Identification of a Magnetic Levitation System

For
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Maglev Trains

JR-Maglev MLX01 reached 581 km/h (Japan)

superconducting magnets which allow for a larger gap, and repulsive-type Electro-Dynamic Suspension (EDS).
Magnetic Bearings

- support moving machinery without physical contact
- advantages include very low and predictable friction, ability to run without lubrication and in a vacuum
- industrial machines such as compressors, turbines, pumps, motors and generators
Research Experimentation
Outline

1. System Dynamic Model
   1. Nonlinear Model
   2. Linearized Model

2. System in the LAB
   1. Feedback® MAGLEV System
   2. Control Loop

3. Experiment
   1. Hardware
   2. Software
   3. Data

4. Identification
   1. Models
   2. Results
   3. Analysis

5. Future Directions
System Model

References for Model:


Free-Body Diagram
Free-Body Diagram

Input: Voltage / Output: Ball Position

\[ M \ddot{x} = Mg - F(x, i) \]

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

with \( L(x) = L_c + \frac{L_0X_0}{x} \)

\[ \Rightarrow F(x, i) \approx K_L \frac{i^2}{x^2} \]

\( L(x) \) Total Inductance

\( L_c \) Coil Inductance

\( L_0X_0 \) Operating Points
Free-Body Diagram

**Input:** Voltage / **Output:** Ball Position

\[ M \ddot{x} = Mg - K_L \frac{i^2}{x^2} \]

*with* \( V = R_c i + L_c \frac{di}{dt} \approx K_c i \)

Assume no dynamics

\( R_c \) Coil Resistance \hspace{1cm} \( V \) Input: Voltage
Nonlinear Model

\[ \ddot{x} = g - \frac{K_L K_c^2 V^2}{M} \frac{V^2}{x^2} \]

\[ \ddot{x} = g - K_s \frac{V^2}{x^2} \]

**Input:** Voltage / **Output:** Ball Position
Linearization

\[ \ddot{x} = g - K_s \frac{V^2}{x^2} \]

For some Operating Points \( X_0, V_0 \)

\[ \dot{x} = f(x, V) \]

\[ \dot{x} = \left. \frac{\partial f}{\partial x} \right|_{x_0, V_0} \cdot x + \left. \frac{\partial f}{\partial V} \right|_{x_0, V_0} \cdot V \]

\[ \ddot{x} = \frac{2K_s V_0^2}{X_0^3} x - \frac{2K_s V_0}{X_0^2} V \]
Transfer Function

\[ \ddot{x} = \frac{2K_s V_0^2}{X_0^3} x - \frac{2K_s V_0}{X_0^2} V \]

\[ \frac{x(s)}{V(s)} = \frac{-\frac{2K_s V_0}{X_0^2}}{(s^2 - \frac{2K_s V_0^2}{X_0^3})} \]

So,

\[ \frac{x(s)}{V(s)} = \frac{b}{(s^2 + a^2)} \]

2\textsuperscript{nd} order system
MAGLEV in Lab

- In closed-loop

- Photosensor (IR) for position
  - Sensor = 2.5V -> furthest from magnet
  - Sensor = -2.5 -> closest to magnet

- Set-point manually changed

- Analog Controller onboard
Closed-Loop System

Set-Point

disturbance

Controller

MAGLEV

$\nu$

$x$

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14
Controller

\[ G_c(s) = \frac{K(s + k_1)}{s + k_2} \]

Lead/Lag Compensator
Experiment

Set-Point

Controller

MAGLEV

Identification OL

Identification CL

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Experiment

Disturbance Generation

Signals Acquisition

NI USB-6008:
12 bit resolution,
Up to 10kHz sampling rate

2 PCs!!
Software

• Collected data Using:
  – “VI Logger”

• Data-logging software
• Scheduling features
• Flexible adjustments
• Choose sampling speed

• Disturbance Generation:
  – “LabVIEW”

