Magnetic Levitation Experiment

Quanser Consulting
ADVANCED TEACHING SYSTEMS

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Quanser Consulting Inc.

1 Description

The “maglev” experiment consists of an electromagnet encased in a rectangular enclosure. One electromagnet pole faces a black post upon which a 2.54 cm steel ball rests. The ball elevation from the post is measured using a sensor embedded in the post. The post is designed such that with the ball at rest on its surface it is 14mm from the face of the electromagnet. The purpose of the experiment is to design a controller that levitates the ball from the post and the ball position tracks a desired trajectory.

2 Mathematical Model

2.1 Electrical system

The coil used in the electromagnet has an inductance and a resistance. The voltage applied to the coil results in a current governed by the differential equation:

$$V = i\, R_l + L \frac{di}{dt}$$

The ***actual system*** is equipped with resistor Rs in series with the coil whose voltage Vs can be measured using the A/D. The measured voltage can be used to compute the current in the coil. The sense resistor in the circuit results in the equation :

$$V = i\,(R_l + R_s) + L \frac{di}{dt}$$

The state space equations for the current is given by:

$$\begin{bmatrix} \dot{i} \\ \dot{\zeta}_i \end{bmatrix} = \begin{bmatrix} -\frac{R_l+R_s}{L} & 0 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} i \\ \zeta \end{bmatrix} + \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} V$$

we have introduced an integrator for the current ($\dot{\zeta}_i = i$)for reasons which shall become clearer in the control system design section.

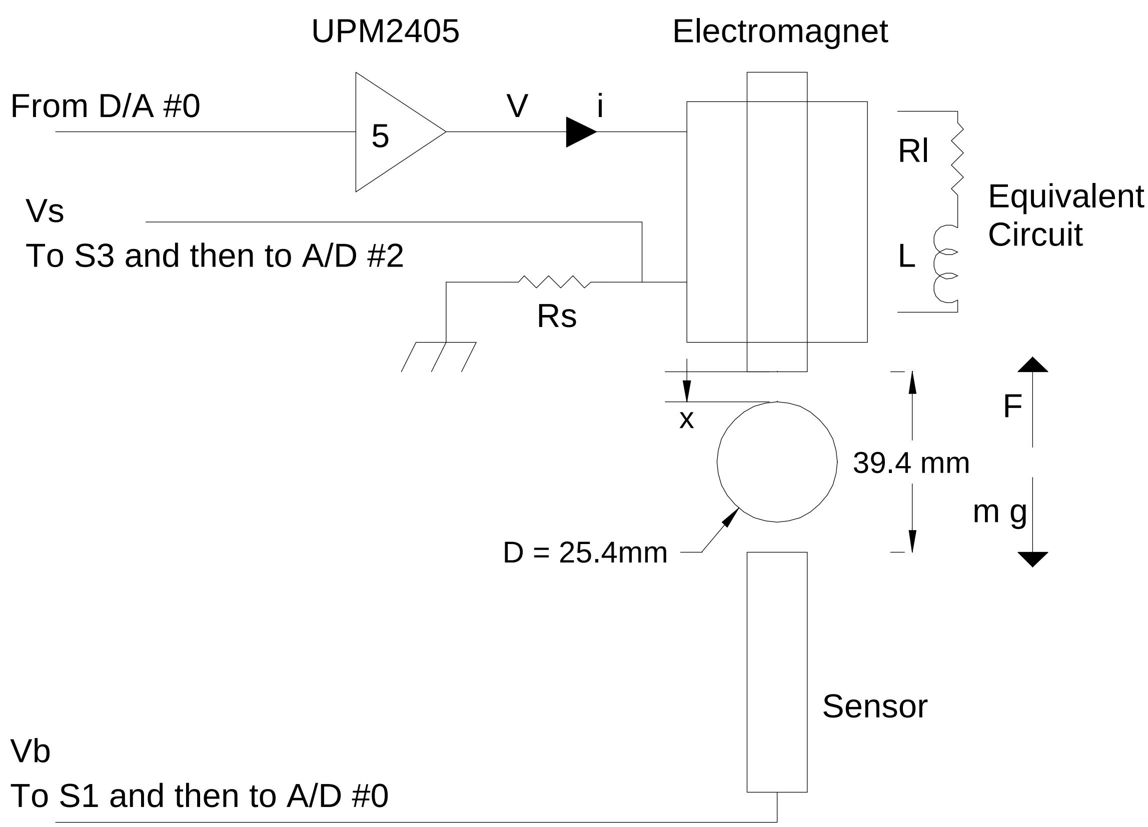
Note that the sense resistor is only 1 Ω compared to the coil's 10 Ω resistance. The relationship between the voltage measured across Rs is:

$$V_s = i\ R_s$$

then the current can be obtain from measuring Vs as:

$$i = \frac{V_s}{R_s}$$

and since Rs is 1 Ω then i = Vs.



