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MAGNETIC LEVITATION TESTBED FOR CONTROLS EDUCATION

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ABSTRACT

This paper describes a magnetically levitated testbed for use in undergraduate and graduate controls education. Key components of the testbed include an electromagnetic coil to create the magnetic field, a ferrous object for levitation, a position sensor for height determination, and a controller for feedback adjustment of the coil current. In this paper the unit's design, development, and use in educational arenas are discussed.

INTRODUCTION

In magnetic levitation an object is suspended in a near frictionless environment without contact to a mechanical system. Examples of magnetic levitation include magnetic bearings, high-speed maglev trains, and magnetic vibration isolation systems. The success of these maglev systems requires feedback control to ensure achieving the desired gap distance and suspension stiffness.

Most magnetic levitation devices designed for laboratory use rely on the method of electromagnetic levitation in which an electromagnet is used to <u>attract</u> a ferromagnetic object. A pictorial of one such testbed is shown in Figure 1. The aim of the device is to keep a ferromagnetic object suspended in midair by adjusting the field strength of the electromagnet. To create the magnetic field current is passed through a coil.

In the operation of these types of devices the weight of the levitated object is equilibrated by the electromagnetic force. These maglev systems are open-loop unstable; feedback controllers are necessary to achieve stability and desired performance. Moreover, these systems are nonlinear, because of inherent nonlinearities associated with the electromagnetic field. To develop a controller, models of these systems are generally linearized about an operating point, and then regulator-type feedback controllers are designed based on the root locus or frequency response shaping techniques. The most popular controllers are the classical PID or lead-lag compensators. Linear quadratic control with a Kalman filter for state estimation, sliding mode control, as well as backstepping methods have also been investigated.

Scope

Magnetic levitation devices are used in courses at the authors' respective institutions. At RPI, maglev devices are an integral part of the undergraduate mechatronics course (Green, *et.al.*, 1995). At

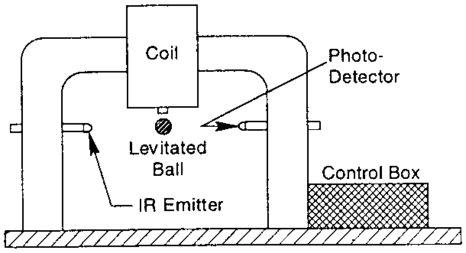

Figure 1. Magnetic Levitation Device

Georgia Tech, maglev devices are used in controls courses as well as part of the design experience. At Marquette, students use maglev devices in the laboratory part of the course "Mechanical Measurements & Instrumentation" where they make measurements of the coil temperature as different objects are levitated. They also learn about automated data acquisition via LabVIEW, with Virtual Instruments to record coil current and temperature (determined from thermistor resistance calculations.)

This paper describes the development, basic operation, and use of a tabletop maglev device in undergraduate engineering programs. It is our contention that the maglev device serves as an excellent educational testbed enhancing the experimental experiences of engineering students, exciting them with the power of control, and exposing them to mechatronic systems.

EXPERIMENTAL APPARATUS

Overview of Physical System

The physical system consists of three primary components: the sensor, the actuator, and the controller.

The sensor system is an infrared (IR) emitter-photodetector pair. A constant voltage is sent to the IR emitter, which sends out a beam of infrared light that is detected by the photodetector. The photodetector acts equivalently to a variable resistor. The output of the photodetector is directly proportional to the amount of infrared light it receives. As the amount of detected light increases (which can occur as the levitated object falls), the photodetector output increases, and vice versa.

Whereas the sensor is the photodetector, the actuator is the electromagnet. By proper adjustment of the current to the coil an electromagnetic field is created enabling levitation of a ferrous object. The electromagnet typically consists of a coil of copper wire wrapped around a steel core.

The controller uses the sensor signal as feedback to adjust the current in the electromagnet to levitate the object. The controller circuit implements a feedback network that provides the controls logic. Both analog and digital controllers can be implemented.

Principle of Operation

The photodetector output voltage is relatively low, and must be amplified to drive a power transistor for generating current to the coil. This is accomplished by a (non-inverting) operational amplifier (op-amp). The op-amp also serves a buffering function, minimizing loading effects. Other components in the circuit, resistors and capacitors, are used to implement the controller, making it possible to achieve stable and robust levitation with this device. One successful strategy is a *lead compensator*. The design of the compensator is discussed later in the paper.

