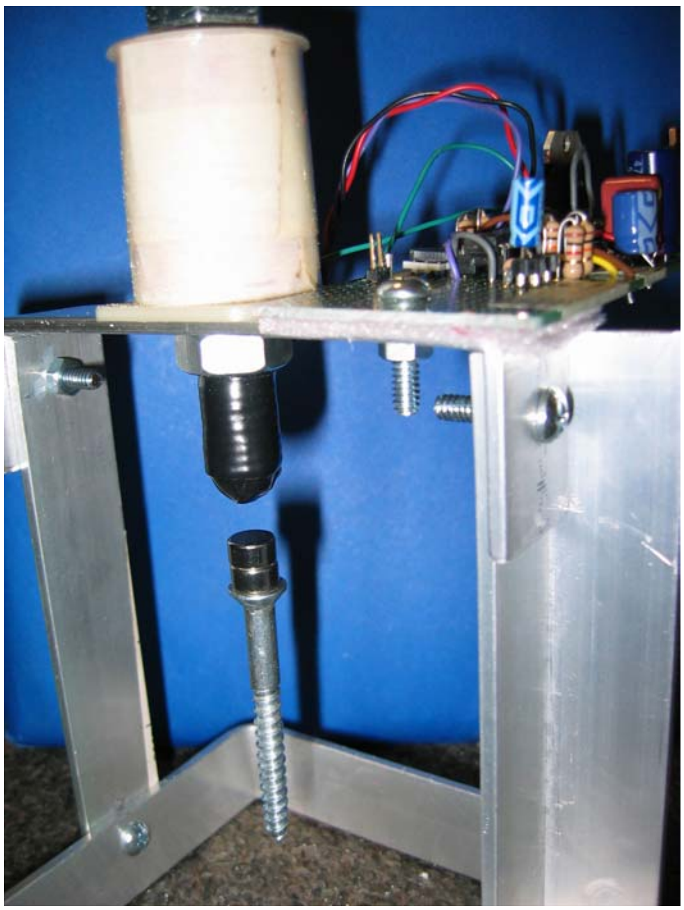
6.302 Design Project

Magnetic Levitation System



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Characterizing the Basic Model:

I began by building the basic model of a feedback controlled magnetic levitation system as pictured below. This allowed me to then make measurements and observations which gave insight into the fundamental properties of the uncompensated system.