2.2 Electro-mechanical System

The force experienced by the ball using the electromagnet is given by:

$$F = m\ g - G_i\ (\frac{i}{x})^2$$

where i is the current in Ampere, x is the distance from the electromagnet face in **mm** and g is in **mm/sec^2.**

This results in the following differential equation for the ball dynamics:

$$F = m\ g - G_i\ (\frac{i}{x})^2 = m\ \ddot{x}$$

G_i is the magnetic force constant for the electromagnet/ball pair and **m** is the mass of the ball in Kgms

linearizing about a quiescent point (i_0 , x_0) we obtain the equations:

$$\ddot{x} = \frac{2\ G_i\ i_0^2}{x_0^3\ m}\ x - \frac{2\ G_i\ i_0}{x_0^2\ m}\ i$$

which in state space form becomes:

$$\begin{bmatrix} \dot{x} \\ \ddot{x} \\ \dot{\zeta}_x \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ \frac{2\ G_i\ i_0^2}{x_0^3\ m} & 0 & 0 \\ 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} x \\ \dot{x} \\ \zeta_x \end{bmatrix} + \begin{bmatrix} -\frac{2\ G_i\ i_0}{x_0^2\ m} \\ 0 \\ 0 \end{bmatrix} i$$

3 Control System Design

In order to control the ball position, we need to control the current in the electromagnet.

The electromagnet control loop is designed using the equations:

$$\begin{bmatrix} \dot{i} \\ \dot{\zeta}_i \end{bmatrix} = \begin{bmatrix} -\frac{R_l+R_s}{L} & 0 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} i \\ \zeta \end{bmatrix} + \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} V$$

The current is measured using a 1 ohm resistor in series with the coil. By wiring the system to the A/D, S3 on the amplifier will measure the voltage Vs across the sense resistor. The current is given by Vs/ Rs.

In order to track a desired current, the current control loop is designed using the feedback:

$$V = kip\ (i-i_c) + kii\int (i-i_c)$$

The gain are obtained by using the linear quadratic regulator. The open loop model for current is:

$$\begin{bmatrix} \dot{i} \\ \dot{\zeta}_i \end{bmatrix} = \begin{bmatrix} 0 & -26.6 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} i \\ \zeta \end{bmatrix} + \begin{bmatrix} 2.42 \\ 0 \end{bmatrix} V$$

```
q = diag([100 100])
r= .01
```

This results in the gains:

ki = [100.3   89.6] for the current loop.

The closed loop eigenvalues for the current loop are: **-242.3 and -1.0**

For the ball position control loop the open loop state space equations are:

$$\begin{bmatrix} \dot{x} \\ \ddot{x} \\ \dot{\zeta}_x \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ 2800 & 0 & 0 \\ 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} x \\ \dot{x} \\ \zeta_x \end{bmatrix} + \begin{bmatrix} -19600 \\ 0 \\ 0 \end{bmatrix} i$$

Using lqr in MATLAB and

```
q = diag([1 .1 1])
r =4500
```

results in the gains:

k = [-0.2872 -0.0072 -0.0149]

The closed loop eigenvalues are: -24.18 -116.4 -0.10

In order to implement the controller two loops are implemented:

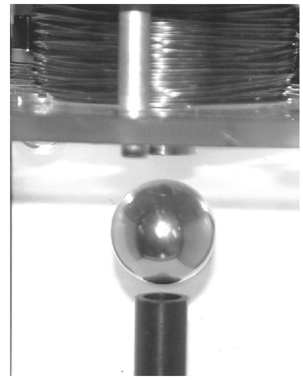
$$i_c = k(1)\ (x - x_c) - k(2)\ \dot{x} - k(3)\ \int (x - x_c)$$

where x is the ball position in mm and xc is the commanded ball position in mm. This loop generates a commanded current ic for the current control loop which is implemented as:

$$V = ki(1)\ (i - i_c) - ki(2)\ \int (i - i_c)$$

where i is the measured current and ic is the current commanded by the ball position loop.

4 Implementation and results



The system is implemented using Simulink and WinCon.

The controller is in the file **q_maglev.mdl**. It is ready to run using WinCon by loading q_mqglev.wcl or **q_maglev.wcp**.

Place the ball on the black post. Wire up the system as described and power the amplifier up. The two lights should go on inside the chamber. Start WinCon and load **q_maglev.wcp**. Click start. This should levitate the ball to midway as shown in the photo across. Click Stop when you are finished.

