stiffness and damping. The transfer function of this controller is given by

$$G(z) = \frac{K_I}{z - e^{-\tau/\tau_I}}\left(K_P + \frac{K_D(z-1)}{\tau_D(z - e^{-\tau/\tau_D})}\right)$$

where $\tau$ is the sampling interval, $\tau_D$ and $\tau_I$ are the time constants of the integrator and the differentiator, $K_I, K_D$ are the gains of them, respectively. The $K_P$ is the gain of the proportional path.

A software package called Digital Filter Design Package (DFDP) is available to design the digital filters. The designed filters are FIR filters, which can be described generally as:

$$y(n) = \sum_{i=0}^{N-1} h(i)x(n-i)$$

where $h(i)$ are the coefficients of the filters, $x(n-i)$ and $y(n)$ is the inputs and outputs, $N$ is the taps of the filters. It is a advantage of the FIR filters that it can be easily designed as a filter with linear phase response. Compared with IIR filter, this advantage makes

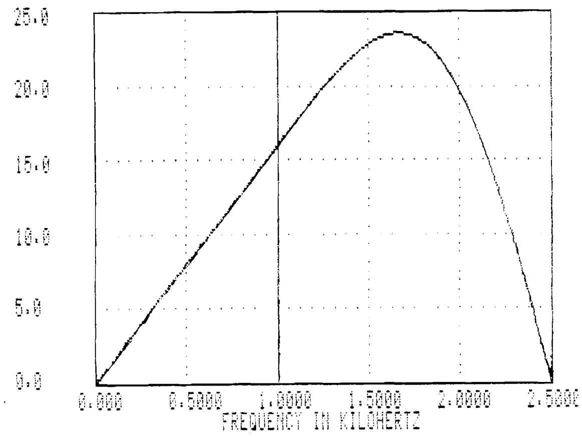



Figure 2: Magnitude Response of Differentiator

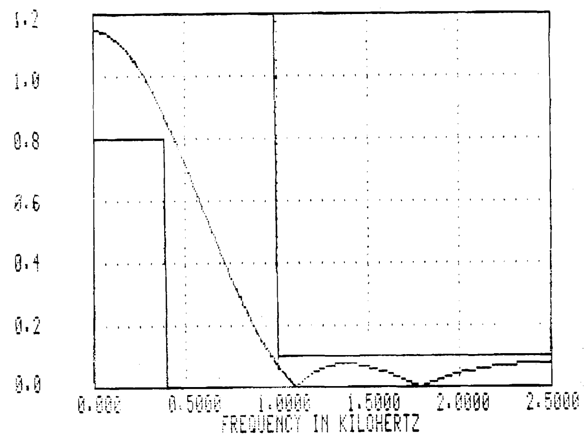



Figure 3: Magnitude Response of Low-pass Filter

it relatively easy to handle the phase response. For a linear phase response FIR filter, the phase response can be given as follow.

For even unit impulse response filter:

$$\phi(\omega) = -\frac{N-1}{2}\omega$$

For odd unit impulse response filter (such as differentiator):

$$\phi(\omega) = \frac{\pi}{2} - \frac{N-1}{2}\omega$$

We can see that the larger the taps $N$ is, the larger the phase lag is. And a $N$ taps FIR filter needs $N$ times of multiplication, addition and memory access, respectively, which also will increase the phase lag of the filter. In order to reduce the phase lag, the filters with smaller taps are used.

The characteristics of the differentiator and the low pass filter used to construct the controller are shown

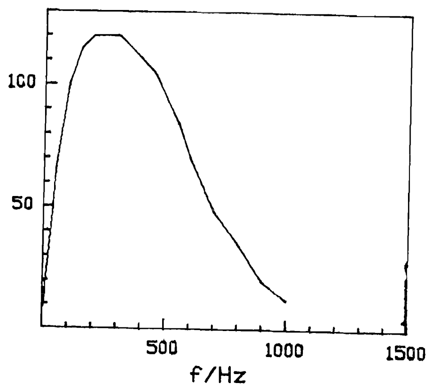



Figure 4: Open Loop Frequency Response of Controller

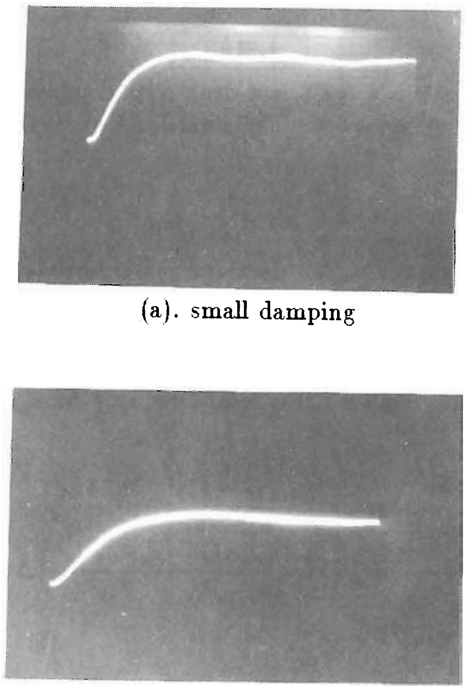
in Figure 2 and Figure 3. In a constructed controller, the characteristics can be changed easily by altering the results of proportional path, the differentiator and the low pass filter respectively. Left shifting the results of proportional path or low pass filter in memory will increase the stiffness of the rotor, while left shifting the results of the differentiator will increase the damping of the rotor. But this method has its limitations: the results only can be increased or decreased with the factor of two and the shifting operation may cause the results overflow or underflow.

