AC 2007-345: MAGNETIC LEVITATION SYSTEMS USING ANALOG AND DIGITAL PHASE-LEAD CONTROLLERS

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Magnetic Levitation Systems Using Analog and Digital Phase-Lead Controllers

Abstract

This paper addresses real-time magnetic levitation control with analog and digital controllers. The objective is to keep a ferromagnetic object suspended, without contact, beneath an electromagnet. The electromagnetic force must be adjusted to counteract the weight of the object and account for disturbances. This is accomplished by measuring the location of the object using a non-contact sensor, and adjusting the current in the electromagnet based on this measurement in order to maintain the object at a predetermined location. The system is both inherently nonlinear and open-loop unstable. Negative feedback and phase-lead controllers are designed to stabilize this magnetic levitation system. The controllers are designed using MATLAB. Analog controllers are implemented using resistors, capacitors, and operational amplifiers. Digital controllers are implemented using the TMS320C6711 DSK. In the case of digital controllers, controller coefficients are included in a C language program that implements the phase-lead controller. The Code Composer Studio that came with the TMS320C6711 DSK is then used to compile the C program and load it to the C6711 DSK. Both one-dimensional and two-dimensional systems are built and successfully tested. Theses maglev control systems (non-linear, open-loop unstable) are good examples to complement the DC motor control system (linear, open-loop stable) currently taught in many control systems courses in electrical and mechanical engineering majors. Combined with the new DSP technologies, this will make the control systems courses more exciting. On the other hand, adding another application in control to the DSP (or signals and systems) courses will make theses seemingly theoretical courses more interesting. With a good understanding of the C6711 DSK, Students can then use the newest DSP technologies to explore other applications.

1. Introduction

Control theory is one of the major areas in electrical engineering. This author has been teaching control systems courses for the past 18 years and has seen most control systems text books using the classical DC motor control as primary examples and laboratory projects. On the other hand, many new and challenging control systems are emerging and one of them is the magnetic levitation (maglev) system. Maglev train systems have been built in Japan, Germany, and recently in Shanghai, China. The one in China can reach a speed of 430km/h (268mi/h) [1]. At this speed, a maglev train could match gate-to-gate air-travel time on routes of less than 1000 km. Compelling advantages of maglev train include susceptible to weather delays (than flying), quiet ride since it is a non contact system, and environmentally friendly. The Shanghai maglev line is the first of several maglev projects planned for later this decade, including those in Munich (Germany), Pittsburgh, and Baltimore-Washington, D.C. Still more maglev projects are under study, including Las Vegas-Los Angles, Los Angles-Palmdale, and Atlanta [1]. Other applications in the research stage include maglev propulsion to launch aircraft from carriers and maglev booster-assist for space shuttle launching [1]. Another related area of major development is digital signal processing (DSP). DSP is one of the most rapidly advancing areas in electrical engineering and DSP technologies are being used widely in control, communication, image processing, speech coding, parallel processing, instrumentation and testing, and much more [2,3,4]. There is clearly a need for students in control systems course in electrical engineering to be exposed to these new technologies and systems. According to a report from the Coordinated Science Laboratory at University of Illinois [5], "there is a strong need for curriculum reform in undergraduate systems and control engineering education. Moreover, it is the responsibility of the entire control engineering community to undertake this reform and to develop curricular materials to support it." The reason for the need is that "most engineering curricular provide opportunity for undergraduates to be exposed to control engineering through only a single course… with a focus primarily on analysis and design of linear time-invariant systems. This course often does not convey to students the wide applicability in virtually every engineering discipline, or their wide ranging impact on modern society." The report went on to say that "in light of this, a core control course should introduce the student to a set of credible and progressively more challenging control problems in a context encompassing not only the control design, but also specifications for its software/hardware implementation." Therefore we need to "encourage the development of new courses and course materials that would significantly broaden the standard control systems course at the undergraduate level."