4.1 Feedforward current

The integrator in the ball position loop is designed to compensate for the gravitational bias. It would be better if we pre-compute the current required to maintain the ball at a desired level and regulate the current about that quiescent value. This pre-computed current is the feedforward current and is calculated from

$$m\,g = G_i\left(\frac{i}{x}\right)^2$$

$$i^2 = \frac{m\,g}{G_i}x^2$$

Thus the commanded position is used to precalculate the current required to maintain the ball in position. This current is of course not accurate and that is why we still need the integrator to remove any bias . The controller is required to compensate for dynamic disturbances.

You may want to estimate the relationship between current and position using experimental data. The dbest way to do this is to command the position to track a ***very slow*** sine wave of a small amplitude (eg 3 mm) such that the acceleration of the ball is very small. You then measure the current and position and plot them using a WinCon plot. Save the data into a Matlab file and then use the data to fit the curve:

$i^2 = kf_1\,x^2 + kf_2$ using the matlab function:

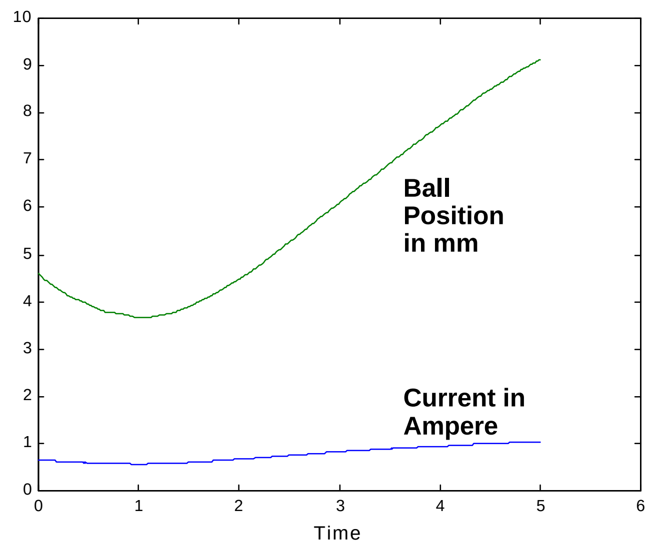
```
kf = polyfit(pos_sq,curr_sq,1);
```

where pos_sq is an array of x^2 values and curr_sq is an array of i^2 values.

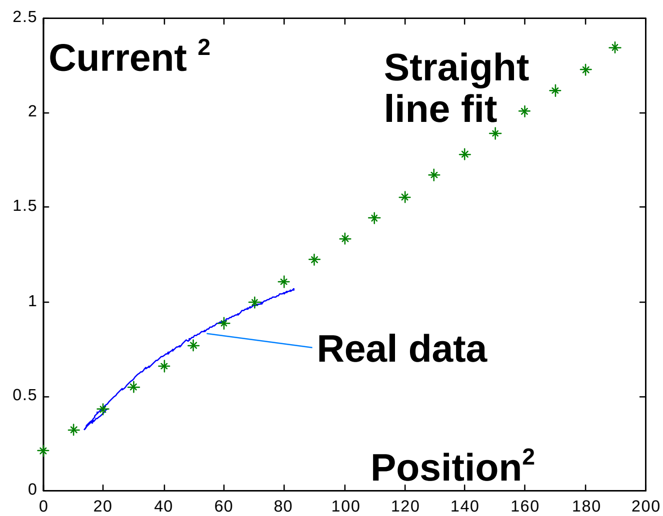
Using this method you can obtain a better fit for your system parameters. The current is then pre-computed using:

$$i = \sqrt{kf_1 \ x^2 + kf_2}$$

An example of this technique is shown below. The figure below shows the ball position



and the current when the ball is tracking a slow sine wave.
This data is imported into Matlab and is fitted to a straight line using:




```
kf =
polyfit(pos_sq,curr_sq,1
)
```

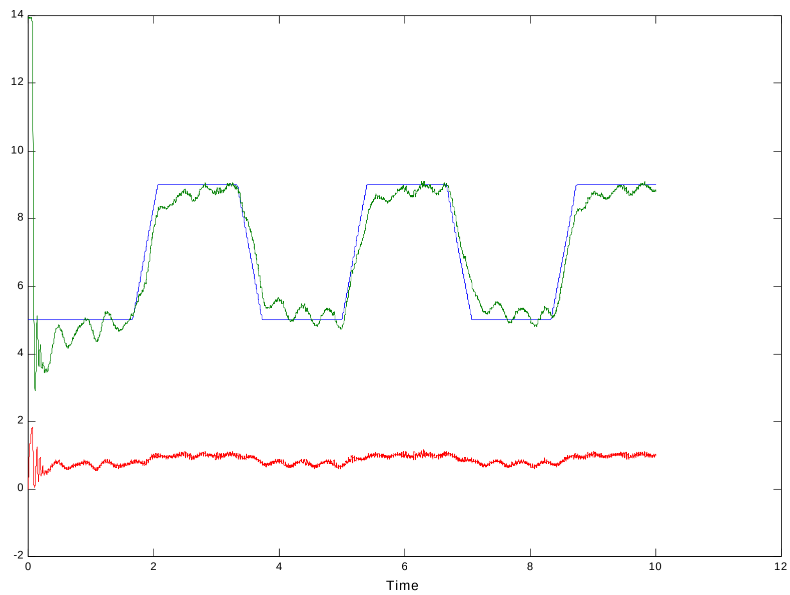
resulting in **kf = [.0112 0.2]** which is slightly off from the nominal values of **[0.02 0]** resulting in **Gi = 59406** as opposed to **Gi = 32654**

