SWARTHMORE COLLEGE

PROPOSAL AND PLAN

SIMULTANEOUS LEVITATION & POWER BY INDUCTION

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E90: SENIOR DESIGN PROJECT
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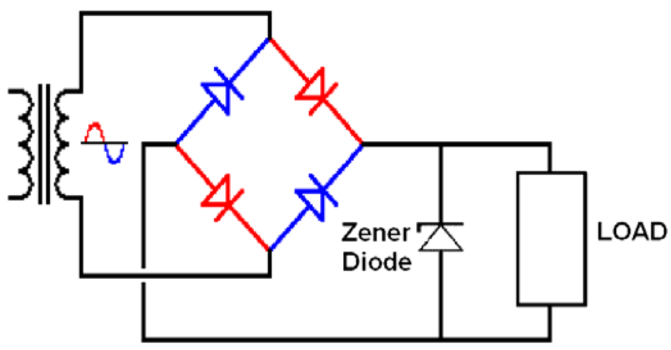
ABSTRACT

The goal of this project is to simultaneously levitate and power an autonomous device in a controlled manner. The system of particular interest—a conductive ring, driven by a solenoid—could be used to power machinery mounted on the ring without the means of an onboard power supply. This induced power is supplied by the stored momentum of the magnetic field generated by the solenoid when the field is altered. The induced current in the ring can be rectified and used to run electrical components on the ring itself, without the added weight of a battery. Thus, the design of this control unit could lead to the eventual design of a circuit that can run automatically from induced power, and could be controlled to move in three dimensions by adjustment of feedback controlled electromagnets.

INTRODUCTION

Applications for an autonomous levitation system range from design of small sensor devices to explore tight spaces such as vertical pipes or ducts where defects must be mapped, to uses as discrete surveillance systems. Expansion of the idea to a three-dimensional control system could be advantageous to applications requiring minimal friction and as in bearings or transport systems. Indeed, current magnetic levitation train technologies rely on three expensive methods of levitation and propulsion which could be somewhat curbed by more efficient use of energy. EDS (*Electrodynamic Suspension*)-type Mag-Lev's rely on superconducting materials which require constant cooling by heavy, expensive liquid helium refrigeration systems in order to maintain perfect conductivity. Permanent magnet systems such as the *Inductrack* rely on a passive magnetic field but can only achieve levitation at high speeds. These systems must also use an external propulsion system to move and guide the train. EMS (*Electromagnetic Suspension*) trains are the in most widespread use and rely on feedback controlled electromagnets to both levitate and propel the train. These require high currents but have the advantage of supplying continuous levitation and providing propulsion. Simultaneous power by induction could allow for more efficient use of the energy required to run this type of train allowing onboard electronics formerly run by heavy auxiliary battery systems to use the power typically lost during the levitation process.

Difficulties arise in control of such a system due to the intrinsic nonlinearity of the repulsive force with respect to supplied current, and the nonlinear relation to the induced current and position of the suspended device. The latter case can easily be accommodated to supply an onboard chip with power through use of zener diode (within a certain tolerance of position). Position control can be accomplished by feeding back the intensity of an IR LED or radio antenna powered on the suspended loop (included in the LOAD in the figure to the right) to a sensor driven state estimator connected to the electromagnet. The equations of motion relating the levitation force to the input to the magnet can be linearized about an equilibrium point and the appropriate state estimator implemented.



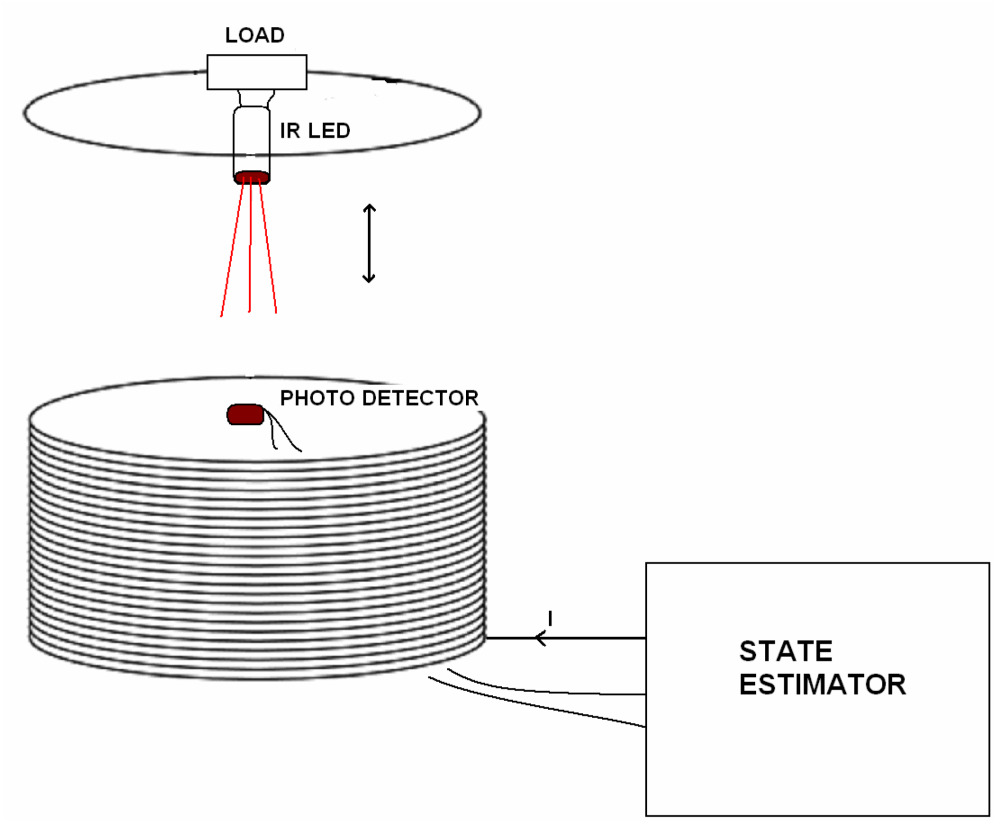


Fig.1: Photoelectric Position Feedback System in Proposed Levitation Device.

