MTE 360 Automatic Control Systems: Lab #1

System Identification, P-Control, and Time and Frequency Responses

1. Introduction

This handout lays out the steps you will need to perform the first lab. The lab relies on Simulink and the Matlab Real-Time Workshop to interface with the hardware. If you have never used Simulink before, make sure to go to the Simulink Tutorial provided by our TA. If you have never used Simulink before, make sure to go to the Simulink Tutorial (or watch the tutorial record) provided by our TAs and posted on the course Teams page (MTE 360-Fall 2023) under General channel or find the link on LEARN>MATLAB/Simulink Tutorial. If you have further MATLAB/Simulink questions, please contact the TAs and/or the instructor.

Laboratory activity will be conducted in groups of four to five students. It is the students' responsibility to conduct the experiments and save their own data after each test. Each group will hand in one lab report (max. 9 pages), prepared collectively by the members of that group, each in the format of a technical report. Specifically, your report should address all the questions included in this lab handout. Communication with other groups is not allowed.

In this laboratory, you will become familiar with the basic principles of control engineering (system identification and basic feedback control). You will also become acquainted with the Quanser Linear Motion Cart (shown in Figure 1) setup, which you will use in proceeding lab sessions.

A detailed description regarding the modelling and control of Quanser Linear Motion Cart system is provided in the complimentary handout titled "Lab Background Information." We strongly advise you to go through and read the descriptions.

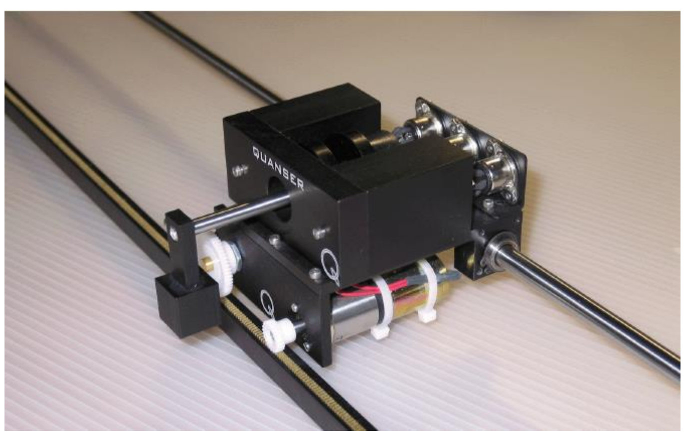

Figure 1: Quanzer linear cart setup.

Control engineering practice typically consists of three main tasks:

1) Identifying a model for the system to be controlled

2) Analyzing the behaviour of the modelled system

3) Designing and tuning an appropriate controller

In many cases, the above tasks are executed iteratively, one after another, until the desired performance, stability, tracking and robustness characteristics are realized. This laboratory is designed to give a flavor of these tasks, which are frequently used in real-world controller design for applications such as robotics, CNC machine tools, disk drives, or autopilot systems.

2. Pre-Lab

Build a model of the cart system in Simulink. This can be done by recreating Figure 4 of the Lab Background information handout with the model parameters defined in Table 1. Justify the correctness of your model by applying different inputs to the system and check whether the output makes sense or not (for example, you can apply a square wave pulse to the system and compare the measured steady-state gain with what you computed from the system parameters).

Your lab report does not need to include the results of this section. This is more of a practice to become familiar with Simulink block diagrams for simulation of the lab apparatus and have a better understanding of the dynamical system you are dealing with in the lab. Ask TAs for help if needed.

3. Getting Started

Follow the instructions below:

1) Make a copy of the existing folder **MTE360_F23** located on the desktop of the lab computers. Rename it with your group number. From the copied folder, open up the Simulink template file.
2) Compose your model using Simulink blocks.
3) Once the Simulink model is finalized, clock on “Monitor and Tune” in the “Hardware” tab to run the setup. Make sure the run time is set to 8s.
4) Ensure the data was recorded by checking for it in the Matlab workspace. Save the data with a separate name each time, as Simulink will overwrite the data recorded during previous runs.
5) When interpreting your data, try to avoid using the first few seconds to avoid the transient effects.

