# Position Control of DC Brushed Motor in Simulink

EE 3320: Lab 3

Spring 2020

# 1 Position Control Module Overview

## 1.1 Module Objective

i Learn how to work with Simulink to model and simulate dynamical systems

ii Learn about the fundamentals of PD and PID controllers

iii Learn about methods of tuning and testing PD and PID controllers

iv Implement PD and PID controllers on a simulated brushed DC motor system

## 1.2 Report Requirements

1. The check-off and report for this lab will be completed entirely electronically.
2. Only one report should be submitted per group. Try to collaborate on the lab in your groups, but ensure everyone is involved in the lab procedure. (Zoom/Skype/Discord/etc. have screen-share capabilities)
3. The report must contain all results with detailed explanations. Questions asked throughout the procedure should be answered and supported by your results.
4. Please follow the standard double-column IEEE report format. Format requirements can be found on the ECE department's website.

## 1.3 Simulink Model Explanation

The Simulink model can be created based on this model, shown in Fig. 1.

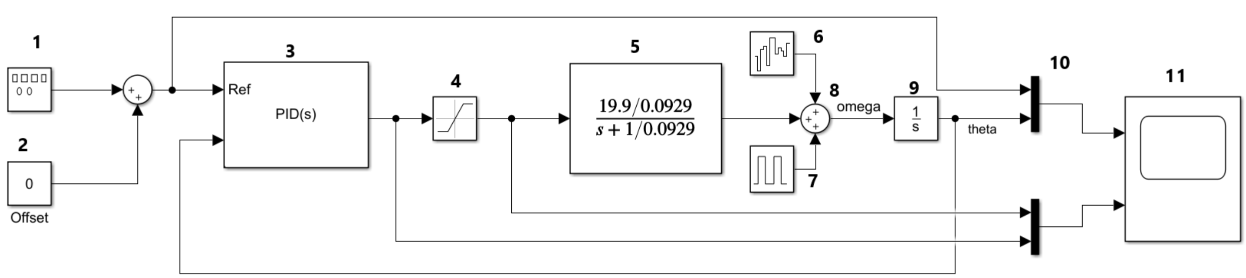



Fig. 1: Simulink Model to be used for testing position control of a simulated brushed DC motor. The blocks are defined as: (1) Reference Signal Generator, (2) Reference Signal Offset, (3) PID Controller, (4) Control Signal Saturation, (5) Plant Transfer Function, (6) Measurement Noise, (7) Disturbance Pulse Generator, (8) Integrator Block, (9) Signal Sum Block, (10) Signal Multiplexer (Mux), and (11) Output and Control Signal Scope.

### 1.3.1 Reference Signal Generator

The reference signal generator will be used to set to either a Square, Sine, or Sawtooth waveform at various Amplitudes and Frequencies.

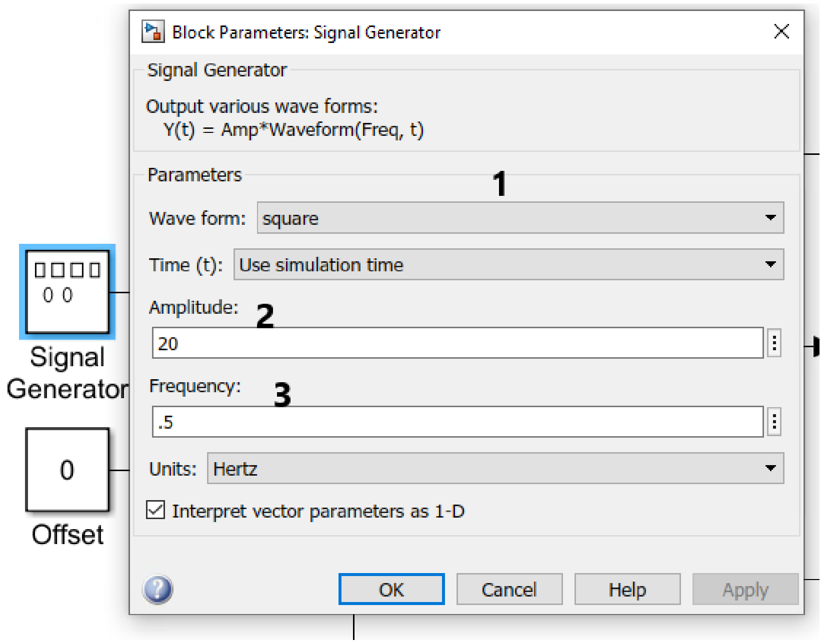



Fig. 2: The Reference Signal Generator. There are settings for: (1) Signal Waveform, (2) Amplitude, and (3) Frequency.

### 1.3.2 Reference Signal Offset

The reference signal offset is a constant that is adjusted to act as a DC component of the reference signal.

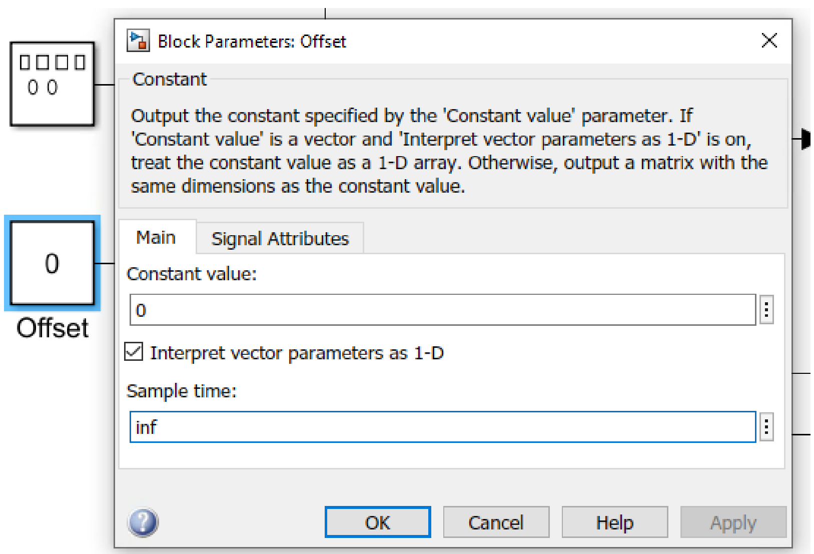



Fig. 3: The constant block used to designate the DC offset of the reference signal.

### 1.3.3 PID Controller

The PID Controller is a built in PID Controller block with three parameters to tune: $k_p$, $k_i$, $k_d$, $b_{sp}$, and $b_{sd}$.

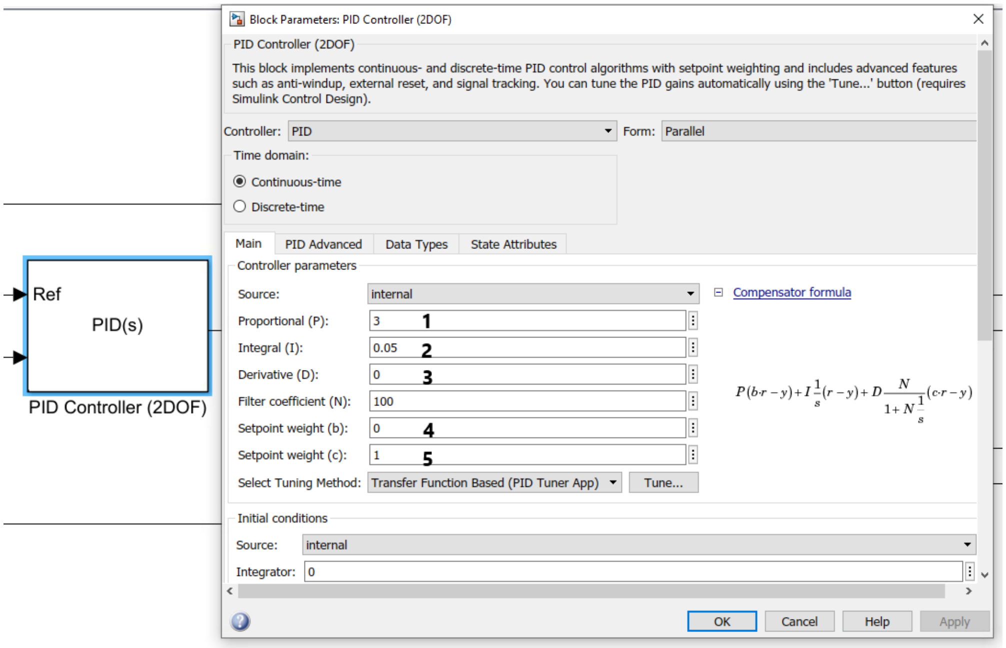



Fig. 4: PI Controller that is used to implement P, PD, and PID control of the system. The parameters to be tuned are (1) $k_p$ (P), (2) $k_i$ (I), (3) $k_d$ (D), (4) $b_{sp}$ (b), and (5) $b_{sd}$ (c).

