ON SELF-SENSING MAGNETIC LEVITATED SYSTEMS

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ABSTRACT

As a test-case for magnetic bearings and propulsion a 1 degree of freedom self-sensing magnetically levitated steel ball is under study. In this paper an overview of the design of a levitation system is given. It will appear that the easiest implementation of self-sensing magnetic levitation is to use a current controlled coil, and add a high frequency current to the actuating current for measuring the inductance of the coil. Therefor the voltage over the coil is demodulated using synchronous AM demodulation.

An accuracy analysis is made for 1 DOF self-sensing magnetic levitation systems. Finally, upper bounds for the accuracy of such a system are given. It will appear that self-sensing magnetic leviation cannot be used in the system it was proposed for, therefore no experimental results will be given in this paper.

1 INTRODUCTION

At the Eindhoven University of Technology, Department of Electrical Engineering, Measurement and Control Section [1], research is carried out on magnetic levitation and propulsion. Aim is a magnetically levitated and controlled mirror for the deflection system of a 3D laser interferometer. The position and orientation of this mirror must be controlled extremely accurate and fast, therefore ordinary ball-bearings cannot be used. [Bosch and Damen, 1997] To fulfil the speed requirements for the system, the mirror must be constructed as small and as light as possible, leaving virtually no place for actuator and sensor.

As a pilot-project for the 6 degree of freedom (DOF) magnetically beared and propulsed mirror, a 1 DOF magnetically levitated ball is examined. This system is depicted in figure 1. With the 6 DOF magnetically levitated mirror in mind, the possibilities to use *self-sensing* magnetic levitation [Vischer and Bleuler, 1993], [Vischer, 1988], [Vischer and Bleuler, 1990], [Mizuno and Bleuler, 1992], [Bleuler et al., 1994] are studied, because in that case no additional position sensor is necessary, which will reduce costs and space.

In self-sensing systems, the position of the object to be levitated (in this case a steel ball) is obtained by measuring the inductance of the coil, which varies depending on the position of the levitated object.

In this paper the plant is considered to be the coil together with the ball. The actuator is considered to be the voltage or current source which supplies power to the coil. (Both options are discussed.) The sensor is considered as the device or system which yields a measurement for the position of the ball. In the self-sensing implementation, the sensor covers part of the actuator, the plant and some electronics. The levitation system is the total of plant, actuator, sensor and controller.

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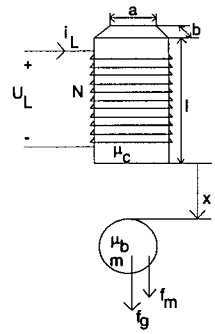

a	0.025	[m]
b	0.025	[m]
l	0.10	[m]
N	1000	
m	0.08	[kg]
r	0.01	[m]
μ_b	1000	
μ_c	1000	

Figure 1: Magnetically levitated ball.

2 DERIVING SYSTEM EQUATIONS

The physical properties of the magnetic levitation process for the ball are defined in figure 1. The system consists of a steel ball, radius $r = 1[cm]$ with relative permeability $\mu_b = 1000$ and mass $m = 80[g]$. It is levitated with an I-shaped ferrox coil with a square cross-section of $6.25[cm^2]$, length $l = 10[cm]$ and relative permeability $\mu_c = 1000$. An I-shaped coil is used to guarantee stability in all directions except the vertical. The levitated object is a ball because of it's rotation symmetry. Therefore the levitation problem under study has only 1 DOF.

2.1 DIFFERENTIAL EQUATIONS

As the system is self-sensing, the relation between the position of the ball and the inductance of the coil plays a key role. A model is fitted on measurement data of the inductance L of the coil for various distances x between the ball and the coil. For levitation of a ball with an I-shaped coil and relatively large x, L turns out to be well approximated by:

$$L = L_s + L_m(x) = L_s + L_c \cdot e^{-\frac{x}{x_c}} \tag{1}$$

For the system considered here, the model parameters are given in (2) when x is in the range 0.005...0.030[m].

$$\begin{aligned} L_s &= 102.89[mH] \\ L_c &= 4.941[mH] \\ x_c &= 7.246 \cdot 10^{-3}[m] \end{aligned} \tag{2}$$

In models for the inductance of the coil as a function of the position of the levitated object used for various other levitation systems, the induction of the coil is usually taken inversely proportional to the square of the distance between the object and the coil. [Bleuler et al., 1994] Formula (1) appeared to represent the measurement data substantially better in this application, in the given range for x. This can be explained by the fact that in this application an I-shaped coil is used, whereas in other levitation systems U or E-shaped coils are used. Apparently the scattering of the magnetic field lines cannot be neglected.

