VELOCITY-CONTROLLED MAGNETIC BEARINGS WITH SOLID CORES

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SUMMARY

A methodology for designing velocity-controlled magnetic bearings with laminated cores has been extended to those with solid cores. The eddy-current effect of the solid cores is modeled as an opposing magnetomotive force. The bearing control dynamics is formulated in a dimensionless fashion which can be readily reviewed on a root-locus plot for stability. This facilitates the controller design and tuning process for solid core magnetic bearings using no displacement sensors.

INTRODUCTION

To make inexpensive active magnetic bearings, there have been developing efforts to spare displacement sensors in the bearing control. The displacement sensors not only are costly, but also are reliability burden and the source of non-collocation instability. Recently, Chen [1] has developed a method for designing this type (commonly called self-sensing or sensorless) of magnetic bearings. Chen's method divides the bearing control system into three major parts with independent functions. These parts are called velocity feedback controller (VFC), velocity estimator (VE) and self-starter (SS). The design approach has clearly shown that the bearings without displacement sensors, apply in essence the feedback control of rotor velocity. The velocity can be estimated by analog or digital means based on the current and back EMF measurements at the magnetizing coils, or even measured directly using an inexpensive velocity sensor. Any effort attempting to re-create the rotor absolute displacements seems unnecessary, because there naturally exist a reference of the absolute displacement for the control. This reference is at a location in the bearing clearance where all static forces balance each other.

The other control method utilizes observers [2] to estimate the system states, i.e., the rotor displacement, velocity and dynamic current, based on similar measurements at the magnetizing coils. There are five or six unknown observer parameters for each control axis. Thus, tuning the controller with the observers is difficult. Chen's method which utilizes a separate velocity estimator reduces the number of unknowns to three in the tuning process. Most importantly, it retains the physical insight during that process.

It is the purpose of this paper to extend Chen's method and apply it to the magnetic bearings with solid cores. Specifically, the formulation of VFC and VE will be modified to accommodate the retarded control response due to eddy currents in solid cores. Also it will be demonstrated, via an numerical transient simulation of a flywheel thrust bearing design, that SS is easy to design and works well, contrary to many beliefs.

VELOCITY FEEDBACK CONTROL FORMULATION

A thrust magnetic bearing such as the one shown in Figure 1 usually has solid cores because it is difficult to make the bearing with silicon steel laminations aligned in the radial direction. There is also a great incentive for many industrial applications to make radial magnetic bearings with solid cores in order to reduce manufacturing cost. Figure 2 shows such a bearing with a homopolar

