Speed Control Simulink Lab

EE 3320: Lab 2

Spring 2020

1 Speed 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 PI controllers

iii Learn about methods of tuning and testing PI controllers

iv Implement a PI controller 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 used in this lab is provided. A detailed model can be seen in Fig. 1.

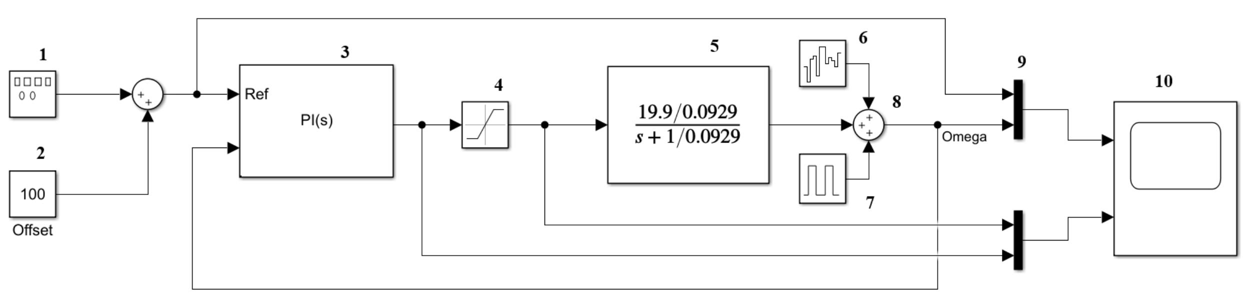


Fig. 1: Simulink Model to be used for testing speed control of a simulated brushed DC motor. The blocks are defined as: (1) Reference Signal Generator, (2) Reference Signal Offset, (3) PI Controller, (4) Control Signal Saturation, (5) Plant Transfer Function, (6) Measurement Noise, (7) Disturbance Pulse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

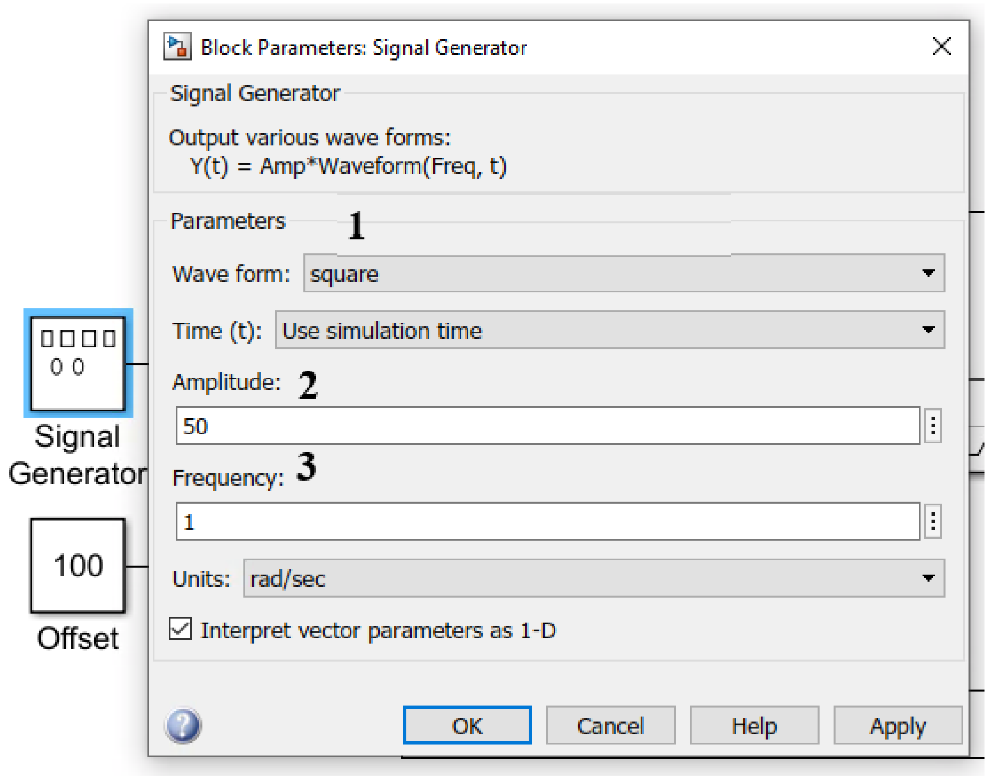


Fig. 2: The Reference Signal Generator. There are settings for: (1) Signal Waveform, (2) Amplitude, and (3) Frequency.

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.

1.3.3 PI Controller

The PI Controller is a built in PID Controller block with three parameters to tune: k_p, k_i, and b.