Another consideration is the fact that the ring rests in astable equilibrium with respect to its horizontal degrees of freedom. This might require a counterweight or a multi-solenoid solution but also allows for the possibility of designing a multi-dimensional control system.

QUALIFICATIONS

I am a double major in Physics and Engineering at Swarthmore College. As such I have knowledge of possible in energy conversion techniques and ideas for application. In this case magnetic to electrical. I also have interest in control and have already modeled and simulated a usable feedback such a system for the controlled levitation device as mentioned above.

TECHNICAL OVERVIEW

I. The Equations of Motion:

This treatment will only cover the motion of the ring in one dimension. I will derive the equations of motion for the system by balancing the gravitational force on the ring with the force that arises from the magnetic field of the solenoid. We will find that these equations are highly nonlinear which can be converted into a set of state variables and then linearized using standard techniques[1].

The device, which is shown below, consists of a conductive ring with radius r_{ring} and resistance R_{ring} displaced a distance Z above a solenoid of N turns with radius R_{sol} and current i_{sol} running through it:

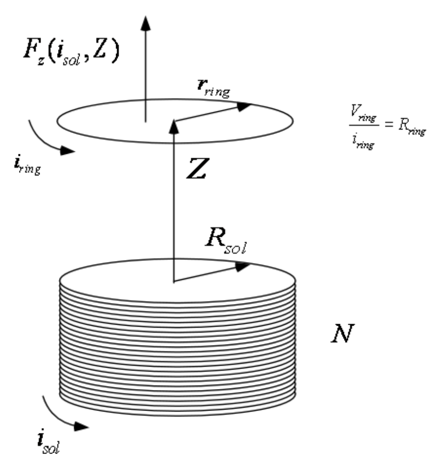


Fig.2: The system. A current $i(t)$ is driven through the solenoid. This current will produce a force F_z on the ring that is proportional to the current and to the height Z of the ring itself.

[1] Phillips and Harbor, Ch. 10.

We begin by defining the force on the ring by using the Lorentz Force Law, which states that the repulsive force on a unit with a current *I* due to a magnetic field $\vec{B}$ is given by:

$$\vec{F} = \oint I\left(dl \times \vec{B}\right) \tag{1}$$

The total force on the ring will then be the integral of the Lorentz law (1), applied to some differential length dl in the ring. We know from symmetry that the net force must be in the $\hat{z}$ direction: all other components will cancel out when we take the integral around the loop. From (1) above we get:

$$F_z = \oint dl \cdot I_{\hat{\theta}} \cdot B_r \tag{2}$$

where we have taken the scalar components of the vector quantities $\vec{B}$ and $I_{\hat{\theta}}$ as we are only interested in one component of each (we set $B = B_{\hat{r}}$ and $I = I_{\hat{\theta}}$). We find that the current and the magnetic component are symmetric around the loop, so the integral is becomes trivial, and we get:

$$F_z = 2\pi r \cdot I_{ring} \cdot B_r \tag{3}$$

Now, we can use the geometry of the system to find B_r. We take as a control volume a cylinder the size of the ring, with radius r, and some differential height dz:

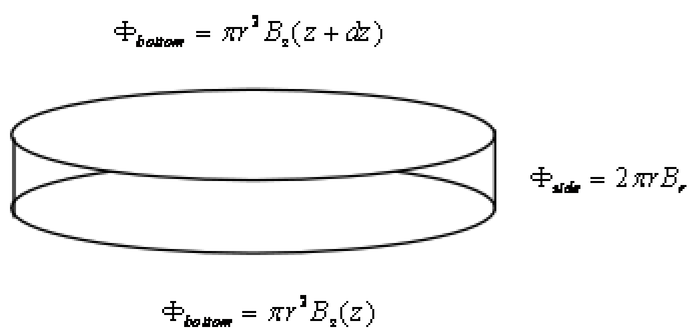


Fig.3: The flux diagram for the cylindrical control volume. We see that the total flux must be equal to zero, so the flux lost through the sides must be the net flux gained through the top and bottom.

We must have a total flux equal to zero in our control volume, since it only contains empty space. We know we gain some flux through the bottom, lose some through the top, and also lose some through the sides. We have expressed these values above as a product of the magnetic flux density and the surface area. By setting the total flux equal to zero to satisfy this continuity condition, we get:

$$0 = 2\pi r B_r - \pi r^2 \frac{\partial \vec{B}}{\partial z} \tag{4.a}$$

which simplifies to:

$$B_r = \frac{-r}{2}\frac{dB_z}{dz} \tag{4.b}$$

Then,

$$F_z = -\pi r^2 \cdot I_{ring} \cdot \frac{dB}{dz} = -\pi r^2 \cdot \frac{dB}{dz} \cdot \frac{V_{ring}}{R_{ring}} \tag{5}$$

where V_{ring} is the induced EMF in the ring, which is given by Faraday's Law:[2]

$$\begin{aligned} V_{\text{EMF}} &= -\frac{d\Phi}{dt} = -A \cdot \frac{dB_z}{dt} \\ &= -\pi r^2 \mu_0 N \frac{R_{sol}{}^2}{\left(R_{sol}{}^2 + Z(t)^2\right)^{-3/2}} \cdot \frac{di_{sol}(t)}{dt} \end{aligned} \tag{6.a}$$

where N is the number of windings in the solenoid and where we have assume that Z *(t)* does not change appreciably in time. Thus, the simple result for the induced voltage is

$$V_{\text{EMF}} = -\frac{K}{\left(R_{sol}{}^2 + Z(t)^2\right)^{-3/2}} \cdot \frac{di_{sol}(t-\theta)}{dt} \tag{6.b}$$

where K is a constant lumping up the messy system parameters and theta is some phase lag owing to the self inductance of the ring (we will return to this later).

