MAGNETIC BEARINGS WITH WEIGHT BIAS ACTUATORS FOR HIGH DYNAMIC RESPONSE

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ABSTRACT
A magnetic bearing with high static load capacity requires special design of the magnets to meet both static load and slew rate requirements. It requires a balance between the size of the magnet and the magnitude of source voltage. The proposed magnetic bearing scheme simplifies the design process by using one or more constant current electromagnets.

INTRODUCTION

Most magnetic bearing designs today use a pair of opposing actuators to control each axis. Magnetic bearing design process involves trade-off between the design parameters such as voltage supply, power loss, actuator pole face size, coil size, and overall packaging size to meet the application requirements. In applications with high static loads such as gravitational force, the bearing configuration presented may simplify the design process to provide an optimum design. The proposed configuration splits the static and dynamic loads between weight bias actuators and control actuators. This design allows the power amplifier that controls current through the control magnet to operate with a lower voltage supply. Since the weight bias actuators do not require any slew rate, the actuator coil can be sized to reduce the power loss.

This paper describes a one degree of freedom magnetic bearing system with weight bias actuators. It also presents simulation results for a flywheel system supported by magnetic bearing with weight bias actuators.

A prototype of the flywheel system that uses the magnetic bearing design is currently being fabricated. Simulation with prototype controller, power amplifiers, and actuators in the loop shows that the system can levitate and control the imbalance forces of flywheel. The prototype will be operational sometime this year.

THEORY

Operation of an actively-controlled magnetic bearing is well documented in the literature [1, 2, 3]. Figure 1 shows the configuration of the proposed system.

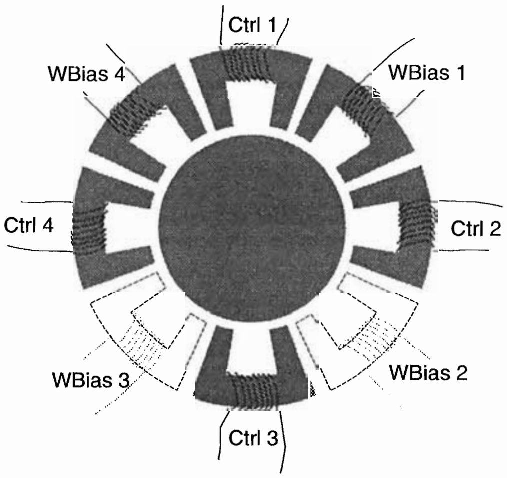

FIGURE 1: A Magnetic Radial Bearing Configuration With Weight Bias Actuators

The magnetic bearing system that supports the flywheel has four control and two weight bias actuators[4]. The weight bias actuators carry the majority of the static load, leaving the disturbance and residual static load to the control actuators. For an ideal electromagnet actuator, the force slew rate, dF/dt, is approximately

$$\frac{dF}{dt} = 4f_{leak}\frac{\mu_0 n^2 A}{\left(2g + \frac{l}{\mu_{(B)}}\right)^2} \cdot i\frac{di}{dt} \quad (1)$$

where

F = *force*
t = *time*
f_{leak} = *derating factor for fringe and leakage*
μ_0 = *permeability of air/vacuum*
n = *number of turns*
A = *projected pole face area*
i = *coil current*
g = *gap*
l = *mean magnetic path length*
μ = *relative permeability of core*

The equation above shows that the force slew rate is directly proportional to the current, which means the force slew rate of the actuator approaches zero as the current approaches zero. However, when higher currents are applied to an actuator, the magnetic flux density of the core begins to saturate, which causes the relative permeability of the core to decrease and approach unity. The system loses the ability to control the force as the result of low relative permeability of the core. Limited compensation is possible using a higher supply voltage. Most magnetic bearing systems avoid such problems by operating within the linear range of the core material. However, for a magnetic bearing system with high static load, operating the conventional magnetic bearing within linear range may require a substantial increase in the size of the magnets. During the development of the flywheel system, the design team came to the conclusion that a conventional magnetic bearing system capable of meeting the force requirement cannot fit in the available bearing space.
The solution presented in this paper uses secondary actuators (weight bias), to minimize the static load carried by the primary actuators (control). The control actuators deal with the disturbances and residual force, while the weight bias actuators bear most of the static load. Since the control actuators carry a smaller load, the coil size can be smaller, resulting in lower resistance and inductance. This gives a better slew rate for a given voltage supply. The weight bias bearing is designed to operate closer to saturation. By providing larger coil space, the actuator can operate at lower current density. As long as the current stiffness of the control actuators overcomes the negative stiffness of the control and weight bias actuators, the magnetic bearing system will remain stable.

DYNAMIC MODEL

A dynamic model of a magnetic bearing system supporting a mass is presented first to show how the control and weight bias actuators operate together. The model is based on the following assumptions.

