ME552 Fall 19 Lab 2: Magnetic Levitation System

Lab Assignment

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Lab 2 Guidelines:

I. Hardware demonstration deadline: October 4th, Friday, Mechatronics Lab Section

II. For the hardware demonstration, please demonstrate a working magnetic levitation system.

  a. You will also be evaluated for the quality of your bread-board circuit layout and wiring. Please do a clean job so that your circuit and wiring looks uncluttered and well organized.

  b. You will also be evaluated for the quality of your LabVIEW code. Again, both the front panel and the block diagram should be uncluttered and well-organized.

  c. You will also be evaluated on the robustness of your controller and system. This will be tested by using other objects such as bolts of varying weights; you will be allowed to change the bias voltage and controller gains for the demo.

III. Lab assignment submission deadline: October 4th, Friday, 9:00am on Canvas. The submission should be on Canvas only. You may want to keep a copy for your own records.

IV. There is ONLY ONE submission required per team. However, there are strict requirements placed on a fair contribution from each team member. Each person should contribute equally to the experiments and the written assignment. In particular, for the assignment each person of the team must be intellectually involved in each problem. You should not divide up the various questions among various members of team. Each team should discuss and work together on each component of the submission. At the time of assignment submission, each student will be required to turn in a confidential PEER EVALUATION under Quizzes section on Canvas. PEER EVALUATION for this assignment is due by 9:00am October 4th. Failure to submit peer evaluation will cause penalties to your individual score of lab 2.

V. Any questions/clarifications related this assignment should be posted on Canvas → Discussions → Lab 2: Magnetic Levitation System.

It is recommended to export the measured data into MATLAB and carry out the plotting using MATLAB (LabVIEW is powerful in data acquisition; MATLAB is powerful in data post-processing).

Questions (6 questions, Total 128 pts):

1. **Overall System Modeling (21pts)**

   The goal of this question is to develop a model for Mag-Lev hardware (driver, coil, ball, sensor, etc.).

   The Mag-Lev case study lecture slides introduce a basic model of the overall physical system. In this question, you will derive and present a detailed model of the OVERALL physical system encompassing all aspects such as the sensor, electronic circuits, actuator and driver, electromagnetic actuator, mechanical system, etc. (excluding the opto-electric aspects of the sensor). You can break down the overall physical system into smaller sub-systems as you see appropriate.

   a. **Assumptions.** For each sub-system, list all the key modeling assumptions and mathematical approximations (e.g. bias current is 0 for OpAmp) **(3)**. In your judgment as an engineer, justify these assumptions and approximations (e.g. in OpAmp circuit, operational current is on the order of 100μA, which is much larger than bias current level of 0.1μA; thus we can assume bias current to be negligible) **(3)**. Which of these are the most prone to breaking down, and why **(1)**?

   b. **Mathematical Model**. Provide a mathematical model for each sub-system based on your assumptions **(3)**.

   c. **Block Diagram**. Present a block-diagram (either hand sketched or drawn on a computer) of the closed-loop system. Show all the necessary details on the block-diagram: show feedback / feedforward path of control, label all blocks, label all connecting lines, and label all sources of disturbance / noise. **(3)**

   d. **Bias Voltage**. In your control system, what does the bias voltage signify - what is its physical meaning **(1)**? Is it part of feedback control or part of feedforward control **(1)**? Why is this bias voltage necessary for your control system to work as desired (what happens if you eliminate bias voltage from your control system)? **(1)**

   e. **Driver**. What should be the saturation limits on the analog output of your LabView VI? Provide justification. **(1)**

      Does the polarity of the electromagnetic coil matter in the current driver circuit? In other words, does it matter if you inverse the sign of analog output? Why or why not? **(1)**

      What is the maximum current that the electromagnetic coil could ever see if there are circuit failures, including short circuit and open circuit? Provide physical and simple mathematical arguments based on information available on datasheet. What considerations one should make in deciding the current limit for the coil? **(3)**

2. **Hardware and System ID (18 pts)**

   a. **Sensing Scheme.** In your model for the sensing scheme in part (a.), do you find the sensing scheme to provide a linear relation between the ball position and an output voltage signal? If this relation is non-linear, do you have to linearize the sensor response and assume linear behavior around the linearization point, to be able to use Linear Controls theory? Or is it possible to work with a non-linear sensor and still use Linear Controls subsequently without linearizing the sensor response **(5)**?

      Note that we are adding a buffer at the output of the sensor set-up; what's the purpose of adding such a buffer **(1)**? In your experiment, if we eliminate this buffer, is it going to affect the system? Why or why not? **(1)** Provide proper technical justification.

