Closed Loop Magnetic Levitation Control of a Rotary Inductrack System

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Presentation Outline

I. Introduction
   A. Background and Previous Work
   B. Original Goals
   C. System Block Diagram

II. Current Progress
   A. Analog Circuitry
   B. Controller
   C. Status of the Project

III. Conclusion
   A. Patents
   B. References
   C. Questions
Halbach Array of Magnets

Figure 3-1
Halbach Array in an Actual Bullet Train

Figure 4-1
Inductrack System without and with Safety Enclosure
Copper Inductrack Rail

Figure 6-1
Magnetic Field Interaction

Figure 7-1

Figure 7-2
Relevant Equations

Vertical Force:

$$F_y(\omega_e, y) = \frac{B^2 \omega A}{2 k L d_c} \left[ \frac{1}{1 + \left( \frac{R}{\omega_e L} \right)^2} \right] e^{-2ky} \quad [N]$$

Equation 8-1

Drag Force:

$$F_x(\omega_e, y) = \frac{B^2 \omega A}{2 k L d_c} \left[ \frac{R}{\omega_e L} \right] \left[ \frac{1}{1 + \left( \frac{R}{\omega_e L} \right)^2} \right] e^{-2ky} \quad [N]$$

Equation 8-2
Common DC Motor Circuit Schematic

Figure 9-1
Experimental Values Used for Motor Model

\[ R = 2.00 \ \Omega \quad L = 0.0216 \ \text{H} \]

\[ k_t = 0.615 \ \text{Nm/}A \quad k_v = 0.615 \ \text{V/(rad/s)} \]

\[ T_{cf} = 0.5105 \ \text{Nm} \quad B = 0.0061 \ \text{Nm/(rad/s)} \]

\[ J = 0.216 \ \text{kg m}^2 \]
Motor Model

Figure 11-1
Objectives

• Selection of suitable platform for controller implementation, which will allow a user to enter desired levitation height.
• Use of the selected platform to generate a PWM signal to drive the power electronics.
• Design system to be autonomous.
• Selection and design of appropriate power electronics which will allow control of the PWM signal.
Controller Transfer Function
Using Matlab

Controller Transfer Function:
\[ C(s) = k_p \frac{S + Z}{S} \]

A more realistic Transfer Function:
\[ C(s) = k_p \frac{s + Z}{s(s + p)} \]
A lead network with integral action

Design Specification 1: steady state error = 0
Design Specification 2: Less than 10% overshoot. \( \zeta = 0.707 \)
Design Specification 3: \( t_s < 6 \) seconds

Figure 13-1
Converting Continuous Time Controller to Discrete Time

\[ C(s) = 75.71 \frac{s + 1.56}{s(s + 76.92)} \]

Equation 14-1

Discrete Time Controller:

\[ T_s = 0.01 \text{ sec} \]

\[ C(z) = \frac{0.5453 + 0.5369z^{-1}}{1 - 1.463z^{-1} + 0.4634z^{-2}} \]

Equation 14-1
Closed Loop Control Simulation

Christopher Smith
Senior Capstone Project: CLCML
1/29/13
Experimentally determined motor model transfer function
Dayton Permanent Magnet DC Motor Model 4226A

Figure 15-1
Displacement

Figure 16-1
Angular Velocity
Control Voltage

Figure 18-1
Discrete Time Controller:

\[ T_s = 0.01 \text{ sec} \]

\[ C(z) = \frac{0.5453 + 0.5369 z^{-1}}{1 - 1.463 z^{-1} + 0.4634 z^{-2}} \]

Equation 19-1
Xilinx Blockset

Figure 20-1
Xilinx Blockset

Figure 21-1
Xilinx Blockset Simulation

Figure 22-1
Xilinx Blockset Simulation

Figure 23-1
Xilinx Blockset Simulation

Figure 24-1
High Level Block Diagram

User Input

Controller

PWM

Motor

Power MOSFET

Displacement Sensor

Inertia Load

Optical Encoder

Figure 25-1
Performance Specifications for Controller

• The controller platform selected is a Spartan 3E FPGA board.

• The controller shall sample displacement at least every 10 ms.

• The controller shall generate PWM control signal within 10 ms.
Controller Simulation

Figure 28-1
## Experimental Data for Look-Up Table

<table>
<thead>
<tr>
<th>Input Voltage</th>
<th>Displacement Sensor Voltage</th>
<th>Encoder Frequency</th>
<th>Velocity</th>
<th>Height</th>
<th>Displacement</th>
<th>Electrical Frequency</th>
<th>Height</th>
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<td>V_a [V]</td>
<td>[V]</td>
<td>F_enc [Hz]</td>
<td>v_enc [rpm]</td>
<td>\omega_e [rad/s]</td>
<td>v [m/s]</td>
<td>y [mm]</td>
<td>[mm]</td>
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<td>3.3</td>
<td>0.8</td>
<td>7.000</td>
<td>0.000</td>
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<td>3.7280</td>
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<td>84.0</td>
<td>8.8</td>
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<td>10.975</td>
<td>3.975</td>
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</table>
Converting Electrical Frequency to Displacement

\[ y(\omega_e) = 0.002228 \times \ln\left( \frac{232.69}{1 + \frac{9.55 \times 10^6}{\omega_e^2}} \right) \]  
\[ \text{m} \]

Equation 30-1

\[ \omega_e = \sqrt{\frac{9.55 \times 10^6}{-1 + 232.69 e^{-\frac{y}{0.002228}}} } \]  
\[ \text{rad/s} \]

Equation 30-2
Preliminary PWM Flowchart

Start = User Input

Check User Input
Set Percent = Input

If count < Percent
then
PWM_out = 1
Count++
else
If count < 100
then
PWM_out = 0
Count++
else

Figure 31-1
FPGA PWM Results

Figure 32-1
Analog Circuit Schematic

\[ R_g = \frac{3120_{vout}}{3120_{Imax}} \]
\[ I_i = 3.3 - 1.1/R_i \]
Application of Circuit with Pittman Motor

Figure 34-1
Analog Circuit Results

Figure 35-1

Figure 35-2

Figure 35-3
Status of the Project

Figure 36-1
Status of the Project

• Analog Circuitry

• Controller

• VHDL Modules
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
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  October 7, 2003

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  Laminated Track Design for Inductrack Maglev System
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• Coffey; Howard T.
  Propulsion and stabilization for magnetically levitated vehicles
  U.S. Patent 5,222,436
  June 29, 2003

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  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

• Lamb; Karl J.; Merrill; Toby; Gossage; Scott D.; Sparks; Michael T.; Barrett; Michael S.
  U.S. Patent 6,510,799
  January 28, 2003
References