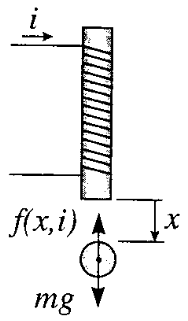

Figure 2. Free-Body Diagram of Maglev Testbed

The amplified signal from the op-amp is the input to the base of a power transistor. (A power transistor is required to achieve high coil current needed to levitate objects.) The base current controls the output of the transistor. If the base signal is sufficiently small, the transistor will be shut off, and there will be no output voltage or current. A variable resistor is used to fine-tune the gain of the op-amp. Because no two circuit components are exactly alike, the input to the base of the transistor must be finely tuned so that stable levitation is possible; otherwise the levitated object might oscillate in, or fall out of, the magnetic field under the coil. A diode in parallel with the coil protects the power supply from back-emf in the coil.

The principle of operation is as follows. The photodetector output is directly proportional to the amount of IR light it senses. If there is no object under the coil, the photodetector output will be at its maximum value with the detector fully sensing the light coming from the emitter diode. The photodetector signal is amplified and sent to the base of the transistor, which allows current to flow through the transistor and into the coil. When a ferrous object is placed under the coil, the magnetic field draws the object toward it. As this happens, the object starts to block the IR light sensed by the photodetector. This causes the output of the detector to decrease until the signal it is sending to the base of the transistor is so small that the transistor is shut off. The current through the coil then decreases, the object falls, the detector begins to sense more light from the emitter and its output increases so that the transistor is turned on and the coil begins to pull the object upward again. This cycle repeats itself over and over again. As noted before, the variable resistor in the circuit is used to fine-tune the switching process so that it appears as though the ball is floating (levitating) in midair. If the resistance changes slightly, oscillations in the motion of the object can be seen.

Construction of Prototype

Recently, several articles in the popular press (Cicon, 1996; Williams, 1996) have described construction projects involving maglev devices. These articles present the plans, including the circuit diagram for the controller, for a hobbyist to build a maglev testbed. Another source of information is a hardware design project reported in (Shahian and Hassul, 1993).

Magnetic levitation can be demonstrated using an actual physical device that is portable, *i.e.*, small (<30cm high) and lightweight, and visually-appealing. The physical structure of the device consists of a stand into which is mounted both the electromagnet and the sensor. At RPI the stand consists of standard aluminum stock, a square base plate and three machined aluminum rectangles. The structure for the maglev device at Marquette is made from PVC pipe and various PVC fittings, forming an inverted U, mounted on a wooden base. The electromagnet is mounted in the top center of the structure, and the position sensors are mounted within the legs.

The electromagnet can be obtained inexpensively from surplus suppliers, or constructed in-house by winding copper wire around a standard steel shoulder screw. (At RPI the electromagnet is made by spinning a standard ¼-20 alloy steel screw on a lathe while 26 gauge copper wire is fed in even layers of approximately 3000 windings.) The IR sensor as well as electronic circuit components are readily available at neighborhood electronic supply stores.

At each of our institutions, maglev devices have been constructed as part of undergraduate student projects. We believe there is pedagogical advantage to having students involved in the construction of these devices. Maglev devices are also available commercially, and come complete with fully debugged hardware and control software.

Maglev Modeling

A free-body diagram of a maglev device levitating an object of mass m vertically in a gravity field is depicted in Figure 2. The magnitude of the force f exerted across an air gap x by an electromagnet through which current i flows is described by

$$f(x,i) = -\frac{i^2}{2}\frac{dL(x)}{dx} \qquad (1)$$

where the total inductance L

$$L(x) = L_l + \frac{L_0 x_0}{x} \qquad (2)$$

consists of L_l, the inductance of the electromagnet (coil) in the absence of the levitated object, and L_0, the additional inductance contributed by its presence. The parameters are characterized by the geometry and construction of the electromagnet, and can be determined experimentally. Equation (1) results from the direct application of Ampere's circuit law and Faraday's inductive law.

Substituting equation (2) into (1) yields

$$f = \frac{L_0 x_0}{2}\left(\frac{i}{x}\right)^2 = C\left(\frac{i}{x}\right)^2 \qquad (3)$$

where $C=L_0x_0/2$ can be determined experimentally. The force equation can be linearized to obtain

$$f = C\left(\frac{I_0}{X_0}\right)^2 + \left(\frac{2CI_0}{X_0^2}\right)i - \left(\frac{2CI_0^2}{X_0^3}\right)x \qquad (4)$$

where I_0 and X_0 are the equilibrium values, and i and x are now incremental variables. At equilibrium, the gravitational force is balanced by the magnetic force on the levitated object, f_0, which is the first term on the right hand side in equation (4). The incremental magnetic force required to maintain equilibrium, f_l, is

$$f_l = \left(\frac{2CI_0}{X_0^2}\right)i - \left(\frac{2CI_0^2}{X_0^3}\right)x \qquad (5)$$

where $f_l = f - f_0$ is the force to be controlled.

