ANALOG AND LABVIEW-BASED CONTROL OF A MAGLEV SYSTEM WITH NI-ELVIS

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ABSTRACT
This paper investigates the control of a low cost vertical-axis maglev system for mechatronics and controls education. The tabletop maglev system consists of an electromagnetic coil that levitates a ferrous object using an infrared sensor to determine the object’s position. Based on the sensor output, the controller adjusts the coil current, thus changing the magnetic field controlling the levitated object’s position. A second electromagnetic coil is used to provide known disturbances. The paper develops the underlying theory for magnetic levitation and presents the results of experiments with classical controllers implemented both as analog circuits and in software-based virtual instruments. Analog controllers, such as PID-type controllers, were implemented as simple circuits on National Instruments’ Educational Laboratory Virtual Instrumentation Suite (NI-ELVIS) prototyping board. NI-ELVIS offers a LabVIEW-based prototyping environment for readily experimenting with different controller circuits. It consists of a multifunction data acquisition device and a custom-designed benchtop workstation with a prototyping board. In addition to analog control circuits, a suite of LabVIEW-based controllers were developed which offer in software a rapid way to change control strategies and gains and explore the effect on the physical system.

INTRODUCTION
Levitation is the stable equilibrium of an object without contact and can be achieved using electric or magnetic forces. In a magnetic levitation, or maglev, system a ferromagnetic object is suspended in air using electromagnetic forces. These forces cancel the effect of gravity, effectively levitating the object and achieving stable equilibrium. In this paper, comparisons of control strategies implemented in hardware and software are conducted. The controllers are analyzed for stability, robustness, system response, and mechanical impedance.

The maglev physical system investigated here is a laboratory prototype often studied in engineering education. It is representative of real-world applications of maglev technology in bearings and high speed transportation systems (Nagurka and Wang, 1997). Tabletop maglev systems are available commercially from manufacturers such as Quanser and ECP (http://www.quanser.com/ and http://www.ecpsystems.com/), and descriptions of simple test stands showcasing the principles of maglev have been described in the literature (e.g., Cicion, 1996; Xie, 2003).

In theory, the magnetic force produced by passing current through an electromagnet can exactly counteract the weight of the object. In practice, the electromagnetic force is sensitive to small disturbances that can induce acceleration forces on the levitated object, causing the object to be unbalanced. The main function of the controller is to maintain both static and dynamic equilibrium between the magnetic force and the object’s weight, in the face of disturbances, using the input of the sensor to obtain the position of the object.

Though various strategies for non-linear control currently exist, this paper focuses on the application of classical linear controllers to a linearized model of the non-linear maglev system. The controllers provide robust closed-loop performance of maglev systems that can levitate a variety of suspended masses despite disturbances (both mechanical and electrical). Analog PID-type control circuits are implemented using National Instruments Educational Laboratory Virtual Instrumentation Suite (NI ELVIS). In addition, the controllers are implemented digitally (in software) using NI LabVIEW™.

Fig. 1: Maglev Testbed Developed at Marquette University Shown Levitating AA Battery. (Power Supply for Electromagnet in Background Shows 18.0V at 1.60A.)
A tabletop single-axis maglev system, shown in Fig. 1, was first developed as a Marquette University senior design project (Craig, et al, 1998). The system is approximately 25 cm wide and 40 cm tall and requires power supplies for the electromagnet (18V, 3A) and the control circuitry (15V, 0.5A). The testbed, which had been used to explore different control strategies, was modified by inserting a second electromagnetic coil below the levitated object for providing known disturbances, as shown in Fig. 2.

![Fig. 2: Dual Coil Single Axis Maglev System](image)

**MODEL DEVELOPMENT**

The basic components of the maglev system include a sensor (infrared emitter-detector pair), an actuator (the electromagnet), and a controller. The sensor is a phototransistor with a resistor and can be modeled as a simple gain element. The sensor produces a voltage, \( v_s \), proportional to the object’s position, \( x \), with a gain, \( \beta \), which is linear around the operating point and can be determined experimentally (Green, 1997)

\[
v_s = \beta x \quad (1)
\]

A free-body diagram for a simple maglev system levitating an object of mass, \( m \), is shown in Fig 3. The motion of the object is constrained to the vertical axis, and it is also assumed that the center of mass coincides exactly with the point of application of the electromagnetic forces.

