Closed Loop Control of Halbach Array Magnetic Levitation System Height

(CLCML)

Senior Project Proposal

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abstract - This document contains information about Bradley University's 2012-2013 Senior Capstone Project proposal to implement closed loop control of a Halbach array magnetic levitation system height. The project will expand upon the previous years' progress of generating magnetic levitation using a Halbach array of magnets and a rotary inductrack. A complete system block diagram and its subsystems will be used to show how the system is modeled. Based on the system model, a controller will be designed to satisfy performance specifications. A microcontroller will implement the closed-loop control of the magnetic levitation height of the Halbach array. After implementation, research will be made into the feasibility of the fabrication of a flat, circular inductrack and motorized Halbach array system that could accommodate linear motion until breakpoint velocity is reached for magnetic levitation.

Project Summary

The objective of CLCML is to model the previous year's magnetic levitation system and implement closed loop control of the magnetic levitation height. The current system uses a method of a passive rotary inductrack and Halbach array of magnets to generate magnetic levitation. The system stability will be improved and a safety enclosure will be used. The system will be modeled and a controller will be designed to meet performance specifications. A microcontroller will be used to control the DC motor speed. Finally, research will be made to determine feasibility of future projects in this field.

Previous Work

Dr. Richard F. Post pioneered the use of the inductrack with a Halbach array of magnets to generate magnetic levitation. His inductrack team at Lawrence Livermore National Laboratory formulated the governing equations of the Halbach array-inductrack relationship that will be used to model the current system. Dr. Post's work is the foundation of Paul Friend's research compiled for his 2003-2004 Senior Capstone Project at Bradley University. Mr. Friend designed and implemented the first magnetic levitation system at Bradley University. Mr. Friend also created a MATLAB Graphical User Interface to simulate the Halbach array-inductrack relationship using different methods and parameters. Using Paul Friend's research, Glenn Zomchek designed a magnetic levitation system using a rotary inductrack method for his 2006-2007 Senior Capstone Project. Mr. Zomchek obtained successful levitation of 0.45 millimeters. Building on Glenn Zomchek's system, Dirk DeDecker and Jesse VanIseghem redesigned the magnetic levitation system to have a larger rotary inductrack wheel for their 2011-2012 Senior Capstone Project. The DeDecker-VanIseghem system (shown in Figure 1) is the current one in use and it achieved 3.7 millimeters of vertical displacement. The previous year's research and labor has been a great asset to this year's CLCML Senior Capstone Project.

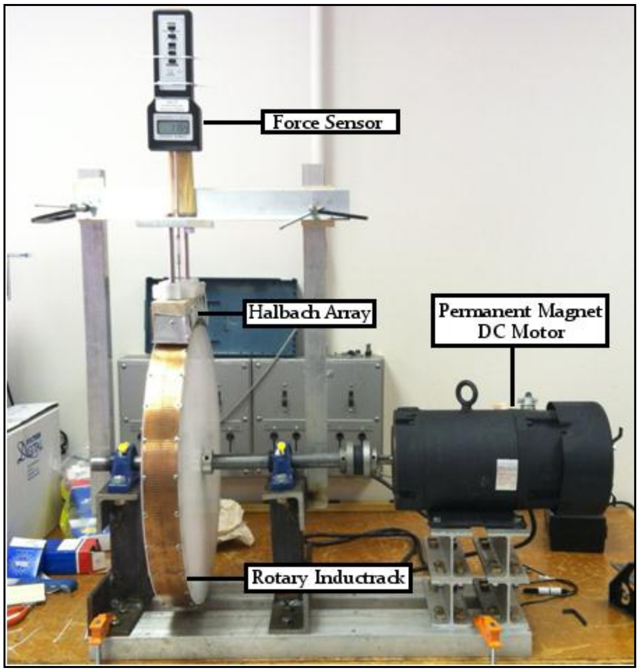

Fig. 1. DeDecker-VanIseghem Inductrack System

System Block Diagram

The objective of CLCML is to achieve closed-loop control of the magnetic levitation height of the Halbach array of magnets. Shown in Figure 2 is the top level system block diagram.