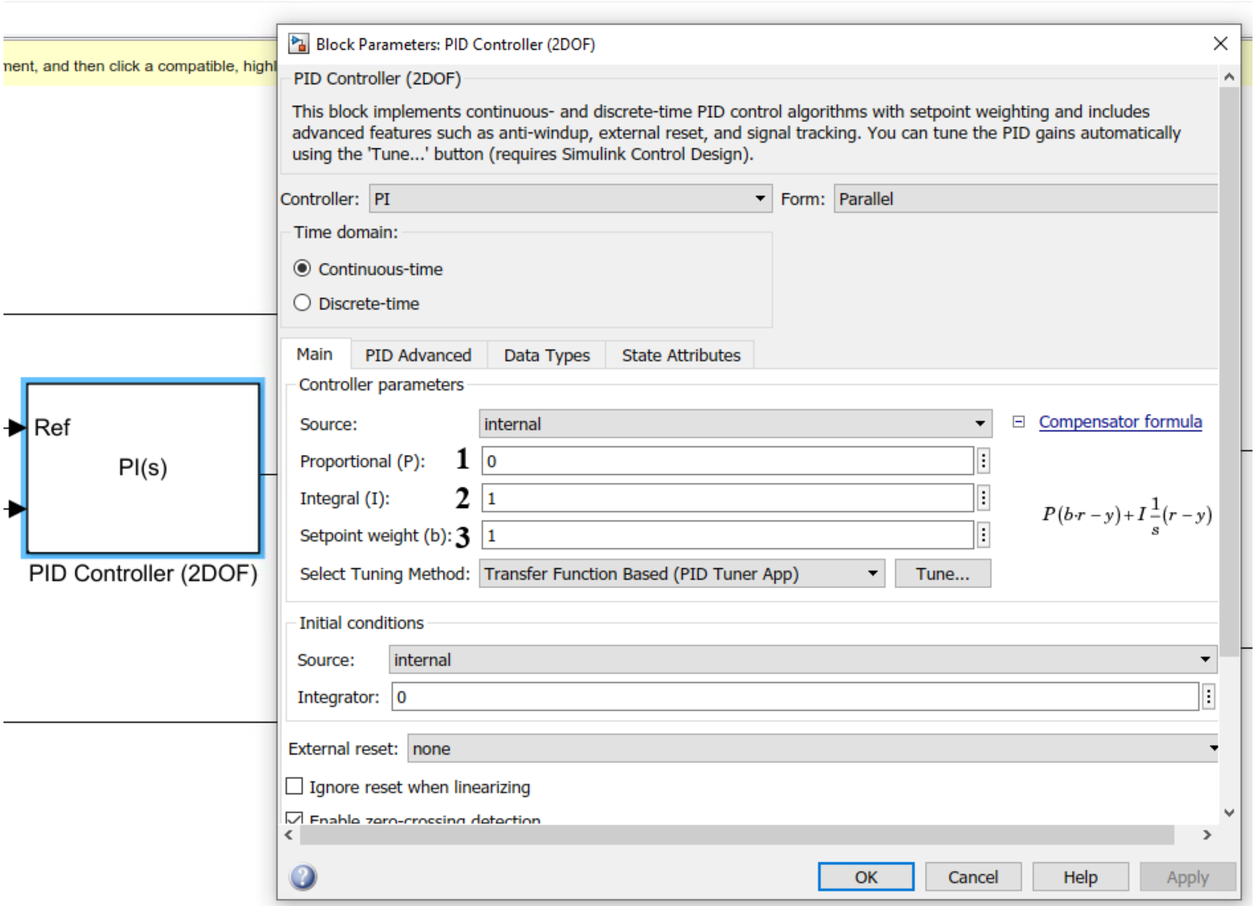


Fig. 3: PI Controller that is used to implement P, I, and PI control of the system. The parameters to be tuned are (1) k_p, (2) k_i, and (3) b_{sp}.

1.3.4 Control Signal Saturation

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

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 $\tau = 0.0929$.

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.

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.

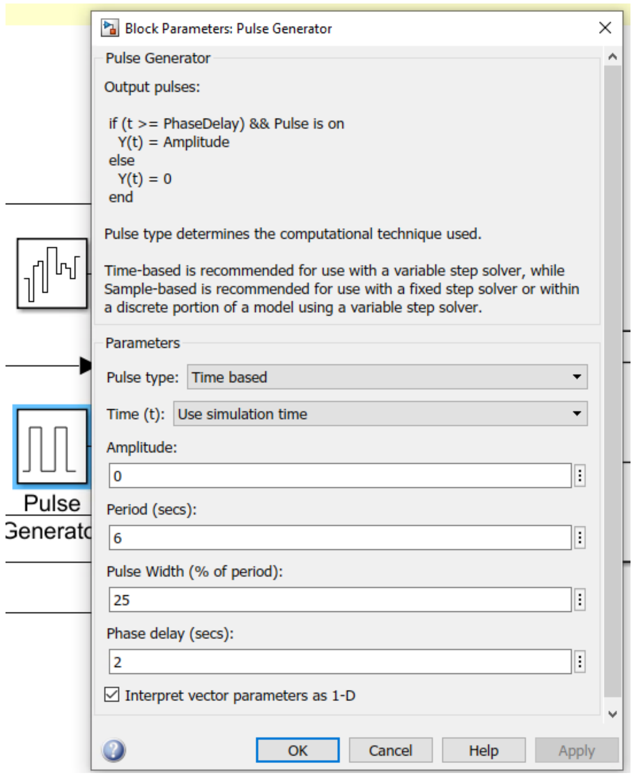


Fig. 4: A pulse generator to test the ability for a system to respond to disturbances. Only the amplitude needs to be adjusted.

1.3.8 Signal Sum Block

Sum Blocks allow for the addition and subtraction of signals.

1.3.9 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.

