MECH 421: Mechatronics System Instrumentation
2020/21 Winter Session – Term 2

Lab 3 – Position Control System

Pre-lab due: Mar 22, 2021
Lab report due: Apr 9, 2021

1 Objectives

- Mechanical system identification based on frequency response measurement.
- Position control design via loop shaping.
- Control algorithm implementation on a real-time computer.

2 Lab Description

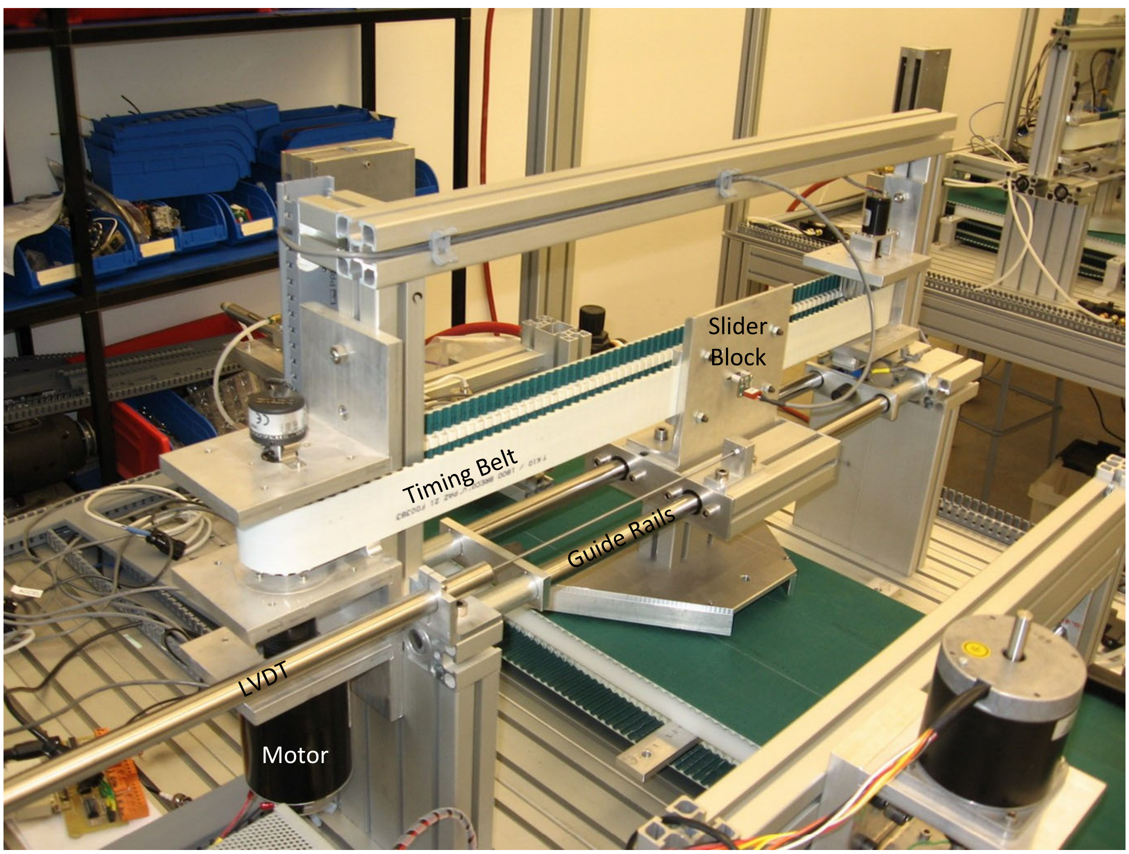

Figure 1: Picture of the lateral positioning stage.