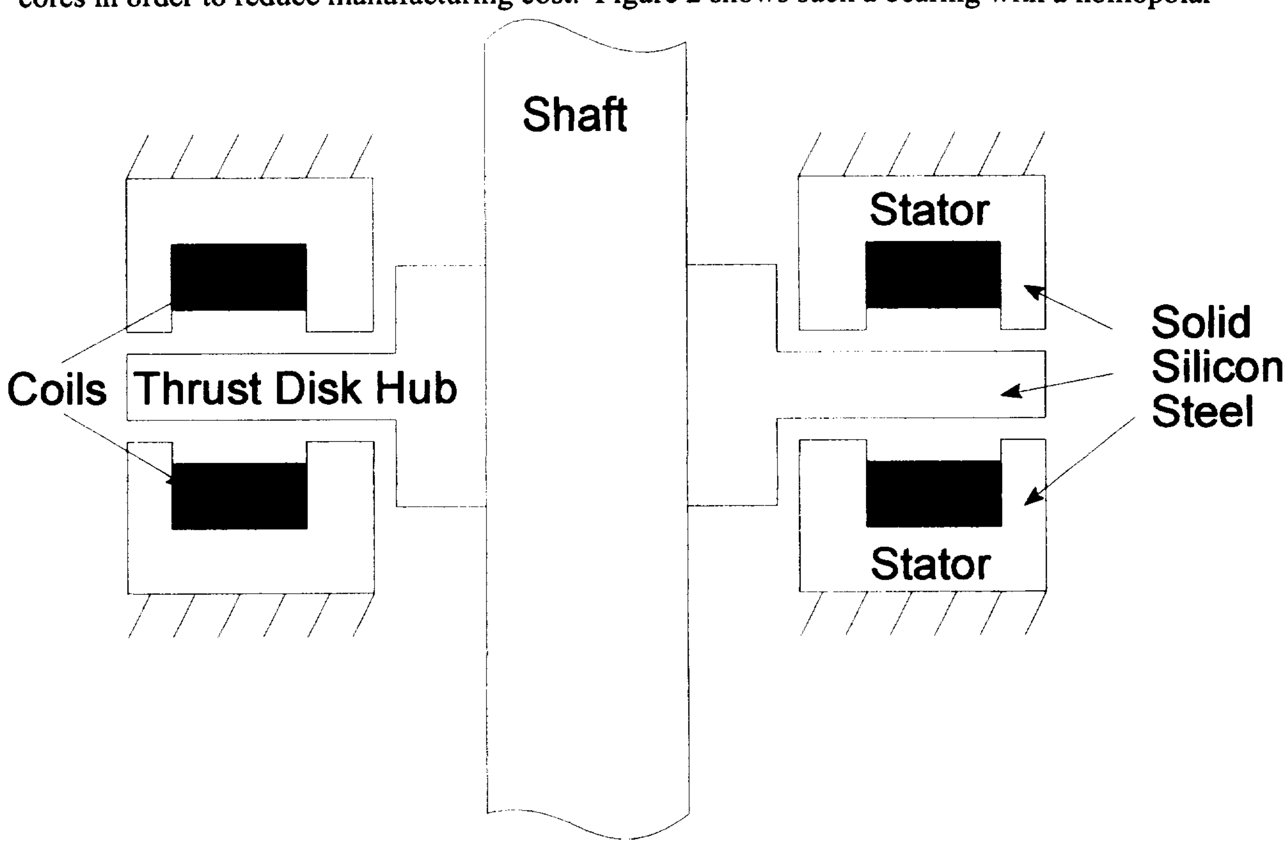

Figure 1. Typical magnetic thrust bearing with solid cores.

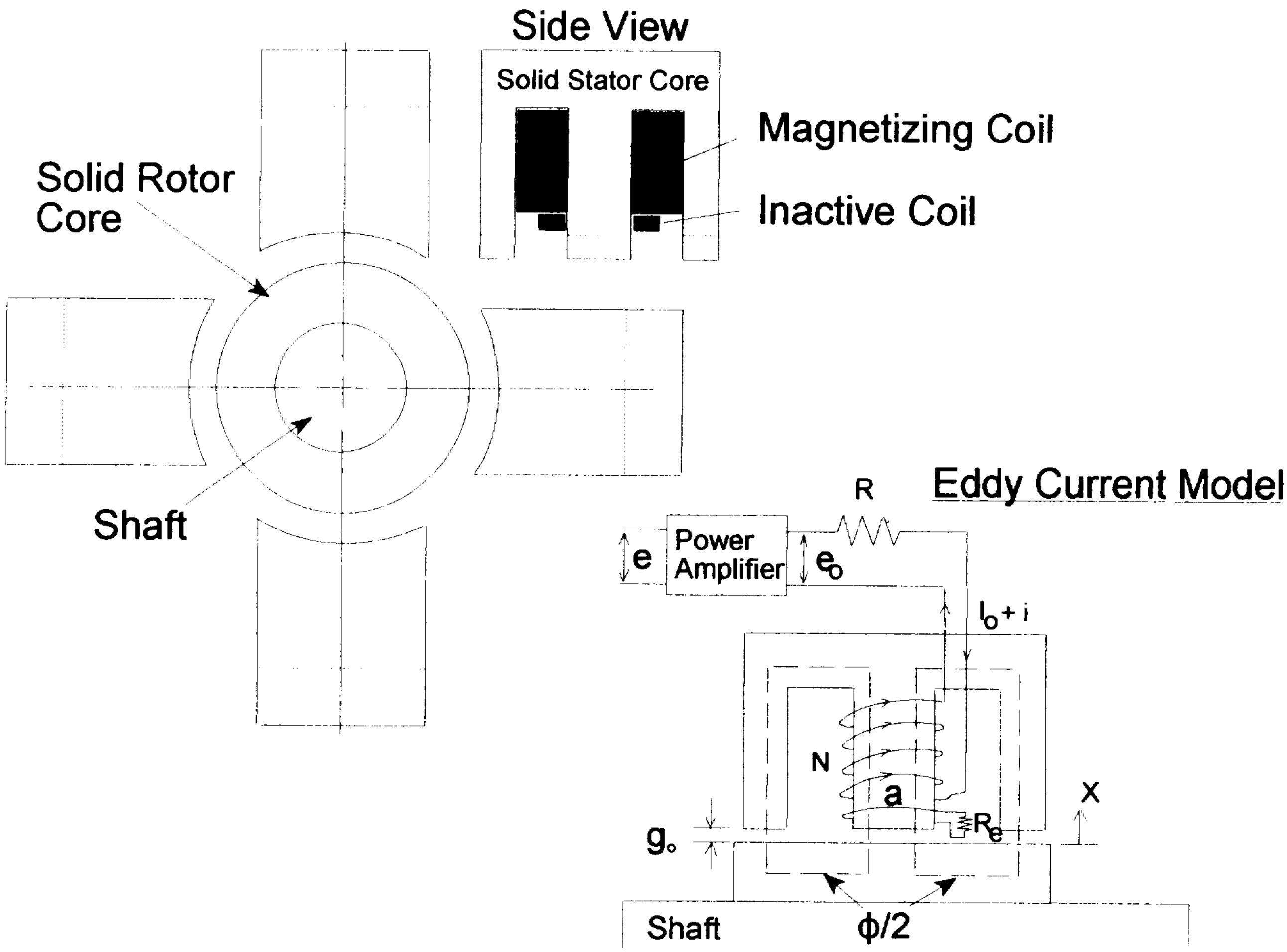

Figure 2. Radial bearing with homopolar solid cores.