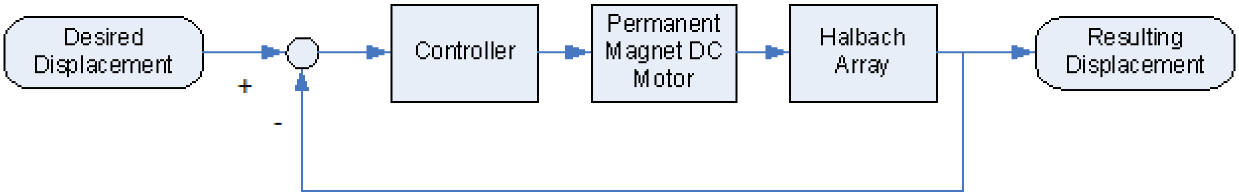

Fig. 2. High Level System Block Diagram

The system block diagram shows a negative feedback system. The input to the controller is levitation displacement error. In order to achieve closed-loop control of the levitation height, models of the Halbach array-inductrack and the DC motor will be made. Then the controller will be designed based on the resulting models to improve the system stability, accuracy and response time.

Subsystems

Halbach Array of Magnets

A magnetic Halbach array is a specific orientation of magnets designed to direct each magnet's field below the array while nearly canceling the magnetic field above the array. Shown in Figure 3 are the magnetic fields generated by a Halbach array of magnets. The Halbach array was designed by Klaus Halbach for use with particle accelerators. The resulting magnetic field is sinusoidal. The wavelength of this field can be calculated based on the length of the magnet array as shown in Figure 4. The wavelength λ is measured as the distance between the midway points of each end magnet. If the magnets are all the same length, λ is equal to the total length of the magnet array minus the length of one magnet.

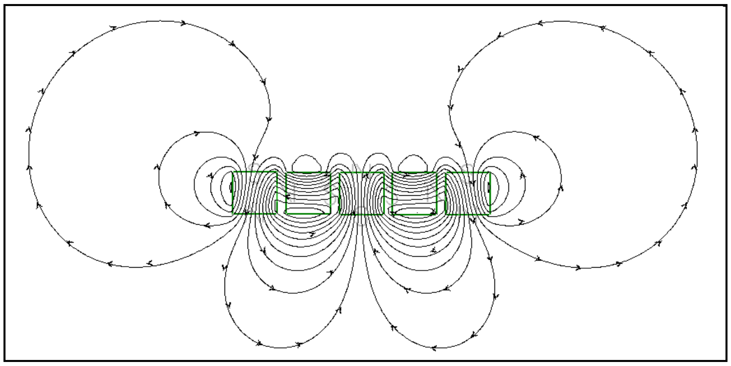

Fig. 3. Halbach Array Magnetic Field

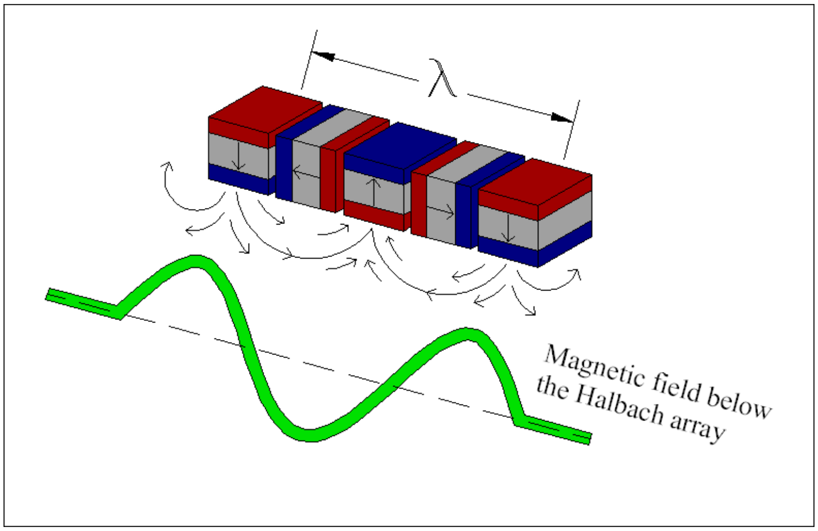

Fig. 4. Sinusoidal Magnetic Field

The peak magnetic field of the sinusoidal field generated by the magnetic Halbach array can be calculated by equation (1):

$$B_o = B_r\left[1 - e^{-\frac{4\pi d}{\lambda}}\right]\frac{\sin(\pi M)}{\pi M} \tag{1}$$