Figure 1 shows a picture of the lateral positioning stage, one of the subsystems of the part sorting machine built in the department. The lateral positioning stage consists of a brushed dc motor, timing belt, slider block, and linear guide rails. The slider block is driven by the motor via the timing belt. There is no gearbox between the rotor and the motor shaft (i.e., direct-drive motor). We use the transconductance amplifier designed in Lab 2 to control the current through the motor. Here are the impedance values.

$$R_1 = 2.2\,\mathrm{k\Omega} \qquad R_2 = 22\,\mathrm{k\Omega} \qquad R_3 = 4.7\,\mathrm{k\Omega} \qquad R_4 = 33\,\mathrm{k\Omega} \qquad C_4 = 4.7\,\mathrm{nF} \qquad R_5 = 1\,\mathrm{k\Omega}$$

In this lab, we use a linear variable differential transformer (LVDT; 75S2DC-5000SR from Sentech) to measure the position of the slider block, and a real-time target[1] (DS1103 from dSPACE) to implement the control algorithm. Figure 2 shows a simplified schematic diagram of the position

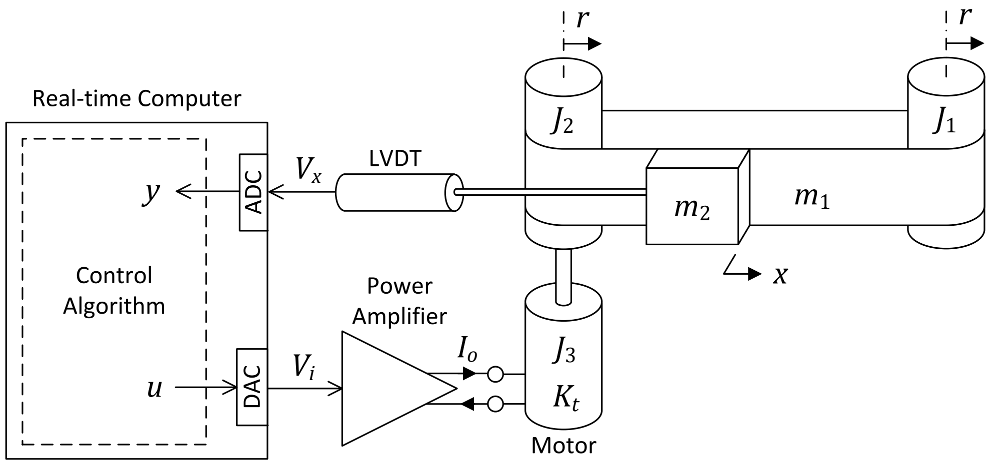

Figure 2: Schematic diagram of the lateral positioning stage and the control system.

control system. The LVDT measures the slider block position x and generates the output signal V_x. The analog-to-digital converter (ADC) converts V_x to a digital signal y, where the conversion gain is $0.1\,\mathrm{V}^{-1}$. Inside the target computer, we implement a control algorithm that generates the control effort u. The digital-to-analog converter (DAC) converts the control effort u to the amplifier input voltage V_i, where the conversion gain $10\,\mathrm{V}$. The voltage V_i is sent to the transconductance power amplifier regulating the motor current I_o. Table 1 summarizes the system parameters.

Table 1: Lateral positioning stage parameters.

Symbol	Quantity	Value
J_1	Idle shaft inertia	$0.000\,190\,\mathrm{kg \cdot m^2}$
J_2	Drive shaft inertia	$0.000\,204\,\mathrm{kg \cdot m^2}$
J_3	Rotor inertia	$0.000\,166\,\mathrm{kg \cdot m^2}$
m_1	Timing-belt mass	$0.4455\,\mathrm{kg}$
m_2	Slider block mass	$4.2882\,\mathrm{kg}$
r	Pulley radius	$0.0316\,\mathrm{m}$
K_t	Motor torque constant	$0.1963\,\mathrm{Nm/A}$
V_x/x	LVDT gain	$0.035\,\mathrm{V/mm}$

[1]A *target computer* is the computer into which a program is loaded and run (cf., host computer).