4.1 [Experiment 1] Parameter Identification through Step Response Measurement

The velocity response of most servo-drive systems can be approximated with the following first-order model[1], as will be derived in class:

$$v(s) = \frac{K_v}{\tau_v s + 1} u(s) \tag{1}$$

where $u(s)$ [v] is the input signal, $v(s)$ is the axis velocity, $\boldsymbol{K_v}$ [(mm/sec)/v] is the velocity gain and τ_v [sec] is the time constant. When a unit step voltage is applied to the input, the following response will be observed in the ideal case:

$$v(t) = K_v(1 - \exp(-t/t_v)) \tag{2}$$

A plot of this theoretical response is shown in Figure 2.

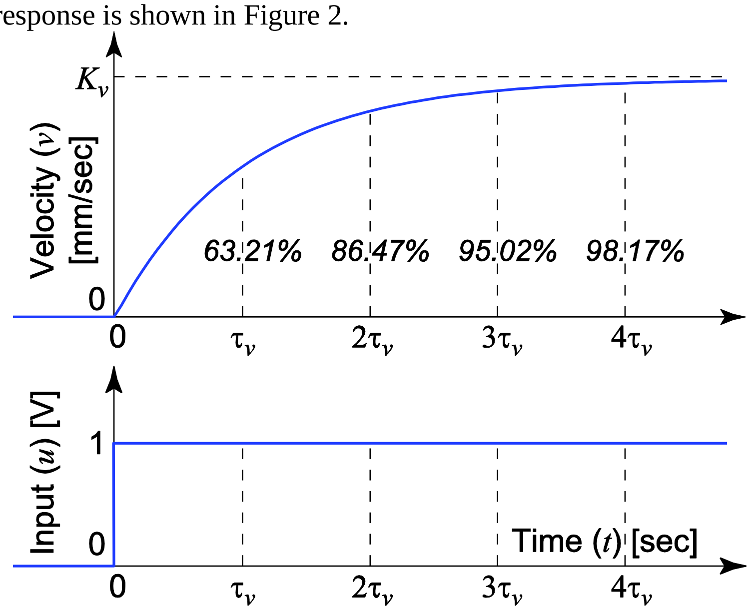

Figure 2: First-order system response to a unit step input with zero initial conditions.

4-1a. Measure the velocity step response of the cart system by applying a square wave input with ±1 [v] amplitude and 1 Hz frequency. You will make the Simulink file shown in Figure 3 to run this experiment. After data collection,

[1] If you experimented with the system parameters in the pre-lab, you might have noticed that the inertia and friction components of the dynamics had a much larger effect than the armature inductance and resistance. This is because the inductance of the armature is relatively small, and so the bandwidth of the electric motor is much greater than that of the inertial dynamics. The result is that we can ignore the faster electric motor dynamics (La ≈ 0) when identifying the system, and work with a simplified (first-order) system model. Note that we are also ignoring the effect of external disturbances in the identification of the motor parameters.

Ensure that the contents of the "scope" blocks are saved into the Workspace. It is a good idea to check the correctness of the data files by retrieving and plotting them in another MATLAB script.

Note: You may not copy and paste this figure directly into your report. You must save the measured data arrays into a file which you will work with. Each group is responsible for saving their data after each experiment.