![Fig 3: Free-body Diagram of a Levitated Object in Electromagnetic Levitation](image)

The magnitude of the force \( f(x,i,t) \) exerted across an air gap \( x(t) \) by an electromagnet through which a current of magnitude \( i(t) \) flows can be obtained using Faraday’s inductive law and Ampere’s circuit law as

\[
f(x,i,t) = -\frac{i(t)^2}{2} \frac{dL(x)}{dx} \quad (2)
\]

where \( L(x) \) is the total inductance of the system

\[
L(x) = L_1 + \frac{L_0 x_o}{x} \quad (3)
\]

where \( L_1 \) is the inductance of the coil in the absence of the levitated object, \( L_0 \) is the additional inductance contributed by its presence and \( x_o \) is the air gap when the levitated object is in equilibrium. The inductance is characterized by the geometry and construction of the electromagnet, and can be determined experimentally.

From (3), the derivative of inductance with respect to position is

\[
\frac{dL(x)}{dx} = -\frac{L_0 x_o}{x^2} \quad (4)
\]

which, on combining with (2), gives

\[
f(x,i,t) = \frac{L_0 x_o}{2} \left( \frac{i(t)}{x(t)} \right)^2 = C \left( \frac{i(t)}{x(t)} \right)^2 \quad (5)
\]

where

\[
C = \frac{L_0 x_o}{2} \quad (6)
\]

is a constant that can be determined experimentally.

Applying Newton’s second law of motion and neglecting the effect of any drag forces, the governing equation of the system can be obtained as:

\[
m \frac{d^2 x(t)}{dt^2} = mg - f(x,i,t) \quad (7)
\]

On combination with (5),

\[
m \frac{d^2 x(t)}{dt^2} = mg - C \left( \frac{i(t)}{x(t)} \right)^2 \quad (8)
\]

For designing a linear control strategy, the non-linear electromagnetic force in (5) is linearized about an equilibrium point, \( x_o \)

\[
f(x,i,t) = C \left( \frac{i_o}{x_o} \right)^2 + \left( \frac{2C_i}{x_o^2} \right) i(t) - \frac{2C_i^2}{x_o^2} x(t) + ... \quad (9)
\]

or

\[
f(x,i,t) = f_o + f_i + ... \quad (10)
\]

where

\[
i = i_o + \delta i, \ x = x_o + \delta x \quad (11,12)
\]

where \( i_o \) and \( x_o \) are the equilibrium values and \( \delta i \) and \( \delta x \) are incremental values for the current and position variables, respectively. In the following analysis, \( i \) and \( x \) represent only the changes ( \( \delta i \) and \( \delta x \)) from equilibrium values of current and position, respectively, and not their absolute values.

From the free body diagram in Fig. 3, at equilibrium the magnetic force on the levitated object equals the gravitational force. By defining \( f_o \) as the force to balance the weight of the object at equilibrium,
\[ f_o = C \left( \frac{i_o}{x_o} \right)^2 = mg \]  \hspace{1cm} (13)

where \( g \) is the acceleration due to gravity.

Neglecting the higher order terms in (9) and (10), the incremental (control) force required for maintaining equilibrium, \( f_i(x,i,t) \), is

\[ f_i(x,i,t) = \left( \frac{2Ci_o}{x_o^2} \right) i(t) - \left( \frac{2Ci_o^2}{x_o^3} \right) x(t) \]  \hspace{1cm} (14)

The governing equation for the levitated object is determined by application of Newton’s second law

\[ \frac{d^2x}{dt^2} = mg - f \]  \hspace{1cm} (15)

On combination with (10), (13), and (14), (15) gives

\[ \frac{d^2x}{dt^2} = mg - f_o \left( \frac{2Ci_o}{x_o^2} \right) i(t) + \left( \frac{2Ci_o^2}{x_o^3} \right) x(t) \]  \hspace{1cm} (16)

Since at equilibrium, (13) applies, (16) becomes

\[ \frac{d^2x}{dt^2} = \left( \frac{2Ci_o}{x_o^2} \right) i(t) + \left( \frac{2Ci_o^2}{x_o^3} \right) x(t) \]  \hspace{1cm} (17)

Taking the Laplace transform of the above equation,

\[ ms^2X(s) = \left( \frac{2Ci_o}{x_o^2} \right) I(s) + \left( \frac{2Ci_o^2}{x_o^3} \right) X(s) \]  \hspace{1cm} (18)

Thus, the transfer function of the system with the change in current to the coil as the input and the change in position of the levitated object as the output is given by

\[ G(s) = \frac{X(s)}{I(s)} = \frac{-\frac{2Ci_o}{x_o^2}}{s^2m - \frac{2Ci_o^2}{x_o^3}} = \frac{-\frac{2Ci_o}{mx_o^3}}{s^2 - \frac{2Ci_o^2}{mx_o^3}} \]  \hspace{1cm} (19)

Since this is a linearized system, \( X(s) \) and \( I(s) \) represent changes from equilibrium values of position and current, respectively. Hence the negative sign implies that with an increase in \( I(s) \), there will be a decrease in \( X(s) \) and vice versa. The transfer function has two poles, one of which is in the right half plane at \( \sqrt{2Ci_o^2/mx_o^3} \), which makes it open-loop unstable. A representation of the maglev system is shown in the block diagram in Fig. 4.