1.3.10 Output and Control Signal Scope

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

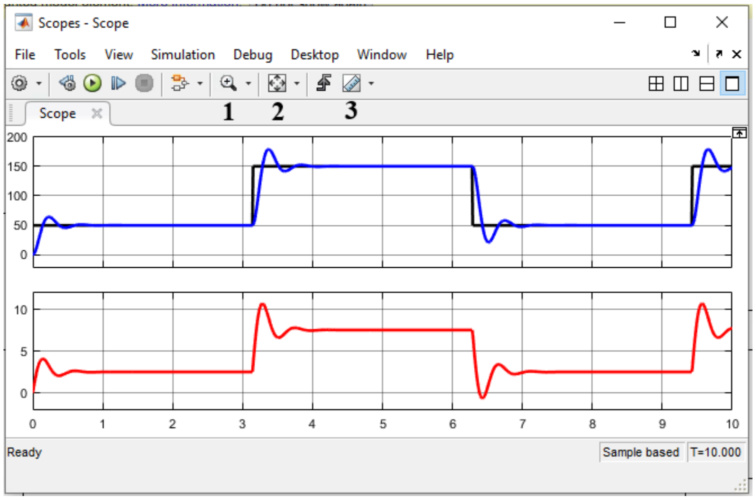


Fig. 5: Scope displaying the plant output and control signal. (1) The zoom is important for finding detail within the signal. (2) Auto-zoom is also useful. (3) Cursors can be placed on the signal to measure it as well.

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

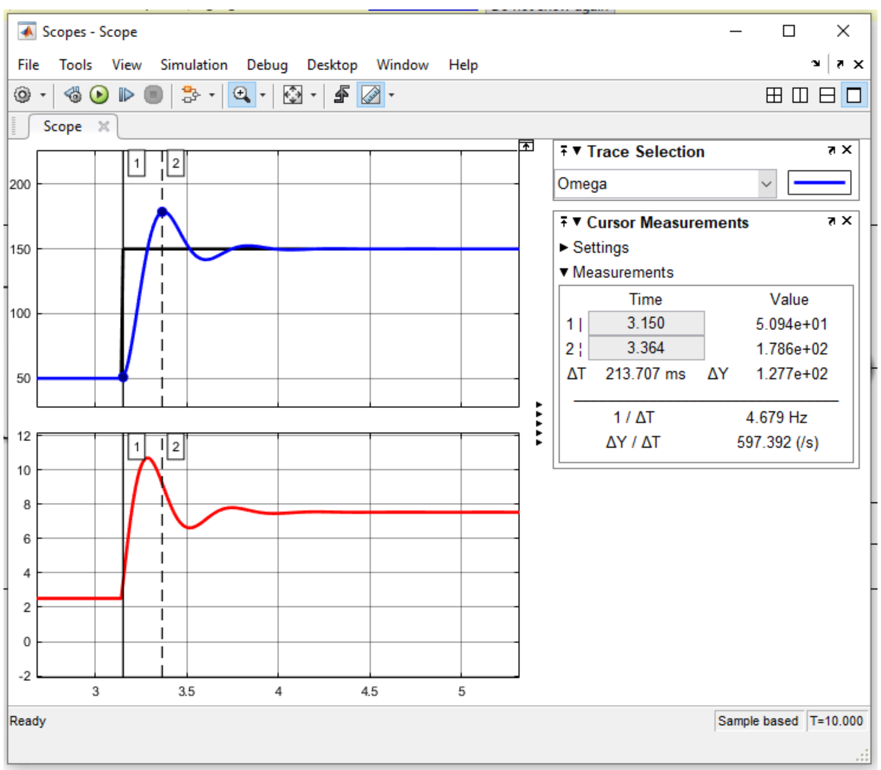


Fig. 6: The measurement tool within the scope.

2 PI Controller Qualitative Analysis

In the pre-lab, the theory of P, I, and PI control were explored theoretically. This section will help to develop an intuitive understanding for the properties of P, I, and PI control. **Be sure to reference the Simulink model explanation when following the procedure.**

2.1 Pure Proportional Control

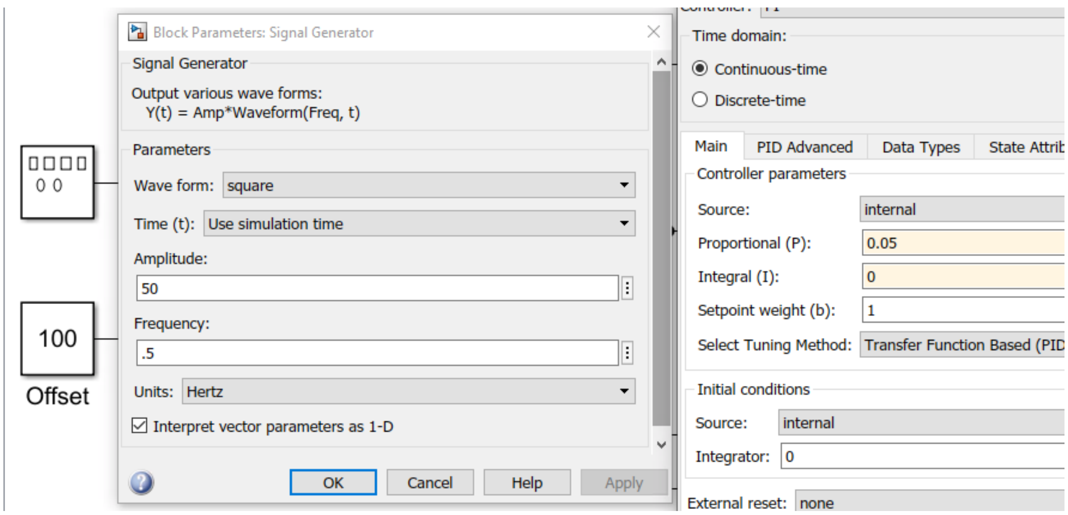
The control law for a pure proportional controller is given as:

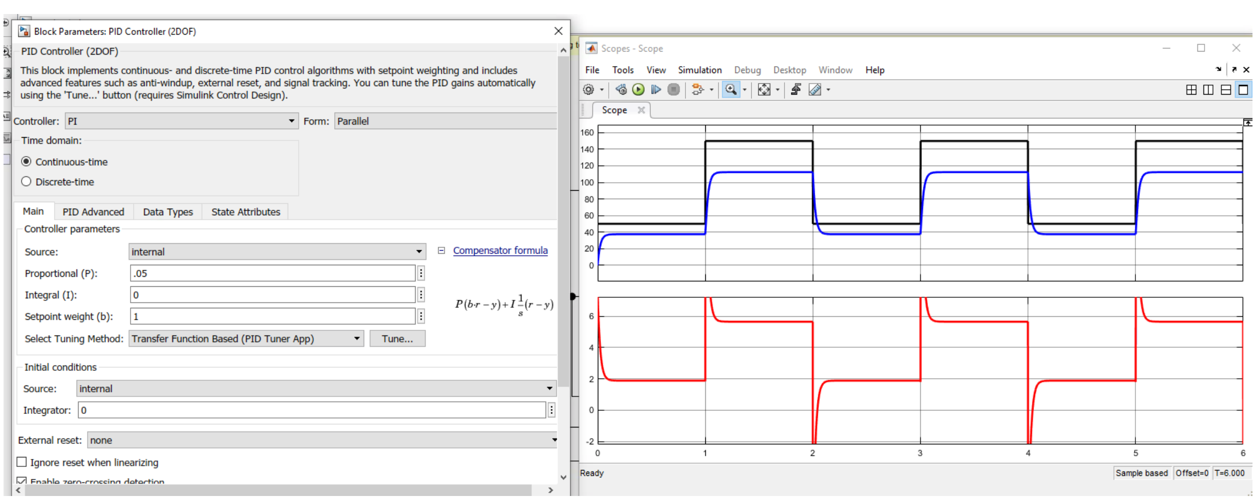
$$u(t) = k_p(b_{sp}r(t) - y(t))) \tag{2}$$

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

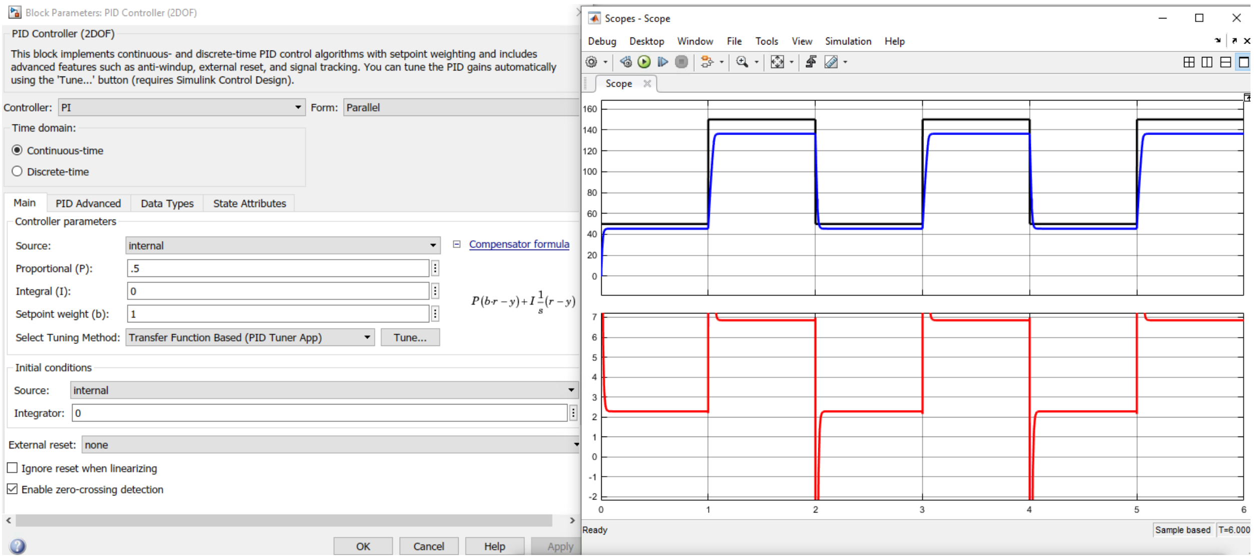
Step 1. Ensure the Simulink model is in a default state (noise and disturbance set to 0) and the following properties are set:

Waveform	**Amplitude**	**Frequency**	**Offset**	k_p	k_i	b_{sp}
Square Wave	50 [rad/s]	0.5 [Hz]	100 [rad/s]	0.05	0	1





Step 2. Incrementally increase k_p by 0.25 and investigate the affect on 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 Pure Integral Control