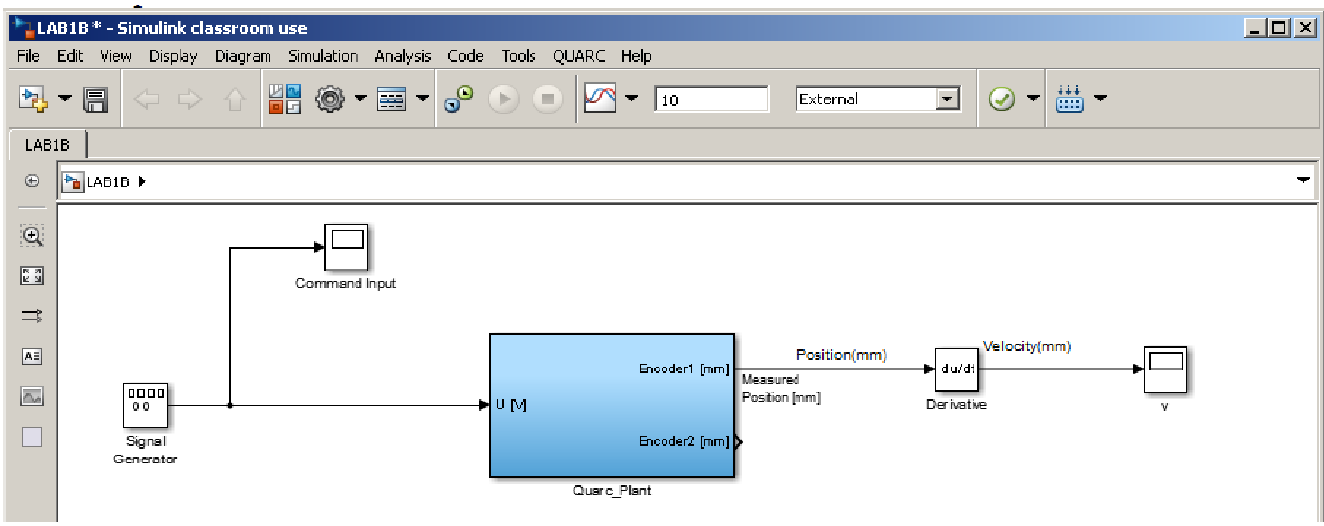

Figure 3: Simulink file for measuring velocity step response.

4.2 [Experiment 2] Proportional (P-type) Position Control

You will now implement your first servo-controller. A block diagram depicting the proportional position control technique is shown in Figure 4. In the figure, $x_r(s)$ [mm] is the commanded position and $x(s)$ [mm] is the actual cart position. $e(s) = x_r(s) - x(s)$ [mm] is the position error, commonly referred to as the "tracking error". $\boldsymbol{K_p}$ [v/mm] is the proportional feedback gain, which generates the input voltage (i.e. control signal) $u(s)$ [v] applied to the amplifier based on how large the position error is. In reality, there is also an equivalent disturbance $d(s)$ [v], which originates from the friction in the cart mechanism. The friction disturbance opposes the cart motion; hence it has a negative sign. The effect of the disturbances on the servo performance will be studied later in class. The velocity of the cart $v(s)$ is integrated once ($1/s$) to produce the position $x(s)$, which is measured and feedback into the control loop.

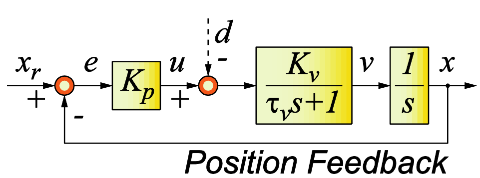

Figure 4: Proportional (P-type) position control.

Create a model of your P-Controller in Simulink and apply it to the identified model (from Experiment 4.1). Once you are satisfied with your simulation, you can go to the next step.

4-2a. Apply your proportional position controller to the cart system according to the Simulink scheme shown in Figure 5. Apply a position command consisting of a ±5.0 [mm] square wave with 0.5 Hz frequency. Try out values of 0.15, 0.25, and 0.5 [v/mm] for K_p. Capture the response from the "scope" block in each case. Save your data after each experiment, rather than copying the MATLAB plots.

You should never try negative or very large K_p ($K_p > 1$ for this setup specifically) since it will lead to instability or put a lot of loads on the system actuators, which will damage the plant and can cause injuries.

Never use negative values for K_p, to avoid the closed-loop system instability and the cart crashing to one end!