configuration. Without laminations, there will be eddy current generated in the cores when dynamic (control) current is applied to the magnetizing coils and the eddy current effect in retarding the bearing response should be considered. The retarding effect is usually measured in terms of gain reduction and phase lagging of magnetic flux with respect to the excitation current applied to the magnetizing coils. Both the gain and phase are functions of excitation frequency and the phase lagging is a serious concern for control. For example, a phase lag of 16 degrees at 40 Hz was recorded in [3]. A similar measurement of 30.5 degrees at 100 Hz was made for a steel core material in [2]. Close examination of these and other similar data has revealed that the eddy-current retarding effect may be approximated by the dynamics of a half-order pole. However, for controlling the low frequency modes of magnetic bearings, a linear approximation is preferred and proper. Thus, the eddy current has been modeled as an opposing magnetomotive force [2,4] by assigning to the solid cores a coil turn with an equivalent resistance. According to [4], the feedback of coil current in the power amplifier itself, i.e., the mechanism providing a current source, is not capable of improving the time lag due to the eddy current. The dynamics of the sub-system (Figure 2) including the power amplifiers, magnetizing coils and the eddy currents in solid cores, can be represented by the following equation:

$$T(dq/dt) + q + (hT)(dx/dt) = G_a e \qquad (1)$$

where T = time constant of eddy-current effect, sec
t = time, sec
q = quasi-current, A
h = a constant related to bias currents and gaps of opposing poles, A/in
x = rotor displacement, in
G_a = power amplifier sensitivity, A/volt
e = power amplifier input, volt.

Without considering bending modes, the rotor equation of motion can be represented by (2).

$$M(d^2x/d^2t) = K_i q + K_m x \qquad (2)$$

where M = rotor mass at the bearing, lb-sec^2/in
K_i = current stiffness, lb/A
K_m = magnetic stiffness, lb/in

A velocity-controlled magnetic bearing axis can be represented by the block diagram of Figure 3 including the dynamics of equations (1) and (2). For a radial magnetic bearing, there are two independent controlled axes as such, and for a thrust bearing, there is one. Note that in reference [1] the VFC for laminated cores includes a first-order low-pass filter for trimming the velocity input in high frequency range. The purpose of the filter was to control the high frequency noise and/or

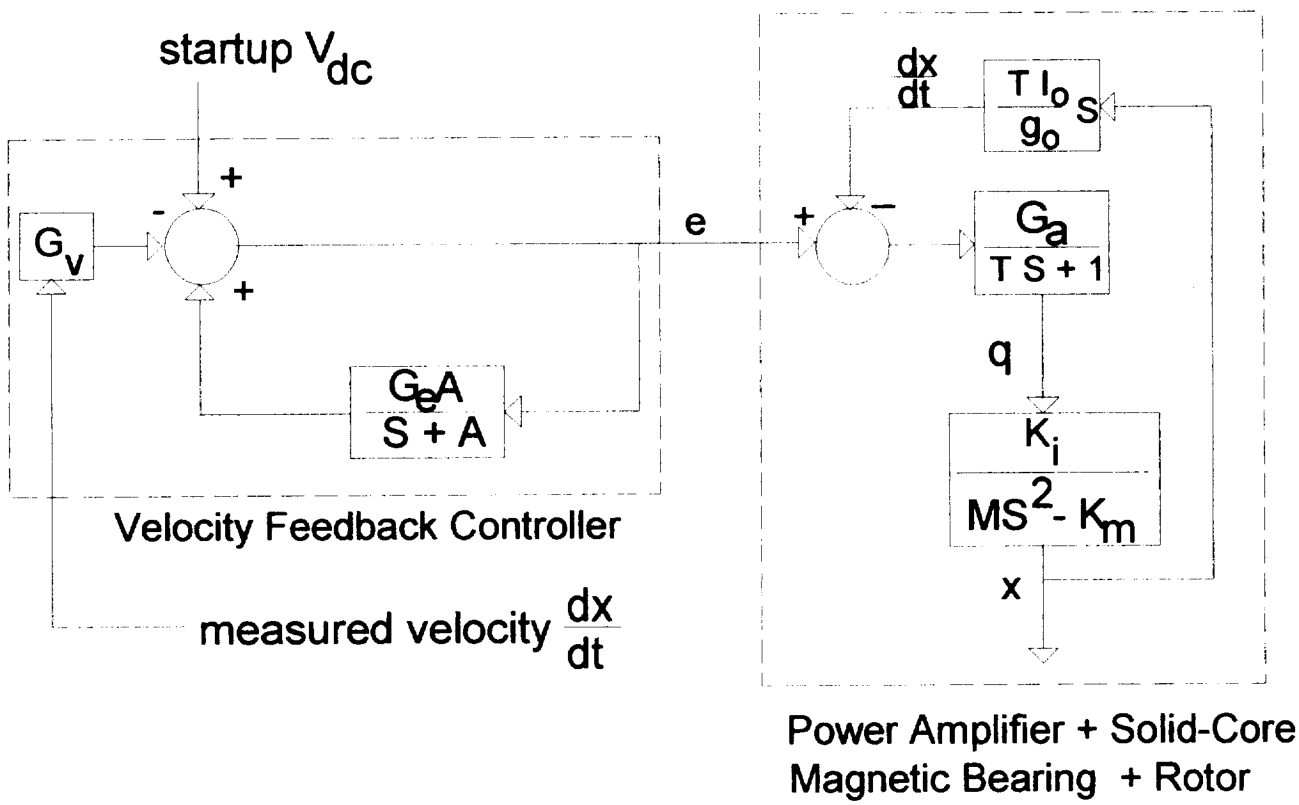

Figure 3. Velocity-controlled magnetic bearing axis with solid cores.