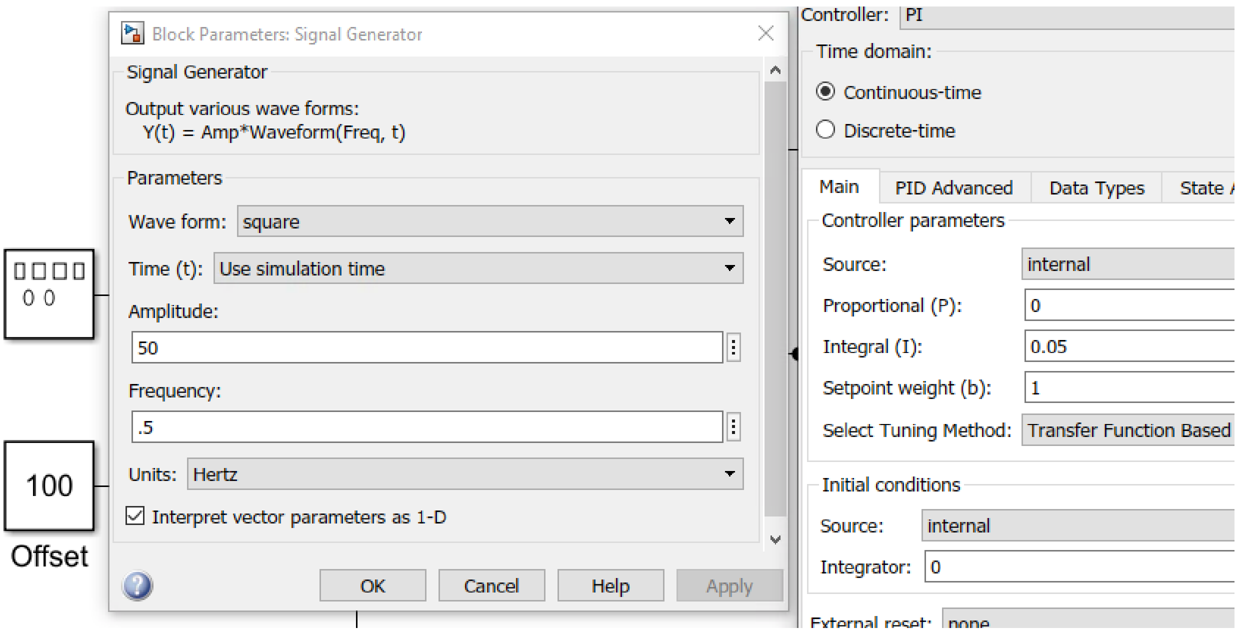
The control law for a pure integral controller is given as:

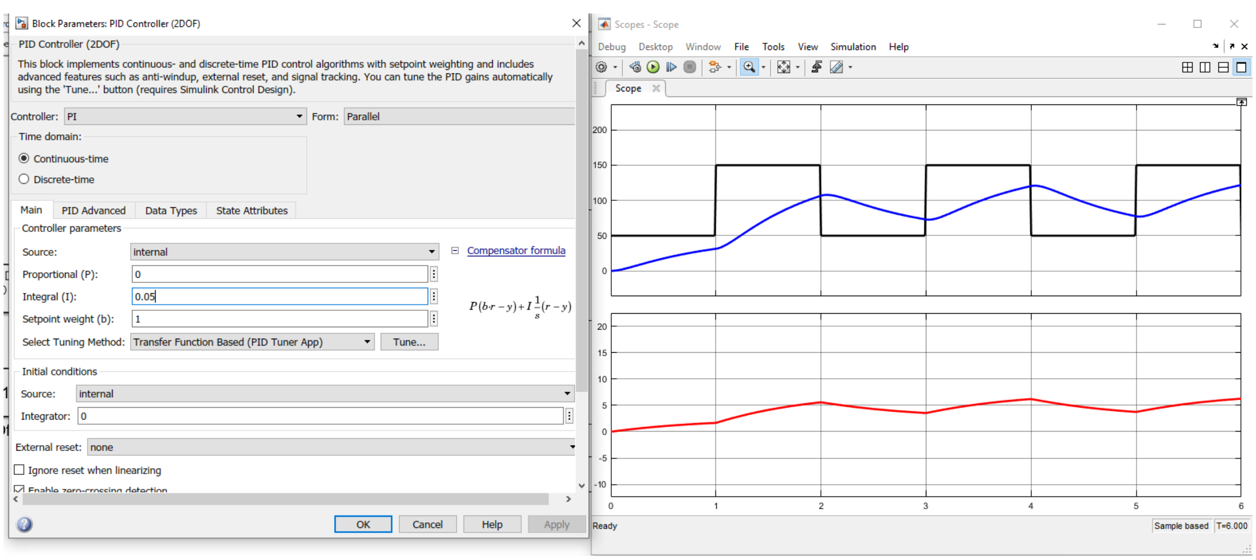
$$u(t) = k_i \int_0^t r(\tau) - y(\tau)\mathrm{d}\tau \tag{3}$$