We also need an expression for $\frac{dB_z}{dz}$, for which we get[3]:

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[2] Griffiths
[3] Griffiths

$$\frac{dB_z}{dz} = \frac{\partial}{\partial z}\left[\frac{\mu_0 i_{sol}(t)N}{2}\frac{R_{sol}{}^2}{\left(R_{sol}{}^2 + Z(t)^2\right)^{3/2}}\right] = -\frac{C \cdot Z(t) \cdot i_{sol}(t)}{\left(R_{sol}{}^2 + Z(t)^2\right)^{5/2}} \tag{7}$$

where we have again grouped constants into C for brevity. Plugging (6) and (7) back into (5), we get:

$$\begin{aligned} F_z &= \frac{2\pi}{R_{ring}}\frac{K}{\left(R_{sol}{}^2 + Z^2\right)^{-3/2}}\frac{C \cdot Z(t)}{\left(R_{sol}{}^2 + Z(t)^2\right)^{5/2}} i_{sol}(t) \cdot i'_{sol}(t-\theta) \\ &= D\frac{Z(t) \cdot i_{sol}(t) \cdot i'_{sol}(t-\theta)}{\left(R_{sol}{}^2 + Z(t)^2\right)} \\ &\approx \frac{D \cdot i_{sol}(t) \cdot i'_{sol}(t-\theta)}{Z(t)} \end{aligned} \tag{8}$$

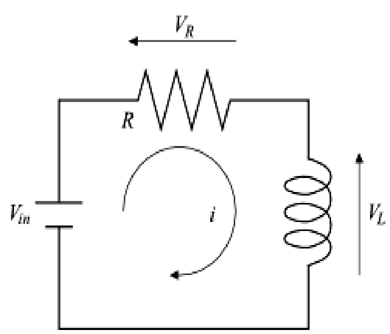
where we have assumed in the last approximation that the distance *Z(t)* above the solenoid is much larger than the radius of the solenoid itself.

We can now find the equations of motion by using Newton's First Law ($F = m\ddot{Z}(t)$). We assume that the only forces acting on the system are gravity and the Lorentz Force, so we wind up getting:

$$m\ddot{Z} = \frac{D \cdot i(t) \cdot i'(t-\theta)}{Z} - mg \tag{9.a}$$

Or

$$\boxed{\ddot{z} = \frac{D}{m}\frac{i(t) \cdot i'(t-\theta)}{Z} - g} \tag{9.b}$$



The derivative term can be misleading here in that the force is not generated by the current of the solenoid; rather, it is generated by the opposing magnetic fields of the ring and the solenoid (which has an *i(t)* dependence) and the ring (which is dependent on the derivative of *i(t)*). The phase lag θ is included here to indicate that the opposing magnetic field of the ring is not necessarily instantaneously induced by the oscillating magnetic field of the solenoid. In fact the ring itself is an inductor and will introduce this phase lag between the generated current and the induced EMF generated by the solenoid current. We can use a simple RL circuit to model this. Notice that the average force is zero unless the field generating current, i_{sol}, is in phase with the induced current's derivative.[4] We can use the self-impedance relationship for the ring to find the phase lag of induced current's derivative in terms of the EMF voltage generated by i_{sol}:[5]

$$i'_{sol}\left(t-\theta\right)=i'_{ring}\left(t\right)=\frac{1}{L}\left(V_{\text{EMF}}\left(t\right)-R\cdot i_{ring}\left(t\right)\right) \tag{10}$$

where R is the resistance of the ring and L is its self-inductance. Taking the Laplace Transform and solving for the transfer function of the derivative we get:

$$T(s)=\frac{1}{R}\cdot\frac{s}{\left(\frac{L}{R}s+1\right)} \tag{11}$$

If we assume a load of 100 kOhms and an inductance of 1 mH we get the following Bode plot:

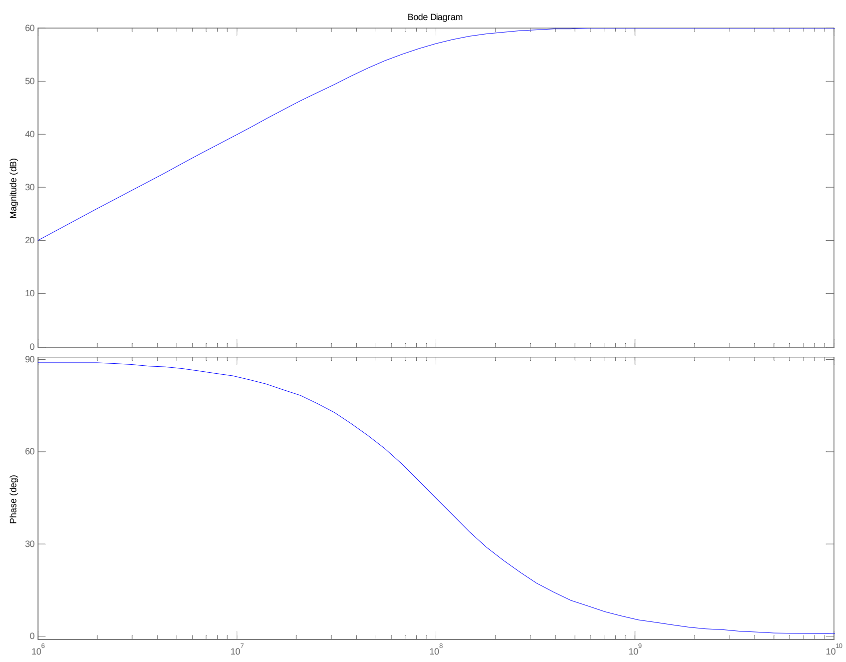


Fig.4: Bode Plot of Current thorough Levitation Ring.