**Fig. 4: Block Diagram of the Closed-Loop Maglev System**

The force constant, \( C \), can be obtained from (13) experimentally by levitating an object of known mass, \( m \), and measuring the current, \( i_o \), and position, \( x_o \). The value of \( L_o \) can then be calculated from (6).

Another way to interpret the transfer function for the maglev system is to consider the sensor output as the system output and the voltage to the electromagnet as the system input. The electromagnet can be represented as a series combination of a resistor and inductor. From Kirchoff’s voltage law, the voltage, \( v \), in the coil can be determined as,

\[ v = R(t) + L \frac{di(t)}{dt} \]  \hspace{1cm} (20)

Combining the Laplace transforms of the above equations, the overall transfer function between the voltage of the electromagnet as input and the sensor voltage as the output is determined as

\[ G_o(s) = \frac{V_o(s)}{V(s)} = \frac{-2\beta C_i_o/mLx_o^3}{s(s+R/L)(s^2 - 2Ci_o^2/mx_o^3)} \]  \hspace{1cm} (21)

Following extensive system identification, the overall transfer function between the sensor output and voltage input to the coil was found to be

\[ G(s) = 824000 \frac{1}{(s+232.0)(s+49.52)(s-49.52)} \]  \hspace{1cm} (22)

The transfer function shows that the system has no zeros and a pole in the right half plane which makes it open-loop unstable.

**CONTROL DESIGN**

Two approaches were used for implementing controllers: (i) analog controllers were implemented using basic electrical components on an NI ELVIS prototyping board, and (ii) digital (software-based) controllers were implemented using NI LabVIEW™. In the latter case, LabVIEW™ was used for developing software based “virtual instruments” which analyze the input signals and generate output signals accordingly which are fed back to the maglev system.

NI ELVIS is a prototyping environment especially suited for university science and engineering laboratories. It consists of LabVIEW™-based virtual instruments, a multifunction data acquisition device, and a custom-designed benchtop workstation and prototyping board. This combination provides a ready-to-use suite of instruments found in educational laboratories. NI ELVIS provides significant functionality to the user, such as the ease of swappable circuit boards, on-board power supplies, function generator, Bode analyzer, etc. Because it is based on LabVIEW™ and provides complete data acquisition and prototyping capabilities, the system is ideal for academic coursework.

Analog controllers, such as lead and PID-type controllers, were implemented on NI-ELVIS prototyping boards as shown in Fig. 5. Using PID control it was found that the system can be stabilized over a range of gains. One set of gains, namely proportional gain \( K_p=0.68 \), integral gain \( K_i=3.12 \), and derivative gain \( K_d=0.0141 \), was implemented with an analog circuit and the system was tested for levitation of different objects. The root locus is shown in Fig. 6 for the case of levitating a spherical metal ball of 8 g. The selected controller gains give a gain margin of 3.42dB at 349 rad/s and a phase margin of 8.94 deg at 279 rad/s. Fig. 7 is an overhead view of the prototyping board with the PID analog control circuit.
LabVIEW™ also provides the ability of conducting control design simulations using the Control Design Toolkit. These toolkits can be utilized to develop a virtual instrument (VI) in LabVIEW™ where the user can design the controller and observe its effect on the maglev system through simulation. Here an NI PCI-6014 E-series DAQ device was used to connect the computer to the maglev apparatus.

Using the PID toolset, various types of PID control VIs can be developed: P, PI, PD, PID, gain-scheduled PID, and PID autotuning algorithms. PID control VIs with LabVIEW™ math and logic functions can be combined to create block diagrams for control strategies. The PID control VIs use standard LabVIEW™ functions and library subVIs to implement the algorithms. Thus, like all other LabVIEW™ VIs, the PID VIs can be modified graphically for this application without writing any text-based code.

The PID VIs use an integral sum correction algorithm that facilitates anti-windup and bumpless manual to automatic transfers. Windup occurs at the upper limit of the controller output, for example, 100%. When the error decreases, the controller output decreases, moving out of the windup area. The integral sum correction algorithm prevents abrupt controller output changes when switching from manual to automatic mode or changing any parameters.

A LabVIEW™ VI was developed using the standard libraries including the control systems toolset and the PID control toolset. The front panel of the VI was designed such that the user can set the variables such as the setpoint, bias, and P, I, and D control gains, as shown in Fig. 8. The front panel also graphically shows the variations of the sensor output, controller output and the setpoint with respect to time. The user can choose the channels (for the data acquisition device) to which the sensor and the analog outputs are connected. The cycle time determines how fast the complete cycle of running the VI is performed. If the cycle time is too high, the controller can not change the current in the coil fast enough to respond to the motion of the levitated object due to any disturbances. Thus, the cycle time should be as low as possible (preferably, 1 microsecond or less) and is limited by the computer processing power and hardware limitations.