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

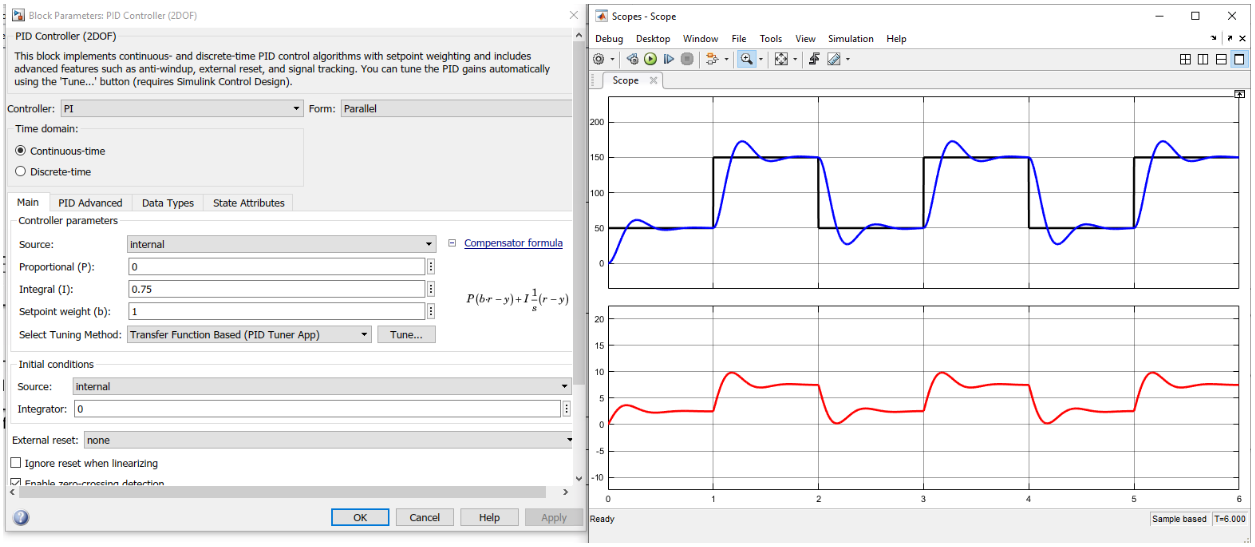
Step 1. Ensure the Simulink model is in a default state (noise and disturbance set to 0) and the following properties are set:

Waveform	**Amplitude**	**Frequency**	**Offset**	k_p	k_i	b_{sp}
Square Wave	50 [rad/s]	0.5 [Hz]	100 [rad/s]	0	0.05	1





Step 2. Incrementally increase k_i by 0.25 and investigate the affect on the closed-loop response. How does increasing k_i affect the response?



Step 3. Does the response have steady-state error? Does k_i have an effect? Select a value that results in a response without overshoot, what is it's settling time?

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.

2.3 Proportional and Integral Control

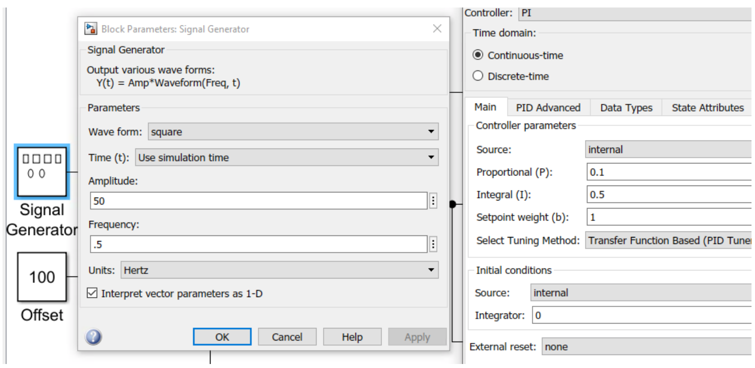
The control law for a PI controller is given as:

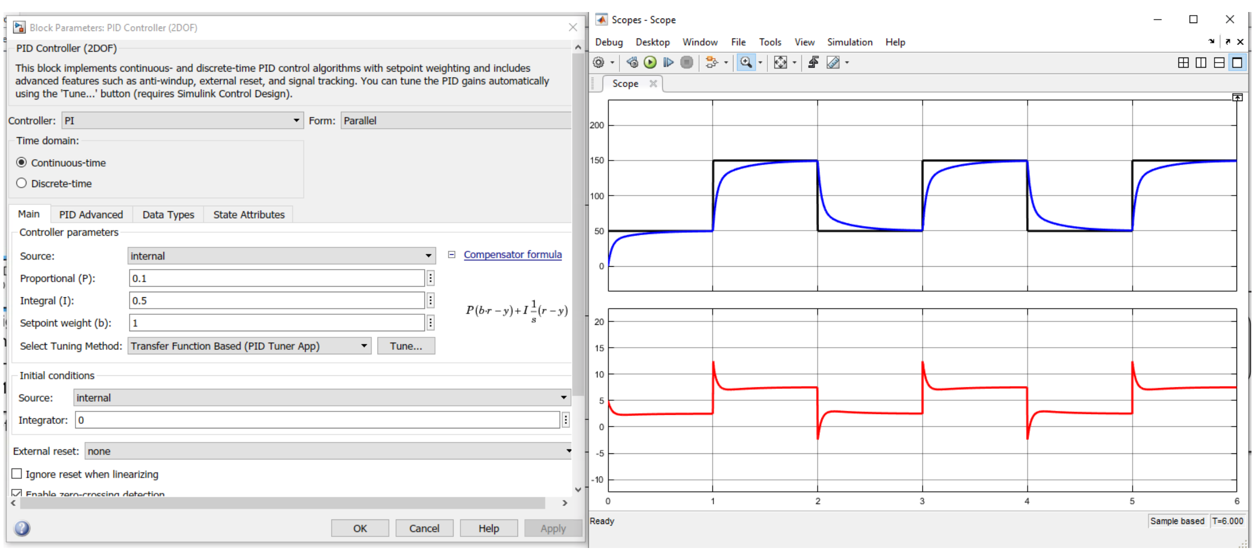
$$u(t) = k_p(b_{sp}r(t) - y(t)) + k_i \int_0^t r(\tau) - y(\tau)\mathrm{d}\tau \tag{4}$$