What is the minimum value of resistance you can use in the emitter circuit? Show your calculations. **(1)** Comment on how the resistance value affects the sensing performance (what's the effect if resistance value is too large / too small). **(1)**

b. **Linearization.** Linearize any non-linear components / aspects for each of your sub-system models above to obtain linear models for each sub-system (except for sensing scheme) **(2)**. Combine these sub-system models to derive a linear mathematical model for your OVERALL physical system **(2)**. Reduce this linear model to an LTI transfer function between an input and an output **(1)**. This represents your open loop plant transfer function.

c. **Parameter Identification.** Conduct "parameter identification" for any physical parameters that are "needed" in your non-linear and/or linear models. This would involve direct measurements or simple experiments to isolate a particular parameter or group of parameters that you are trying to estimate. In case of the linear model, this step will allow you to express your final open-loop transfer function in a numerical form. Please note that the parameter values provided in the lecture slides are from an older version of the experimental set-up and do not exactly correspond to your experimental set-up. For each parameter, briefly describe how you estimated the parameter **(3)**. List numerical values of all parameters in a Table **(1)**. Pay attention to the unit system.

3. **<u>Simulation (21 pts)</u>**

a. **Modeling in Simulink.** Next, create two Simulink representations of the overall physical system – one based on the modeling from part (a.) above, which may contain various kinds of non-linearity, and the other based on your linear model from part (b.). Choose the following Simulation parameters: Start time: 0, Stop time: 2 sec, Solver Type: Fixed Step, Solver: ode5. You will need the parameters from part (d.) above in these Simulink representations. Make sure Simulink block diagram is clean and readable. Show screenshots of your Simulink models. Show all details (do not just show a parent block without implementation details). Properly organize your screenshots to make sure the figures in your report are readable. Include all relevant screenshots under the appendix. **(8 for linear + 8 for nonlinear)**

b. **Linear / Non-linear Model Comparison.** Now run a few simulations in Simulink with various initial conditions, and compare the time-response predicted by the linear and non-linear models. Compare the output of these two models by plotting the ball displacement predicted by each on the same graph **(2)**. Investigate when and how the two predictions deviate **(2)**. This should provide you with some indication of how effective your "linearization assumptions" are. Briefly comment on this comparison and the effectiveness of these assumptions **(1)**.

4. **<u>Control System Design (20 pts)</u>**

The goal of this question is to design a controller in Simulink that you believe to work well. Based on the above derived linearized model of the open-loop physical system, design a Lead controller using the MATLAB function called sisotool. If you are new to this control system design tool/function, then use MATLAB's "Help" menu.

a. **Sign Convention.** Negative feedback is critical to stable control. Note your sign convention when modeling each sub-system in Question 1. Provide a block diagram to show how you are ensuring that the overall feedback loop in your above controller implementation provides a negative (or stabilizing) feedback **(3)**.

b. **Controller Design.** Design a Lead controller in sisotool. A Lead controller has following form:

$$C(s) = K\frac{s + z_1}{s + p_1}$$

which is essentially a PD controller plus a pole far from origin. Show root-locus plot with your Lead controller **(2)**. From this plot, pick and report the gain stability margin **(2)**. Now that you have designed a controller, what is the closed-loop transfer function for the overall system **(3)**? Provide a closed-loop bode plot of the overall system **(4)**. What is the expected closed-loop bandwidth **(1)**?

When designing a controller, there is NO universal rule that applies to all scenarios. However, you should always consider:

- Stability.
- S.S. Error. How much steady state error is allowed for your application? Is steady state error itself a hard requirement, or steady state error is only affecting other system properties (e.g. accuracy of model)?
- Lag. When designing a controller, you would like a large phase and gain margins for good stability. Note that there might be some physical limitations (e.g. loop rate) that would affect the phase of your system.
- Modeling Accuracy. There is always a gap between model and reality. What's not modeled? How is it going to affect stability and command tracking?
- Hardware Limitation.
    - Resolution of Analog Input, Analog Output, and Sensor. It is impossible to eliminate steady state error that is on the same level of sensor resolution. Similarly, AI and AO also limit how much steady state error you can eliminate.
    - Saturation. If your control signal is saturated, then the feedback loop is broken, and control signal might not be able to stabilize the system.

c. **Controller Performance Simulation.** Implement this controller in linear and non-linear Simulink models of the system (created in Problem 1 above). Using these, demonstrate a stable closed-loop time-response of the system **(3)**. You should start with a ball position that is slightly deviated from equilibrium (using an appropriate initial condition) and see if it comes back to the equilibrium position. You can then make this starting position further and further away from the equilibrium position and see if it comes back in the two cases. Observe and report any differences that you see between closed-loop response of the linear and the non-linear system models **(2)**. Provide images of the appropriate system response plots in answering this question.