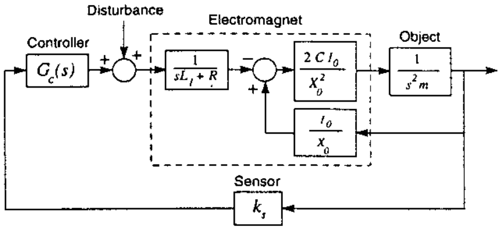

Figure 3. Block Diagram of Maglev System Model

The voltage-current relationship for the electromagnet, modeled as a series combination of a resistor and inductor, is

$$v = Ri + L(x)\frac{di}{dt} \qquad (6)$$

Under the assumption that the levitated object remains close to its equilibrium position, then $x=x_0$, and thus $L(x)=L_l+L_0$. By additionally assuming that $L_l >> L_0$, equation (6) can be written

$$v = Ri + L_1\frac{di}{dt} \qquad (7)$$

The governing equation for the levitated object is determined by application of Newton's second law. For the one degree-of-freedom system, a force balance yields

$$m\frac{d^2x}{dt^2} = -f_1 \qquad (8)$$

The sensor can be modeled as a simple gain element

$$v_s = k_s x \qquad (9)$$

where v_s is the sensor output voltage, and k_s is the experimentally derived gain between the object's position and the output voltage.

From the equations above, the overall transfer function between the input voltage to the electromagnet and the output voltage of the sensor can be determined.

$$G(s) = \frac{V_s(s)}{V(s)} = \frac{-2k_sCI_0/mL_lX_0^2}{(s+R/L_l)(s^2 - 2CI_0^2/mX_0^3)} \qquad (10)$$

A block diagram of the maglev system model, showing feedback compensation, is shown in Figure 3. A mathematical model of the system is developed in more detail by Green, *et.al.* (1995).

MAGLEV EXPERIMENTS

Using a maglev testbed many important topics can be addressed, including the instability of a dynamic system (since the maglev device is open-loop unstable), the nonlinearity of the dynamic system model (since the electromagnetic force is a nonlinear function of current and gap), the identification of parameters, the requirement for feedback control to achieve stability and desired system performance, measurement of position (achieved indirectly via optical means), etc.

Our experience has been that the testbed generates student excitement and interest. There is a natural fascination with a device that seemingly defies gravity. (Some have referred to the device as an anti-gravity machine.)

Physical System Modeling

As a physical system for use in controls education the maglev testbed offers many advantages: the motion can be modeled as occurring along a single axis, the testbed provides an example of linearization about an operating (equilibrium) point, the testbed is open-loop unstable motivating the need for closed-loop control to achieve stability, the system is an integrated electromechanical system. (Typically, the only coupled system students see is an electric motor.) Balancing the advantages is the disadvantage of a small range of operation (vertical adjustment) for the system, which can limit the visualization of control.

Analog Control Experiments

The uncompensated root locus is shown in Figure 4 for a particular maglev system design. The plot shows the positive open-loop pole, and demonstrates that the system cannot be stabilized by simply increasing the system gain. One approach to stabilize the system, that is, to move the root locus into the left hand plane, is to augment the system with a lead compensator. A zero is added in the left-hand plane between the first left-hand plane pole and the origin, and a pole, necessary for controller realization, is added deeper into the left-hand plane.

Figure 5 portrays the compensated root locus for a particular lead compensator design. It indicates that the system will be stable only for a limited range of gains. Figure 6 shows the circuit schematic of a lead compensator. An active compensator isolates the controller from the system and eliminates loading effects. Having students test controllers using both active and passive designs provides an opportunity to study loading (coupled impedance effects).

Many additional experiments can be conducted, including explorations of different compensators, such as PID controllers as well as more advanced controllers, and determining the sensor characteristics (time constant). The power of simulating different controllers and then implementing them offers students a real-world testbed to understand the implications of their designs.