Motivated by the above two reasons and with the support in part by the National Science Foundation, this author successfully developed and tested one- and two-dimensional maglev systems using analog and digital controllers. The objective is to keep a one- and two-dimensional ferromagnetic object suspended, without contact, beneath an electromagnet. The electromagnetic force must be adjusted to counteract the weight of the object and account for disturbances. This is accomplished by measuring the location of the object using a non-contact sensor, and adjusting the current in the electromagnet based on this measurement in order to maintain the object at a predetermined location. The system is both inherently nonlinear and open-loop unstable. Negative feedback and phase-lead controllers are designed to stabilize this magnetic levitation system. The controllers are designed using MATLAB. Analog controllers are implemented using resistors, capacitors, and operational amplifiers. Digital controllers are implemented using the TMS320C6711 DSK. In the case of digital controllers, controller coefficients are included in a C language program that implements the phase-lead controller. The Code Composer Studio that came with the TMS320C6711 DSK is then used to compile the C program and load it to the C6711 DSK.

In Section 2, the one-dimensional maglev system is discussed, followed by the two-dimensional maglev system in Section 3. Conclusion and future projects are given in Section 4.

2. One Dimensional Magnetic Levitation System

The one-dimensional maglev was constructed and successfully tested with both an analog and a digital controller. In order to avoid repetition, only the system with an analog controller is discussed here. In the next section, the two-dimensional maglev system with a digital controller is discussed.

The schematic diagram of the system is shown below:

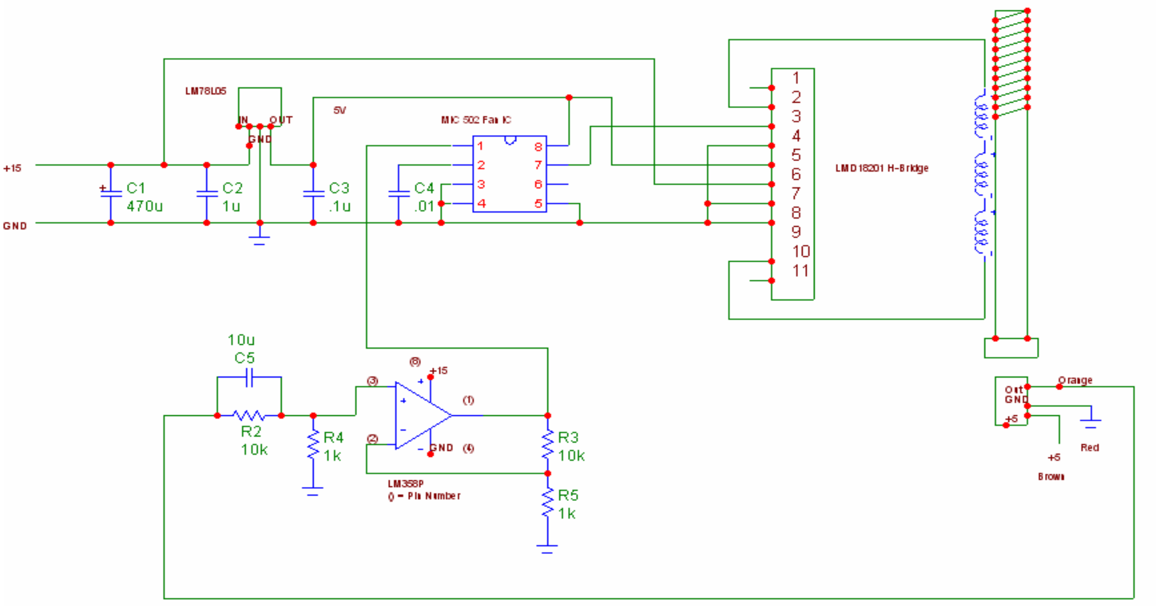

Fig.1. Schematic of the one-dimensional maglev system

The system is a modification of the one in [6] and has the following major components:

Position Sensor

A servo system requires feedback from a position sensor. In this approach a Hall Effect sensor is used with an output that is proportional to the magnetic flux. This means that the closer to a magnet it gets, the greater the signal it produces. The output of this simple three-leaded device is at 50% of a single 5VDC supply in the absence of a nearby magnet. A magnet with a north pole facing the sensor will drive the output in one direction while a south pole will drive it the other way. This produces an ideal servo proportional control signal.