5. Experiments (39 pts)

The goal of this question is to implement your designed controller on hardware, modify the controller parameters (if needed) to achieve stable and robust control, and evaluate controller performance.

a. **Controller Implementation**. Implement your designed controller on your hardware. Modify your controller (bias voltage, controller gains, location of pole / zero, add additional pole / zero, etc.) to its best performance (stability, robustness against disturbance). Show the mathematical expression of the controller you finally implemented on your hardware **(5)**. Include a picture of levitated ball that shows your controller is able to stabilize ball position **(5)**.

b. **Experiment vs. Simulation**. What are the differences (including form of controller and pertinent numerical values) between the theoretical controller designed by simulation and the controller that was implemented in the hardware? List all the differences **(1)**. Comment on reasons for possible differences **(2)**. Implement the controller that you used in your lab experiment on the linear and non-linear Simulink models, and show images of same response plots as in Question 2 part (c) **(2)**. Is there any observable difference when comparing with previous simulation **(1)**?

c. **Range of Operation.** Once you have ensured that the actual Mag-Lev system works in the lab (i.e. the ball levitates) for a given value of V_{bias}, experimentally determine the range of $V_{command}$ over which you can maintain or control the ball position **(3)**. This is done by simply changing the $V_{command}$ by small incremental values.

   Now run a similar exercise using your linear and non-linear Simulink model, and record range of operation. Do you see any agreement between the experimental observation and any of the two models? Please briefly comment on agreement / disagreement, and reasons behind **(3)**.

d. **Frequency Response.** Instead of sending a constant value for $V_{command}$ (Desired voltage in the labview program), use a sine signal with a small amplitude and a low frequency (e.g. 0.01 Hz). For this sinusoidal command input, measure the actual motion of the ball using your LabView VI and record the magnitude and phase (similar to what you did in Lab1). Now keep increasing the frequency in appropriate increments. Is it possible for some frequencies your closed-loop system might go unstable or stop responding to the command input? If so, what is the potential reason **(1)**? Record this experimental data (magnitude, phase, and possible instability) on a frequency plot – this is the experimental Bode plot of your closed-loop system **(10)**. How does this compare to such a plot derived from your linear theoretical model (see question 2, part (b.))? Comment on any discrepancies **(2)**.

e. **Robustness against Bias Voltage.** Bias voltage represents a feed-forward component of your controller. Feed-forward controller counters pre-known disturbance / pre-known kinematics so that feed-back controller better focus on stability and un-known disturbance. If your model is not accurate (e.g. you did not measure mass of ball accurately), then your feed-forward controller cannot cancel pre-known disturbance, and the error would be handled by your feedback controller (it acts as a disturbance for your feedback controller).

   Experimentally determine the range of V_{bias} over which you can maintain or control the ball position **(4)**. This represents your controller robustness against modeling error in feed-forward controller design.

6. Revisit Controller Design (9 pts)

The goal of this question is to revisit the lead controller $C_0(s) = K\frac{s+z_1}{s+p_1}$ in Question 2, and understand what would be the performance if we change it to different form. For following sub-questions, just give an answer based on your ME552 intuition, and you do NOT need to do any experiments (to save your time).

a. One of your colleague declares that: original controller $C_0(s)$ has the same performance as following PD controller

$$C_1(s) = K_P + K_D s = K(s + z_1)$$

Do you agree / disagree? **(1)** What if we implement this controller on hardware with very high sampling frequency (e.g. 1MHz), or implement the controller using a circuit with resistors, capacitors, and OpAmp (like what you did in Lab1)? **(1)** Briefly give your rationale **(1)**. (Hint: think about sampling frequency in your lab)

b. Suppose when implementing $C_0(s)$ on hardware, the ball position is just barely stabilized: a small knock on table would make it unstable. The same colleague suggests using a PID controller (plus a pole far from origin for noise attenuation) , so that the controller becomes

$$C_2(s) = \frac{K_P + K_I/s + K_D s}{s + p_1} = K\frac{(s + z_1)(s + z_2)}{s(s + p_1)}$$

The colleague declares that $C_2(s)$ would better stabilize ball position compared with original controller $C_0(s)$.