3 Pre-lab Assignment

1. Calculate the dc gain and bandwidth of the transconductance from V_i to I_o.

2. Draw a block diagram for the lateral positioning stage and find the plant transfer function

$$P(s) = \frac{Y(s)}{U(s)},$$

   where u is the control effort (DAC input) and y is the measurement (ADC output).

   - Assume that u and y are continuous-time signals.
   - Approximate the amplifier as a first-order system.

3. Draw the Bode plot of $P(s)$ and compare it with the experimentally measured plant frequency response in Figure 3. Discuss the differences between the model and measurements, and explain possible sources of discrepancy in low frequencies and high frequencies.

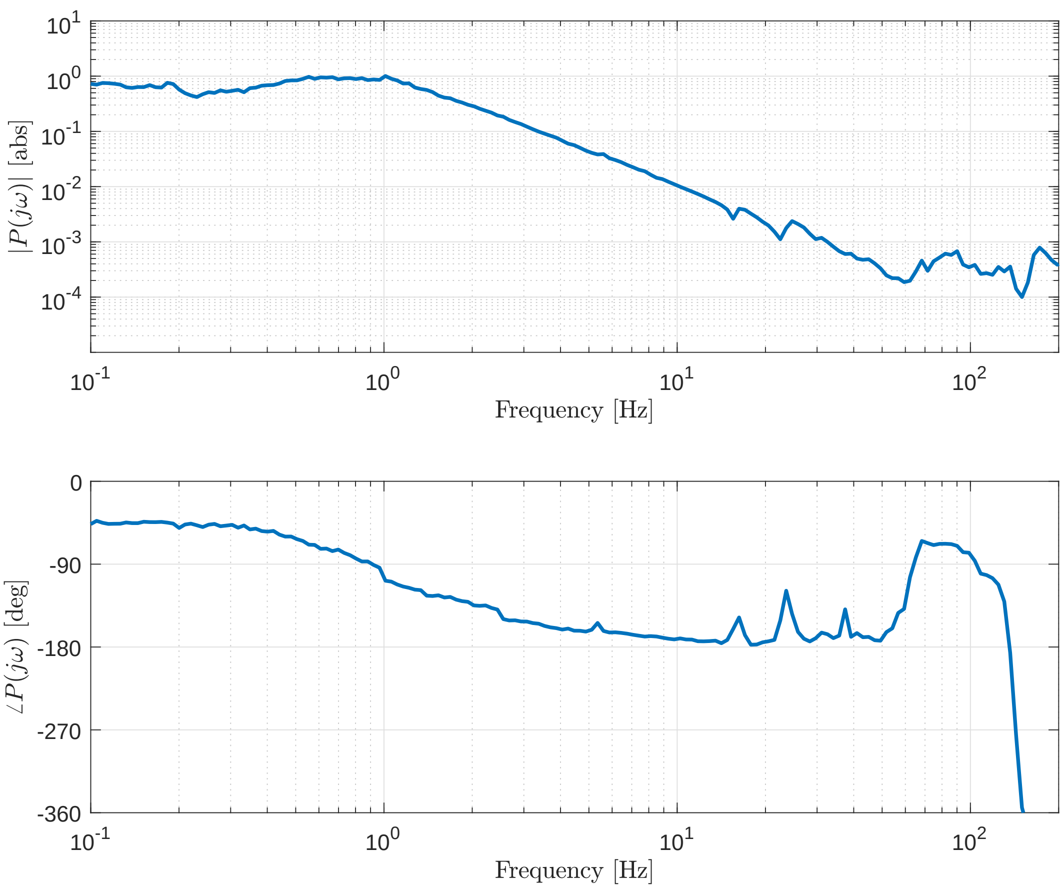

Figure 3: Experimentally measured frequency response of the plant.