PWM Control

The electromagnet is driven by a PWM (pulse with modulation) signal. This is a scheme mostly often used to control the speed of a DC motor. A repeating pulse changes its width to apply more or less power to the device over time. The pulse frequency is set by a capacitor.

Electromagnet Driver

The electromagnet driver should work to achieve a balance of push-and-pull. If the suspended object gets too close to the electromagnet, the electromagnet should push it away. Conversely if it falls too low the electromagnet should work at pulling it back up. The LM1820 driver chip has a built-in H-bridge that can reverse polarity of its output and is perfect for this application.

Analog Phase-Lead Controller

The system is open-loop unstable and a phase-lead controller is needed to increase the phase margin of the system to stabilize it. The open-loop transfer function of the system can be found using the Bode diagram approach to be $G_p(s) = \frac{6.82\times10^7}{s^2 - 8.47\times10^3}$, with its root locus plot given in Figure 2.

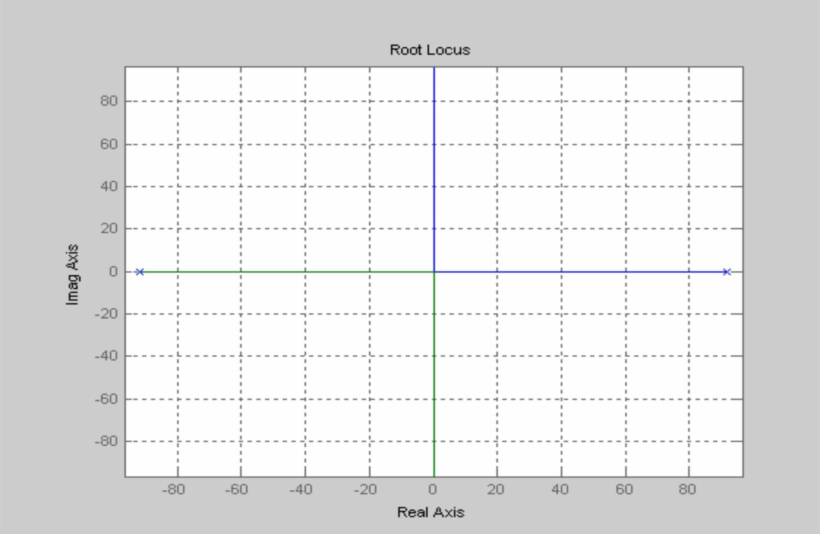

Fig.2. Root locus plot of the system without a controller

It is clear that the because of an open-loop pole located on the right hand side of the s-plane, the system is marginally stable at best. A phase-lead controller is needed to bring the root locus into the stable region. The controller includes a phase-lead RC network and an op-amp circuit. With the RC values given in Figure 1, the controller transfer function is $G_c = \frac{s+10}{s+110}$. The root locus plot of the system with the controller is given in Figure 3.