### 1.3.4 Control Signal Saturation

To replicate the actual system, a limit on the control effort is set to $\pm$ 12 [V].

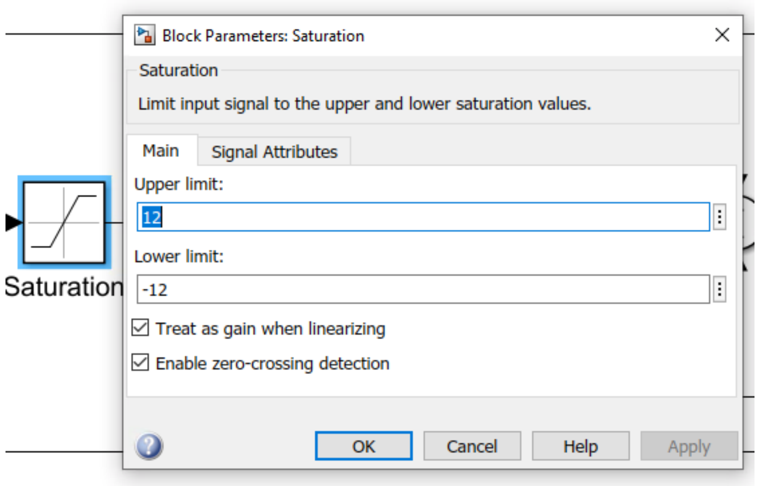



Fig. 5: The Saturation block that limits the control effort entered into the plan.

### 1.3.5 Plant Transfer Function

The plant is modeled using the transfer function obtained for the brushed DC motor from Lab 1:

$$H(s) = \frac{K}{\tau s + 1} \tag{1}$$

where $K = 19.9$ and $\tau = 0.0929$.

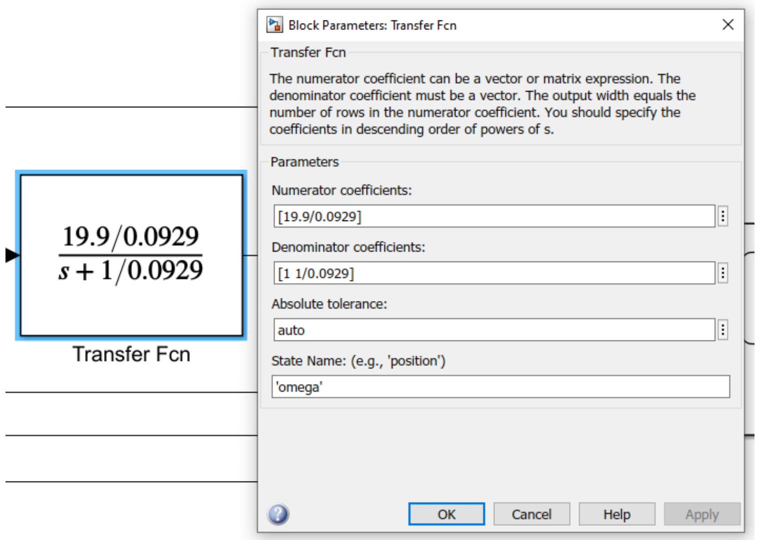



Fig. 6: The transfer function block used to simulate the plant. The transfer function is entered as an array for the numerator and denominator of the transfer function

### 1.3.6 Measurement Noise

To simulate the measurement and system noise, a white noise generator is added to the output of the system. It is set to 0 at default, but the robustness of the system can be tested by introducing noise to the system. It is not necessary to fully complete this lab procedure.

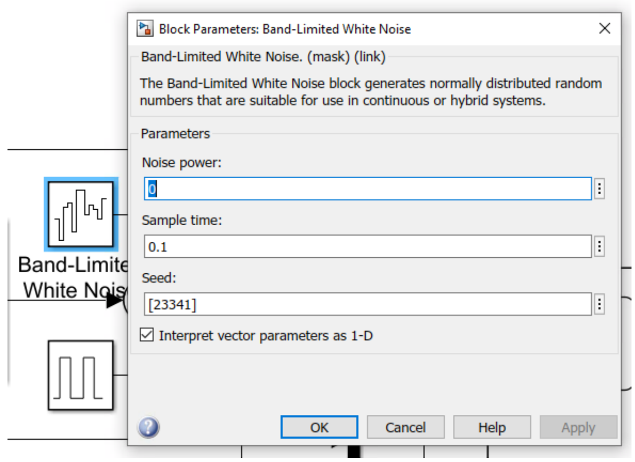



Fig. 7: This band-limited white-noise generator can be used to simulate how a system will respond given normally distributed measurement error and minor disturbance events.

#### 1.3.7 Disturbance Pulse Generator

A pulse generator is added to the output of the model to allow for testing of the system response to a disturbance. The amplitude is set to 0 at default.

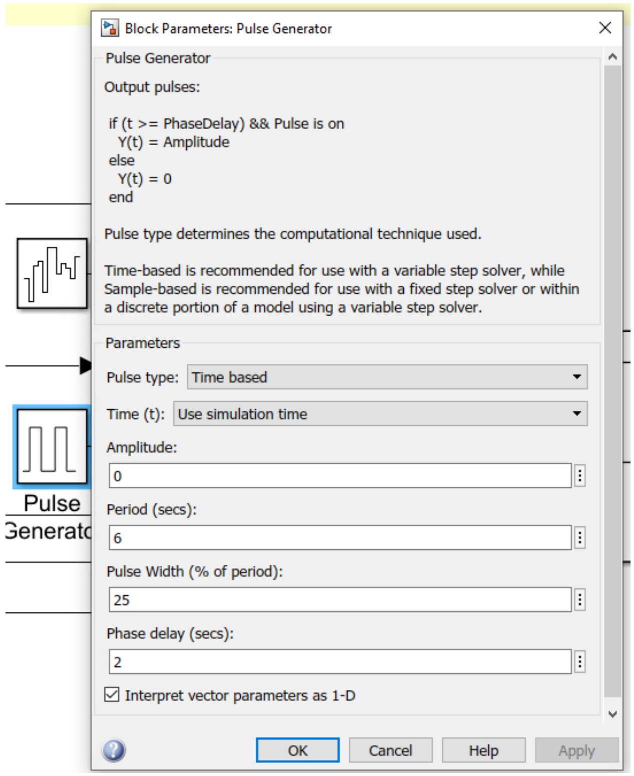



Fig. 8: A pulse generator to test the ability for a system to respond to disturbances. Only the amplitude needs to be adjusted.

#### 1.3.8 Integrator Block

An integrator block is used in this Simulink model to change the output of the system from angular speed ($\omega$) to angular position ($\theta$).

#### 1.3.9 Signal Sum Block

Sum Blocks allow for the addition and subtraction of signals.

#### 1.3.10 Signal Multiplexer (Mux)

A Signal Multiplexer (often just called a Mux) allows for the combination of signals into an array. In this application, signals are combined to allow them to be plotted together on the same plot.