[4] Notice that for any periodic waveform such as a sinusoid, the derivative is 90° out of phase. Thus the average of the signal times its derivative must be an odd function with average zero.
[5] Purcell

where we can see that the phase only approaches zero when the circuit is driven an order of magnitude greater than the pole frequency L/R (in this case 10^8 rad/sec) where it also approaches its maximum gain. Thus, experimentally it appears that the induced force is proportional to the square of the amplitude of the supplied solenoid current over the height of flotation for high driving frequencies with respect to L/R.:

$$\boxed{\ddot{z} \approx k\frac{i^2(t)}{mZ} - g} \tag{9.c}$$

II. Control:

We now must make state substitutions that will allow us to linearize the system. We choose:

$$\begin{aligned} &u(t) = V(t) \\ &x1 = Z \\ &x2 = \dot{Z} \\ &x3 = i = u(t)/R \end{aligned} \tag{12}$$

By inspection

$$\dot{x}1 = x2$$

Plugging in (9) and (10) to the state equations, we find that

$$\begin{aligned} &\dot{x}2 = \frac{D}{m}\frac{x3\cdot\dot{x}3}{x1} - g \\ &\dot{x}3 = \frac{1}{L}\left(u(t) - R\cdot x3\right) \end{aligned} \tag{13}$$

We can use the bottom the second equation in (12) to substitute for the x3dot term in the expression for x2dot. Now, summarizing our results, we can write:

$$\begin{aligned}
\dot{x}1 &= f_1 = x2 \\
\dot{x}2 &= f_2 = \frac{D}{mL}\frac{x3\cdot\left(u(t)-R\cdot x3\right)}{x1} - g \\
\dot{x}3 &= f_3 = \frac{1}{L}\left(u(t)-R\cdot x3\right)
\end{aligned} \tag{14}$$

Now, to linearize the system about some equilibrium, we set the A coefficient matrix equal to:

$$\underline{A} = \begin{pmatrix} \frac{\partial f_1}{\partial x_1} & \frac{\partial f_1}{\partial x_2} & \frac{\partial f_1}{\partial x_3} \\ \frac{\partial f_2}{\partial x_1} & \frac{\partial f_2}{\partial x_2} & \frac{\partial f_2}{\partial x_3} \\ \frac{\partial f_3}{\partial x_1} & \frac{\partial f_3}{\partial x_2} & \frac{\partial f_3}{\partial x_3} \end{pmatrix} = \begin{pmatrix} 0 & 1 & 0 \\ \frac{D}{mL}\frac{x_3\left(u(t)-R\cdot x_3\right)}{x_1^{\,2}} & 0 & \frac{D}{2mL}\frac{2u(t)-x_3}{x_1} \\ 0 & 0 & -\frac{R}{L} \end{pmatrix} \tag{15}$$

Now the B matrix becomes:

$$\underline{B} = \begin{pmatrix} \frac{\partial f_1}{\partial u} \\ \frac{\partial f_2}{\partial u} \\ \frac{\partial f_3}{\partial u} \end{pmatrix} = \begin{pmatrix} 0 \\ \frac{D}{mL}\frac{x_3}{x_1} \\ 1/L \end{pmatrix} \tag{16}$$

with the output equation:

$$y(t) = \begin{pmatrix} 1 & 0 & 0 \end{pmatrix}\cdot\underline{x}(t) \tag{17}$$

III. Example Design of the State Estimator:

If we pick $D/mL = 1$, $Z(0) = 1$, $V(0) = 10$, R = 10, and $L = 1/10$ (for simplicity) then we get the results:

$$
\begin{aligned}
x_1(0) &= 1 \\
x_2(0) &= 0 \\
x_3(0) &= 1
\end{aligned}
$$

Which can be combined to produce:

$$
\begin{aligned}
\underline{A} &= \begin{pmatrix} 0 & 1 & 0 \\ 0 & 0 & 9.5 \\ 0 & 0 & -100 \end{pmatrix} \\
\underline{B} &= \begin{pmatrix} 0 \\ 1 \\ 10 \end{pmatrix} \\
\underline{C} &= \begin{pmatrix} 1 & 0 & 0 \end{pmatrix}
\end{aligned}
\tag{18}
$$

We will first design the state feedback system such that it is optimized in the standard fashion ($\varsigma = .707$) with a reasonable settling time of $T_s = 3s$ ($\tau \approx T_s/4 = ¾ s = .25s$). We wish to place poles in the system which meets such a requirement, thus, we must inspect the corresponding characteristic equation:

$$
\begin{aligned}
& s^2 + 2\zeta\omega_n s + \omega_n{}^2 \\
&= s^2 + 2\frac{1}{\tau}s + \left(\frac{1}{\zeta\tau}\right)^2 \\
&= s^2 + 2.6725s + 3.5721 \\
&= 0
\end{aligned}
$$

$$
s_{1,2} = -1.336 \pm 1.336j
$$

We need one more pole, however, since our system is third order. Let us pick it to be at $s_3 = -13.36$ so that it does not greatly alter the response contributed by the desired poles but still allows for a fast system. So the placed poles are:

$$
\underline{\text{Pp}} = [-1.336 + 1.336j \qquad -1.336 - 1.336j \quad -13.36] \tag{19}
$$