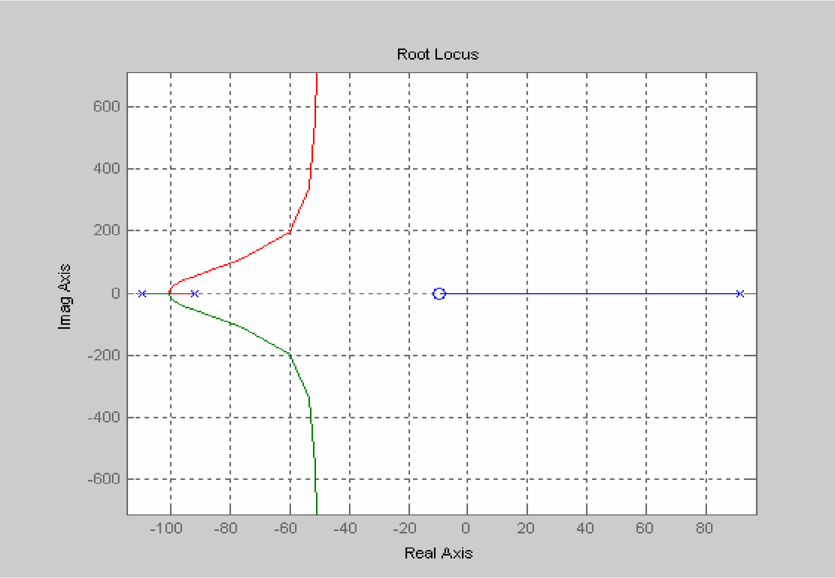

Fig.3. Root locus plot of the system with a phase-lead controller

As can be seen in Figure 3, all three closed-loop poles can be found on the left hand side of the complex plane and the system becomes stable with the phase-lead controller added. The system works as expected. Figure 4 shows the actual system with the controlled object floating.

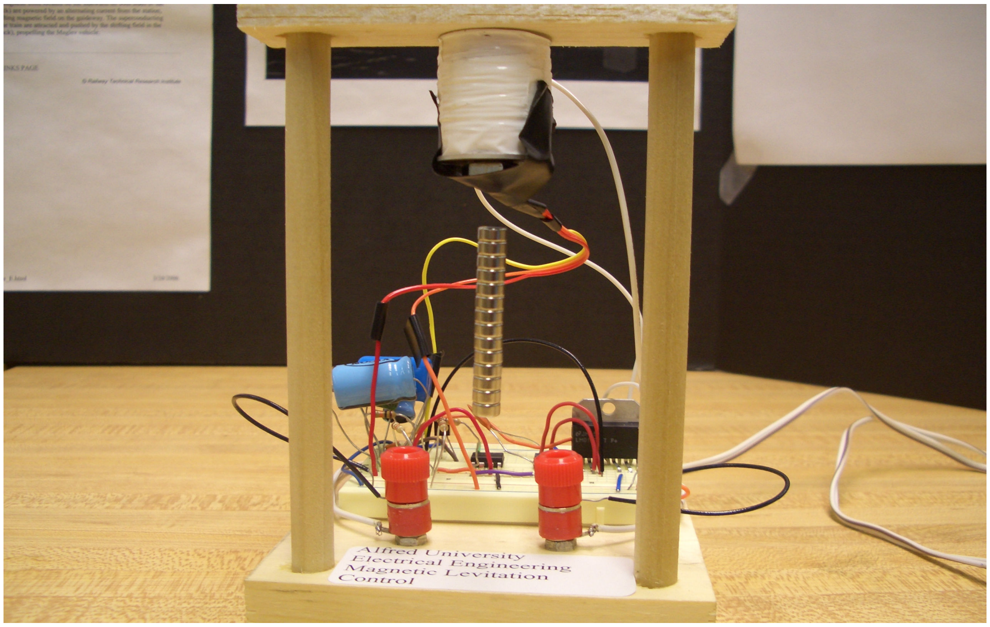

Fig. 4. The one-dimensional maglev system.

The system is used as an example in the Control Systems course at Alfred University to teach system modeling, transient responses analysis, root locus methods, and frequency response analysis. Since the system is relatively simple and easy to build, it was also used as lab in the freshman lab class ELEC100 Discoveries Labs. A total of 20 such systems were successfully built. Below is a picture of the lab:

Fig.5. Students in the Discoveries Labs class building the maglev system.