structural resonances. However for bearings with solid cores, the response retarding effect of eddy current is naturally a low-pass mechanism. Therefore, there is no need for an additional low-pass filter in VFC, and it is thus eliminated. The key element of VFC is an inner loop with a positive feedback. The loop contains a low-pass filter with a gain G_e and a time constant 1/A. The corresponding characteristic equation of the controlled axis is:

$$1 + KS(S+A)/[TS^3+S^2+T(H-1)S-1](S-A_r) = 0 \tag{3}$$

where S = Laplace variable
$A_r = (G_e-1)A$
$K = K_i\,G/MB$
$H = K_i\,h/MB^2$
$G = G_aG_v$
$B = \sqrt{K_m/M}$

The parameters S, A, A_r in (3) are all normalized by the artificial parameter B called the bias frequency which is a measure of the strength of the bias flux in the magnetic bearing. Also, the time constant T is normalized by 1/B and it is partly due to the eddy-current effect and partly due to inductance of the coils. For a magnetic bearing with laminated cores and using current-source power amplifiers, the time constant T becomes small and the pole terms in the square parenthesis of (3) is reduced to $[S^2-1]$ as expected.

SELECTION OF VELOCITY FEEDBACK CONTROLLER PARAMETERS

The time constant T can be experimentally determined by clamping down the rotor concentrically in a bearing and measuring magnetic flux versus the applied sinusoidal excitation currents at different frequencies. The measured data are then fitted to a first-order low-pass network to determine the values of G_a and T. For example, based on the gain and phase lag data of [2], the time constant due to eddy current is estimated as 0.001 second for a steel material.

The constant h is a function of bias current (I_o) and nominal air gap (g_o). For simplicity, equal bias currents for the opposite electromagnet coils will be assumed subsequently. It can be readily shown that:

$$h = I_o/g_o \quad \text{and} \quad K_i/K_m = g_o/I_o \tag{4}$$

Therefore, the normalized h value is : $H = K_i\,h/MB^2 = K_i/K_m h = 1.0$.

The VFC has three parameters to be determined and they are A, G_e and G_v. Instead of using G_e and G_v, the parameters A_r and K of (3) will be used in the following discussion for convenience. The selection process of VFC parameters can be assisted by using root-locus plots of the characteristic equation. To illustrate the process, we shall use a design example of a magnetic thrust bearing for an energy storage flywheel rotor as follows.

Shown in Figure 4 is the flywheel rotor with two passive radial magnetic bearings and an active thrust magnetic bearing. The latter is the subject of our discussion. The rotor axial velocity is