The gain matrix is then determined using Ackerman's Formula[6]:

$$\underline{K} = [.0245 \quad .0365 \quad -9.6028] \tag{20}$$

Then, the equation of motion becomes:

$$\dot{\underline{x}}(t) = \underline{A}\underline{x}(t) - \underline{B}\underline{K}\underline{x}(t) \tag{21}$$

The response to the initial conditions ($x_1 = z_0 = 1$, $x_2 = dz_0/dt = 0$, $x_3 = e_0/R = 1$) is shown below:

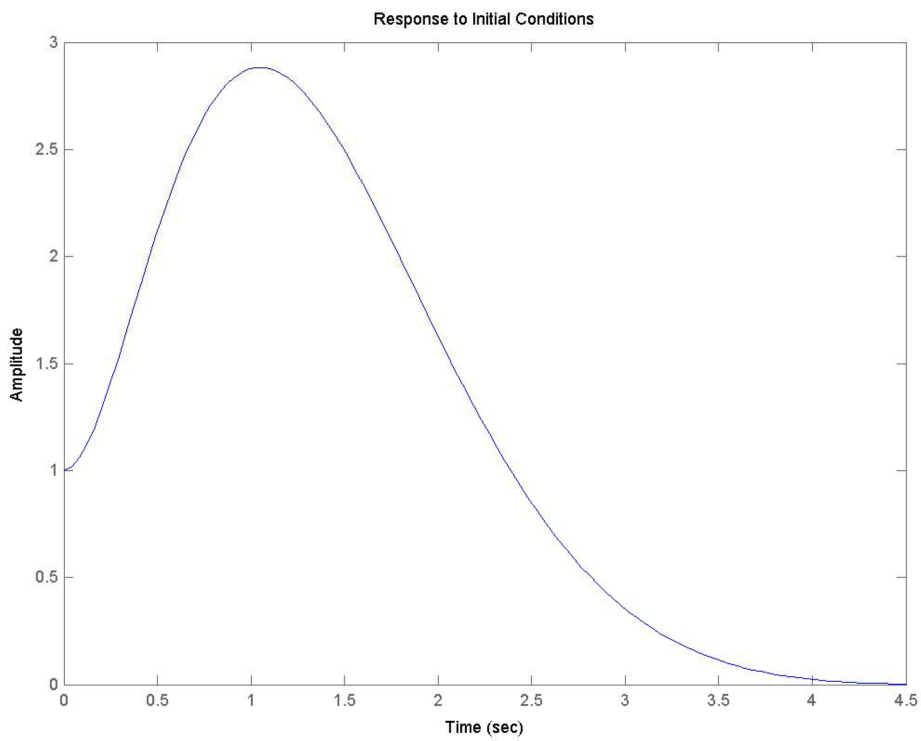


Fig.5: System Response to Initial Conditions.

We would now like to design a state estimator to control the response of the system. Since our system is nonlinear, we would like to minimize overshoot, because the linear state equations do not

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[6] Using the MatLab Code:
>> K = acker[A,B,Pp];

apply far from the desired conditions. Thus, we select a critically damped response ($\zeta = 1$). We also want to make the response four times faster than the uncontrolled system, so we would like to set the time constant, $\tau = 3/16 = .1875s$. These conditions force us to have a denominator in s space given by

$$d(s) = \left(s + \frac{1}{.1875}\right)^3 = (s + 5.3)^3 \tag{22}$$

And so we set the array of our estimator poles $P_e = \begin{bmatrix} -5.3 & -5.3 & -5.3 \end{bmatrix}$, and use the code given on pp. 421[7] to find a G matrix of:

$$G = \begin{bmatrix} .7635 \\ .4282 \\ -8.4528 \end{bmatrix} \tag{23}$$

And so, from the code on page 422[8], we get:

$$G_{ec}(s) = \frac{-1875s^2 + 3.852s + 3641}{s^3 - 80.09s^2 + 16840s + 16920} \tag{24}$$

And

$$G_p(s) = \frac{s^2 + 196s + 195}{s^3 + 100s^2} \tag{25}$$

From the Bode Plot below, we find the phase margin is 64.4 degrees and that locally the system is stable.

[7] Phillips and Harbor, Pp. 421
[8] P+H, 422

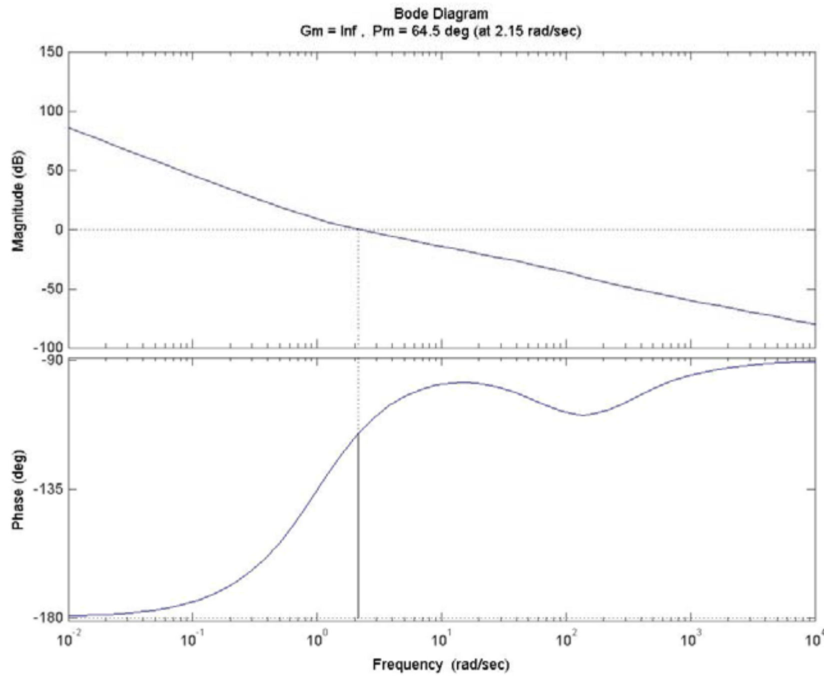

Fig.6: Open Loop Frequency Response of Estimated System.