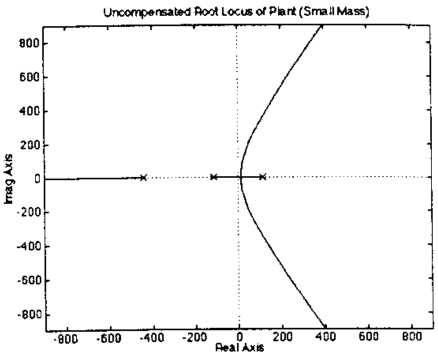

Figure 4. Uncompensated Root Locus

Digital Control Experiments

While the maglev system is especially useful in teaching undergraduate classical (continuous) controls courses, it also an effective platform in a digital controls course as well. There are several approaches in digital controls curricula that have been used in conjunction with the maglev system; the two most important ones are quantization and effects of sampling frequency. For this system, quantization is typically not of significant interest due to the target's small range of motion. For example, if the sensor full range is 4 mm and a 12 bit A/D board is used, then the resolution (quantization value) of the system is slightly better than 1 μm. This is far higher resolution than is needed to control the system. To make quantization a significant issue, the word size of the A/D board can be artificially reduced to a lower number of bits. The sampling frequency is another system variable that can be analyzed with the set-up. As the smallest system time constant is on the order of 100 ms, sampling

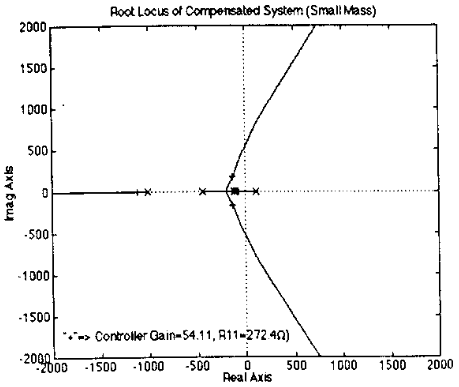

Figure 5. Compensated Root Locus

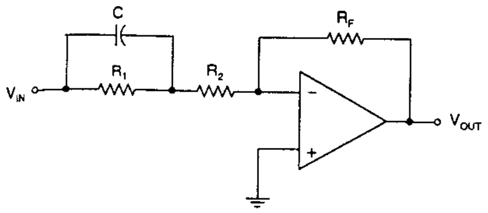

Figure 6. Analog Control Circuit

rates of 1 kHz or higher will permit the student to design the controller using continuous design tools, exclusively, and then map directly to a digital implementation. However, at lower frequencies (approximately 500 Hz) it can be seen that such an approach will not work as the continuous system is no longer a reasonable approximation of the discretized system. In these cases control design must be implemented using digital control tools.

Other Experiments

Other experiments can conducted using the maglev system to demonstrate various engineering principles. These include:

- **Basic concepts in statics** can be presented by conducting center of mass experiments with objects of different shapes and mass distributions. A variety of ferrous components, washers, screws, etc. as well as balls of different diameters can be suspended in the system. (At Marquette a AA battery is levitated; this is effective since the rotation about the long axis can be observed.)

- **Efficiency** measurements on the system can be made by measuring current required to maintain stability, heat dissipation associated with wire resistance and component heating, and total power loss.

- **Modulation of stiffness and damping** can be accomplished using closed-loop control. Tests that involve the measurement of force, displacement, and equivalent stiffness of levitated object demonstrate this effect.

- **Sensor identification experiments** can be performed to determine the relationship between the sensor voltage and the position of an object in the gap beneath the electromagnet. (To determine the characteristic of measured sensor voltage as a function of object position, a rig may be constructed to vertically adjust the object position.)

- **Transistor parameter identification experiments** can be conducted. In one experiment the goal is to determine the values of the DC current gain of the power transistor and the equilibrium current at the base of the transistor which is necessary to levitate the object at the desired gap size. In another experiment, the goal is to determine the validity of the current-amplifier model for the transistor.

- **Experiments to determine constants** can be conducted to determine the coil resistance and inductance, sensor gain, the control constant, etc.

- **Frequency response experiments** can be performed by direct measurement of voltage (control voltage over sensor voltage).

SUMMARY

This paper describes the use of a magnetic levitation device as a testbed for studying modeling, stability, controller design, and other system dynamic performance issues. The control objective is to keep a ferromagnetic object suspended in midair by controlling the current through an electromagnet. The electromagnetic force must be adjusted to counteract the weight of the object and account for disturbances. This may be accomplished by sensing the location of the object and controlling the current in the electromagnet in order to maintain the object at a predetermined location.

Maglev testbeds have been used successfully in undergraduate and graduate courses in feedback controls, mechatronics, and mechanical measurement & instrumentation. They are an effective teaching aid, both as a demonstration device in the classroom as well as part of laboratory training related to controller design. They offer insights into concepts such as stability, robustness, sensitivity, as well as limitations of linear approaches applied to an inherently nonlinear system. They teach students the importance of integrated electromechanical design. They are a real-world example demonstrating the power of closed-loop control, which is the secret behind the stunning presentation of an object that seems to defy gravity!

ACKNOWLEDGMENTS

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