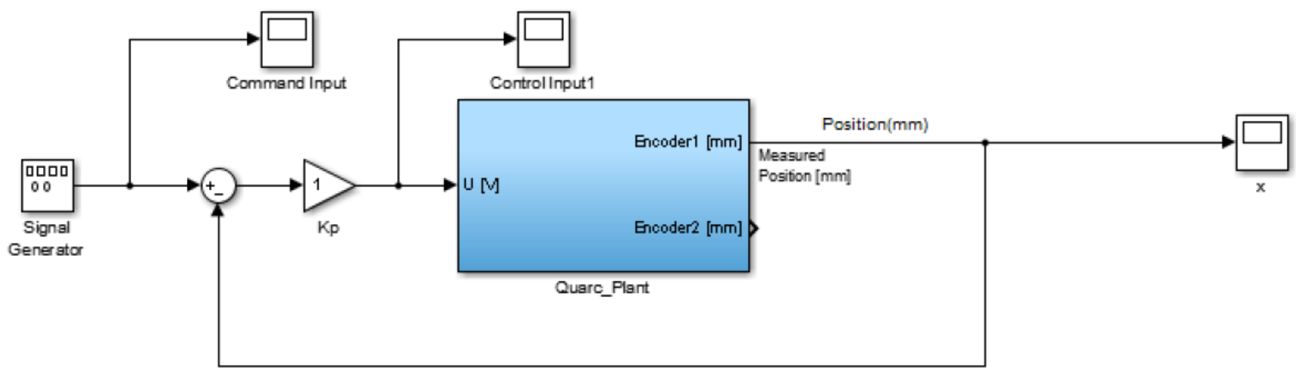

Figure 5: Simulink file for proportional position control.

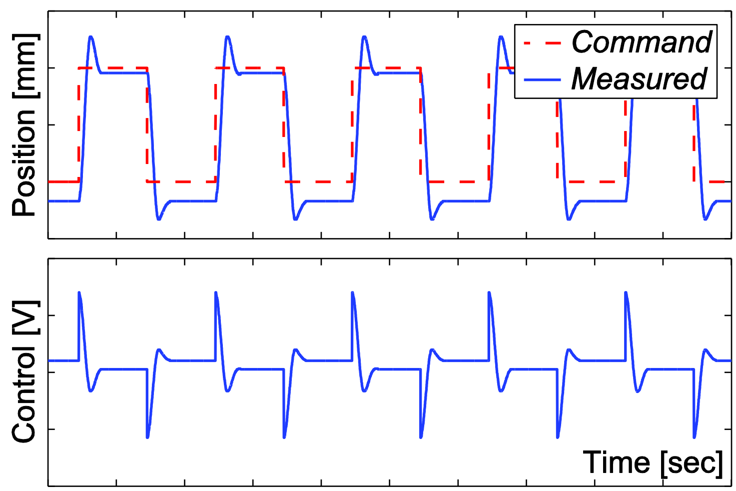

Figure 6: Sample step response for P-control.

4.3 [Experiment 3] Closed-loop System Identification using Bode Plot

The frequency response of a linear dynamic system can be identified by applying sinusoidal excitations at different frequencies and measuring the relative amplitude and phase shift between the input and the output. For a linear closed-loop system with Transfer Function $G_{cl}(s)$, input $X_r(s) = L\{x_r(t)\}$, and the output $X(s) = L\{x(t)\}$, such that

$$X(s) = G_{cl}(s)X_r(s),$$

when a sinusoidal signal $x_r(t)$ is applied to the input, the steady-state response ($x(t)$ at steady state) will be as shown in Figure 7. In the figure, Δx_r is the peak-to-peak amplitude of the excitation and Δx is the peak-to-peak amplitude of the output. T $[sec]$ is the period of excitation and $t_\phi[sec]$ is the time lag between the input and the output. The gain and phase of the transfer function at the frequency $f = \frac{1}{T}$ $[Hz]$ can be computed as: $|G_{cl}| = \Delta x / \Delta x_r$ and $\angle G_{cl} = 360° \times t_\phi / T$.