The magnetic reluctance force exerted on the ball f_m as a function of the current i_L through the coil and the position x of the ball can be calculated using the magnetic field energy W_m (assuming linear magnetic material):

$$f_m = \frac{-\partial W_m(\Phi, x)}{\partial x} \overset{\text{lin magn mat}}{=} \frac{1}{2} i_L^2 \frac{dL}{dx} \tag{3}$$

where Φ is the magnetic flux.

Substituting (1) in (3) gives:

$$f_m = -\frac{1}{2}\frac{L_c}{x_c}e^{-\frac{x}{x_c}} \cdot i_L^2 \tag{4}$$

where L_c and x_c are process parameters as defined in (2).

The voltage U_L over the coil, given a certain current through the coil i_L is given by:

$$\begin{aligned} U_L &= R_L \cdot i_L + \frac{d\Phi}{dt} \\ &= R_L \cdot i_L + \frac{\partial \Phi}{\partial i_L} \cdot \frac{di_L}{dt} + \frac{\partial \Phi}{\partial x} \cdot \frac{dx}{dt} \\ &\overset{\text{lin magn mat}}{=} R_L \cdot i_L + L\frac{di_L}{dt} + i_L \frac{dL}{dx} \cdot \frac{dx}{dt} \end{aligned} \tag{5}$$

where $\Phi = i_L \cdot L$ is again the magnetic flux and R_L is the ohmic resistance of the coil.

When assumed that the ball moves in the vertical direction only, a non-linear differential equation with the position x of the ball and the current i_L through the coil can be derived, using (4) and Newton's law:

$$m\ddot{x} = f_g - \frac{1}{2} i_L^2 \frac{L_c}{x_c} e^{-\frac{x}{x_c}} \tag{6}$$

where m is the mass of the ball and f_g is the gravitational force, given by $f_g = m \cdot g$ where g is the gravitational acceleration.

Equation (6) can be used when designing a *current controlled* system, which means that the current through the coil i_L is considered as the input of the process, and the voltage U_L over the coil as the output.

An other possibility is to design a *voltage controlled process*, which means that the voltage U_L over the coil is considered as the input of the process, and the current i_L is the output. For this equations (6) and (5) can be used.

In this example, one can see the duality between input and output for certain systems. [Willems, 1998]

2.2 TRANSFER FUNCTIONS

The non-linear differential equation (6) can be linearised in a certain operating point to obtain the linearised transfer function of the system.

For the current controlled system, the transfer function $H_i(s)$ about the operating point $(i_{L,0}, x_0)$ is:

$$H_i(s) = \frac{\Delta x}{\Delta i_L} = -\frac{\sqrt{\frac{2\frac{L_c}{x_c} g e^{-\frac{x_0}{x_c}}}{m}}}{\left(s + \sqrt{\frac{g}{x_c}}\right)\left(s - \sqrt{\frac{g}{x_c}}\right)} \tag{7}$$

A current $i_{L,0}$ is necessary to hold the plant in the operating point. This current $i_{L,0}$ is given by:

$$i_{L,0} = \sqrt{\frac{2mg}{\frac{L_c}{x_c} e^{-\frac{x_0}{x_c}}}} \tag{8}$$

When (8) is again substituted in (7), this gives the following simple equation:

$$H_i(s) = -\frac{\frac{2g}{i_{L,0}}}{\left(s + \sqrt{\frac{g}{x_c}}\right)\left(s - \sqrt{\frac{g}{x_c}}\right)} \tag{9}$$