### 1.3.11 Output and Control Signal Scope

The scope is used to observe and precisely measure the plant output, along with the control signal.

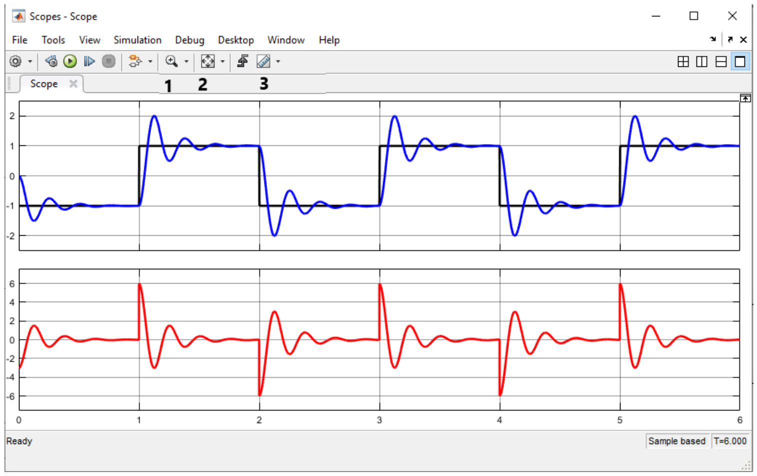



Fig. 9: Scope displaying the plant output and control signal. (1) The zoom is important for finding detail within the signal. (2) Auto-zoom is also useful. (3) Cursors can be placed on the signal to measure it as well.

Additionally, the cursor menu allows for signals to be measured and compared at various times.

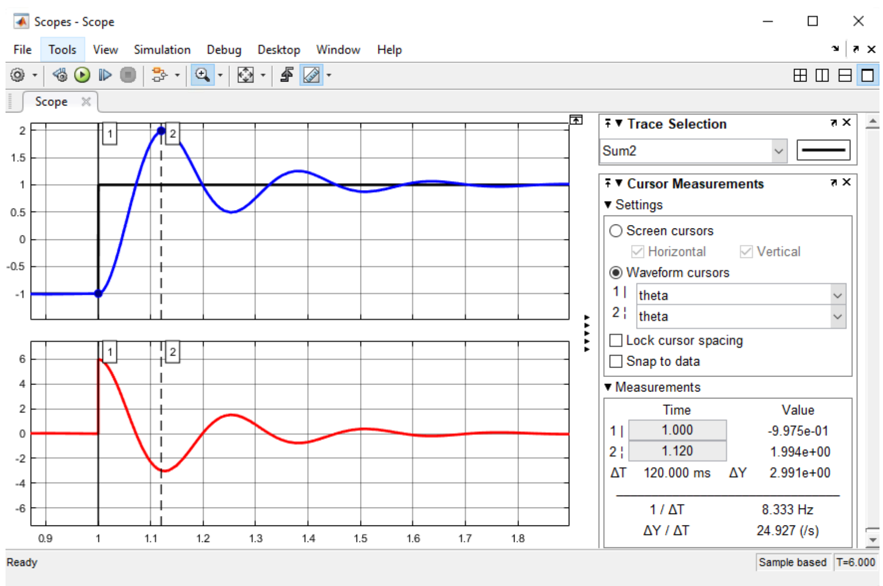



Fig. 10: The measurement tool within the scope.

# 2 PD Controller Qualitative Analysis

In the pre-lab, the theory of P, PD, and PID controllers were explored theoretically. In this section, an intuitive understanding will be developed for implementing both P and PD controllers.

## 2.1 Pure Proportional Control

The control law for a pure proportional controller is given as:

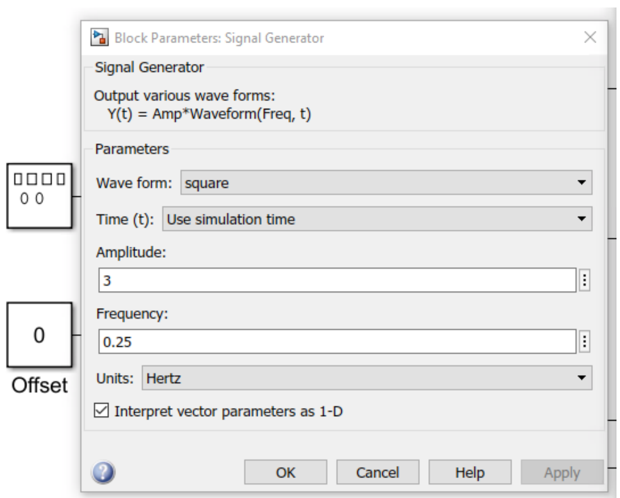
$$u(t) = k_p(b_{sp}r(t) - y(t)) \tag{2}$$

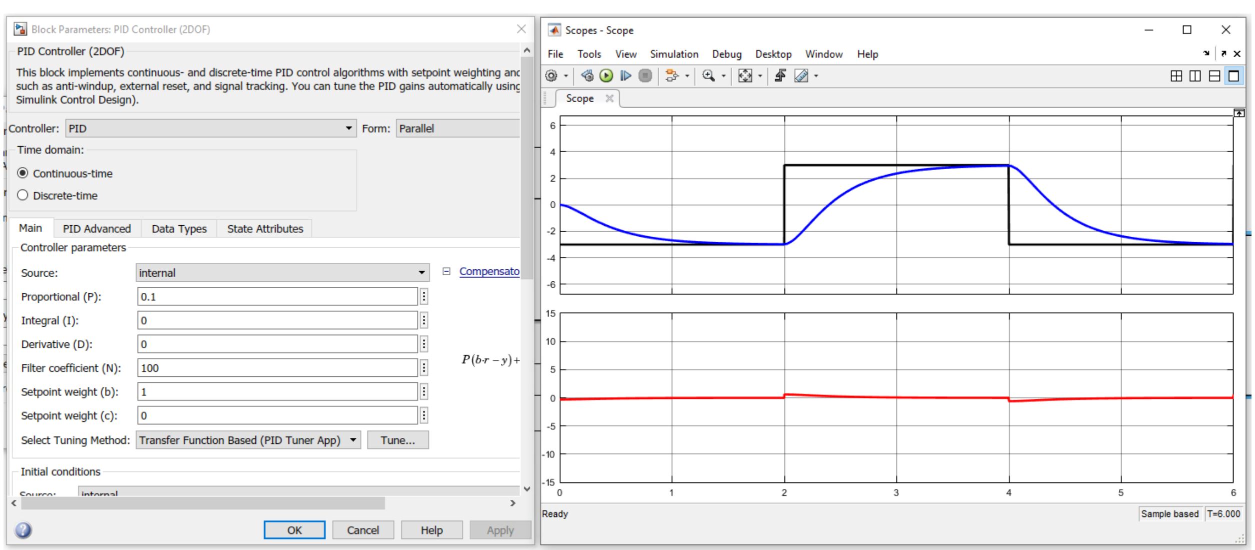
Explore the properties of a pure P controller by following this procedure:

Step 1. Ensure the Simulink model is in a default state (noise and disturbance set to 0) and the following properties are set:

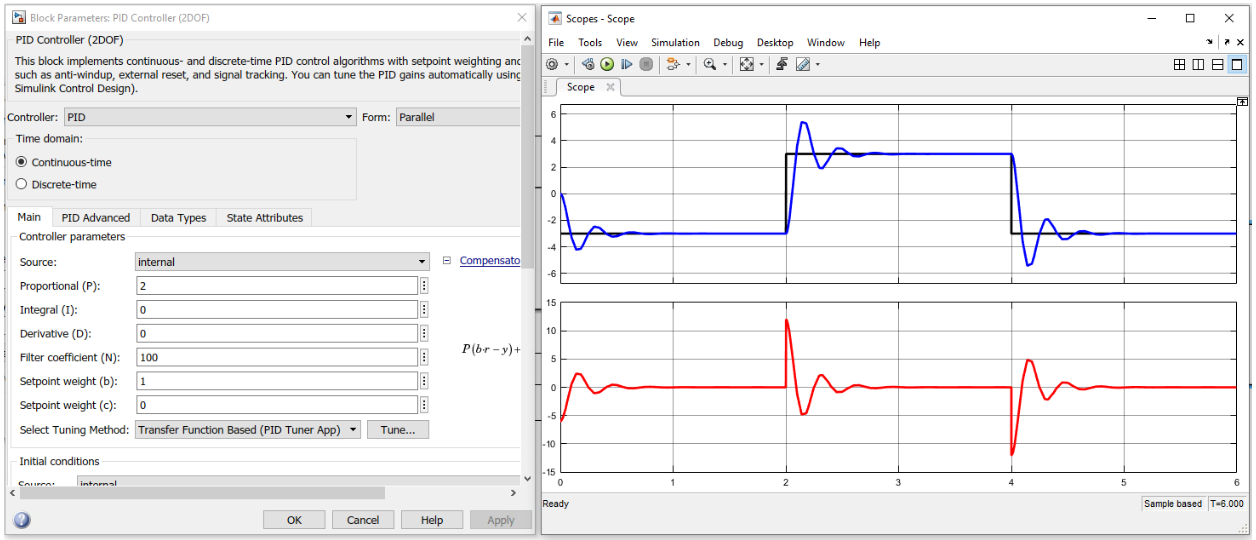
| **Waveform** | **Amplitude** | **Frequency** | **Offset** | $k_p$ (P) | $k_i$ (I) | $k_d$ (D) | $b_{sp}$ (b) | $b_{sd}$ (c) |
|---|---|---|---|---|---|---|---|---|
| Square Wave | 3 [rad] | 0.25 [Hz] | 0 [rad] | 0.1 | 0 | 0 | 1 | 0 |

If you need help identifying the parameters, refer to Fig. 1, 2, and 4.



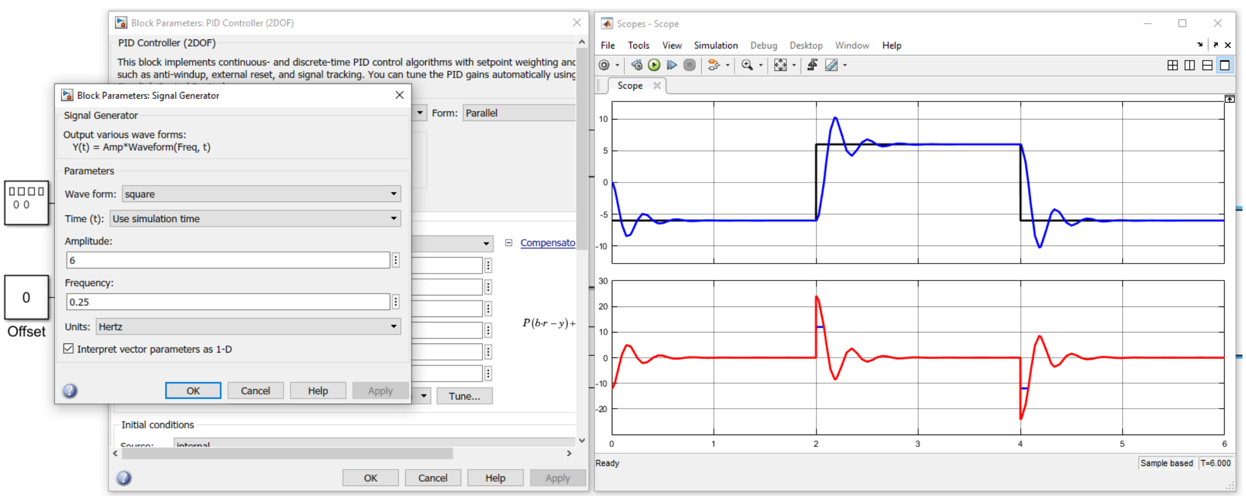



Step 2. Investigate the affect of the proportional gain by setting $k_p = 1$, 2, and 4 then observing the closed-loop response. How does increasing $k_p$ affect the response?




Step 3. Does the response have steady-state error? Does changing $k_p$ have an effect?

Step 4. Now increase the amplitude of the reference signal. Does the control signal saturate? at what points?




Step 5. Summarize your findings in your report. Answer the questions and include results to support your claims.

## 2.2 Proportional and Derivative (PD) Control

The control law for a proportional and derivative (PD) controller is given as:

$$u(t) = k_p(b_{sp}r(t) - y(t)) + k_d\left(b_{sd}\left(\frac{\mathrm{d}}{\mathrm{d}t}r(t)\right) - \left(\frac{\mathrm{d}}{\mathrm{d}t}y(t)\right)\right) \tag{3}$$

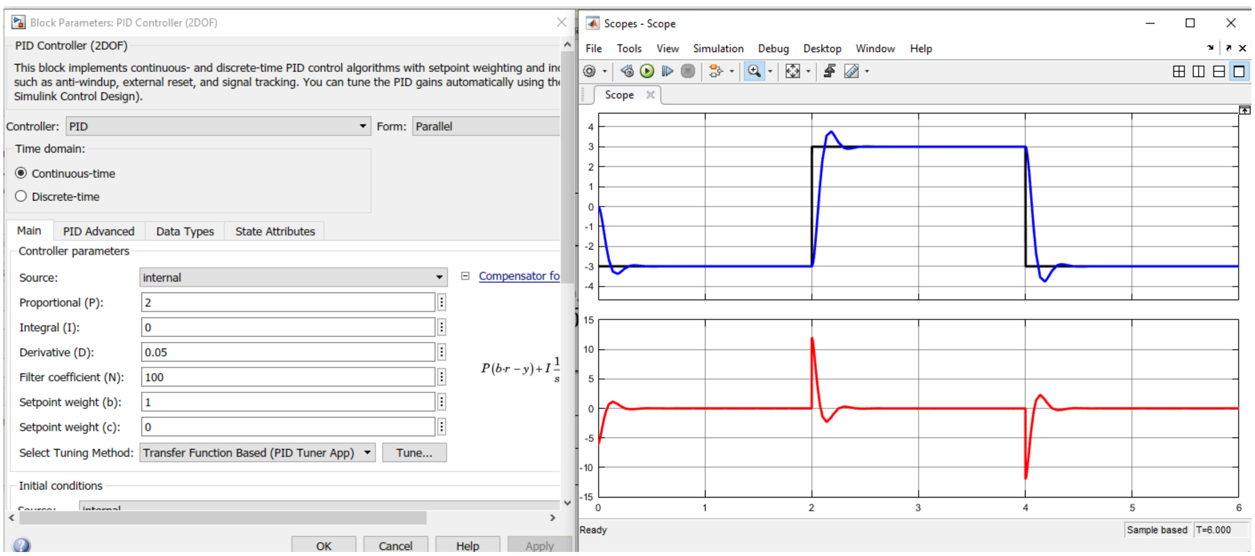
Explore the properties of a PD controller by following this procedure:

Step 1. Ensure the Simulink model is in a default state (noise and disturbance set to 0) and the following properties are set:

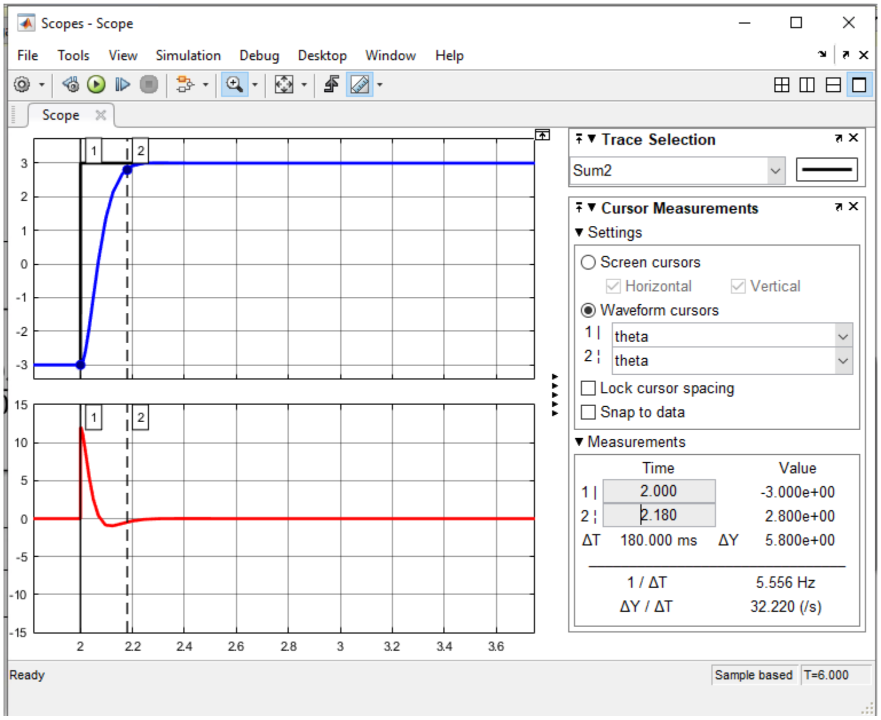
| **Waveform** | **Amplitude** | **Frequency** | **Offset** | $k_p$ (P) | $k_i$ (I) | $k_d$ (D) | $b_{sp}$ (b) | $b_{sd}$ (c) |
|---|---|---|---|---|---|---|---|---|
| Square Wave | 3 [rad] | 0.25 [Hz] | 0 [rad] | 2 | 0 | 0 | 1 | 1 |

If you need help identifying the parameters, refer to Fig. 1, 2, and 4.

Step 2. Investigate the affect of the derivative gain by setting $k_d =$ 0, 0.05, 0.1, and 0.15 then observing the closed-loop response. How does increasing $k_d$ affect the response?



Step 3. Determine a derivative gain ($k_d$) which gives a response without overshoot. What is the settling time for this response?




Step 4. Summarize your findings in your report. Answer the questions and include results to support your claims.

# 3 Design For Response Parameters

This section experimentally tests the calculated gains found in the pre-lab.

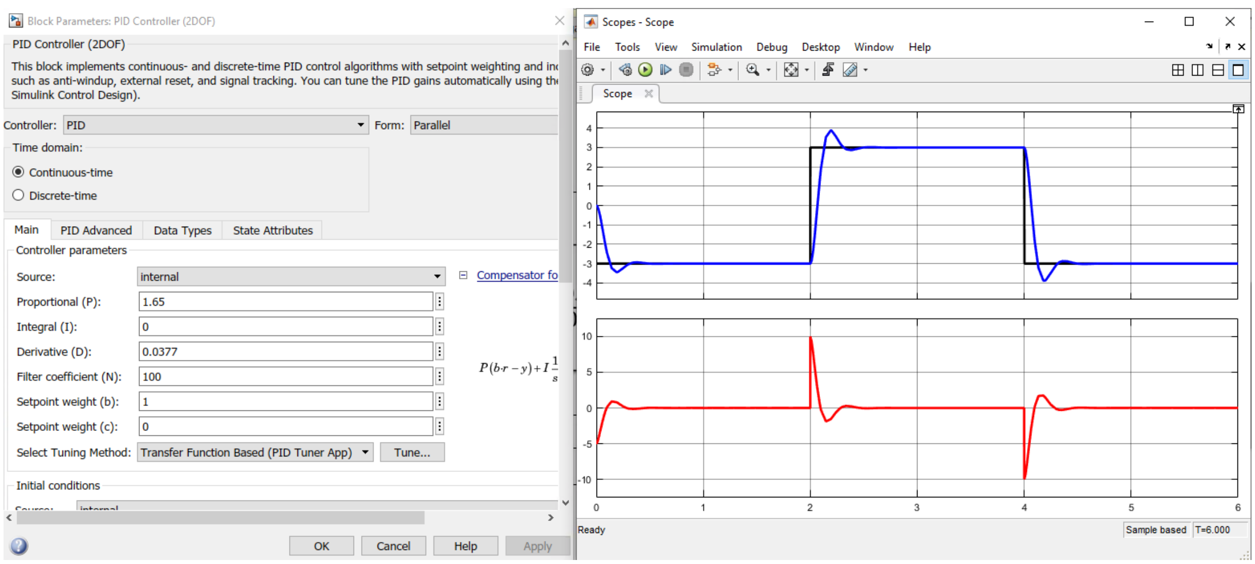
## 3.1 Proportional and Derivative (PD) Control

Experimentally verify the PD controller design from Section 5.5.3 of the pre-lab by following this procedure:

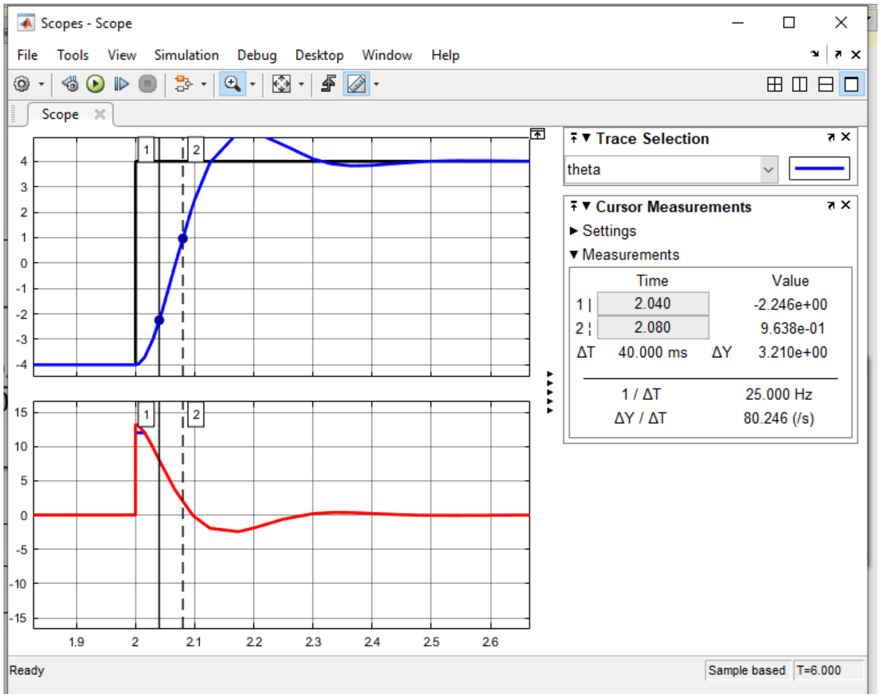
Step 1. Ensure the Simulink model is in a default state (noise and disturbance set to 0) and set the following properties, where $k_p$, $k_d$, and $b_{sd}$ are the parameters calculated in Section 5.5.3 (Question 4 and 7) of the pre-lab:

| **Waveform** | **Amplitude** | **Frequency** | **Offset** | $k_p$ (P) | $k_i$ (I) | $k_d$ (D) | $b_{sp}$ (b) | $b_{sd}$ (c) |
|---|---|---|---|---|---|---|---|---|
| Square Wave | 3 [rad] | 0.25 [Hz] | 0 [rad] | $k_p$ | 0 | $k_d$ | 1 | $b_{sd}$ |

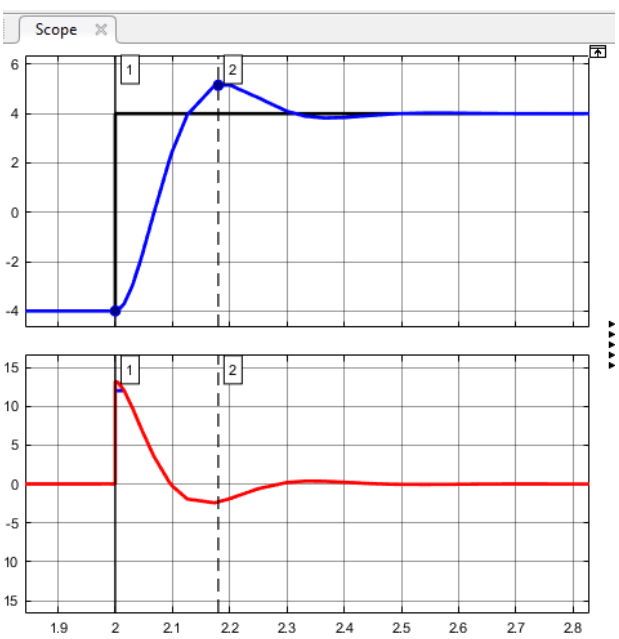
If you need help identifying the parameters, refer to Fig. 1, 2, and 4.