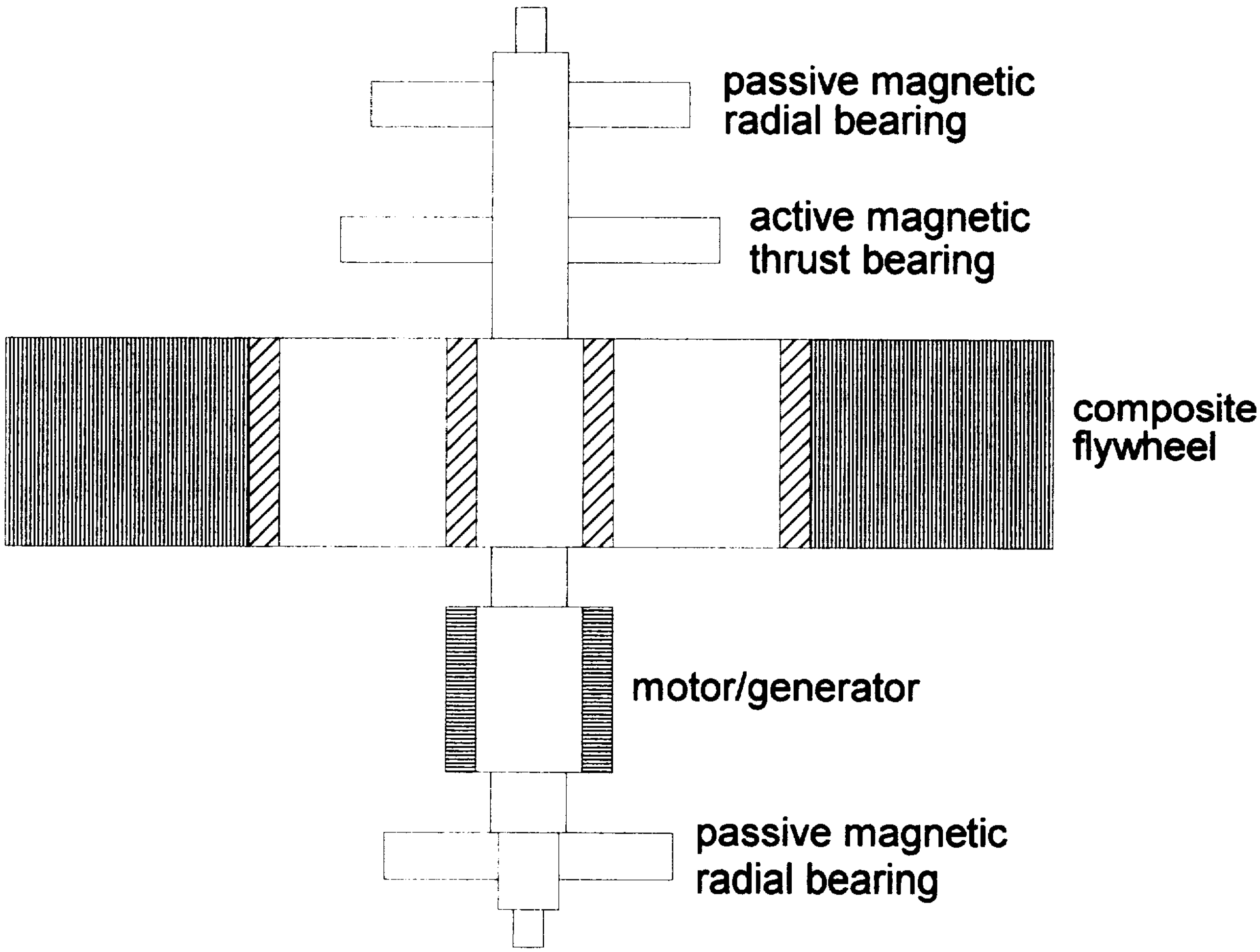

Figure 4. Flywheel rotor.

measured by using a variable reluctance (magnetic) sensor which is commercially available and inexpensive.

The pertinent data for the thrust bearing VFC design are listed in Table 1. Note that the passive radial magnetic bearings are made of permanent magnetic rings, and each has an axial magnetic (negative) stiffness of 7.0×10^5 N/m. Their total value is represented by K_{mb} in Table 1.

Table 1 - Pertinent Data For Thrust Bearing VFC Design

Rotor weight	22Kg
Load capacity	1000 N
Outer diameter	100 mm
Inner diameter	50 mm
Bias current I_o	3 A
Nominal air gap g_o	0.38 mm
Current stiffness K_i	363 N/A
Magnetic stiffness K_{ma}	$2.85x10^6$ N/m
Axial stiffness of radial bearings K_{mb}	$1.40x10^6$ N/m

To use equation (3) for determining the VFC unknown parameters, we shall first calculate the bias frequency B using the data of Table 1.

$$K_m = 2.85x10^6 \text{ N/m} + 1.40x10^6 \text{ N/m} = 4.25x10^6 \text{ N/m}$$

$$B = \sqrt{K_m/M} = \sqrt{4.25x10^6 /22} = 440 \text{ rad/sec} = 70 \text{ Hz}$$

Taking the eddy current time constant for the bearing solid cores as 0.001 sec, then its normalized value is:

$$T = (0.001 \text{ sec})(B) = 0.44$$

Choosing the normalized values A=0.8 and A_r = 0.4, The root loci of (3) with the above T and H values are plotted in Figure 5. For the normalized gain K =2.5, the system shows two pairs of complex conjugate roots:

$$- 0.25 \pm j\, 0.42 \qquad \text{and} \qquad - 70 \pm j\, 1.84$$

Both modes are reasonably damped. The first mode frequency is 29.4 Hz (=0.42 x 70 Hz) and the second mode frequency is 129 Hz (=1.84 x 70 Hz). Apparently the second or the mode with higher frequency is more affected by the eddy current in solid cores. The selection of the values of A and A_r determines the locations of a pole and a zero for K = 0. The selection dictates the shapes of the root loci. One may choose the desired shapes from a pre-calculated, non-dimensional data bank and determine the unknown K, A and A_r. It is basically a pole placement design method. For this particular example, using different values of A and A_r may result in a set of more damped roots with lower modal frequencies.