This controller provides an output with the step response shown below. The percentage overshoot is 20% and the settling time is about four times faster than the uncontrolled system as expected.

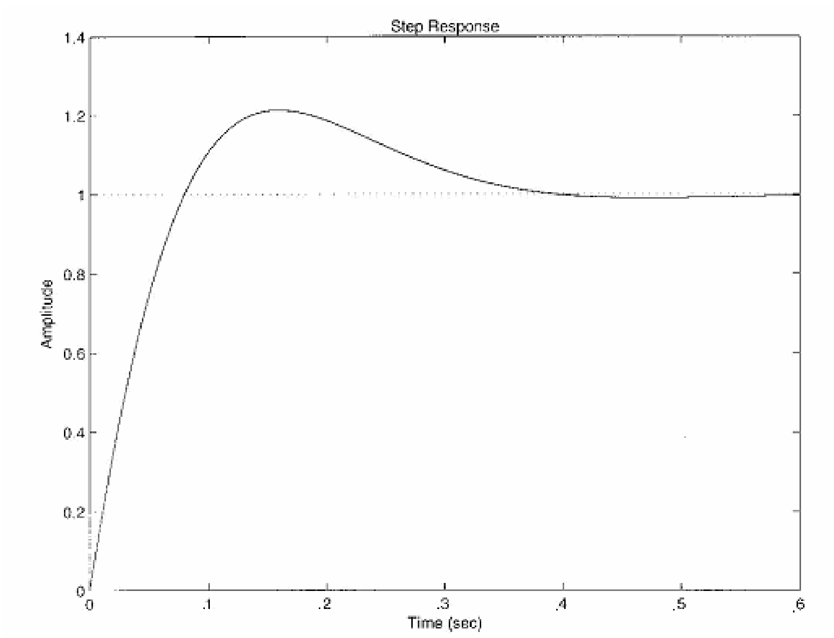

Fig.7: Step Response of the Controlled System.

It is important to note here that the physical system will **NOT** respond in any fashion to a constant current. The equations of motion merely appear to reduce to DI^2/Z in the high frequency limit as discussed in **PART I**. In actuality, the system will only respond to an oscillating input of which a constant amplitude (or RMS input) is analogous to the step input/response of the simulation.

In theory, we could push the response time to anything we'd like, but because the model is only locally linear, faster response times with higher overshoots could push the system into unstable nonlinear regions.

IV. Implementation:

The device to be built and tested will consist of a vertical levitation solenoid and a horizontally constrained flotation loop or coil. A rectifier circuit consisting of several diodes and an IR or visible feedback LED will transmit position information to a calibrated photodiode. The output of the photodiode will be averaged over a clock cycle and output into a computer which will linearize the equations of motion around a user given equilibrium point and implement the proper estimator to quickly guide the floatation device to the desired height.

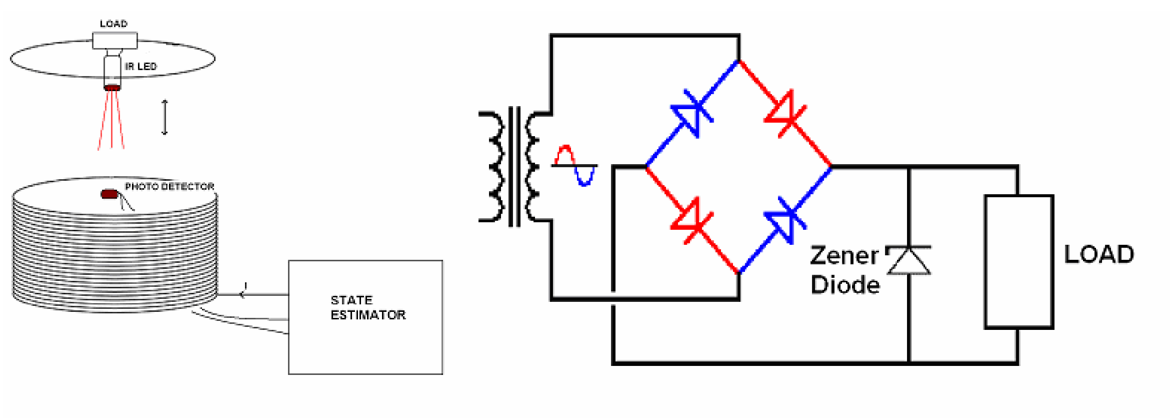

Fig.8: The Levitation System.

Earnshaw's Theorem states that a stable equilibrium cannot be established normal to the direction of a static field. If time allows, a smaller apparatus will be built out of several small electromagnets to dynamically control the horizontal displacement of a powered floatation loop.

Right now we can make some rough estimations as to how much current we can generate in the ring. The induced EMF is proportional to the rate of change of the magnetic field which is proportional to the time derivative of the solenoid current. Thus, if we input an AC current with an amplitude of 1 A, then the amplitude of the induced EMF is the area of the ring times $2\pi f$ where f is the driving frequency. If the ring is four inches in diameter then the amplitude of the EMF voltage comes out to be about 50 V if driven at kilohertz or about 500 V if driven at megahertz. If the total resistance of the ring and load is 10 kΩ, then the corresponding amperage in the ring is 5 mA or 50 mA, respectively. This corresponds to a power of 25 W. If I am only to power an LED for position feedback, the maximum load impendence should only be on the order of Ohms, and the required RMS current of only 30 mA would be easily supplied.