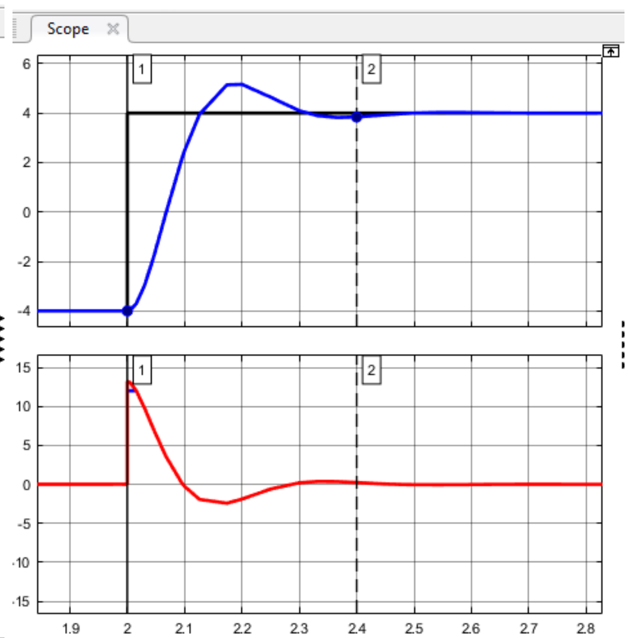


Step 2. Increase and decrease the amplitude of the reference signal until the control signal is just below the saturation point. How does this maximum $R_{max}$ compare to the one from Section 5.5.3 question 8?




Step 3. Measure the present overshoot and peak time. Does this meet the desired response requirements? Do any adjustments need to be made to the parameters calculated in Section 5.5.3 Question 4 and 7 to meet the requirements?




Step 4. Summarize your findings in your report. Answer the questions and include results to support your claims.

# 4 Tracking Changing Wave-forms

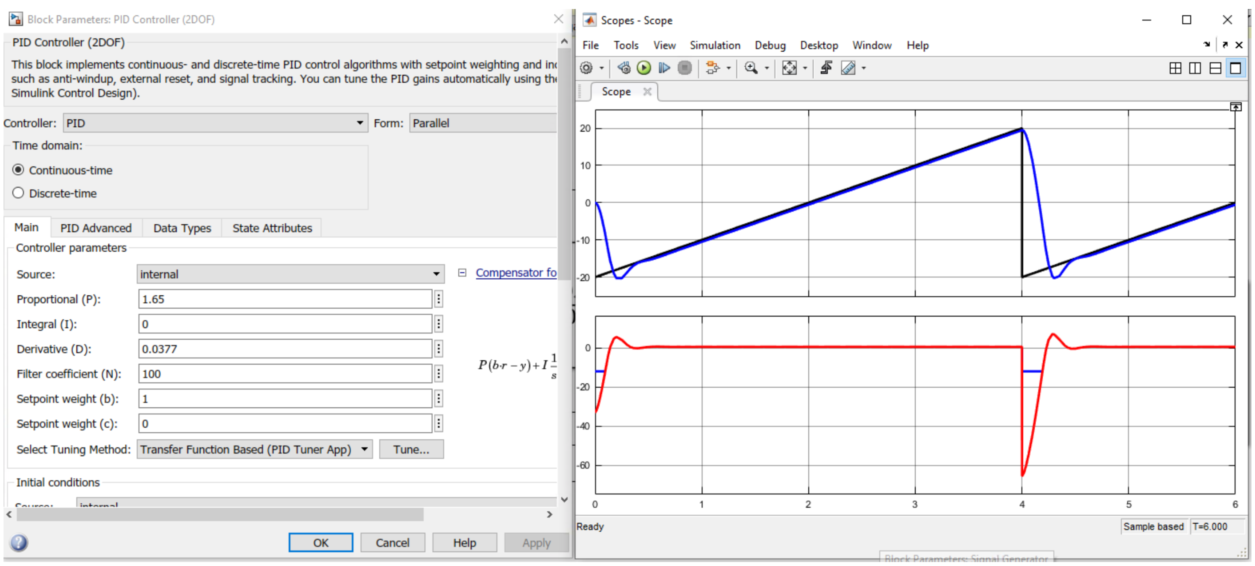
This section observes the ability for closed-loop control with a changing reference signal. This includes analyzing the steady-state error for a sawtooth waveform, as well as, observing the phase shift of a response to a sinusoidal reference signal.

## 4.1 Tracking a Ramp Signal

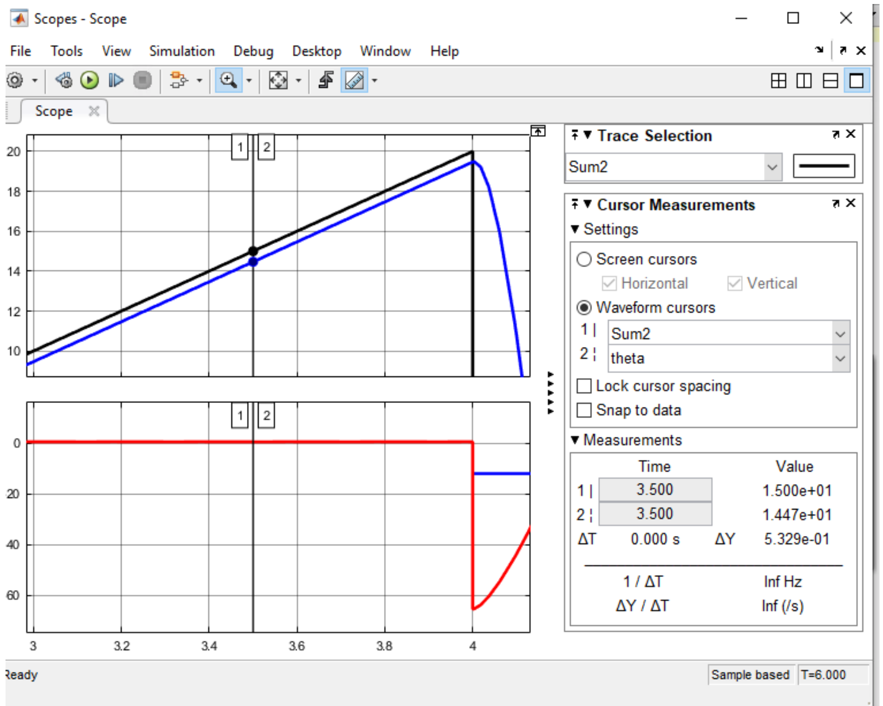
Follow this procedure:

Step 1. Ensure the Simulink model is in a default state (noise and disturbance set to 0) and set the following properties, where $k_p$, $k_d$, and $b_{sd}$ are the parameters calculated in Section 5.5.3 (Question 4 and 7) of the pre-lab:

| **Waveform** | **Amplitude** | **Frequency** | **Offset** | $k_p$ (P) | $k_i$ (I) | $k_d$ (D) | $b_{sp}$ (b) | $b_{sd}$ (c) |
|---|---|---|---|---|---|---|---|---|
| Sawtooth | - 20 [rad] | 0.25 [Hz] | 0 [rad] | $k_p$ | 0 | $k_d$ | 1 | $b_{sd}$ |



Step 2. Observe the tracking error of the signal. Does it exits? If so, is it constant or oscillating?