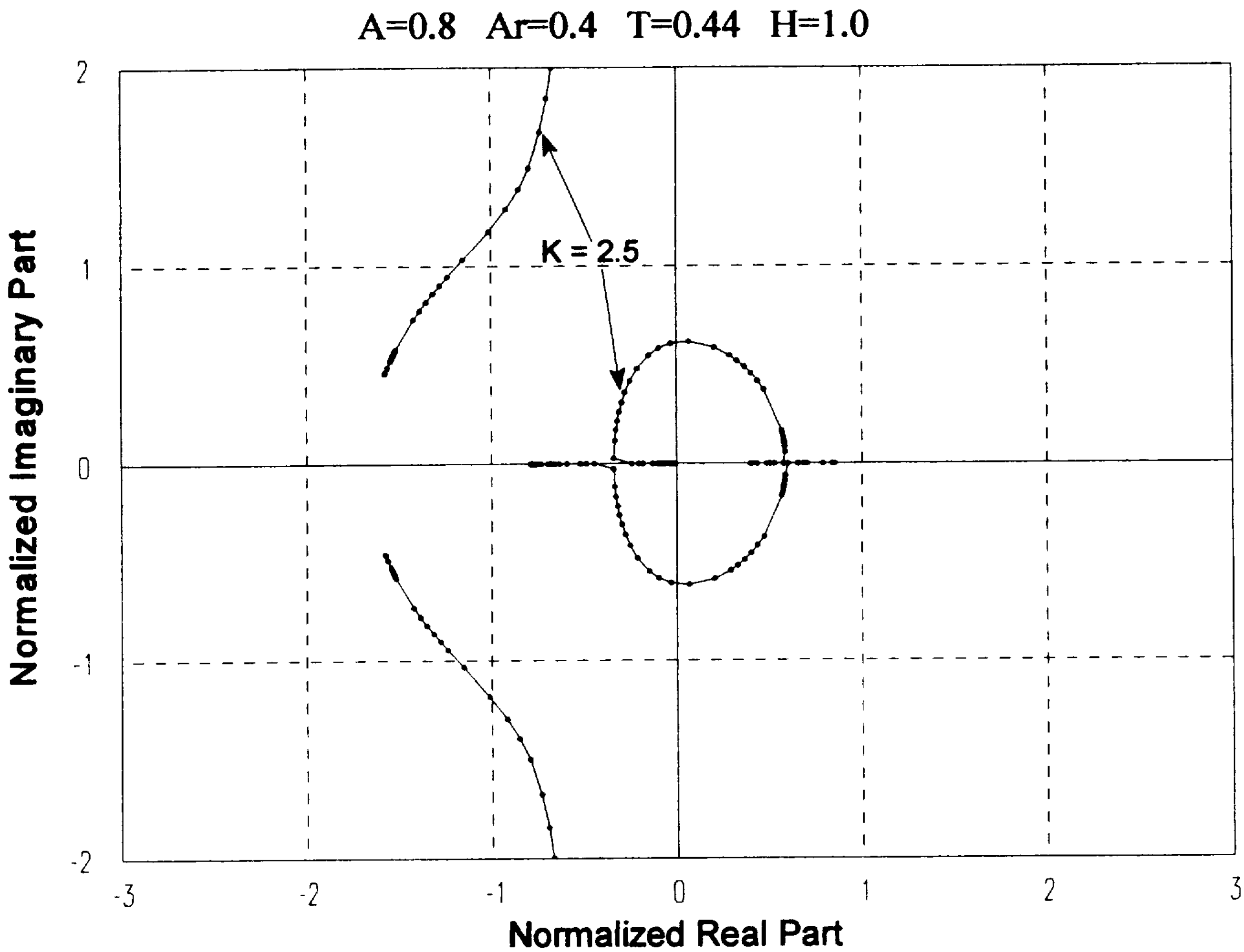

Figure 5. Root loci for a solid core bearing control axis.

A hidden design issue is how high the bias frequency B should be set. A high value of B implies a large static stiffness K_m which is desirable. However, for the solid-core bearings, the normalized time constant T is increased and the control system is likely to have one lightly damped mode. With the normalized root-locus method described above, this design issue can be easily examined in details for each application.

It should be emphasized that high-frequency bending modes in active magnetic systems are dealt with similarly regardless as to whether the bearings are conventionally PID-controlled or velocity-controlled. In other words, gain and phase compensations such as using notch-filters or lead-lag circuits, are provided in high-frequency range to stabilize these modes, if necessary.

VELOCITY ESTIMATOR FORMULATION

Similar to (1), the following equation [4] relates the voltage across the coil (e_o), the quasi-current (q) and the rotor vibration velocity (dx/dt):

$$T_o(dq/dt) + q + (hT_o)(dx/dt) = e_o/R \tag{5}$$

where

$T_o = (N^2/R + 1/R_e)/R_m$
N = coil turns
R = coil electric resistance
R_e = equivalent electric resistance of eddy current in solid cores
R_m = air gap reluctance = $2g_o/\mu_o a$
μ_o = air permeability
a = pole area.

Unlike the coil current (I_o+i of Figure 2), the quasi-current q is an artificial term not directly measurable. But, it can be readily shown [2] that

$$q = I(1+\Delta) - e_o\Delta/R \tag{6}$$

where

$\Delta = R/N^2 R_e$

Combining (5) and (6), it is straightforward to make a velocity estimator for the solid core magnetic bearing. However, such a scheme suffers the common drawback of being sensitive to the coil temperature [1], because the resistance varies significantly with the coil temperature. While temperature compensation is one of the possible solutions, it complicates the estimator design.

Another possible solution of less complication is to measure the flux using an inactive coil [1]. There is no current flowing in the inactive coil, and its resistance and thus the temperature has no bearing to the measured voltage signal. The voltage across the inactive coil is:

$$V = -n(d\phi/dt) \tag{7}$$

where

ϕ = dynamic magnetic flux
n = inactive coil turns.

It is also readily shown from the solid core model that:

$$T_o(d\phi/dt) + \phi + (hN/R_m)x = (N/R\ R_m)e_o \tag{8}$$

Combining (7) and (8), the rotor velocity of a solid core bearing can be estimated using a scheme presented in Figure 6.