B_o = Peak magnetic field

d = Thickness of magnet

B_r = Individual magnet's strength

M = # of magnets per wavelength

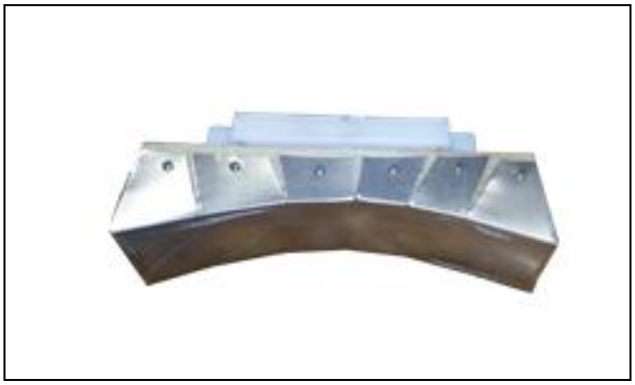

Fig. 5. DeDecker-VanIseghem Designed Halbach Array Device

The magnetic Halbach array used in the current system is shown in Figure 5. Mr. DeDecker and Mr. VanIseghem calculated the peak magnetic field strength of this Halbach array based on the following design parameters:

λ = 0.028 meters

d = 0.006 meters

B_r = 1.21 Tesla

M = 4 magnets

Therefore,

B_o = 0.8060 Tesla

Inductrack

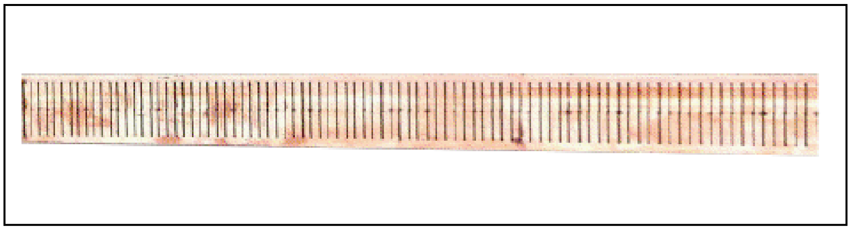

Fig. 6. Copper Inductrack

The inductrack is an array of inductors designed to interact with a Halbach array of magnets to produce magnetic levitation. The copper track shown in Figure 6 is the current inductrack in use. It is screwed into place around the rotary wheel that is connected to the DC motor shaft. Dr. Post's inductrack team found that when the inductrack rotates undeneath the Halbach array device, the changing magnetic field induces a magnetic flux relationship of equation (2):

$$\Phi(t) = \frac{wB_0}{k} e^{-ky} \sin(\omega t) \left[1 - e^{-ky}\right] \tag{2}$$

k = wave number = $2\pi/\lambda$

w = width of the inductrack

ω = kv, v = tangential veloicity of the inductrack

y = vertical displacement

This induced magnetic flux generates a current and a voltage given by equations (3) and (4):

$$i(t) = \frac{\Phi_0}{L} \left[\frac{1}{1+\left(\frac{R}{\omega L}\right)^2}\right] \left[\sin(\omega t) + \frac{R}{\omega L} \cos(\omega t)\right] \tag{3}$$

$$v(t) = \omega \Phi_0 \cos(\omega t) \tag{4}$$

Φ_0 = Peak magentic flux = $\frac{wB_0}{k} e^{-ky}$

R = track resistance

L = track inductance

The Halbach array-inductrack system can be modeled as a simple RL circuit as shown in Figure 7. Note that $v(t)$ defined by equation (4) above represents the voltage induced by the passing Halbach array device, while resistance and inductance represent the passive inductrack properties. As the frquency of $v(t)$ increases, which is analgous to track tangential velocity, phase lag will increase. The phase lag of the voltage causes the magnetic field generated by the inductrack to lag and eventually align itself with the Halbach array device's magnetic field.