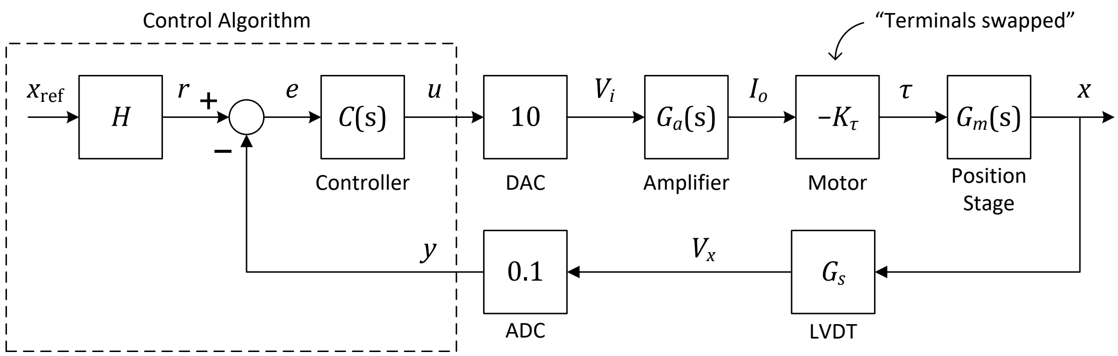

Figure 4: Block diagram of the position control system.

4. Referring to Figure 4, design a controller $C(s)$ that generates the control effort u based on the position measurement y and the reference r. Also, find the constant gain block H that makes x [mm] $= x_{\text{ref}}$ [mm] when $e = 0$.

   The data for Figure 3 is available on Canvas (`Lab3-Plant-FRF-2021.mat`). Using the data, design a controller $C(s)$ that shapes the loop to satisfy the following requirements. Do not use the transfer function $P(s)$ obtained in Question 2. Use the measured data directly. (Tip: use `C_frf = squeeze(freqresp(C,freq,'Hz'))` for the controller frequency response).

   - Phase margin $\phi_m > 60°$
   - As high a cross-over frequency as possible
   - Zero steady-state error for a step position reference x_{ref}

5. Create a Simulink model that implements the modeled plant $P(s)$, controller $C(s)$, and the gain block H. Use the transfer function $P(s)$ obtained in Question 2, or one that can fit the measured data. The controller $C(s)$ can include multiple sub-blocks.

   Simulate the step response of the closed-loop system from x_{ref} [mm] to x [mm] and evaluate the performance in terms of rise time and overshoot.

4 Lab Assignment

In this lab, we design and implement the control algorithm in a dSPACE real-time target via Simulink graphical programming language. Request the TA to set up the hardware and software environment. We use some non-standard Simulink blocks for the lab, including DAC driver block, ADC driver block, and dynamic signal analyzer (DSA) block[2]. Request the TA to provide those blocks and necessary instructions.

1. Measure the frequency response of the plant $P(s)$ from u to y using the DSA block. Appropriately set the DSA parameters (e.g., frequency points, excitation amplitudes, and cycle numbers) to obtain good identification results. Be sure to include a saturation block to limit the control effort u such that $|V_i| < 3\,\mathrm{V}$. This is to prevent overcurrent through the motor winding.

2. Once you obtain a satisfactory frequency response result, design and implement a controller $C(s)$ for the following requirements.

   - Phase margin $\phi_m > 60^\circ$
   - As high a crossover frequency as possible
   - Zero steady-state error for a step position reference r

3. Measure the frequency response of the loop transfer function $L(j\omega)$, and verify the achieved crossover frequency and phase margin.

4. Measure the step response of the closed-loop system from r to y for three different step amplitudes of x_{ref} [mm]. Record the rise time and overshoot for each amplitude.

In the lab report, include the frequency responses of the plant $P(j\omega)$ and loop transfer function $L(j\omega)$. Also, include the measured step responses of the closed-loop system and discuss the effect of different amplitudes.

[2]The DSA block was developed to measure frequency responses of systems in Simulink environment. It applies an excitation signal to the system, record two signals using channel 1 and channel 2, and compute the magnitude and phase difference between the two signals.