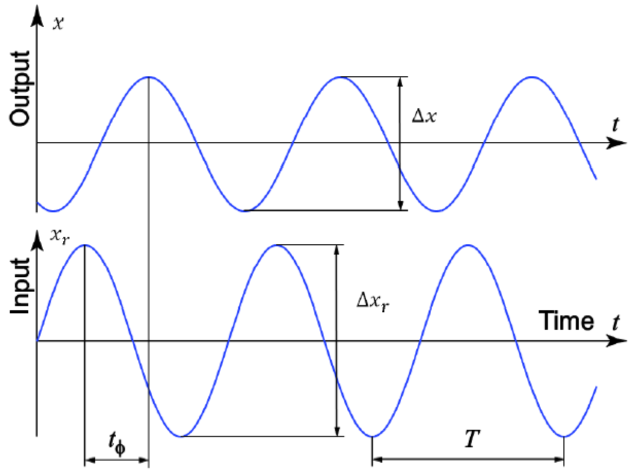

Figure 7: Sinusoidal response of a linear dynamic system.

It is also possible to evaluate the frequency response corresponding to transfer functions analytically, if their mathematical expression is known. The gain and phase are determined by computing the magnitude and angle of $G_{cl}(jw) = G_{cl}(s)|_{s=jw}$. In either measurement-based or analytical calculation, by trying out different values for f (or $\omega = 2\pi f$), it is possible to determine the frequency response of a dynamic system for a wide frequency range. Frequency response analysis provides important insight into issues like tracking performance, disturbance rejection, stability and robustness margins, etc.

4.3a. In Simulink, use the setup shown in Figure 8. Set the Proportional Gain K_P to **1.0** [V/mm] and measure the frequency response of the closed-loop position control system by applying sine wave position commands with $\pm$**2.0** [mm] amplitude. Use the following freqs: f=0.5, 1, 2.5, 5, 10, 25, 50 (Hz). Save input signal (x_r), output signal (x) and control input signal (u) measurements. **Note: In testing frequencies over 5Hz, do not run the setup for longer than 5 seconds at a time.**

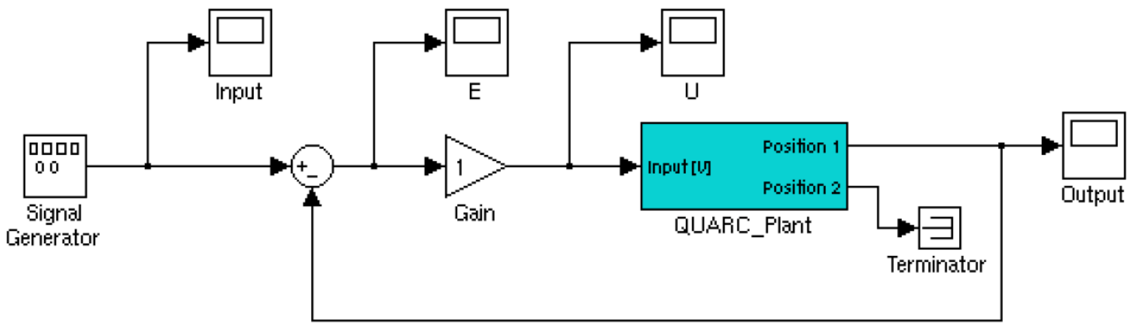

Figure 8: Simulink block diagram for frequency response test.

Make sure to save your data after each experiment and show what you saved to the lab TA before leaving.

5) Post-Lab instructions

Report format and submission: (please check General Lab Report Guideline first)

Aside from the parameters calculated and extracted from experimental results, your lab report should include the following plots:

a) A Plot showing your velocity step response and how you obtained your plant parameters from it.

b) A Plot showing your velocity step response overlaid with the simulated velocity step response.

c) Three Plots showing the response, tracking error and the input voltage of the P-Controller applied to the cart system and the estimated plant overlaid on each other.

d) The table showing the measured values from the frequency response domain including the input, the output, time lag, gain and phase for each frequency.

e) A plot showing the theoretical closed-loop frequency response overlaid with the measured ones.