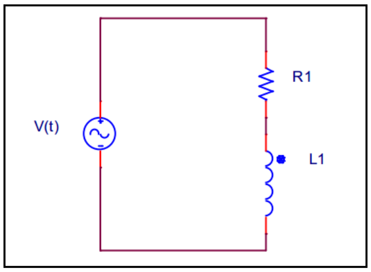

Fig. 7. RL Circuit Model for Halbach array-Inductrack System

This phenomenom can be observed in the series of pictures in Figure 8. The dial on the right side represents velocity so that the pictures from top to bottom represent increasing velocity. Observe that, as velocity increases, the induced magnetic field lag increases. At high velocity, lower picture, that induced magnetic field lag reaches a maximum where the like magnetic poles align, causing maximum vetical magnetic repulsion. Another way to view this relationship is on the following page through a Bode phase plot shown in Figure 9.

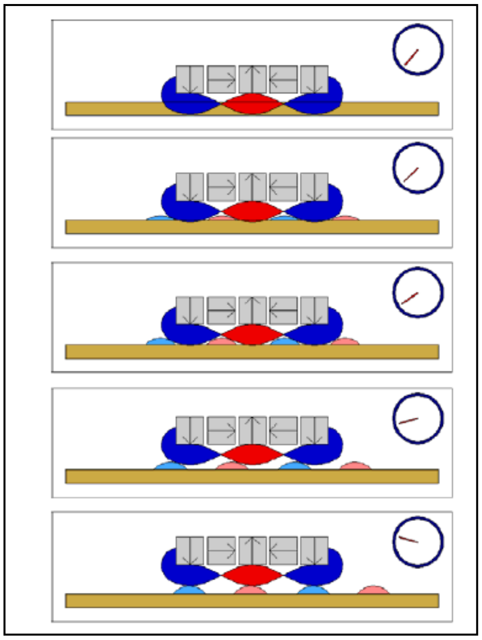

Fig. 8. Phase Lag-Velocity Relationship

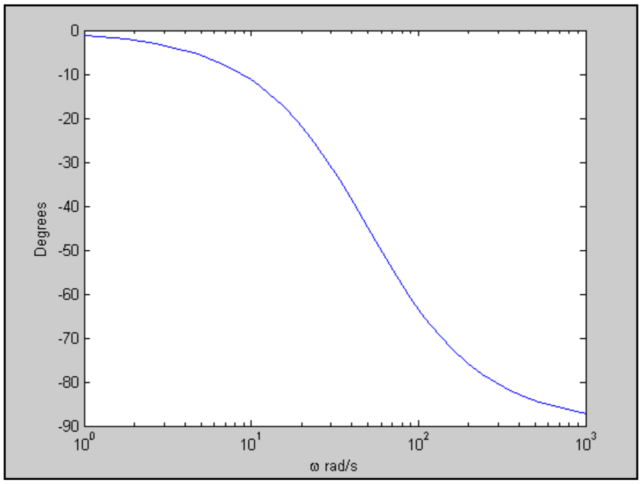

Fig. 9. Bode Phase Plot of a Series RL Circuit

Shown in Figure 9 is the Bode phase plot for a series RL circuit. The pole will occur at $\omega_0 = -R/L$, which corresponds to a phase lag of 45 degrees. At high frequency, phase lag approaches 90 degrees. The inductrack fabricated by Mr. DeDecker and Mr. VanIseghem was designed to maximize track inductance while minimizing track resistance. This design choice was intended to shift the pole frequency towards the origin so that phase lag, and thus magnetic repulsion, would occur at a lower velocity.

The track resistance and inductance can be determined by equations (5) and (6):

$$R = R_c \frac{l}{A} \tag{5}$$

$$L = \frac{\mu_0 P_c}{2\pi k d_c} \tag{6}$$

R_c = resistivity of copper = 1.68x10^{-8} Ωm

l = length of the inductrack

A = crossectional area of the inductrack

μ_0 = permeability of free space = 4πx10^{-7} H/m

P_c = mean perimeter of inductrack

d_c = Spacing of inductors

Mr. DeDecker and Mr. VanIseghem calculated the following inductrack properties:

R = 1.90 x 10^{-5} Ω

L = 7.532 x 10^{-8} H.