For the voltage controlled system, the transfer function $H_U(s)$ about the operating point $(U_{L,0}, x_0)$ can be calculated by combining (6) and (5) and linearising the result. This yields:

$$H_U(s) = \frac{\Delta x}{\Delta U_L} = -\frac{2gR_L}{U_{L,0}} \cdot \frac{1}{(L_s + L_c e^{\frac{x_0}{x_c}}) \cdot s^3 + R_L \cdot s^2 + \left(\frac{4mg^2R_L^2}{U_{L,0}^2} - (L_s + L_c e^{\frac{x_0}{x_c}})\frac{g}{x_c}\right) \cdot s + R_L \frac{g}{x_c}} \tag{10}$$

Where $U_{L,0}$ is the voltage necessary to hold the process in the operating point. This voltage $U_{L,0}$ is given by:

$$U_{L,0} = R_L \cdot \sqrt{\frac{2mg}{\frac{L_c}{x_c} e^{-\frac{x_0}{x_c}}}} \tag{11}$$

When examining the linearised transfer functions given in (9) and (10) it can be observed that the current controlled plant has two poles, symmetrical round the imaginary axis. This means that the plant is open loop unstable. The position of the poles of the current controlled process does *not* depend on the operating point $(i_{L,0}, x_0)$.

In contrary to the current controlled system, the voltage controlled system has three poles, which position does depend on the operating point $(U_{L,0}, x_0)$. The voltage controlled system is open loop unstable, too.

Another observation is that the gains of the plants depend exponentially on the position of the ball. Consequently, a non linear controller using gain scheduling techniques will suite very well in this application.

Notice that the gains of the transfer functions are negative. This can be understood by the fact that when increasing the current or the voltage over the coil the distance between the ball and the coil tends to decrease.

Looking from the control point of view, it is much easier to use a current controlled process, because this system is only second order, and the position of the poles, does not depend on the operating point. Note that the last advantage may become void, if an other magnetic topology is chosen.

3 ACTUATOR AND SENSOR DESIGN

From the previous section we are left with two options: The magnetic levitation system can be either *current controlled* or *voltage controlled.* As the levitation system is *self-sensing*, the inductance of the coil is measured for obtaining an estimate for the position of the ball. The inductance can be measured in several ways. Three different manners are analysed here.

- *Measuring the oscillation frequency of an LC-oscillator*, consisting of the coil and an additional capacitor. This oscillation frequency can be measured in different ways, for example using a phase-locked loop (PLL). Three problems arise. First is that this oscillation in the voltage over the coil, and the current through the coil, must not have any influence on the (low frequency) actuating current through or voltage over the coil. Therefore this oscillation frequency must be (very) high. Second problem is that the frequency deviation Δf of the LC-oscillator is very small, because the variation of the inductance ΔL of its nominal value L_{nom} by variation in the position Δx of the levitated object is only minor. Finally, the low frequency actuating current i_L, and the high frequency inductance measurement current i_{HF} must be forced through the coil independently. This is impossible by definition when the system is voltage controlled.

- *Measuring the quality factor (Q-factor) of an LC-oscillator*, consisting of the coil and an additional capacitor. Three problems arise. The first is (again) that the oscillation frequency of the LC-oscillator must be very high. The second is that the Q-factor of the LC-oscillator not only depends on the inductance L of the coil, but also on the series resistance R_L of it. As this resistance is temperature dependent, the inductance measurement has to be compensated for temperature changes of the coil. The third problem is again that using an LC-oscillator is impossible in a voltage controlled system.

- *Measuring L with a high frequency current* with constant frequency, phase and amplitude added to the actuating current, when the system is current controlled, or with a high frequency voltage with constant frequency, phase and amplitude added to the actuating voltage, when the system is voltage controlled. The high frequency voltage over, respectively the current through, the coil is a measure for the inductance of the coil. [Sivadasan, 1996]

For the three proposed methods as described above, one can see that the first option has serious noise and accuracy problems, because the deviation ΔL of the inductance of the coil from its nominal value L_{nom} is small, and the frequency of the LC-oscillator is proportional to $\sqrt{\Delta L}$. The second suffers from temperature drift. Therefor the third option is the most suitable way to measure the inductance of the coil in this application. It will be discussed in detail in the next subsection.