The analog output is then amplified using an analog circuit with a power transistor and transmitted to the coil. The circuit is implemented using an NI ELVIS prototyping board, as before. Fig. 9 shows a picture of the implemented circuit.
DESIGN INVESTIGATIONS

A second coil was added to the maglev system, as shown in Fig. 10, in order to give the system known disturbances to fairly test and compare controller designs. By varying the current in this second coil, a disturbance force proportional to the value of current can be injected. A function generator can also be used to produce desired force waveforms (square wave, sine wave, ramp, etc.). This force pulls the levitated object downwards towards the second coil, acting effectively as a known mechanical disturbance.

A levitated object under the effect of an electromagnetic force can be visualized as an equivalent spring-mass-damper system, as shown in Fig. 11. An equivalent or effective stiffness and damping act as a result of the closed-loop control. Due to the non-linear nature of the system, the spring action is non-linear. By placing a second coil, as shown in Fig. 10, below the levitated object, an effective force can be applied to the levitated object (approximately 0.01 N by passing a current of 3A in the second coil). The variation in the position can be determined from the sensor output.

To determine the effective stiffness, a graph of force versus displacement was developed. Fig. 12 shows such a plot of force versus displacement for an analog lead compensator. The experiment is repeated for a set of five spherical masses and the behavior was found to be consistent. The stiffness is very low for small displacements of the body and increases as the displacement is increased. The data follows a second order fit. The plot also shows the effect of the controller action to the open-loop force vs. displacement relationship of (5), where the force is inversely proportional to the squared displacement unlike the directly proportional relationship seen here.

To help uncover the effective damping, experimental impulse response tests of the analog and LabVIEW™ based controllers were conducted. An example of the sensor output as a result of an impulse stimulus is shown in Fig. 13. In general, the LabVIEW™ versions of the control strategies show an exaggerated and unsymmetrical response and longer settling times as compared to their analog versions. This may be attributed to the inherent approximation in the digital versions due to discretization. Additional investigations of the effects of disturbances were conducted (Sinha, 2005).

The controllers developed were also tested for levitating masses of assorted shapes and sizes, including spheres, rings, cylinders, and rectangular objects. Some objects, such as the 9V battery depicted in Fig. 14, adopt stable positions offset from a vertical axis, reflecting the fact that the center of mass and the effective point through which the counterbalancing
electromagnetic force acts do not coincide, in similarity to the concept of buoyancy.

**Fig. 13: Impulse Response of Analog PID Controller Showing Damping**

To gain insight into the robustness of the controllers, a variety of masses were levitated under the effect of known static and dynamic disturbances. A wide range of objects can successfully be stabilized, although for each object the levitating force generated is limited by the magnitude of current that can flow through the coil and how fast that current can be changed. Future work is needed to quantify the robustness and identify control designs and tuning strategies that offer maximum robustness and bandwidth (Yaniv and Nagurka, 2004).

**Fig. 14: Levitation of 9-Volt Battery (47.4g).**

**CLOSING**

The paper presents the modeling and control of a single degree-of-freedom magnetic levitation system. The physical system uses a position sensor, electromagnetic coil, and a controller. This system is an example of a non-linear system controlled successfully using classic linear control strategies.

In addition to circuits of different classical controllers implemented as analog circuits using National Instrument’s ELVIS system, software based controllers in LabVIEW™ were developed. ELVIS was used to provide students with the opportunity to explore the system and controller performance by using its integrated data acquisition system and built-in features such as function generators, Bode analyzers, oscilloscope, etc. LabVIEW™ controllers offer the ability to dynamically change the controller type and its parameters and observe the effect on the system in real-time. By using LabVIEW™, the viability of designing software based controllers for real-life applications is explored.

The project is an example of a mechatronics experiment in which students address real-world design and implementation issues. These include the design of a practical differentiator and an anti-windup circuit for the PID controller. In addition, given the physical realities, the system model changes and the controllers must be robust enough to accommodate this. (A large amount of current passing through the coil heats it up and this changes the resistance of the coil and hence the system model.) Understanding the system requires a multi-disciplinary engineering approach involving multiple steps, including performing system identification, simulating the system, designing and implementing the controllers through two approaches (hardware and software), determining effective properties, such as effective stiffness and damping, etc.

Many other possible extensions and experiments can be envisioned, all enhancing the pedagogical value of the maglev testbed for controls and mechatronics education. The students can also be creative in extending the experiments.

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**REFERENCES**