Maximum levitation height is more difficult to estimate. The average force is equal to the RMS current times the circumference of the ring times the radial component of the magnetic field (see Equation 3). This can be calculated if one knows the geometry of the solenoid. However, since I am buying a pre-made electromagnet, I must first characterize it to determine the lump parameter D (See Equation 9) which determines the strength of the magnet. I have successful levitated a steel ring of about 500 g at the top of a foot-long electromagnet powered by current from a wall outlet. This is about ten times the weight of what I expect to be lifting. Assuming that the falloff in force is proportional to the inverse of the ring's height, this would lead me to suspect that I could float a small device about 10 feet in the air. This might be practical; however, I only plan to attempt flotation to about one foot.

BUDGET & RESOURCES

Most parts required to design and implement the said flotation device are already available in the Swarthmore Engineering Department. Costs will include purchasing of several small electromagnets ($244 total) for horizontal control and a photoelectric positioning sensor ($30). I will use a stronger electromagnet provided by the Swarthmore Physics Department as the main levitation solenoid of the horizontally constrained system to attain maximum flotation and induced power. Although this magnet is large and bulky as it is usually used for demonstrational purposes, it is robust and a comparatively strong electromagnet would cost over $400 for one unit. Marc Chang will be aiding me next semester so the total costs should be within our combined budget of $400.

PLANNING & MANAGEMANT

I. Activity Durations:

I have assigned nine major tasks and two possible extensions major tasks that must be completed within the time allotted until the project deadline in May 2006. These tasks are summarized as follows:

A) Preliminary Design (**Completed**)

B) Materials Acquisition (**Partially Completed**)

C) System Characterization

D) Design of External Position Feedback System

E) Levitation and Control Testing & Optimization

F) Design of the Rectifier Circuit

G) Autonomous Power Testing

H) Design of Self-Powered Feedback System

I) Full Vertical System Implementation

J) Ext. A: Maintaining Horizontal Stability

K) Ext. B: Horizontal Position Control

L) Report Summary

Each task's duration, effort, requirements are described in the Activities Summary below:

Table 1: Activities Summary.

Activity	Needs	Feeds	Duration (weeks)	Effort (hours)
A	-	B	3	40
B	A	C, D	2	5
C	B	D, F	1	15
D	B	H	2	50
E	C, D	I	1	20
F	C	G	.5	10
G	F	H, L	.5	5

H	D, G	I	.5	10
I	E, H	J	2	30
J	I	K	2	40
K	J	-	1	20
L	G, K	-	1	40
Total	**-**	**-**	**16.5**	**285**

Establishing the Critical Path with earliest and latest start times (by week number),

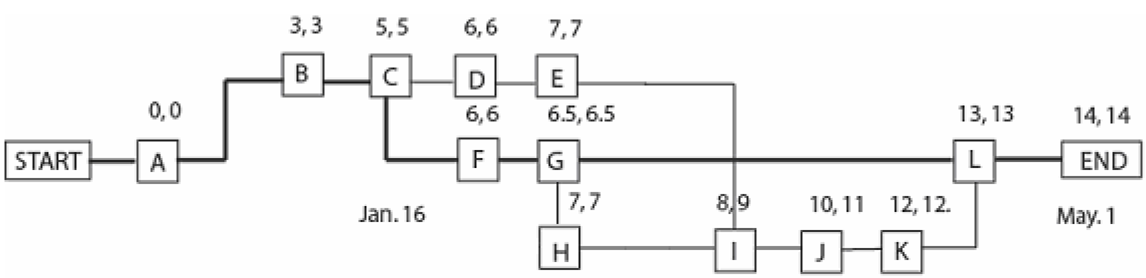

Fig.8: Critical Path Evaluation.

we find that the total duration is fourteen weeks. Right now I have already obtained all electromagnets I might need and am in currently in the decision process of deciding which positioning system I wish to purchase. By January 16 I should be well on my way to task C, leaving me ample time (8 to 10 weeks) to meet the May 2006 deadline.

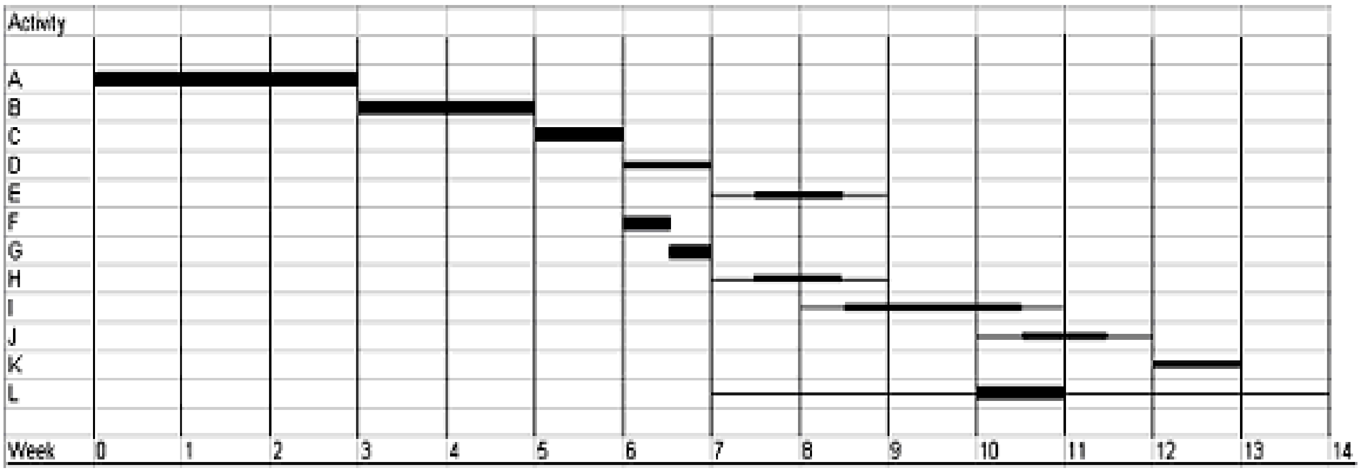

Chart 1: Milestone Chart.