Note that the inductance of the coil is measured actively, i.e. with an explicit measurement signal. This is necessary because else no distinction can be made between a constant external force on the levitated object, and a position deviation. [Vischer and Bleuler, 1993]

3.1 SENSOR

The accuracy of the inductance measurement of the coil depends on whether the system is current controlled or voltage controlled. First the inductance measurement principle, as described above, will be examined in detail for the current controlled system, and after that for the voltage controlled system.

3.1.1 Current controlled

As the coil has a certain serial resistance R_L, the high frequency voltage $U_{L,HF}$ over the coil by the high frequency current $i_{L,HF}$ with frequency ω_{HF} is not a direct measure for the inductance of the coil L, as can be seen from:

$$U_{L,HF} = (R_L + j\omega_{HF} L) \cdot i_{L,HF} \tag{12}$$

There are two ways to overcome this problem. The first is to choose ω_{HF} high, so $\omega_{HF} \cdot L \gg R_L$. This will lead to a certain (but small) error, depending on the measuring frequency ω_{HF}. However, very high frequency currents cannot be supplied to the coil, due to the high impedance of the coil at high frequencies. This will inevitably lead to noise problems.

The second solution is not to measure the amplitude of $U_{L,HF}$, but the amplitude of the voltage which is 90° out of phase with the applied current.

Equation (12) can be rewritten as:

$$\begin{aligned} i_{L,HF} &= \hat{\imath}_{L,HF} \cdot \sin(\omega_{HF} t) \\ U_{L,HF} &= \hat{U}_{L,HF} \cdot \sin(\omega_{HF} t + \phi) \\ \hat{U}_{L,HF} &= \hat{\imath}_{L,HF} \sqrt{\omega_{HF}^2 L^2 + R_L^2} \\ \phi &= \arcsin\left(\frac{\omega_{HF} L}{\sqrt{\omega_{HF}^2 L^2 + R_L^2}}\right) \end{aligned} \tag{13}$$

where t is time, $\hat{U}_{L,HF}$ is the amplitude of the high frequency voltage over the coil, $\hat{\imath}_{L,HF}$ is the amplitude of the high frequency current through the coil and ϕ is the phase lag between this voltage and current. This leads to:

$$L = \frac{\hat{U}_{L,HF} \cdot \sin(\phi)}{\hat{\imath}_L \cdot \omega_{HF}} \tag{14}$$

A phase diagram of $U_{L,HF}$, decomposed in the voltage over the inductance $U_{ind,HF}$ and its serial resistance $U_{res,HF}$, and the current through the coil $i_{L,HF}$ is given in figure 2.

This diagram shows that $U_{ind,HF}$ is always 90° out of phase with $i_{L,HF}$. When the measured voltage $U_{L,HF}$ is multiplied by $\cos(\omega_{HF} t)$ and after that is lead through a low pass filter with bandwidth $\omega_{LPfilter}$, this gives a measure for the inductance of the coil: (This is also called synchronous AM demodulation [Shanmugam, 1979])

$$\begin{aligned} U_{dem} &= \left(\hat{U}_{L,HF} \cdot \sin(\omega_{HF} t + \phi) + U_{actuating}\right) cdot \cos(\omega_{HF} t) \\ &= \frac{1}{2}\hat{U}_{L,HF} \sin(\phi) + \frac{1}{2}\sin(2\omega_{HF} t + \phi) + U_{actuating} \cos(\omega_{HF} t) \\ &\overset{low\,pass}{=} \frac{1}{2}\hat{U}_{L,HF} \sin(\phi) \end{aligned} \tag{15}$$

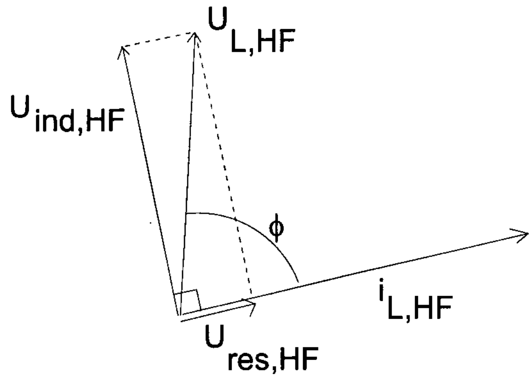

Figure 2: Vector diagram of inductance measurement signal.