All plots' axes need to be fully labeled and each plot requires a caption. More information is provided as bellow:

For parameter identification through step response measurement

5-1a. Using the measured data in Part 4-1a, determine the values of the velocity gain K_v and the time constant τ_v.

5-1b. Construct a Simulink model of the system using the identified gain K_v and time constant τ_v parameters obtained in 5-1a. Simulate the theoretical velocity response using this Simulink model, applying the input signal profile (u) you had captured during the experiment.

5-1c. In your Lab1 report, provide a plot showing the velocity step response you obtained in Part 4-1a. Explain how you obtained/identified the values of plant parameters K_v and τ_v in Part 5-1a.

5-1d. Provide a plot of the measured and simulated step response graphs overlaid on top of each other (i.e. v_{meas} from Part 4-1a and $v_{ave}$from Part 5-1b vs. time). Comment on the similarities and/or discrepancies between the two, reflecting your engineering judgement. In addition, plot the input profile (u vs. t) underneath the velocity response graph. The time axes should be identical. You may ask TAs to show/explain the details of how these plots should look.

For Proportional (P-type) Position Control

5-2a. The P-controlled closed loop system can be represented with an equivalent 2nd order model as shown in Figure 9. In the simplified model, ω_n [rad/sec] represents natural frequency and ζ represents damping ratio of the closed loop poles **(you will learn about the closed-loop poles and details of second-order systems later in the course)**. Rewrite the closed-loop transfer function in the form of a standard 2nd order system (Figure 10, right panel) and report the values of ω_n and ζ in terms of K_p, and compute their values for $K_p = 0.15, 0.25$ and 0.5 [V/mm].

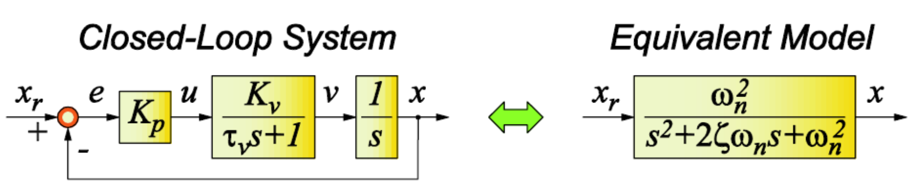

Figure 9: Equivalent 2nd order model for P-controlled servo system.

5-2b. Plot the closed-loop position step response for different values of K_p (i.e. 0.15, 0.25, and 0.5 [V/mm]) in the format shown in Figure *10*: Sample step response for P-control.Figure 10.

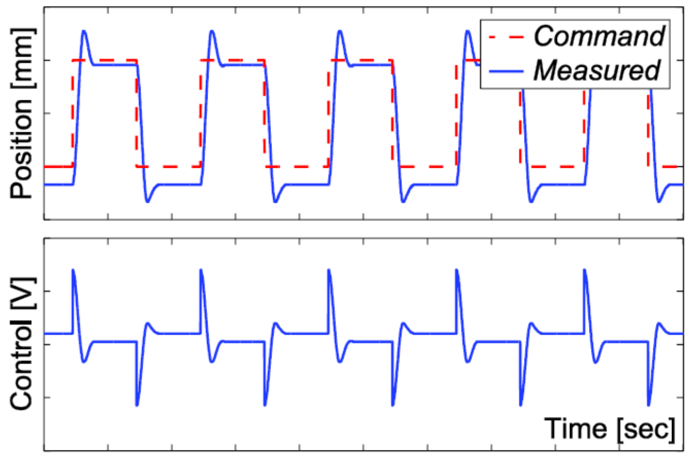

Figure 10: Sample step response for P-control.

5-2c. Include a plot in your report showing your experimental P-Control closed loop system output overlaid with the simulated one and accompanied by a subplot showing the actual control signal and simulated control signal. You may ask the TAs to show/explain the details of how these plots should look like.

<u>For Bode Plot Based Identification of Closed-loop Frequency Response</u>

5-3a. Summarize your measurements from 4.3a **in the table provided at the end of the document**.
Hint: Use the "Zoom In" and "Data Cursor" tools located in the toolbar of the plot to read values accurately.