3. Two-Dimensional Magnetic Levitation System

A two-dimensional maglev system was built and successfully tested. The one with an analog controller was similar to the one-dimensional system and hence is omitted here. The system with a digital controller is described below. Following is a block diagram of the system under consideration

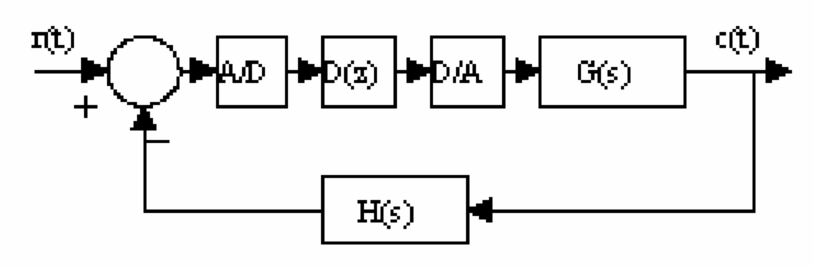

Fig 6. Block diagram of the maglev system with digital controller

In Figure 6, r(t) is the input (or set point), c(t) is the output, D(z) is the digital controller, G(s) is the maglev system transfer function, and H(s) is the sensor transfer function. A digital phase-lead controller has the following form [7]:

$$D(z) = \frac{a_0 + a_1 z^{-1}}{1 - b_0 z^{-1}} \qquad (1)$$

For programming convenience, let

$$D(z) = D(z)\frac{M(z)}{M(z)} = \frac{Y(z)}{X(z)}$$

where X(z) and Y(z) are the input and output of the controller in the z-domain, respectively, then

$$Y(z) = (a_0 + a_1 z^{-1})M(z) \tag{2}$$

and

$$X(z) = (1 - b_0 z^{-1})M(z)\,. \tag{3}$$

Using the inverse z-transformation,

$$y(k) = a_0 m(k) + a_1 m(k-1) \tag{4}$$

and

$$m(k) = x(k) + b_0 m(k-1)\,. \tag{5}$$

The implementation of the controller using the C6711 DSK is described as follows.

The C program to implement the phase lead controller is shown in Fig. 7. Controller coefficients a_0, a_1, and b_0 in equations (4) and (5) are calculated using MATLAB and stored in a separate coefficient file "phase_lead.cof" and is included in the C program. The input sample is then processed according to equations (4) and (5). One of the features of the C6711 is that it can perform multiplication and addition/subtraction in parallel. This is especially suitable for processing difference equations such as in (4) and (5). An output signal y(k) is generated and the delays m(k) are updated. Continuous processing takes place within a loop starting at the label ISR in the program in figure 7. Initial delays are set to zero in the statement with "short dly". The sampling frequency is fixed to be 8 KHz in the C6711 DSK. The designed phase-lead controller *D*(z) has the following parameters:

$$D(z) = \frac{1.0000 - 0.9901z^{-1}}{1.0000 - 0.9891z^{-1}}$$

The stable system is shown in Figure 8.

```
//Phase_lead controller using the IIR structure
//Coefficients a's and b's from MATLAB

#include "phase_lead.cof"              //Controller coefficient file
short dly[stages][1] = {0};    //delay samples per stage

interrupt void c_int11()       //ISR
{
 int i, input;
 int un, yn;

 input = input_sample();     //input signal
 for (i = 0; i < stages; i++)
  {
   un=input-((b[i][0]*dly[i][0])>>15) - ((b[i][1]*dly[i][1])>>15);

   yn=((a[i][0]*un)>>15)+((a[i][1]*dly[i][0])>>15)+((a[i][2]*dly[i][1])>>15);

   dly[i][1] = dly[i][0];        //update delays
   dly[i][0] = un;            //update delays
   input = yn;                           //intermediate output
  }
   output_sample(yn);         //output final result for time n
   return;                               //return from ISR
}

void main()
{
  comm_intr();               //init DSK, codec, McBSP
  while(1);                                      //infinite loop
}
```