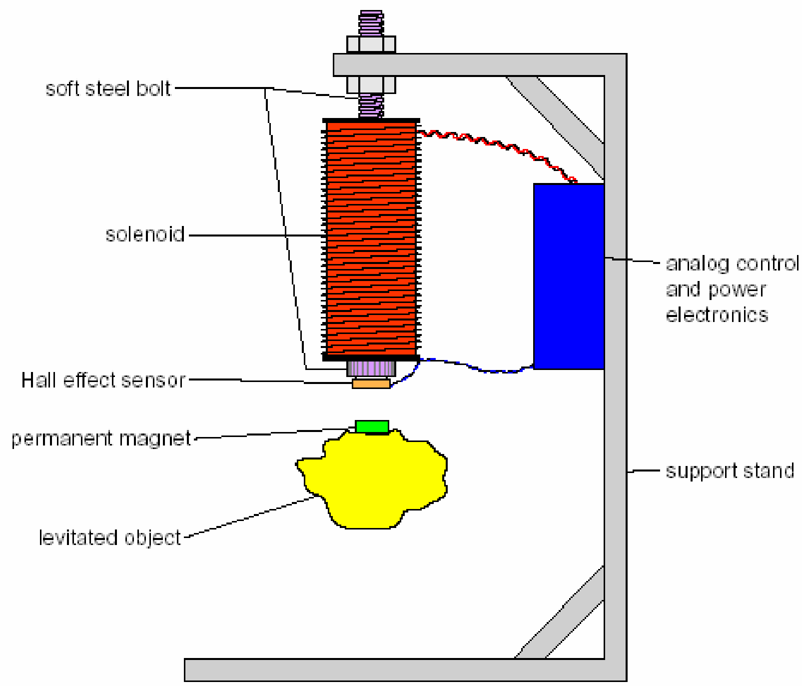
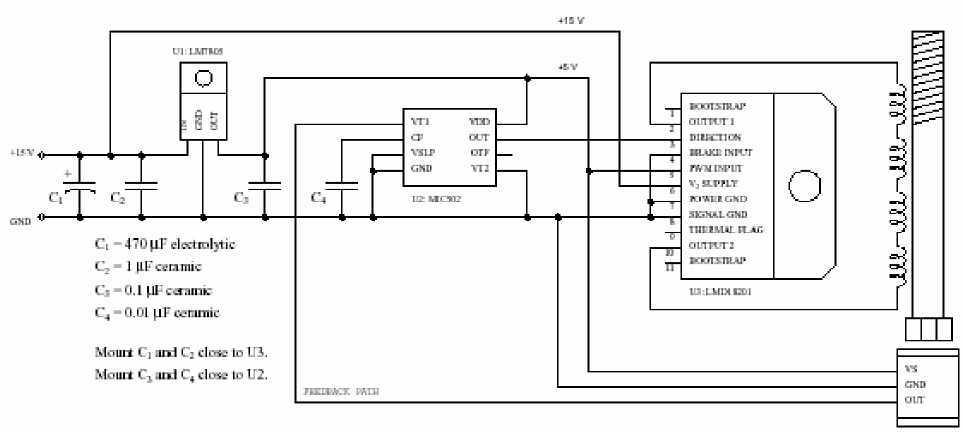
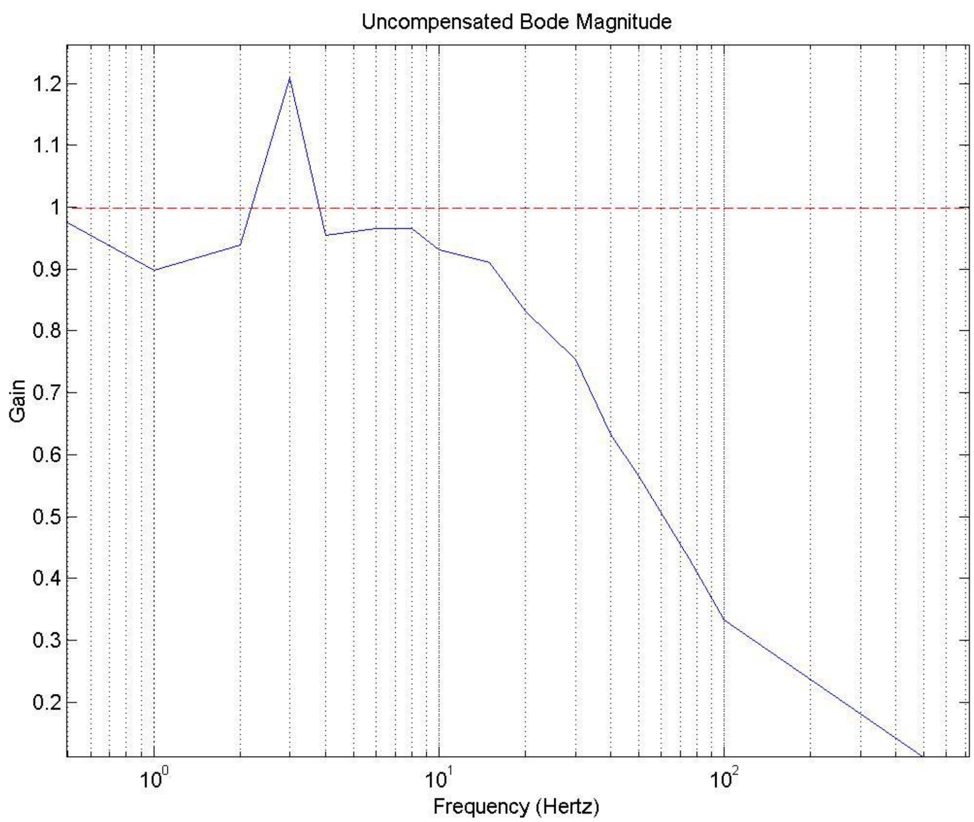