Substituting (13) in (15) yields:

$$L_{measured} = \frac{\hat{U}_{L,HF} \cdot \sin(\phi)}{\hat{i}_L \cdot \omega_{HF}} = \frac{2 \cdot U_{dem}}{\hat{i}_L \omega_{HF}} \tag{16}$$

Formula (16) shows that the output voltage of the synchronous AM-demodulator is proportional to the inductance of the coil. $\hat{i}_L$ and ω_{HF} are known constants. Using relation (1) the position of the ball can be obtained.

3.1.2 Voltage Controlled

When the levitation system is voltage controlled in stead of current controlled, calculation of the relation between the output voltage of the demodulator and the inductance of the coil is slightly different. In this case it is *not* possible to measure the current which is 90° out of phase with the voltage. (See figure 2) Therefore both the amplitude and the phase of the high frequency current through the coil must be measured. (Note that $i_{L,HF}$ must be measured with a series resistor R_s)

When the voltage over the series resistance R_s is multiplied by $\cos(\omega_{HF}t)$ and after that is lead through a low pass filter with bandwidth $\omega_{LPfilter}$, this yields:

$$\begin{aligned} U_{dem} &= \left(\hat{U}_{R_s,HF} \cdot \sin(\omega_{HF}t + \phi) + U_{actuating}\right) \cdot \cos(\omega_{HF}t) \\ &= \frac{1}{2}\hat{U}_{R_s,HF} \sin(\phi) + \frac{1}{2}\sin(2\omega_{HF}t + \phi) + U_{actuating}\cos(\omega_{HF}t) \\ &\overset{low\ pass}{=} \frac{1}{2}\hat{U}_{R_s,HF} \sin(\phi) \end{aligned} \tag{17}$$

Substituting (13) in (17) gives:

$$L_{measured} = \frac{2R_s\hat{U}_s \cdot U_{dem}}{\hat{U}_{R_s,HF} \cdot \omega_{HF}} \tag{18}$$

Equation (18) shows that the output voltage of the synchronous AM demodulator is proportional to the inductance of the coil. R_s, ω and $\hat{U}_{L,HF}$ are constants. However, $\hat{U}_{R_s}$ is *not* a constant and must be measured separately. This is a serious disadvantage.

Comparing (16) and (18) suggests that the easiest way to implement self-sensing magnetic levitation is to use a current controlled system, with an additional high frequency current for measuring the inductance of the coil. Note that also from a control point of view (see section 2), it appeared that it was best to use a current controlled process.

3.2 ACTUATOR

As a high frequency current is used to measure the inductance of the coil, the current source must be able to supply this measurement current, as well as the actuating current. [2] [3] This means that the small signal bandwidth of the current source must be high.

Note that explicitly the *small signal* bandwidth is mentioned. The small signal bandwidth is defined as the highest frequency of a small signal on the input, for which the output of the current source can track the input with a maximum error of $3dB$. The large signal bandwidth of the current source is dictated by its maximum output voltage and the impedance of the coil, and is defined by the highest frequency for which the current source is able to supply its maximum current to the coil, without the output voltage clipping to its maximum.

When the current source has a high bandwidth it is likely to oscillate or suffer from excessive high frequency output voltage noise. As the output voltage of the current source is used to obtain the inductance of the coil, this is a serious problem. The output voltage noise arises from the fact that high frequency voltages over the coil, do not lead to high frequency currents through the coil (which are observable by the current source) because of the high impedance of the coil at high frequencies. Also high frequency noise on the input of the current source, is 'amplified' by the inductor.

An H_∞-controller can be designed to optimize between the tracking error of the current source for high frequencies and suppressing output voltage noise.