However, after a few simulations, they suspected that the calculated R and L did not match the actual track resistance and inductance. The track properties will have to be confirmed.

The vertical force produced by the Halbach array-inductrack system is given by equation (7):

$$F_y = \frac{B_0^2 w}{2kL}\left[\frac{1}{1+\left(\frac{R}{\omega L}\right)^2}\right] e^{-2ky} \text{ N} \tag{7}$$

With the previous design equations, the Halbach array-inductrack relationship can be modeled as shown in Figure 10.

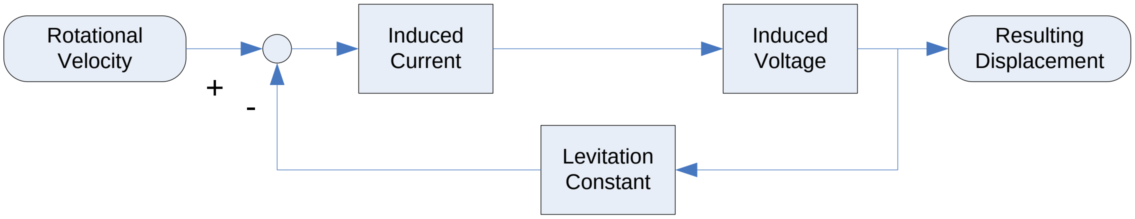

Fig. 10. Halbach Array - Inductrack Subsystem

When the design equations are used to model the subsystem, trials of the system will be performed to ensure the accuracy of the system. It is desired to be precise within +- 5% from 500 RPM to 2000 RPM. A force sensor will record data at these velocities and will be compared with a simulation of the subsystem in Simulink. It should be noted that this is a nonlinear system and will complicate the controller design if it cannot be made approximately linear.

DC Motor Modeling

The 20-year-old permanent magnet DC motor will have to be modeled since no datasheet could be found. A general block diagram for motor modeling is shown in Figure 11.

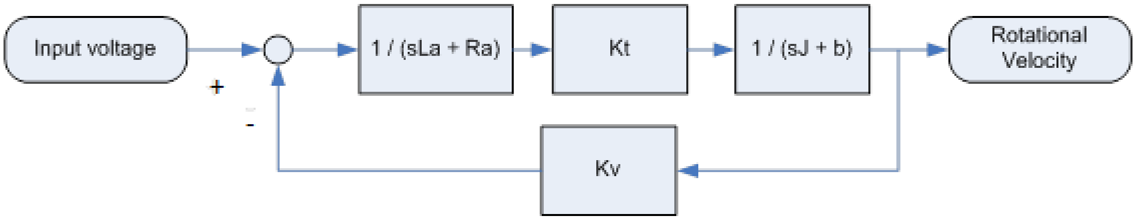

Fig. 11. Motor Model Subsystem

Experiments will be performed using equations (8), (9) and (10) to model the subsystem:

$$\omega_m = \frac{V_S - I_A R_A}{K_V} \text{ [rad/s]} \tag{8}$$

$$K_T I_A - T_C - b\omega_m = 0 \tag{9}$$

$$-J_A \frac{d\omega_m}{dt} - T_C - b\omega_m = 0 \tag{10}$$

The variables are

ω_m = machine rotational speed

I_A = amature current

V_S = source voltage

K_T = K_V = torque constant = velocity constant

b = motor viscous friction

R_A = amature resistance

T_C = columbic friction

J_A = moment of inertia

Motor modeling requires a locked-rotor experiment as well as a coast-down experiment. Equations (8) – (10) will be used to determine the subsystem properties. The motor model is to be accurate within +/- 5%. A tachometer will be used to compare experimental rotational speed to a simulation speed of the subsystem in Simulink.

Controller

The controller will be designed based on the following specifications:

- The maximum overshoot of the system shall be less than 10%.
- The steady state error shall be less than 0.01 centimeters.
- The settling time shall be less than 50 milliseconds.
- The rise time shall be minimized based on the other specifications.

The settling time specification may have to be modified based on the motor's capabilities. A reasonable settling time specification will be determined based on the motor response time to input voltage during motor modeling.