Fig.7. C program for the digital phase-lead controller

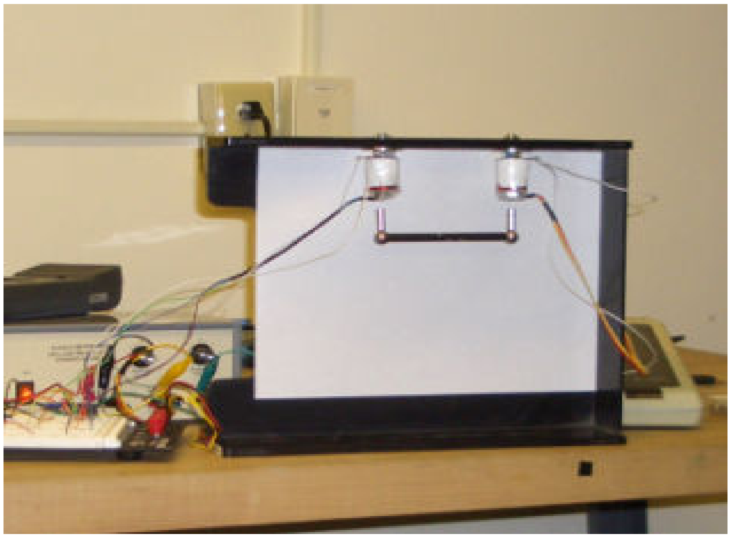

Fig.8. The two-dimensional maglev system.

4. Conclusion and Future Project

Low cost one- and two-dimensional magnetic levitation systems are built and successfully tested. The maglev control systems (non-linear, open-loop unstable) are good examples to complement the DC motor control system (linear, open-loop stable) currently taught in many control systems course in electrical and mechanical engineering majors. Combined with the new DSP technologies, this will make the control systems courses more exciting. On the other hand, adding another application in control to the DSP (or signals and systems) courses will make theses seemingly theoretical courses more interesting. With a good understanding of the C6711 DSK, Students can then use the newest DSP technologies to explore other applications. Therefore, this project is not just about adding an isolated example into the existing courses, it introduces new ways how control and DSP courses can be taught, and will significantly impact the teaching of these two major electrical engineering and mechanical areas (control and DSP). The new materials can also be easily adapted by other institutions due to the low costs involved. Besides the C6711 DSK, the cost of the parts for each magnetic levitation system is less than $80.

One future project in mind is to build a three-dimensional maglev system. We plan to develop a system that forces a levitating magnet to slide along a series of solenoids through use of alternating magnetic fields. Here is a picture of the possible design:

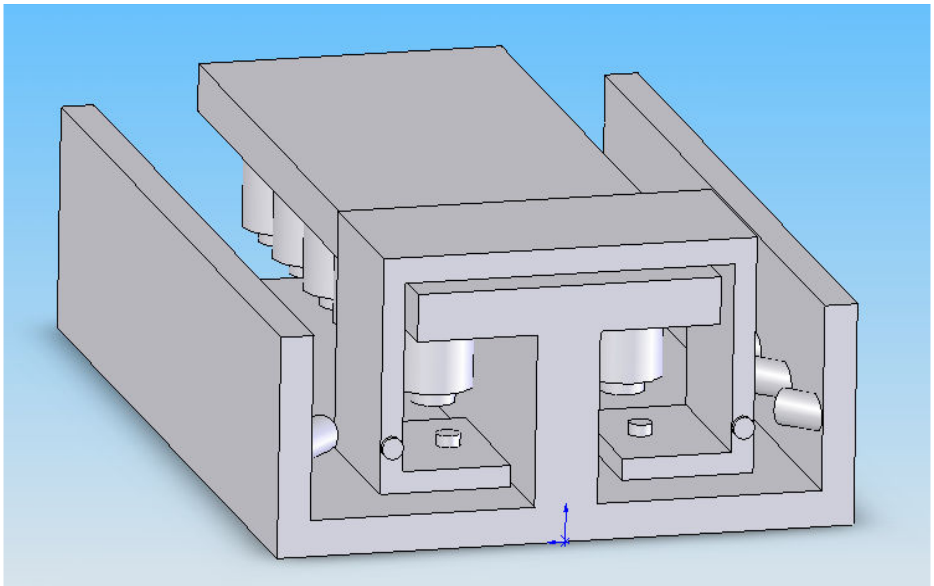

Fig.9. Possible design of a three-dimensional maglev system

We plan to finish this project by the end of 2007.

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