Figure 1: An assembled magnetic levitation system

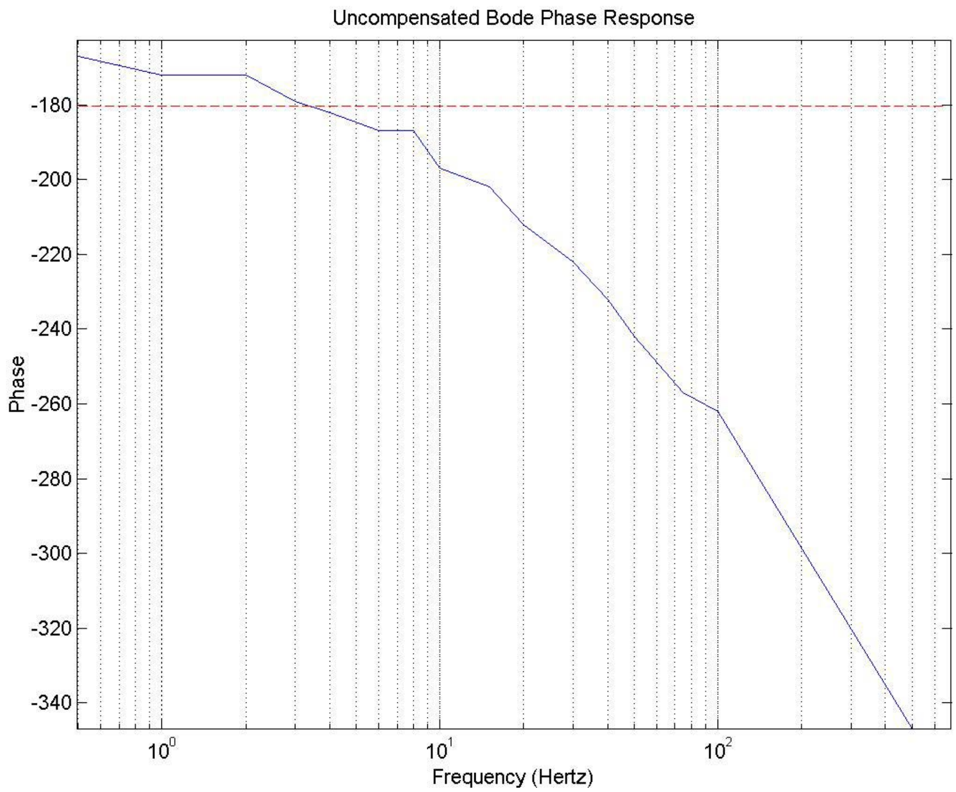


Layout of basic model given in 6.302 Maglev Project Description.

After realizing first hand that the system was in fact unstable, I incorporated an adder into the feedback path so that I could drive the system with an input and try to characterize it by its output. To do this, an inverting adder was built using ¼ of an LM348 OPAMP in which one of the inputs was the voltage from the hall effect sensor and the other was the voltage input used for testing. I drove the system with a small amplitude sinusoidal signal and recorded the gain and phase shift at the output. This allowed me to generate a bode magnitude and phase plot as shown below.



Crossover frequency is approximately 3.8Hz = 23.9 rad/sec
Peak Magnitude is approximately 1.22



Phase Crossover frequency is approximately 3.5Hz = 22.0 rad/sec

From the above plots the problem can be clearly seen. Since the phase of the output at crossover is slightly more negative than -180 degrees, the system is not stable. While the phase margin at the crossover frequency may only be negative by a couple degrees, it can slowly push the system out of control via sinusoidal amplitudes that are exponentially increasing.

Freq. (Hz)	Gain	Phase
0.5	0.897	-167
1	0.826	-172
2	0.863	-172
3	1.112	-179
4	0.878	-182
6	0.888	-187
8	0.888	-187
10	0.857	-197
15	0.837	-202
20	0.765	-212
30	0.694	-222
40	0.582	-232
50	0.52	-242
75	0.398	-257
100	0.306	-262
500	0.102	-347

Measured raw data.