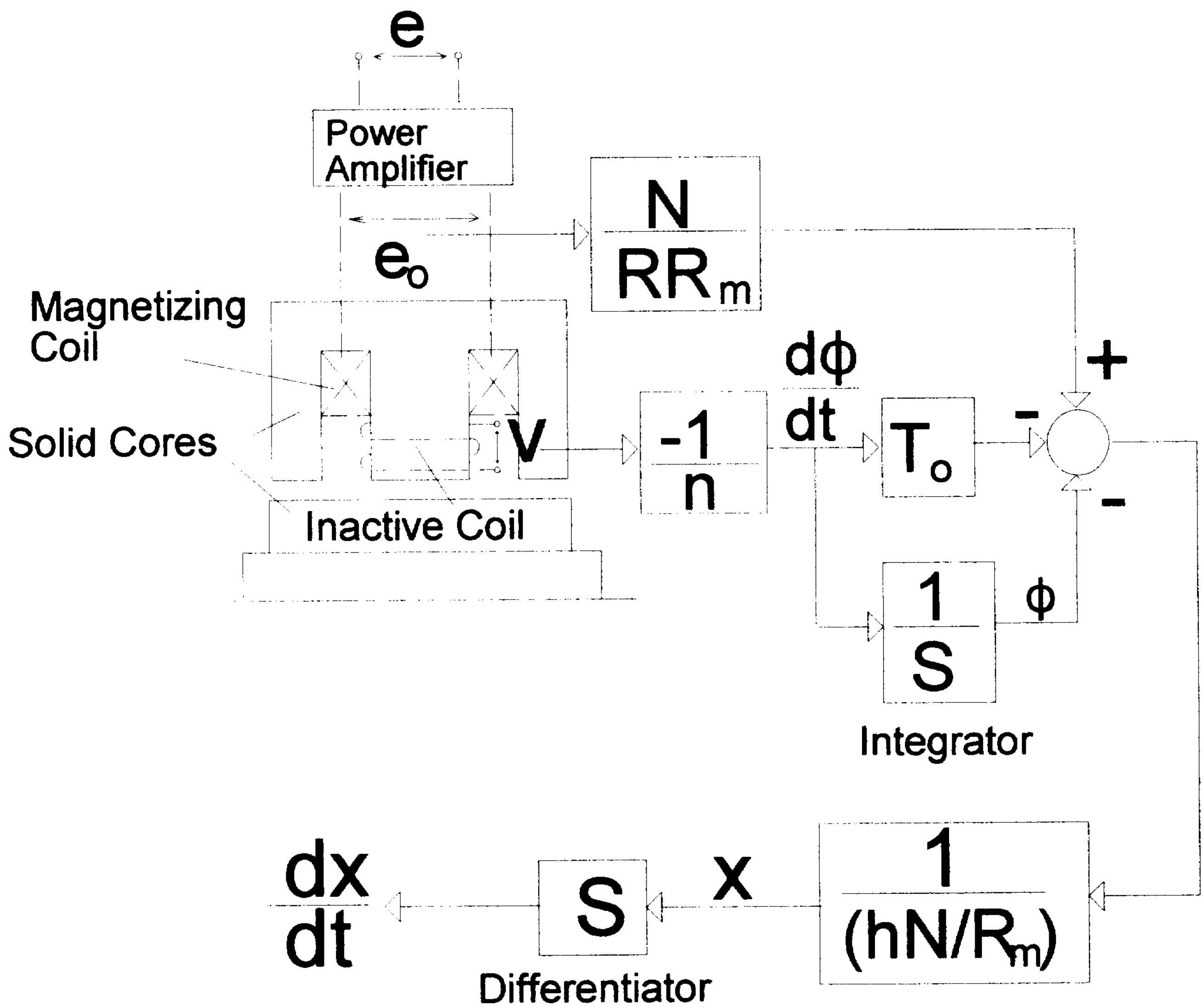

Figure 6. Velocity estimator for magnetic bearings with solid cores.

SELF-STARTER DESIGN AND SIMULATED PERFORMANCE

Contrary to what many may believe, the velocity-controlled magnetic bearings are easy to start. As shown in Figure 3, a small DC voltage V_{dc} is injected at the velocity input terminal of VFC for the startup. One should know that the VFC by itself is unstable. Its output "e" is usually saturated or latched to ± maximum output. Therefore, the output is electrically grounded before any startup. The electrical ground is then turned off simultaneously when the DC voltage is injected. The polarity of the injected voltage depends on which side of the backup bearing the rotor initially rests.

It is straight forward in designing a magnetic bearing to ensure that the rotor is made to rest on a predetermined side before its lift-off. The DC voltage is turned off after the rotor is levitated.

A transient analysis simulating the dynamics of the thrust bearing and the flywheel rotor (Figure 4) lifting off the bottom backup bearing has been performed. The rotor axial velocity was assumed to be measured directly using a velocity sensor. The rotor initially rests at the bottom backup bearing which is located at a half of the air gap below the thrust bearing center. According to the above startup procedure, a positive DC voltage of 0.010 volt is injected at the VFC input terminal. The controller will integrate the DC voltage and *kick* the rotor upward and *grab* it in the air, so to speak. The simulation result is presented in Figure 7. The results of three cases with different rotor