- gravity loads the bearing in vertical direction.
- the body is rigid.
- the mass center of rotor is offset from the geometric center of rotor.

The control actuators are actively controlled using a proportional-integral-derivative (PID) control algorithm. The weight bias actuator currents are fixed. For such a system, the system of equations in a single axis is

$$m\frac{d^2x}{dt^2} = \left(k_{01}\frac{I_0}{g^2} + k_{02}x\right) + \left(k_{11}\frac{I_1}{g^2} + k_{12}x\right) \quad (2)$$

where

m = *mass*
x = *displacement*
t = *time*
k_{01} = *current stiffness for the control actuator*
k_{02} = *displacement stiffness for the control actuator*
k_{11} = *current stiffness for the weight bias actuator*
k_{12} = *displacement stiffness for the weight bias actuator*
I_0 = *change in current for the control actuator coil*
I_1 = *change in current for the weight bias actuator coil*
g = *nominal gap size*

For PID control, I_0 is

$$I_0 = -K_G x - K_V\frac{dx}{dt} - K_I\int x\,dt \quad (3)$$

where

K_G = *proportional gain*
K_V = *derivative gain*
K_I = *integral gain*

and I_1 is zero, since the current through the weight bias actuator is kept constant. Substituting I_0 and I_1 into Equation 2 gives

$$m\frac{d^2x}{dt^2} - (K_{02} + K_{12})\,x - \frac{K_{01}}{g^2}\left(K_G x + K_V\frac{dx}{dt} + K_I\int x dt\right) = 0 \qquad (4)$$

This system is stable, if

$$\frac{K_G K_{01}}{g^2} \geq (K_{02} + K_{12}) \qquad (5)$$

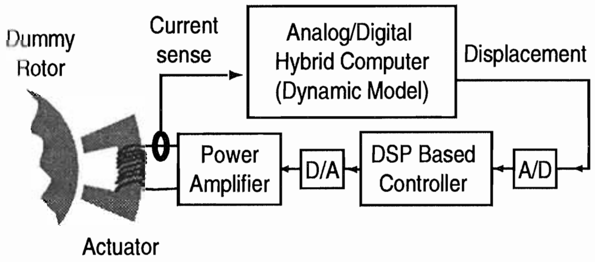

FIGURE 2: Block diagram of simulation model

A full model of a flywheel system (Figure 2) with six degrees of freedom using the above mentioned assumptions has been coded into a digital/analog hybrid computer. To induce dynamic forces, the mass center of the rotor was offset from the geometric center by 0.01 times the nominal gap. A PID controller based on Texas Instruments TMS320C31 DSP also included an automatic balancing algorithm. Displacement output generated by the real time simulation of the rotor dynamics is fed into the controller through analog-to-digital converters. The controller in turn generates appropriate current commands to the power amplifiers that control the current through the electromagnets. The current sense signals from the power amplifiers are then fed back to the real time simulation.

The dimensionless parameters used for the simulation are given in Table 1. Figures 2 and 3 show the nondimentionalized actuator force as a function of magnetomotive force at different clearances. These curves were interpolated from experimental data.

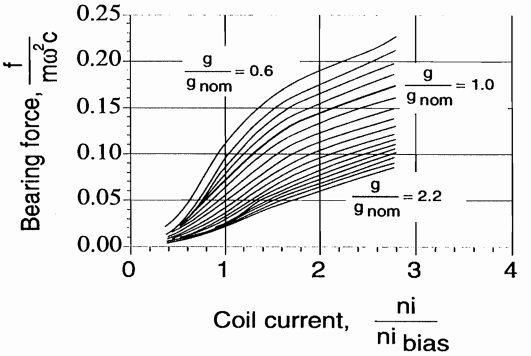

FIGURE 3: Force curves for the control actuator

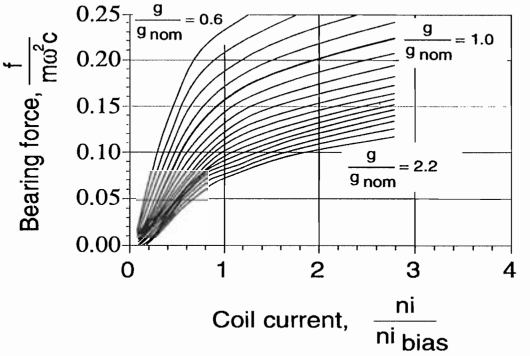

FIGURE 4: Force curves for the weight bias actuator

ANALYSIS RESULTS

The analytical model was used to simulate start-up, run-up, and steady-state operation. Figures 4, 5, and 6 show the displacement and current time trace of top radial actuator (Ctrl 1) as the rotor is being levitated and delevitated, spin-up to operating speed, and as the automatic balancing function is activated.