Using the above fit, you can then pre-compute a more precise model for the actual system you have.

4.2 Tracking results

The Figure below shows the initial response of the ball lifting from the post and tracking a desired ramp sequence. The oscillations are due to the ball swaying right and left rather than vertically. You may touch the ball lightly to dampen out these vibrations. The current is shown in the lower trace. The typical current required to maintain the ball afloat at 7 mm is about 1 Ampere.

You may of course design a better controller than the one shown here!



5 Wiring and Calibration

Use UPM2405 amplifier for this experiment

From	To	Cable	Function
Current Sense	S3 on UPM2405	6 pin mini Din/ 6 pin mini Din	Measure Vs via S3
Ball sensor (bottom connector on Maglev)	S1 on UPM2405	6 pin mini Din/ 6 pin mini Din	Measure ball position Voltage Vb
“To/ A/D” on UPM	MultiQ Analog inputs 0,1,2,3	5 pin Din 4 x RCA	Vb to A/D #0 Vs to A/D #2
MultiQ D/A # 0	UPM “From D/A”	RCA 5 Pin Din Mono	Signal to amplifier
To Load	Coil	6 pin Din / 4 pin Din ***Gain = 5 (green marker)***	Power to Coil

Using this wiring S1 senses ball position using A/D #0 and S3 senses coil current using A/D #1

5.1 Calibration

The ball sensing system is calibrated at the factory but may need re-adjustment when you receive it. The voltage measured on S1 should be zero when the ball is resting on the black post and should be ***between 4.75 and 4.95*** Volts when the ball is held up by (stuck to) the electromagnet.

To calibrate:

Wire the system as described and power up the amplifier.

a) calibrate the zero

Run WinCon - load project ***mag_cal0.wcp*** - this displays the current in the coil and the voltage measured by the position sensor. Adjust the ***offset potentiometer*** on the Maglev to obtain 0 volts. Click stop when you are done and close WinCon.

b) calibrate the maximum voltage

Run WinCon - load project ***mag_cal5.wcp*** - this displays the current in the coil and the voltage measured from the position sensor. The program applies 1.5 amperes to the coil which causes the ball to jump up to the magnet and stay there. Adjust the gain potentiometer on the Maglev to obtain anywhere between ***4.75 to 4.95*** volts on the position sensor. Click stop when you are done and close WinCon.

c) Run the test controller

Put the ball on the post. Run WinCon, load project ***q_maglev.wcp ,*** click start. This should levitate the ball halfway between the post and the magnet (7 mm). If the ball is swaying left and right put your hand in and dampen the motion.

6 Software

File	***Software needed***	***Function***	***Output /Input filenames (I = input file, O = Output file)***	***I/O***
d_maglev.m	MATLAB	Derive feedback gains k_i and k		I O
q_maglev.mdl	SIMULINK WinCon	Design controller Implement controller	q_maglev.wcl	O
q_maglev.wcl	WinCon	Runs the controller	q_maglev.wcl	I
mag_cal0.wcp	WinCon	Calibration at post position (down) Measure voltage and adjust ***offset***	mag_cal0.wcl	I
mag_cal5.wcp	WinCon	Calibration at magnet position (up) Measure voltage and adjust ***gain***	mag_cal5.wcl	I

7 System parameters

Name	Symbol	Value	Units
Electromagnet			
Coil inductance	L	0.4125	Henry
Coil resistance	R	10	Ohm
Current sense Resistor	Rs	1	Ohm
Force Constant	Ki	32654	(mN mm^2)/Amp^2
OR		3.2654e-005	Nm^2/Amp^2
Ball			
Mass	m	.068	Kg
Diameter		2.54	cm
Ball Sensor			
Range		0 to +5	Volts
Sensitivity		2.88 ± 2%	mm/volt *
Travel distance		14	mm

*** When calibrated as described**