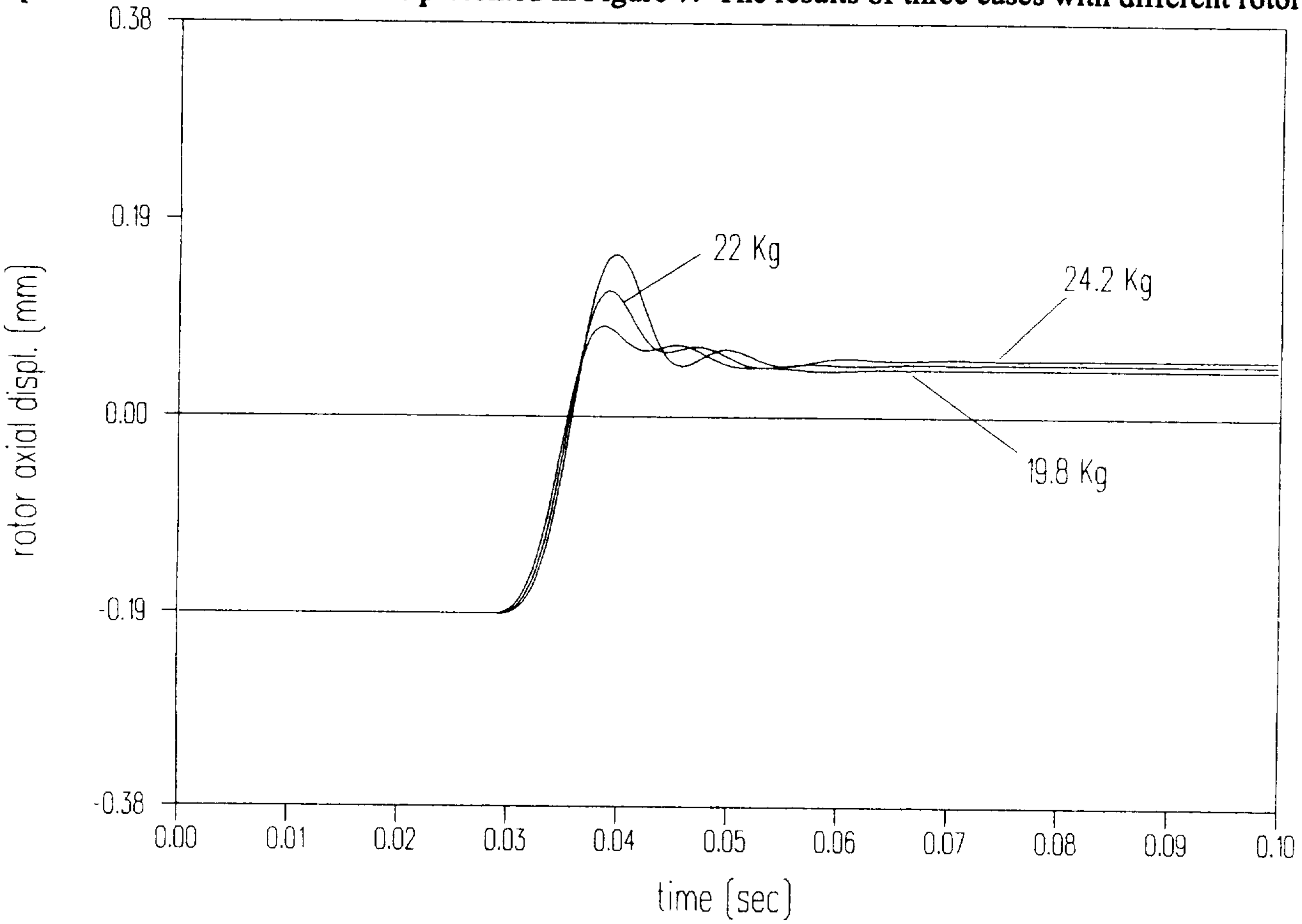

Figure 7. Rotor lift-off simulation under velocity control.

weights, i.e., 22 kg, 10% less and 10% more, are overlapped in the figure for comparison. The results indicate three remarkable aspects:

- The rotor settles above the thrust bearing center. In other words, the thrust runner is closer to the top electromagnet than to the bottom. This is due to our choice of equal bias currents for both the top and bottom coils.

- A heavier rotor would settle at a higher axial position or closer to the top electromagnet, and a lighter rotor would do the opposite. Both this and the previous result show that the rotor will settle at an axial position in the clearance where all the static forces balance each other.
- The rotor response ripples at lift-off are indicative of light damping associated with the second mode. The light damping is due to the solid core eddy current effect.

CONCLUSIONS

Magnetic bearings with solid cores, like those with laminated cores, can be controlled using velocity feedback. The control for a solid core bearing also involves three parts, i.e., Velocity Feedback Controller, Velocity Estimator and Self Starter which have independent functions and can be separately designed. The separation is intended to simplify the control design and tuning process. For the solid core bearings, the VFC is not required to have a low-pass filter and thus simpler. A dimensionless root-locus analytical procedure has been formulated to facilitate the selection of three key parameters of VFC. The VE formulation is quite different from those of laminated cores, because of the eddy-current effect. The SS design is the same as for those laminated bearings.

Finally, using a thrust bearing with solid cores as an example, it has been shown by numerical simulation how the rotor would lift off a backup bearing with the velocity controller and how it would automatically settle at a location in the bearing clearance where all the static forces on the rotor balance each other.

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