Implementation

In order to implement the controller and closed-loop feedback, a microcontroller will be used. The flow of the microcontroller’s logic is as follows:

- The microcontroller will accept a user-defined levitation height through keypad input.
- The microcontroller will calculate the current vertical displacement through a connection with a displacement transducer attached to the Halbach array device.
- The microcontroller will calculate an error signal by subtracting the resulting displacement height from the desired displacement height.
- The microcontroller will calculate the voltage required by the DC motor to achieve the desired displacement based on the transfer function of the closed-loop system.

The microcontroller will sample displacement no sooner than settling time is reached. The control voltage must be calculated by the microcontroller within 1 millisecond.

Circular Linear Track Research

The track must be able to accommodate motion until break velocity is reached. The inductrack design must attempt to minimize break velocity. Additionally, the inductrack design must attempt to minimize leakage flux and eddy currents to maximize efficiency. Analysis of the dimensions and material of the Halbach array device and the flat inductrack will be made with recommendations for feasibility.

Preliminary Work

J.H. Benedict Co. has generously donated their time and expertise in balancing the rotary track. The new balanced wheel will allow for higher rotational velocity during trials. Research for the safety enclosure around the rotating wheel has been made. The enclosure allows for easy access into the system while providing a protective barrier able to withstand the impact of a loose Halbach array magnet at high velocity.

Schedule

The spring semester schedule is as follows:

	Chris	Kyle	Victor
Winter Break	Controller Research	Website Design	µcontroller research
Week 1-3	Controller Design	µcontroller code development	
Week 4-6	µcontroller code development incorporating controller and models		
Week 7-9	µcontroller implementation and testing		
Week 7-9	Flat inductrack research when idle		
Week 10	Preparation for Student Expo		
Week 11	Student Expo		
Week 12-13	Final report and project presentation presentation		
Week 14	Final Presentation		

Equipment List

Safety Enclosure

2x3 – ¼” thick polycarbonate sheet – 5

2x2 – ¼” thick polycarbonate sheet – 1

CRL Brite Anodized Aluminum Inside Corner Extrusion – 4

Various bond material (as needed)

Implementation

μcontroller (to be determined)

Patents

- Richard F. Post

Magnetic Levitation System for Moving Objects

U.S. Patent 5,722,326

March 3, 1998

- Richard F. Post

Inductrack Magnet Configuration

U.S. Patent 6,633,217 B2

October 14, 2003

- Richard F. Post

Inductrack Configuration

U.S. Patent 629,503 B2

October 7, 2003

- Richard F. Post

Laminated Track Design for Inductrack Maglev System

U.S. Patent Pending US 2003/0112105 A1

June 19, 2003

- Coffey; Howard T.

Propulsion and stabilization for magnetically levitated vehicles

U.S. Patent 5,222,436

June 29, 2003

- Coffey; Howard T.

Magnetic Levitation configuration incorporating levitation,

guidance and linear synchronous motor

U.S. Patent 5,253,592

October 19, 1993

- Levi;Enrico; Zabar;Zivan

Air cored, linear induction motor for magnetically levitated

systems

U.S. Patent 5,270,593

November 10, 1992

References

[1] Dirk DeDecker, Jesse VanIseghem. Senior Project. “Development of a Halback Array Magnetic Levitation System”. Final Report, May 2012

[2] Glenn Zomchek. Senior Project. “Redesign of a Rotary Inductrack for Magnetic Levitation Train Demonstration.” Final Report, 2007.

[3] Paul Friend. Senior Project. Magnetic Levitation Technology 1. Final Report, 2004.

[4] Post, Richard F., Ryutov, Dmitri D., “The Inductrack Approach to Magnetic Levitation,” Lawrence Livermore National Laboratory.

[5] Post, Richard F., Ryutov, Dmitri D., “The Inductrack: A Simpler Approach to Magnetic Levitaiton,” Lawrence Livermore National Laboratory.

[6] Post, Richard F., Sam Gurol, and Bob Baldi. "The General Atomics Low Speed Urban Maglev Technology Development Program." Lawrence Livermore National Laboratory and General Atomics.