II. Task Breakdown:

A) *Preliminary Design* (**Completed**)

Preliminary design consisted of research, modeling, and simulation of the system in question. This was described substantially in the preceding sections

B) *Materials Acquisition* (**Partially Completed**)

Because of time constraints, I will not be able to build my own electromagnet suitable for the levitation device. I have already acquired three small electromagnets rated to hold eighty pounds of steel each with an air gap of .01 mm at a total cost of $244. These magnets are substantially weaker than others available on the market, but because of the high cost per item in small quantity, magnets sufficient for vertical levitation could not be purchased. Hopefully, the ones I have bought will prove sufficient for demonstrating the possibility of horizontal control.

For vertical levitation I will borrow a crude but powerful solenoid used for demonstrations in the Swarthmore Physics Department. Its oversized dimensions should not be indicative of the actual size required to generate a comparable magnetic field – this item is simply convenient for free use. I have already levitated steel rings using this magnet; however, the magnet is still in use in the physics department. By December I should be able to borrow it, characterize it, and modify it for use with an external power supply.

There are several types of photoelectric position sensors available. Right now I am thinking about purchasing either a through-beam sensor where the light source is mounted to the ring or a retro-reflective system where the light source is attached to the detector and bounced off a reflector mounted to the ring. Either system should const about $40.

C) *System Characterization*

This task consists of characterizing force versus distance profile of the large demonstration magnet and a four to six inch conductive ring. This data will be fit and linearized according to the model above for implementation into the state estimator.

The voltage across a load resistor mounted on the ring will also be monitored with respect to time, height, and solenoid current. Here also it will be decided whether or not to increase the number of windings in the flotation rig. This should effectively double the weight of the device but quadruple the repulsive force as the total current and repulsive force is dependent on N^2 where N is the number of windings.

D) *Design of External Position Feedback System*

This should be a redux of the example simulation described above with actual system parameters implemented. The task will also involve manually moving the reflector or light source to be later mounted on the device towards and away from the position sensor and checking that the data acquisition software implements the correct state estimator.

E) *Levitation and Control Testing & Optimization*

Here the flotation system controls are fully tested and optimized. The mounted reflector or light source will be attached to the conductive ring which will be constrained to only move in the vertical direction. If a light source is used it will probably be powered by an onboard battery unless the power circuitry is completely finished. The control system will be optimized to maximize speed of position transitions while maintaining stability about the desired location with minimal error. Also it should be established whether control of the current amplitude, frequency, or combination of the above works best for position control.

F) *Design of the Rectifier Circuit*

The rectifier circuit should be readily developed and constructed. It will consist of a full wave rectifier integrated into the conductive ring, a zener diode to maintain a limited voltage to the load, and an LED for use as the load.

G) *Autonomous Power Testing*

Here the rectifier circuit powering an LED above the solenoid will be tested. Input amplitude and frequency to the solenoid will be adjusted to maintain optimal performance of the circuitry (i.e. maximization of LED brightness and minimization of noticeable blinking during the cycles). The LED should provide a similar light output over the specified range of levitation.

H) *Design of Self-Powered Feedback System*

If a through-beam position sensor is used, then the specified light source will replace the LED as the load for use as an autonomously powered feedback unit. Both the source and the receiver must be clocked to detect position at the peak of the on cycle or averaging must take place over a designated time period to determine the correct position with respect to average light intensity. Capacitors could also be used in parallel with the load to smooth out the output of the load light source such that minimal to no clocking must take place.

I) *Full Vertical System Implementation*

This is the concurrent optimization of the vertical control along with the performance of the load circuitry.

J) Ext. A: Maintaining Horizontal Stability

This is subject to time, and anything said here is primarily speculation. This will probably entail the use of several electromagnets to maintain a horizontal equilibrium without the need of mechanical constraints. If I can successfully float a miniature ring above the afore-mentioned magnets I will attempt to create a well of stability using any number of configurations of flotation ring shapes, complex either ferromagnetic or nonmagnetic counterbalances, or even dynamic control of the magnets themselves. If the three small electromagnets are not sufficient in strength to levitate a reasonable material I shall go back to the larger apparatus and construct vertical rings to the levitation device to for horizontal position control at a given height with perpendicularly mounted electromagnets.

K) Ext. B: Horizontal Position Control

Assuming task K is completed, a horizontal position control system should be designed and optimized though simulation. It is unlikely that a physical device could be implemented using only the three, low power electromagnets.

L) Report Summary

This task will carry on during the last several weeks of the project duration and should propose many possible extensions based on my findings.

CONCLUDING REMARKS

By May 1st I should have at the very least a complete proof of concept – meaning a separate but fully functional controlled levitation device and an autonomously powered induction unit providing position feedback to a sensor. I expect to have, however, a complete wireless unit that can be controlled by a computer in one dimension by this time to a height of one foot or greater. If time allows, I would like to tackle the problem of horizontal control as well, and demonstrate the effectiveness of a miniature model using a three-dimensional, dynamic control system.