5-3b. Using the table, plot the gain and phase values versus frequency (**Bode Plots**), in the format shown in Figure 11. Use logarithmic scales for gain $|G_{cl}|$ and frequency ω (rad/sec), and a linear scale for the phase shift $\angle G_{cl}$ (deg).

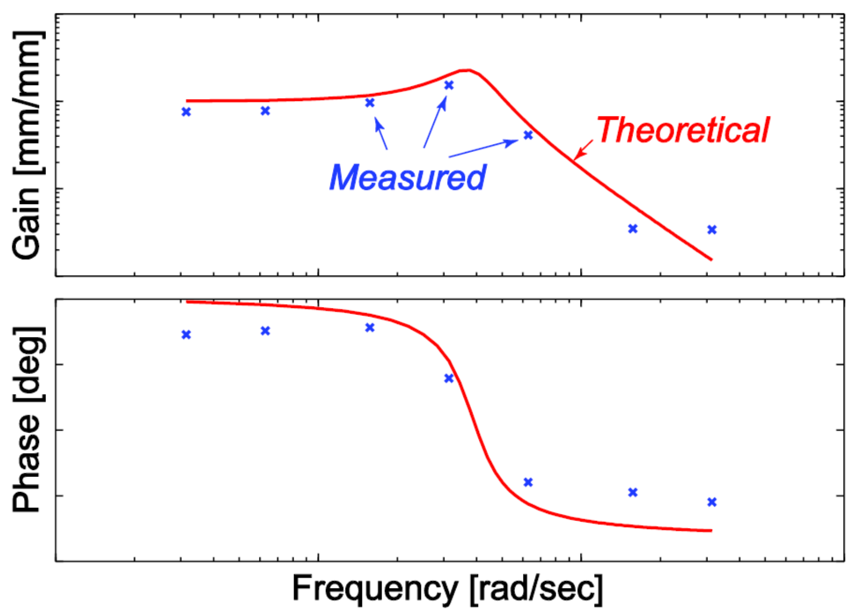

Figure 11: Closed-loop frequency response.

5-3c. Compute the theoretical (equivalent model in Figure 12) frequency response for the frequency $f = \omega/2\pi$ range 0, 1, 2, …, 50 [Hz]. (Use K_v, τ_v values from part 5-1a results to find ω_n, ζ) Overlay the theoretical magnitude and phase values on top of the measured ones, as shown in Figure 11. Comment on the similarities and/or discrepancies between the two.

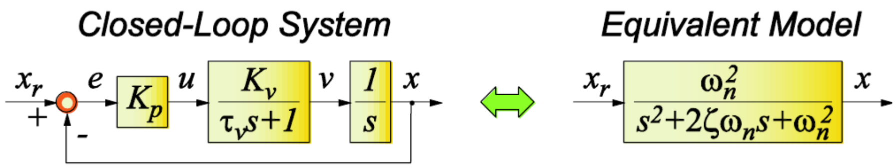

Figure 12: Closed loop P-Controlled System (for designing theoretical figure of Bode gain and phase response).

Before submitting your final report, make sure your report does not contain any redundant plot.

Hint: To obtain the theoretical (model-based) Bode plot as shown in Figure 11, *you can use the following sample MATLAB commands:*

```
>> num = [1 1]; den = [1 1 1];
>> sysD = tf(num,den);
>> w = logspace(-1,2);
>> [mag, phase] = bode(sysD,w);
>> loglog(w,squeeze(mag)),grid;
>> semilogx(w,squeeze(phase)),grid;
```

The transfer function here is defined by "num" and "den" variables representing the numerator and denominator coefficients respectively. (i.e. the transfer function defined here is $(s + 1) / (s^2 + s + 1)$)

Frequency f [Hz]	Input Δx_r [mm]	Output Δx [mm]	Time Lag t_ϕ [sec]	Gain $\lvert G_{cl}\rvert$ [mm/mm]	Phase $\angle G_{cl}$ [deg]
0.5					
1					
2.5					
5					
10					
25					
50					