Changes Made to the Basic System:

1. Over Temperature LED: Using the Thermal Flag Output pin on the LMD18201 H-Bridge chip, an LED and a resistor connected to +5 Volts, I was able to create a user warning light that comes on when the H-Bridge chip is about to overheat. This does not affect the performance of the system and was done purely as a precautionary measure while testing.
2. Bolt Orientation and Shape: To keep the levitated object from being attracted to the area of the Solenoid bolt not covered by the hall effect sensor, I decided to flip the bolt 180 degrees from the suggested orientation. I also turned the bolt on a lathe to shave down the threads on the tip such that the hall effect sensor would cover almost the entire bottom surface.
3. OPAMP Adder: An inverting adder was made using ¼ of an LM348 OPAMP to allow a user input for testing and to increase the system's overall usefulness. In case another hall effect sensor or other sensing device is desired, an extra input to the adder was also included.
4. Variable Gain Inverter: Directly after the adder a variable gain inverter was implemented to keep the magnetic field readings of the correct polarity. This was done using another quarter of the LM348 OPAMP.
5. Levitated Object: I decided to use an object with a center of mass directly below the magnets when held in the desired vertical orientation. For testing I used a 2.5" long steel screw.
6. Power Supply: To accommodate the OPAMP, a new negative 15 Volt power supply was added.
7. The Compensator: Since one of the main reasons for the system being unstable was the slight negative phase margin, I decided to use lead compensation to push the phase margin positive and increase the crossover frequency.

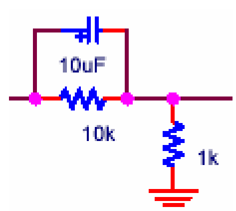
   The Lead Compensator takes on the form as follows:

$$\frac{\alpha\tau \cdot s+1}{\tau \cdot s+1}$$

   For the given maglev system, I chose α **=11** and $\tau = \frac{1}{\omega_{c+}\sqrt{10}}$. Since we

are mostly concerned with increasing the phase around 3.8Hz and we would like to set ω_{c+} > 3.8Hz, a value of approximately 6Hz (37.7 rad/sec) is a good place to start.

Putting this into the equation for τ we get $\tau = \frac{1}{37.7 \cdot \sqrt{10}} = \mathbf{8.388} \times 10^{-3}$**.** To implement the Lead compensator, I used a 10k resistor in parallel with a 10uF capacitor which then led to a 1k resistor to ground.