• You can generate any kind of signals as required:
  – Random Sequence,
  – sinusoids,
  – Etc
Data

• Three set-points:
  – 0, 1, -1

• Sampling rate:
  – 1kHz, i.e. 1000 samples per second

• Disturbance = Random Sequence with small amplitude

• Data Collected for:
  – Disturbance (d)
  – System Output (x)
  – Control Input (V)
Data

- $\text{Data}(0) = 3 \times 41431$ samples
- $\text{Data}(1) = 3 \times 41309$ samples
- $\text{Data}(-1) = 3 \times 39257$ samples
- Sampling Period = 1ms

System Output for set-point 0

Output Magnified

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SYSTEM IDENTIFICATION
Model Structure

• Recall

\[
\frac{x(s)}{V(s)} = \frac{b}{s^2 + a^2}
\]

• Due to discretization

\[
G(z) = \frac{b_0 + b_1 z^{-1}}{1 + a_1 z^{-1} + a_2 z^{-2}}
\]
Other Information

• As hardware sampling period is 1ms
  – we can artificially enlarge the sampling period by ‘skipping’ samples

• Convenient speeds 1~10ms

• It is expected to have:
  – Poles around unit circle
MAGLEV Identification

• Open-loop System Input: V, Output: x

\[
G_0(z) = \frac{4.869 \times 10^{-5} + 0.0001446z^{-1}}{1 - 1.899z^{-1} + 0.8996z^{-2}}
\]

\[
G_1(z) = \frac{-2.9 \times 10^{-6} + 0.0001233z^{-1}}{1 - 1.837z^{-1} + 0.8374z^{-2}}
\]

\[
G_{-1}(z) = \frac{4.37 \times 10^{-5} + 0.0001342z^{-1}}{1 - 1.911z^{-1} + 0.911z^{-2}}
\]
Results Plots

Samples 2000-3000 showing

Set-point = 0

Set-point = 1

Set-point = -1
Results Analysis

• System 1 Poles:
  ▪ 0.9932, 0.9057

• System 2 Poles:
  ▪ 0.9968, 0.8401

• System 3 Poles:
  ▪ 0.9958, 0.9148

• All poles proved to be near the unit circle
Identification Approach 2

• Here, let's make

\[ G(z) = \frac{b_0 + b_1 z^{-1}}{1 + a_1 z^{-1} + z^{-2}} \]

\[ a_2 = 1 \]

• To make poles *exactly* at the unit circle

\[ y(k) + y(k - 2) = -a_1 y(k - 1) + b_0 u(k) + b_1 u(k - 1) \]

- *Y & A* matrices will be different
Results 2

• Tested for Set-Point 0,

\[ G_0(z) = \frac{4.534 \times 10^{-5} + 0.0001398z^{-1}}{1 - 1.999z^{-1} + z^{-2}} \]

• Poles

\[ 0.9997 \pm j0.0257 \rightarrow |0.9997 \pm j0.0257| = 1 \]
Closed-Loop Identification

• Input: *Disturbance*, Output: *x*

\[ G_{CL}(z) = \frac{0.00296 + 8.902 \times 10^{-5} z^{-1}}{1 - 2.289 z^{-1} + 1.723 z^{-2} - 0.4331 z^{-3}} \]

• Poles

\[ 0.9955, 0.6467 \pm j0.1297 \]

• Controller should be tuned!
Future Directions

• Horizontal Motion Dynamics
  – Maybe need of another sensor
  – Or, observable model → Horizontal motion can be estimated

• Going to Continuous-time Analysis:
  – Study effect of discretization

• Improve Controller Design
  – More stable design
Final Remarks

• Acknowledgement:
  – Thanks for Prof. Doraiswami for constant advising

• Interesting Project!
  – Included many concepts together: Modeling, Magnetic Fields, Op-amps, Nonlinearities, Numerical Methods, LabVIEW, Discrete-time Analysis, and of course Identification, etc.
THANKS!

• Q & A