PROTOTYPE

A prototype of the flywheel system is currently being fabricated. The DSP based controller, power amplifiers, and actuators are complete. These components are connected to a digital/analog hybrid computer system in Sundstrand's simulation laboratory (Figure 7 to perform hardware in the loop simulation. The rotor and housing are being fabricated at the time of this writing.

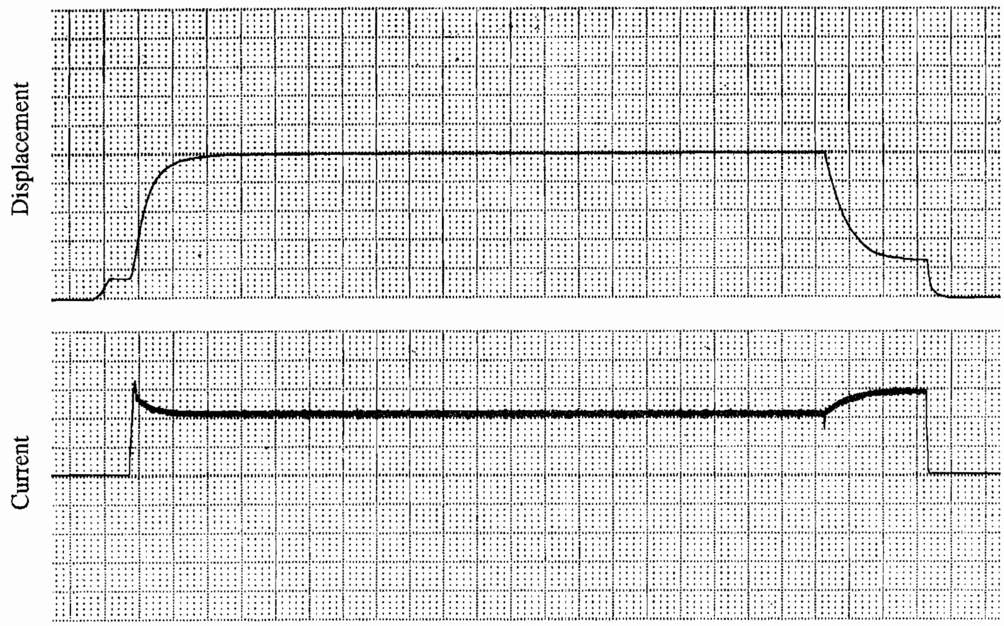

FIGURE 5: Time trace of displacement and coil current for the top radial actuator (Ctrl 1) as the rotor levitates and delevitates

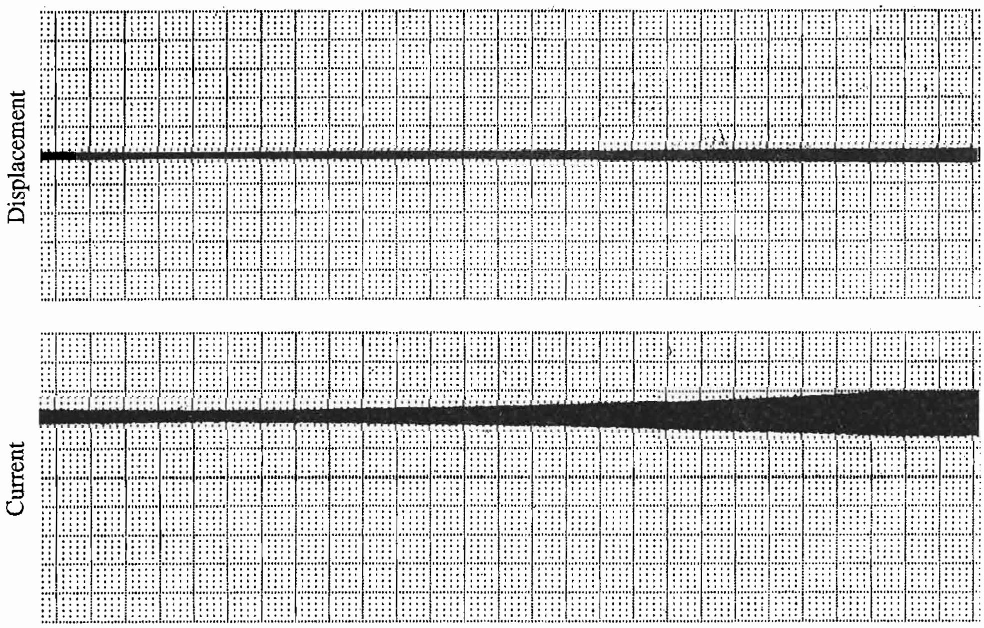

FIGURE 6: Time trace of displacement and coil current for the top radial actuator (Ctrl 1) as the rotor accelerates up to the operating speed.