4 SYSTEM DESIGN

The most important property of a sensor system is its accuracy. This will be discussed for the sensor system as described in the previous section. Because the sensor is integrated in various parts of the levitation system, in this section will be discussed how various system parameters influence the sensor performance.

- The frequency ω_{HF} of $i_{L,HF}$ must be high. This has two reasons. The first is to avoid influence of this current $i_{L,HF}$ on the object to be levitated. The other is that the position of the ball is modulated on this high frequency. To avoid aliasing, the frequency ω_{HF} of the additional inductance measurement signal must be at least:

$$\omega_{HF} \geq 2 \cdot \omega_s \tag{19}$$

  where ω_s is the highest frequency of the controlled mechanical system. Of course, demodulation is easier and noise by the actuating current is less when ω_{HF} is chosen even higher than $2 \cdot \omega_s$.

- The amplitude $\hat{i}_{L,HF}$ of the inductance measurement current. This current cannot be arbitrary large [4], for obtaining a better signal to noise ratio for the inductance measurement, because the impedance of the coil is very high at high frequencies. Thus the current source is not able to supply high currents with high frequency to a coil.

- The bandwidth of the low pass filter $\omega_{LPfilter}$ in the demodulator must be as small as possible, to avoid as much noise from the *modulated* actuating current as possible. However, the bandwidth $\omega_{LPfilter}$ must be at least:

$$\omega_{LPfilter} \geq \omega_s \tag{20}$$

[2] *Of course, two separate current sources can be used, one for supplying the low frequency, high power actuating current, and one for the high frequency, low power measurement signal. However, the bandwidth of the current source for the actuating current still must be high to show a sufficiently high output impedance, which gives the same design criteria as in the case that one current source is used.*

[3] *The fact that a low frequency current, and a high frequency current must be supplied through the coil, might suggest that a switched current source (e.g. a PWM motor driver) can be used. However, this is not the case, because the resistance of the coil influences the (unstabilised) high frequency measurement current through the coil. As the resistance of the coil is temperature dependent, this will give problems.*

[4] *As the magnetic reluctance force f_m is proportional to i_L^2, the measurement current gives a constant bias force. Note that this bias force does* not *depend on the value of actuating current i_L. This constant force can not be compensated for by the actuating current, because only positive forces can be exerted on the ball. Two coils [Vischer and Bleuler, 1993] can be used to solve this problem.*

When the bandwidth of the low pass filter $\omega_{LPfilter}$ satisfies (20), the complete spectrum of the mechanical system can be measured at the output of the demodulator.

- The influence of the actuating current on the signal to noise ratio can be decreased by placing a low-pass filter H_{act} after the output of the controller, with bandwidth $\omega_{act-filter} = \omega_s$. However, this filter cannot have infinite steepness. Thus the part of the actuating current in the inductance measurement band is modulated by the demodulator. This gives errors in the inductance measurement.
- The ratio $\frac{\Delta L}{L_{nom}}$, where ΔL is the maximum deviation of the inductance of the coil about its nominal value L_{nom} by variation of the position Δx of the ball. Although, in most cases this parameter cannot be chosen by the designer, but is a result of other design constraints, it does have a major impact on the signal to noise ratio of the inductance measurement.

  When possible, the variation of the air gap (and so the inductance of the coil) due to variation of the position x of the ball must be as large is possible. This is the case when using E or U-shaped coils.
- Up to now, in this paper magnetic saturation is neglected. However, the accuracy of the sensor deteriorates seriously when the magnetic material of the coil or the ball saturates, as inductance of the coil then depends not only on the position of the ball x but also on the current i_L through the coil.
- Also magnetic hysteresis is neglected in this paper. Because of the high frequency inductance measurement current through the coil, hysteresis effects are reduced.