The open loop frequency responses of the controller are measured. The results are shown in Figure 4. The controller has a phase lead of 30° at 20Hz, which is the resonance frequency of the rotor in axial direction. It can be seen that the magnitude of controller remains high at high frequency. Because the magnetic bearing system has the effect of low pass filter in the closed loop system, the magnitude at high frequency will be reduced. The step response of the system with different stiffness and damping are shown in Figure 5. Under the maximum damping of this controller, the DC gain can be changed from 8.9dB through 16.2dB.

Another controller without low pass filter, which has a phase lead of 60° at 20Hz, is designed. Compared with the previous controller, it has larger damping at the resonance frequency. Under the maximum damping of this controller, its DC gain can be changed from 6.8dB through 18.1dB. It is obvious that the controller with larger phase lead has a larger range of stability and the stiffness can also be larger.

## Analysis of Stiffness and Structure

For a magnetic bearing system shown in Figure 6, we assume that the motion range of the rotor near the reference position is small and the magnetic flux level is well below the saturation in the core material and the fringing and leakage of the magnetic flux are neglected. According to the assumptions, the linearized analysis can be used.



(a). small damping

(b). large damping

Figure 5: Step Response of Closed Loop System

As shown in Figure 6, the magnet force exerted on the rotor at a distance $z$ is,

$$f = \frac{\mu_0 A(n_0 i_0 + ni)^2}{4z^2}$$

where $\mu_0$ is permeability of free space, $A$ is area of magnetic pole, $n_0 i_0$ is magnetomotive force of bias coil, $ni$ is magnetomotive force of control coil.

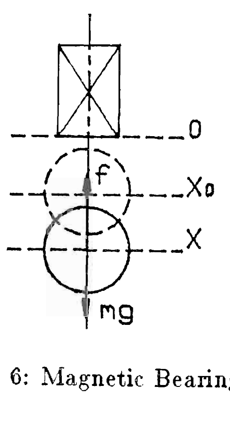



Figure 6: Magnetic Bearing System

At distance $z$, there is an increment $\Delta z$ of $z_0$, then the current in the control coil is,

$$i = k_i \Delta z$$

where $k_i$ is a coefficient dealt with displacement sensitivity of the rotor. The total force exerted on rotor is,

$$\Delta f = f - mg$$

At distance $z_0$, the electromagnetic force is,

$$f_0 = \frac{\mu_0 A n_0^2 i_0^2}{4 z_0^2} = mg$$

So, at distance $z$, the total force is, ( $\Delta z \ll z_0$)

$$\begin{aligned} \Delta f &= f - mg = f - f_0 \\ &= \frac{\mu_0 A (n_0 i_0 + ni)^2}{4z^2} - \frac{\mu_0 A n_0^2 i_0^2}{4 z_0^2} \\ &\doteq \left( \frac{\mu_0 A n_0 i_0 n k_i}{2 z_0^2} - \frac{\mu_0 A n_0^2 i_0^2}{2 z_0^3} \right) \Delta z \end{aligned} \quad (1)$$

The axial stiffness $K$ of the rotor is,

$$K = K_p - K_n = \frac{\Delta f}{\Delta z}$$

where, the $K_p$ is positive stiffness,

$$K_p = \frac{\mu_0 A n_0 i_0 n k_i}{2 z_0^2}$$

the $K_n$ is negative stiffness,

$$K_n = \frac{\mu_0 A n_0^2 i_0^2}{2 z_0^3}$$

The positive stiffness is the effect of control coil and the negative stiffness is the effect of bias coil, which has a negative effect to the stability of the system. It is essential to overcome the negative stiffness by increasing the positive stiffness. Defining

$$z_m = \frac{n_0 i_0}{n k_i}$$

At the position $z > z_m$, we have

$$K_p > K_n$$

So, if the rotor is at the position $z < z_m$, it will have a negative stiffness and move toward the magnet out of control. To avoid this case, we keep the rotor at a distance $z > z_m$ away from the electromagnet on the condition that the rotor is in the linear range of the system.

From Eq.(1), we can see that the stiffness of the rotor can be increased by increasing the reference distance $z_0$, but the power for suspending the rotor also will be increased and may cause the saturation of the core material. Also, increasing the control coil turns $n$ has the drawback of increasing the coil inductance. So, the most effective way to increase the stiffness is to increase the coefficient $k_i$ on the condition that the system is stable. This result can also be used in other magnetic bearing system of permanent magnets with attractive force.

## Conclusions

Analog and digital controllers of the AMB system are designed and constructed. To improve the performance, different kinds of real-time control programs which have different magnitude and phase response are used. The characteristics of the controllers are measured and analyzed. The controllers with large phase lead at resonance frequency of rotor have relatively large range of stability. Hence, stiffness of the rotor can be changed in large range. The maximum stiffness of the rotor also can be increased. This is very important for improving the performance of the AMB system.

The structure of the magnetic bearing system is also discussed in this paper. Within the minimum suspension distance, the rotor will be out of control and moves toward the magnet. The minimum distance is proportional to the magnetomotive force of bias coil and inversely proportional to the control coil turns and the displacement sensitivity of the control system. The method to avoid this case is to keep the position of the rotor at a distance larger than the minimum suspension distance.

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