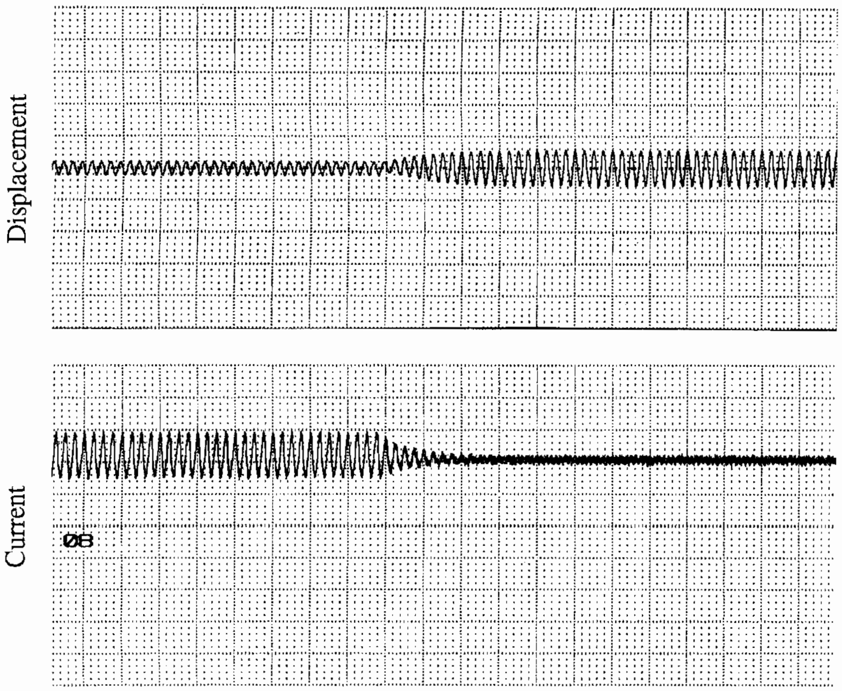

FIGURE 7: Time trace of displacement and coil current for the top radial actuator (Ctrl 1) as the automatic balance function is activated.

TABLE 1: Simulation parameters

Parameter	Value
$L = \ell \bullet 1/r$	*0.6*
$M = m \bullet 1/m$	*1*
$I_p = i_p \bullet 1/mr^2$	*1.816*
$I_t = i_t \bullet 1/mr^2$	*0.908*
$K_x = k_x \bullet 1/m\omega^2$	*see actuator force plots*
$K_i = k_i \bullet I_{bias}/m\omega^2 c$	
ℓ *- length of flywheel, m*	
m - mass of flywheel, kg	
r - radius of radial bearing rotor, m	
ω *- operating speed, rad/s*	
c - nominal gap size, m	
i_p *- polar moment of inertia, N•m•s*^{2}	
i_t *- transverse moment of inertia, N•m•s*^{2}	
k_x *- stiffness, N/m*	
k_i *- current stiffness, N/A*	
I_{bias} *- bias current, A*	

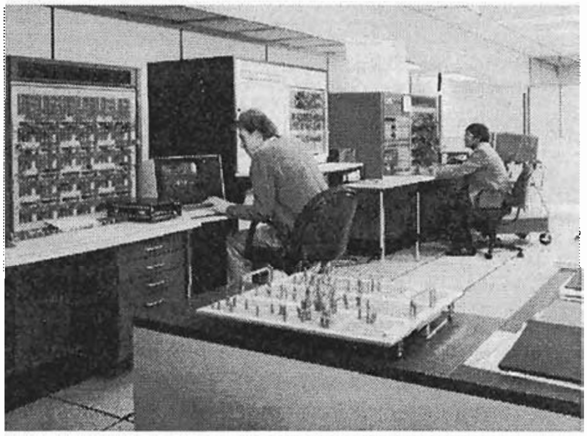

FIGURE 8: Sundstrand's simulation laboratory

CONCLUSION

A magnetic bearing system with a set of primary actuators and a set of secondary actuators was presented. In simulation, the magnetic bearing system with weight bias bearing successfully levitated and controlled the imbalance forces of flywheel. The weight bias actuators reduced the static force on the control actuators, allowing wider force range for the control action. Using a conventional magnetic bearing design for the same application would have required twice the cross-sectional area for the magnetic flux path. The resulting increase in rotor laminations to accommodate higher flux also increases the rotor weight. This increase in rotor weight requires a larger cross-sectional area and more structural strength to accommodate the higher weight. A severe space limitation caused by the flywheel design requirement made the conventional magnetic bearing design impractical.

The magnetic bearing design presented here allows the weight bias actuators to operate closer to saturation, reducing the lamination size for the rotor. However, the weight bias actuators introduce additional negative stiffness to the system, which the control actuators have to compensate.

In a future study, we plan to replace the weight bias actuators with slow response actuators. The digital controller will be reprogrammed to drive the slow response actuators and the fast response actuators appropriately to achieve better overall performance.

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