The disturbance of the position measurement by the actuating current through the coil expressed in the process parameters described above, can be approximated by:

$$(SNR)_{sensor} = \frac{\hat{\imath}_{HF} \cdot \frac{\Delta L}{L_{nom}}}{\Delta i_{L,max} \cdot H_{act}(\omega_{HF})} \tag{21}$$

where the signal to noise ratio $(SNR)_{sensor}$ is expressed as the full scale signal amplitude divided by the amplitude of the disturbance, $i_{L,max}$ is the maximum actuating current, $H_{act}(\omega_{HF})$ is the attenuation of the actuating current at the inductance measurement frequency by the low-pass filter at the output of the controller, $\hat{\imath}_{HF}$ is the amplitude of the measurement current and ΔL is the maximum deviation of the inductance from is nominal value L_{nom}.

5 ACCURACY BOUNDS

For the ball levitation process under study, equation (21) can be used to calculate the accuracy of the sensor. From (2) and (8) the following system parameters can be calculated, assuming the operating point x_0 to be $0.005[m]$, and $\Delta i_{L,max}$ to be approximately $1[A]$:

$$\begin{aligned} L_{nom} &= L_s + L_m(x_0) = 105.4[mH] \\ \Delta L &= L_{m,max} - L_m(x_0) = 2.5[mH] \\ \Delta i_{L,max} &\approx 1[A] \end{aligned} \tag{22}$$

When assumed that $\omega_s = 628[rad/sec]$, $\omega_{HF} = 6280[rad/sec]$ and the amplitude of the measurement current $\hat{\imath}_{L,HF}$ is $10[mA]$ (This gives $\hat{U}_{L,HF} \approx 6.2[V]$) and that the filter at the output of the controller gives a damping of $80dB$ at ω_{HF} (Fourth order low pass filter, considering ω_s) This gives:

$$(SNR)_{sensor} = \frac{10 \cdot 10^{-3} \cdot \frac{2.5 \cdot 10^{-3}}{105.4 \cdot 10^{-3}}}{1 \cdot 0.0001} \approx 2.75 \approx 8.7dB \tag{23}$$

Equation (23) shows that the position accuracy of the self-sensing magnetically levitated ball is not very good.

Upper bounds for the accuracy of self-sensing magnetic levitation can easily be derived. When using E or U-shaped coils [5] the factor $\frac{\Delta L}{L_{nom}}$ can be close to 1. Furthermore when using a very good current source, with high output voltage capability [6] is used, the amplitude of the measurement current $\hat{i}_{L,HF}$ can be as large as 3% of the maximum actuator current $i_{L,max}$ through the coil. The damping of the actuating current at the measuring frequency is assumed to be $80dB$. This gives as upper bound for the signal to noise ration $(SNR)_{max}$:

$$(SNR)_{max} = \frac{3 \cdot 10^{-2}}{0.0001} = 300 \approx 50dB \tag{24}$$

The bound for the signal to noise ratio, indicated by (24), shows that self-sensing magnetic levitation cannot be used for very accurate positioning systems. However, for application where the exact position of the levitated object is not important, for example momentum wheels for energy storage or magnetically levitated trains, self-sensing magnetic levitation is a cheap and robust option.

6 CONCLUSIONS

The total design of a self-sensing magnetic levitation system has been discussed. It appeared that the easiest way to implement self-sensing magnetic levitation is to use a current controlled system, and an extra high frequency current for the inductance measurement. The high frequency voltage by this measurement current can be demodulated using a synchronous AM-demodulator, to obtain a measure for the position of the ball.

The accuracy of the sensor depends on various system parameters, for example the value of the high frequency current and the maximum deviation of the inductance from its nominal value by variation in the position of the levitated object. Saturation of the magnetic material of the coil and the ball must be avoided. Hysteresis effects are reduced by the high frequency measurement current through the coil.

A self-sensing sensor system can definitely not be used for the magnetically levitated mirror for the laser deflection system, as described in section 1. However, it can be used for application where the exact position of the levitated object is less important.

7 ACKNOWLEDGEMENTS

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[5] *The levitated object is then no longer damped in horizontal direction. Therefore the object needs to be controlled actively in the horizontal plane, too. Obviously, this complicates the design of the levitation system considerably.*

[6] *High output voltage capability leads to high power dissipation in the current source. A switched current source cannot be used, because the high frequency inductance measurement current must be supplied to the coil accurately.*

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