Step 3. Calculate the slop, $R_0$, of the input signal given the amplitude and frequency parameters.

Step 4. Measure the tracking error of the signal. How does this compare to analytical estimates from the pre-lab. Adjust the proportional gain, $k_p$, by steps of 0.5 and measure how this effects the steady-state tracking error.

Step 5. Using the gains calculated in Section 5.5.3 of the pre-lab, adjust $b_{sd}$ from 0 to 1 and observe the effect on the position response and tracking error. Summarize the relationship between $b_{sd}$ and the tracking error.

Step 6. Introduce an integral gain into the controller manually by increasing $k_i$ by steps of 1. What is the effect on the response and tracking error?

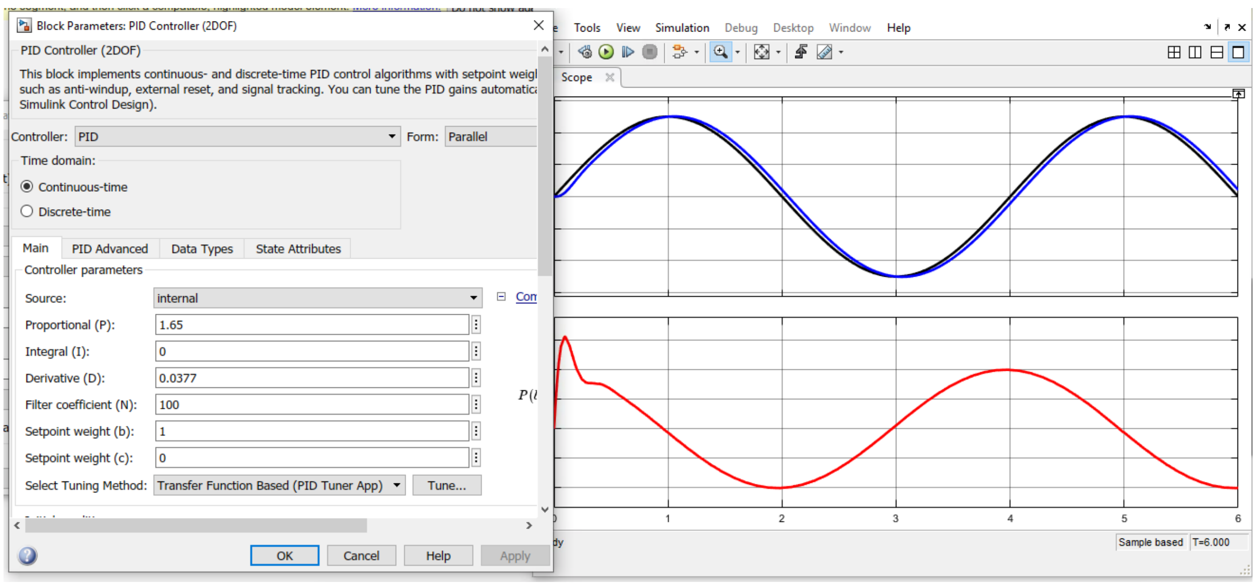
Step 7. Summarize your findings in your report. Make note of your observations and provide results to justify your claims.

## 4.2 Tracking a Sine Wave

Follow this procedure:

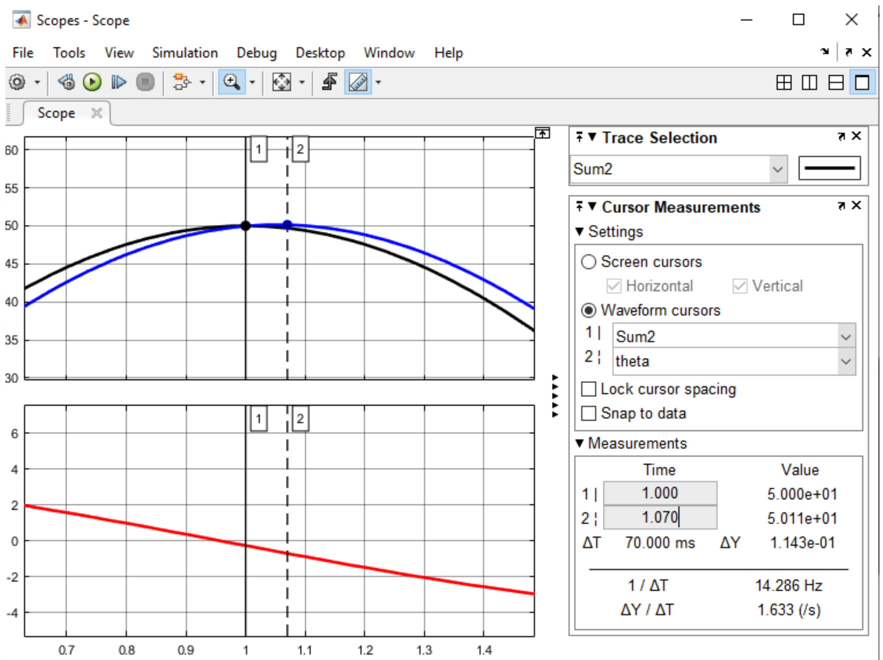
Step 1. Ensure the Simulink model is in a default state (noise and disturbance set to 0) and set the following properties, where $k_p$, $k_d$, and $b_{sd}$ are the parameters calculated in Section 5.5.3 of the pre-lab:

| **Waveform** | **Amplitude** | **Frequency** | **Offset** | $k_p$ (P) | $k_i$ (I) | $k_d$ (D) | $b_{sp}$ (b) | $b_{sd}$ (c) |
|---|---|---|---|---|---|---|---|---|
| Sine Wave | 20 [rad] | 0.25 [Hz] | 0 [rad] | $k_p$ | 0 | $k_d$ | 1 | $b_{sd}$ |



Step 2. Observe the response and calculate the phase shift of the output by measuring the time difference between the two peaks and using (4).

$$\phi = (\Delta t)(2\pi f) \tag{4}$$




Step 3. How does increasing and decreasing $k_p$ affect the phase shift?

Step 4. Introduce an integral gain into the controller manually by increasing $k_i$ by steps of 1. What is the effect on the response and phase shift?

Step 5. Summarize your findings in your report. Make note of your observations and provide results to justify your claims.

# 5 Response to Disturbances

The goal of this section is to test and observe the ability for closed-loop control systems to respond to disturbances. In this lab we will be testing how the system responds to a torque load applied to slow down the motor.

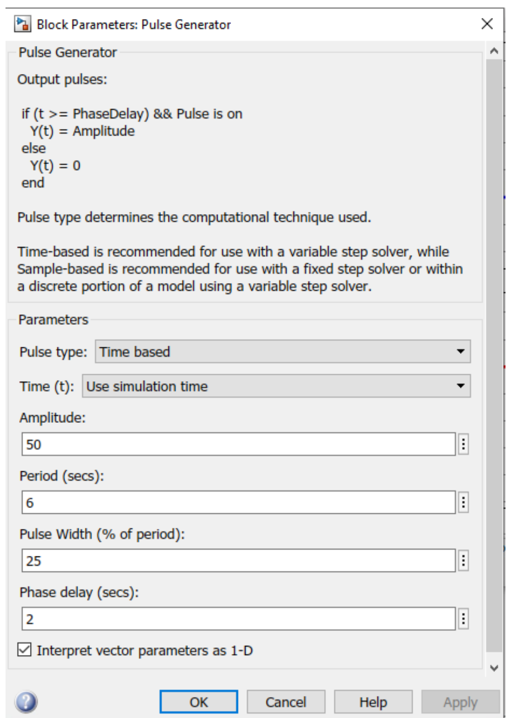
## 5.1 Proportional and Derivative (PD) Control