Do you agree / disagree? **(1)** If you agree, briefly give your rationale; if you disagree, briefly comment on instead of stability, what system performance is $C_2(s)$ more advantageous compared to $C_0(s)$. **(2)**

c. Suppose you figured out that the reason you were unable to stabilize ball position in part (b) is because of a bias in ball position estimation (e.g. an 1mm offset when calibrating the sensor), which leads to an error in force balance at operation point; this error causes a ball position too far from operation point; thus for $C_0(s)$ does not work properly. The same colleague suggests increasing overall loop gain K in $C_0(s)$ to reduce position error (which is steady state error were the system stabilized), which would compensate for modeling error of 1mm offset.

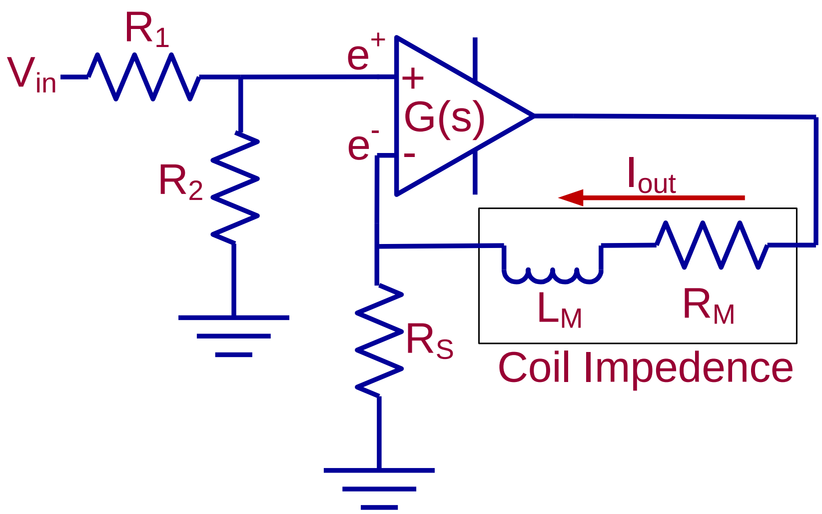
Please briefly comment on what are the potential problems / side effects when we increase loop gain K to reduce positional errors. **(3)**

(Non-Mandatory Question). Perform this question only if you have the time or interest. There is nothing to submit or report on this question and no credit for this question either.

Instead of implementing the Lead controller on your physical system (in the lab experiment) using National Instruments hardware and software (LabView) installed on a PC, design a physical controller using an op-amp circuit (like you did in Lab 1) and implement it on the physical system. In this scheme, there would be no LabView or external PC involved. Compare the performance and robustness of your software based controller (in LabView) versus your hardware controller (op-amp circuit on a breadboard). In your circuit, make sure that you either use ceramic capacitors; or otherwise if you use electrolytic capacitors, pay careful attention to their polarity while connecting to your circuit.

Additional questions to consider (maybe for future or replace some of the above with these)

1. In your experiment while working with a lead (or PD) controller, did you notice any steady state errors? If yes, redesign the controller by adding an integral action. This could either be a PID or a lead-lag controller. Using your modeling and simulation, first make sure that this controller is appropriate for you system. Once done, implement it on the actual physical system using your LabView VI and report your observations. Does this improve your steady state performance? You may have to tune your controller gains a bit to achieve optimal performance.
2. Suggest an alternative sensing scheme that may be used in the ball levitation experiment. Based on relevant sensor specifications such as range, resolution, bandwidth, noise, linearity etc.), find an off-the-shelf sensor. Provide the datasheet of the selected sensor and reasons justifying your selection.
3. Instead of implementing lead or lead-lag controller on your physical system using National Instruments hardware and software installed on a PC, design a physical controller using an op-amp circuit (like you did in Lab 1) and implement it on the physical system. In this scheme, there would be no LabView or external PC involved.
7. The gain of the current driver circuit shown below was derived in the lecture assuming ideal op-amp behavior.



$$\frac{I_{out}}{V_{in}} = \left(\frac{R_2}{R_1 + R_2}\right) \times \frac{1}{R_s}$$

The OP547 op-amp may be approximated as a damped second order system as shown below:

$$G(s) = \frac{A}{(s+a)(s+b)}$$

a. Choose appropriate values of the constants so that the transfer function approximates the open-loop gain and phase plot of OP547 provided in the datasheet. Provide the values of A, a, and b.
b. Calculate (measure/estimate) the nominal values of the resistance and the inductance of the coil.
c. Derive the loop-gain transfer function of the current driver feedback circuit. Provide the bode plot of the loop-gain transfer function and the corresponding gain margin and phase margin.

d. Derive the closed loop transfer function $I_{out}(s)/V_{in}(s)$. Provide the bode plot of the closed loop transfer function. What are the closed loop bandwidth and the closed loop DC gain? Is the bandwidth of the current driver sufficient for the ball levitation experiment?