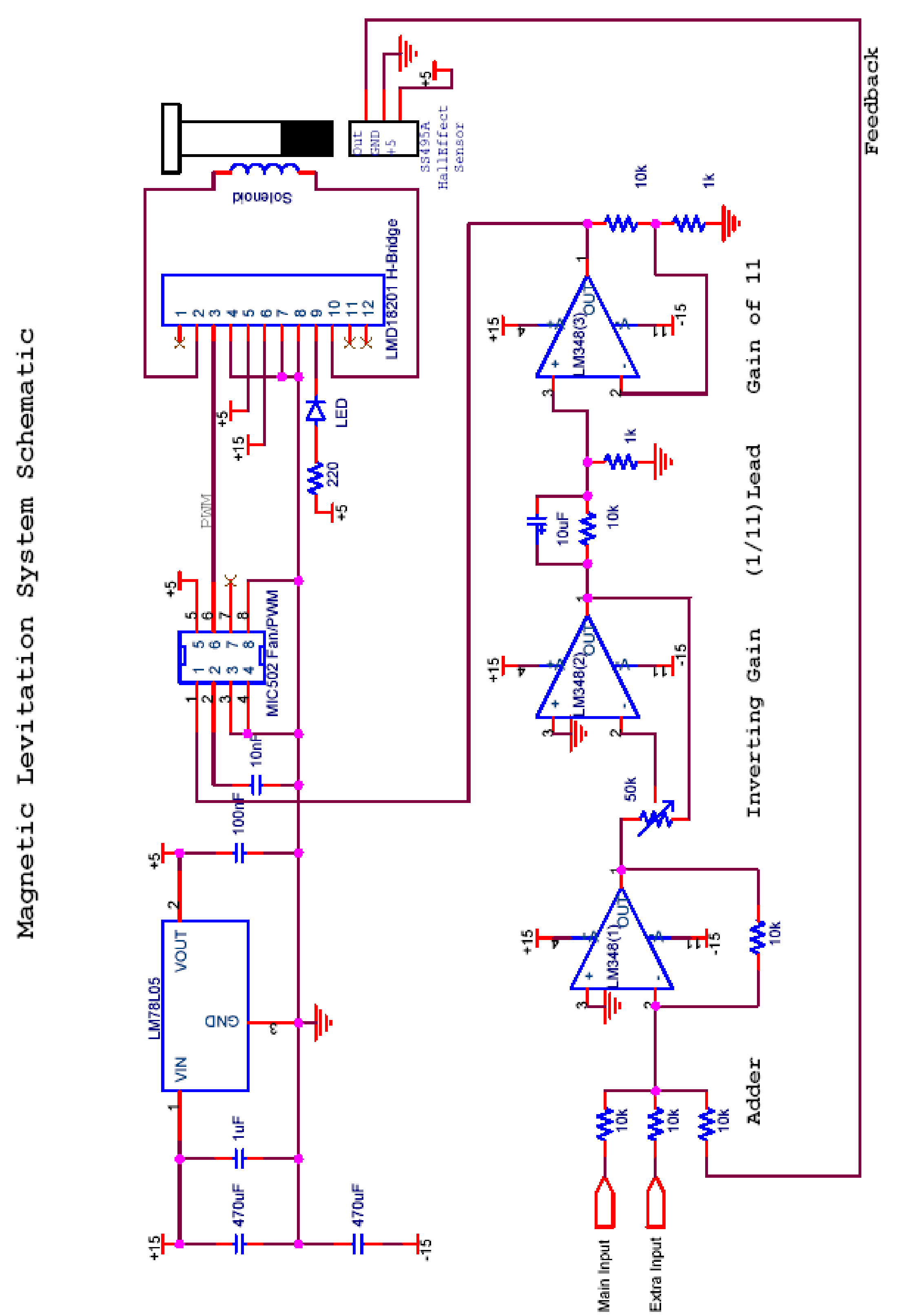


This gives a transfer function of:

$$\frac{1}{\alpha} \cdot \frac{\alpha\tau \cdot s + 1}{\tau \cdot s + 1}$$

This is very close to what is desired. The main drawback is the attenuation factor of $\frac{1}{11}$. To negate this effect, a non-inverting amplifier with a gain of 11 was added to the output of the lead network. Another section of the LM348 OPAMP was used along with two more resistors to achieve the desired gain.

Schematic:



Magnetic Levitation System Schematic
Solenoid
SS495A
HallEffect
Sensor
Out
GND
+5
Feedback
LMD18201 H-Bridge
LED
220
PWM
MIC502 Fan/PWM
10nF
100nF
LM78L05
VIN
VOUT
GND
1uF
470uF
470uF
+15
-15
+5
LM348(1)
LM348(2)
LM348(3)
OUT
10k
1k
10uF
50k
Gain of 11
(1/11)Lead
Inverting Gain
Adder
Main Input
Extra Input

Compensated System Behavior:

The lead compensated system with proportional gain performs quite well. With C_{lead} =10uF and Gain=11.25, the Magnetic Levitation system is stable at rest and dampens small perturbations in the vertical axis very quickly. The bode response looks very similar to before with a few small changes. The magnitude is shifted upward due to the gain and further increased by a factor of 11 at frequencies about one decade above the ω_{c+} = 6Hz (37.7 rad/sec). However, the main difference comes in the form of a phase increase around the crossover frequency. It is this extra phase from the lead compensator that allows the uncompensated system to become stable. While it is very tough to measure the Damping ratio accurately, it appears to be very close to $\zeta = 0.5$. This is very reasonable and much improved as compared to the uncompensated system.

There is still something substantial to be desired. If the perturbations or resonances within the mass cause it to oscillate in the plane normal to the vertical axis, the hall effect sensor cannot measure it. Additional magnetic field sensors or light gates are a possible area for future compensation to help tame these currently undetectable, unstable modes.

References:

1. "Lab 3 Maglev Project", MIT 6.302 website: http://web.mit.edu/6.302/www
2. Control Systems Theory - Gould, Markey, Roberge, Trumper. ©1997
3. LMD18201 Datasheet – National Semiconductor
4. MIC502 Datasheet – Micrel
5. SS490 Datasheet – Honeywell
6. "Levitation" – Marsden, Guy,

   website: http://web.mit.edu/6.302/www/Levitation.pdf