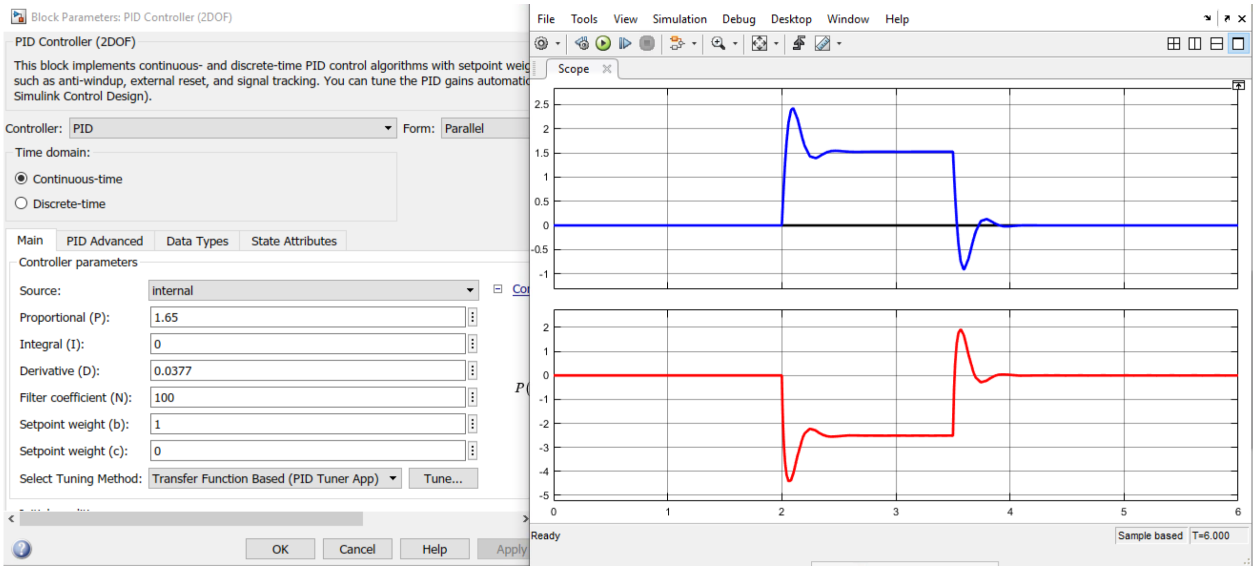
Explore the ability for a PD controller at responding to disturbances by following this procedure:

Step 1. Reconfigure the Simulink model to test disturbance response by setting the following parameters, where $k_p$, $k_d$, and $b_{sd}$ are the parameters calculated in Section 5.5.3 of the pre-lab:

| **Waveform** | **Amplitude** | **Frequency** | **Offset** | $k_p$ (P) | $k_i$ (I) | $k_d$ (D) | $b_{sp}$ (b) | $b_{sd}$ (c) |
|---|---|---|---|---|---|---|---|---|
| Square Wave | 0 [rad] | 0.25 [Hz] | 0 [rad] | $k_p$ | 0 | $k_d$ | 1 | $b_{sd}$ |

Step 2. Set the magnitude of the disturbance pulse generator (Fig. 8) to 50. How does the system react to the disturbance?






Step 3. Modify the proportional gain, $k_p$, and observe how the response changes.

Step 4. Modify the derivative gain, $k_d$, and observe how the response changes.

Step 5. Modify the derivative set-point weighting, $b_{sd}$, and observe how the response changes.

Step 6. Summarize your findings in your report. Answer the questions and include results to support your claims.

## 5.2 Proportional, Integral, and Derivative (PID) Control

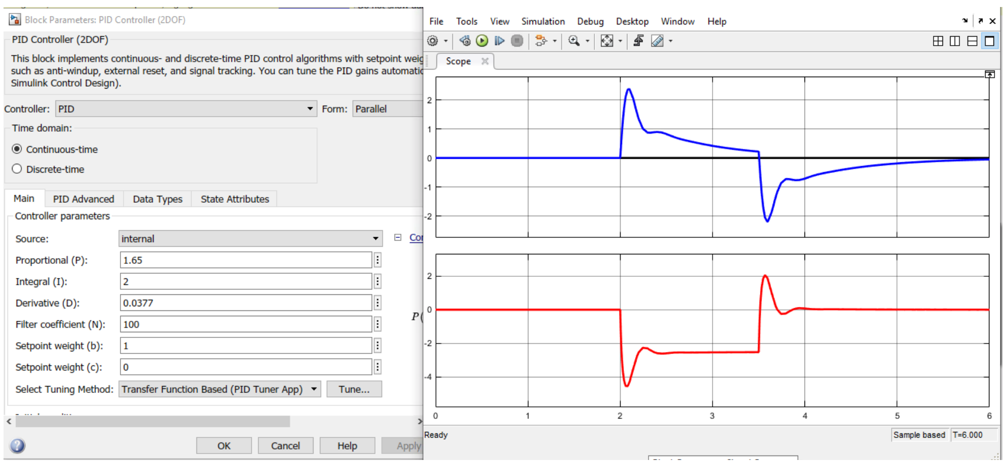
Explore the ability for a PID controller at responding to disturbances by following this procedure:

Step 1. Reconfigure the Simulink model to test disturbance response by setting the following parameters, where $k_p$, $k_d$, and $b_{sd}$ are the parameters calculated in Section 5.5.3 of the pre-lab:

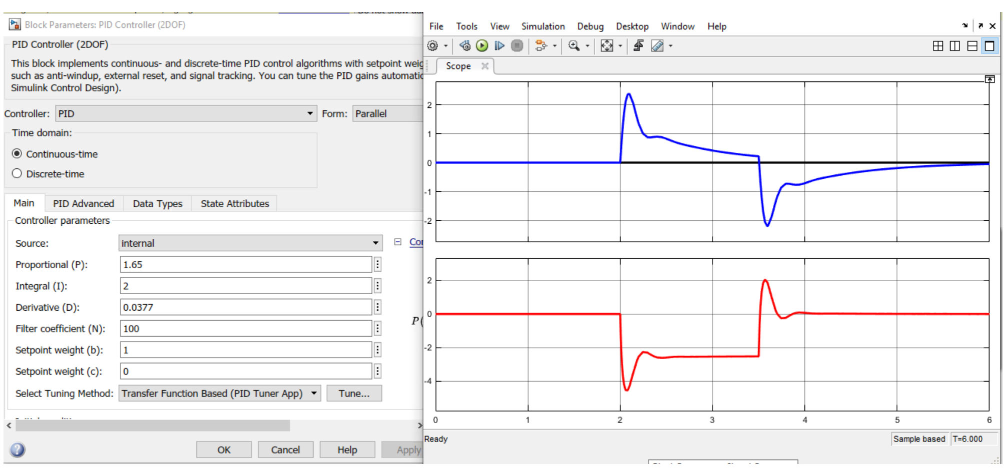
| **Waveform** | **Amplitude** | **Frequency** | **Offset** | $k_p$ (P) | $k_i$ (I) | $k_d$ (D) | $b_{sp}$ (b) | $b_{sd}$ (c) |
|---|---|---|---|---|---|---|---|---|
| Square Wave | 0 [rad] | 0.25 [Hz] | 0 [rad] | $k_p$ | 0 | $k_d$ | 1 | 0 |

Step 2. Set the magnitude of the disturbance pulse generator (Fig. 8) to 50.

Step 3. Introduce an integral gain into the controller manually by increasing $k_i$ by steps of 1. What is the effect on the disturbance response? Select a $k_i$ resulting in a good disturbance response and explain why a PID controller may be preferred over a strictly PD controller.




Step 4. Experimentally test the PID controller gains ($k_p$, $k_i$, and $k_d$) calculated in Section 5.5.3 of the pre-lab (Question 8). Be sure to set $b_{sd} = 1$.




Are these gains effective at responding to a disturbance? Does the response meet the desired specifications?

Step 5. Summarize your findings in your report. Answer the questions and include results to support your claims.