Explore the properties of a PI 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	k_i	b_{sp}
Square Wave	50 [rad/s]	0.5 [Hz]	100 [rad/s]	0.1	0.5	1





Step 2. Keep k_p constant at the default state (Step 1)and adjust k_i from 0 to k_ic. Observe how the error and control signal are affected.

Step 3. Keep k_i constant at the default state (Step 1) and adjust k_p from 0 to k_pc. Observe how the error and control signal are affected.

Step 4. Summarize your findings in your report. Make note of your observations and provide results to justify your claims.

3 Manual Tuning

This section outlines a method to estimate parameters to achieve an effective closed-loop response. Calculations using the critically stable state of a P and I controller are used to generate k_p and k_i.

3.1 Ziegler-Nichols Method

The Ziegler–Nichols tuning method is a heuristic method of tuning PID controllers. It was developed by John G. Ziegler and Nathaniel B. Nichols. It is performed by setting the I (integral), k_i, and D (derivative), k_d, gains to zero. The "P" (proportional) gain, k_p is then increased (from zero) until it reaches the critical gain k_pc, which is the largest gain at which the output of the control loop has stable and consistent oscillations; higher gains than the critical gain have diverging oscillation. k_pc and the oscillation period, T_Pc, are then used to set the k_p, k_i, and k_d gains depending on the type of controller used and behaviour desired. For speed control, we will only be tuning for a PI controller.

The recommended gains for the PI controller are calculated as follows:

$$k_p = 0.4k_{pc} \tag{5}$$

$$T_i = 0.8T_{pc} \tag{6}$$

$$k_i = \frac{k_p}{T_i} \tag{7}$$

It this particular lab, the simulation is unable to effectively replicate the critical operation with uncontrollable oscillations; therefore, the critical gains from the actual system can be used:

$$k_{pc} = 0.41 \ [V \cdot s/rad] \tag{8}$$

$$T_{pc} = 0.09 \ [s] \tag{9}$$

$$k_{ic} = 0.18 \ [V/rad] \tag{10}$$

$$T_{ic} = 0.6 \ [s] \tag{11}$$

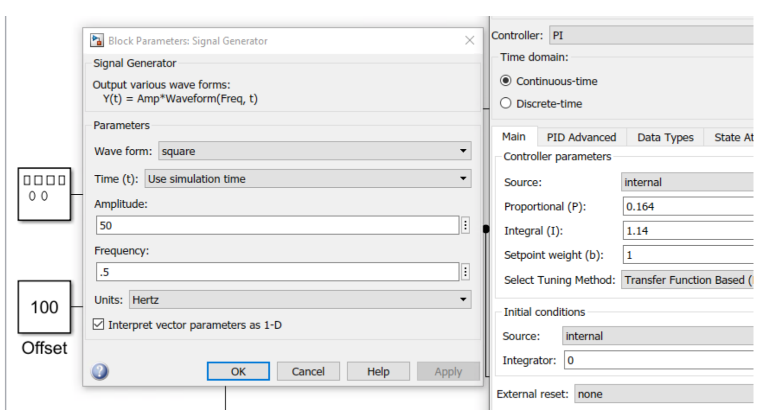
3.2 Ziegler-Nicholas Experimental Procedure

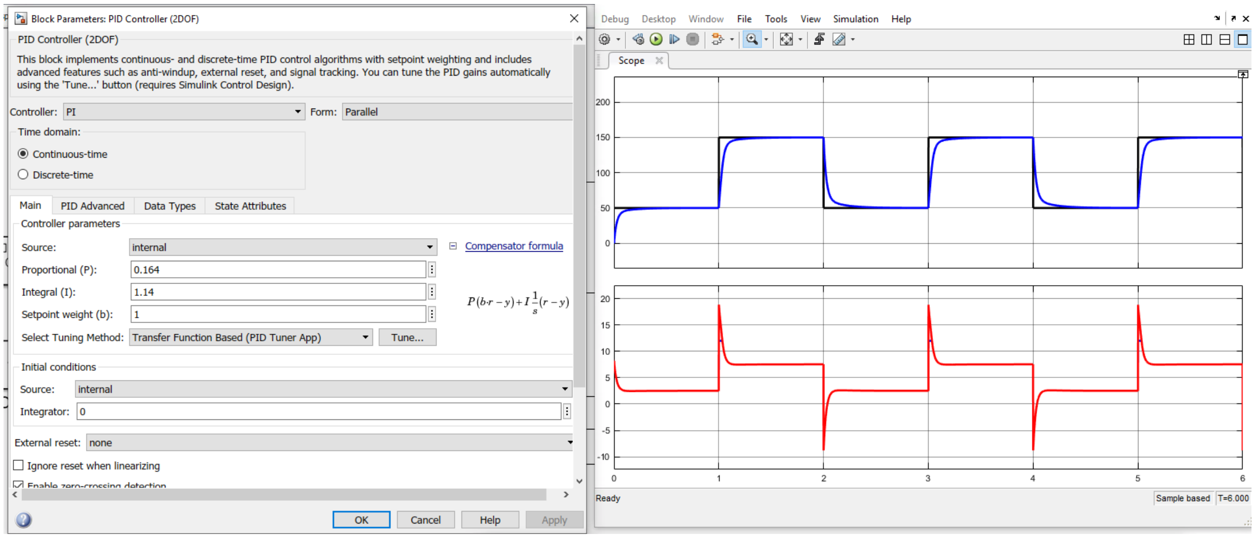
Execute the Ziegler-Nicholas method by following the following procedure:

Step 1. Calculate the estimated PI controller gains (k_p and k_i) using the equations outlined in the previous section ((5), (6), and (7)). The parameters, k_{pc}, T_{pc}, and k_{ic}, can be found in (8), (9), and (10) respectively.

Step 2. Ensure the Simulink model is in a default state (noise and disturbance set to 0) and the following properties are set (using the calculated k_p and k_i):

Waveform	**Amplitude**	**Frequency**	**Offset**	k_p	k_i	b_{sp}
Square Wave	50 [rad/s]	0.5 [Hz]	100 [rad/s]	k_p	k_i	1





What is the 2 % settling time? Note the response characteristics.

Step 3. Using intuition and manually adjust k_p and k_i to provide a slightly under-damped response, while remaining unsaturated. Explain how and why the parameters were tuned to fit the response.

Step 4. Summarize your findings in your report. Make note of your observations and provide results to justify your claims.

3.3 Set-Point Weighting

An additional parameter of a PI controller is the set-point weight, b_{sp}. Investigate the effect of modifying this weight 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. Be sure to set the gains as found through the Ziegler-Nichols method in Section 3.2:

Waveform	**Amplitude**	**Frequency**	**Offset**	k_p	k_i	b_{sp}
Square Wave	50 [rad/s]	0.5 [Hz]	100 [rad/s]	k_p	k_i	1

Investigate how manipulating b_{sp} from 1 to 0 affects the response.

Step 2. Perform an analysis of the control signal (4) to explain how reducing b_sp can cause the observed affect.

Step 3. Summarize your findings in your report. Make note of your observations and provide results to justify your claims.

4 Design For Response Parameters

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

4.1 PI Control Without Set-Point Weighting

Follow 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. Set the gains to those calculated in the prelab- Section 3.5.1 Question 10:

Waveform	**Amplitude**	**Frequency**	**Offset**	k_p	k_i	b_{sp}
Square Wave	50 [rad/s]	0.5 [Hz]	100 [rad/s]	k_p	k_i	0

Step 2. Verify the effective closed-loop control of the system. What is the settling time? Does the response meet the designed requirements?

Step 3. Summarize your findings in your report. Make note of your observations and provide results to justify your claims.

4.2 PI Control With Set-Point Weighting

Follow 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. Set the gains to those calculated in the prelab- Section 3.5.1 Question 11:

Waveform	**Amplitude**	**Frequency**	**Offset**	k_p	k_i	b_{sp}
Square Wave	50 [rad/s]	0.5 [Hz]	100 [rad/s]	k_p	k_i	1

Step 2. Verify the effective closed-loop control of the system. What is the settling time? Does the response meet the designed requirements? How does this compare to the results containing no set-point?

Step 3. Summarize your findings in your report. Make note of your observations and provide results to justify your claims.

5 Tracking Changing Wave-forms

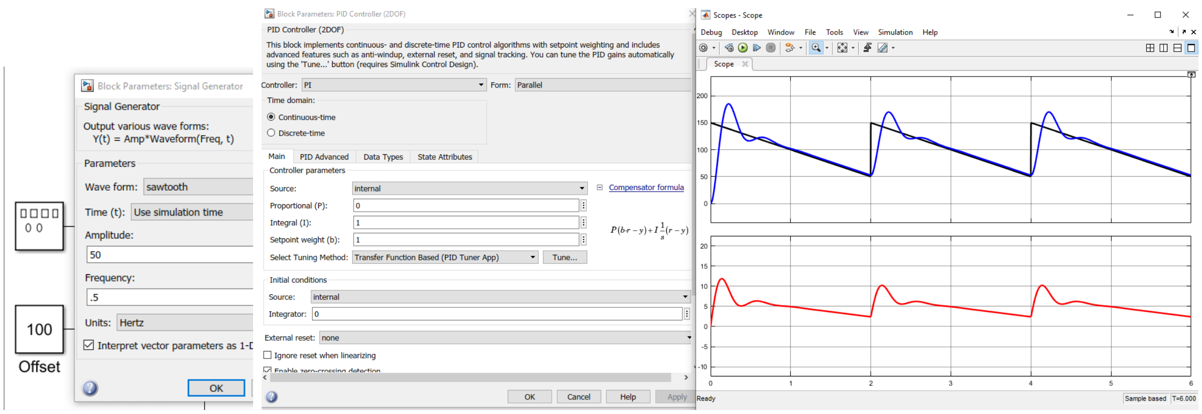
This section observes the ability for closed-loop control with a changing reference signal. This includes analyzing the steady-state error for a sawtooth waveform, as well as, observing the phase shift of a response to a sinusoidal reference signal.

5.1 Tracking a Ramp Signal

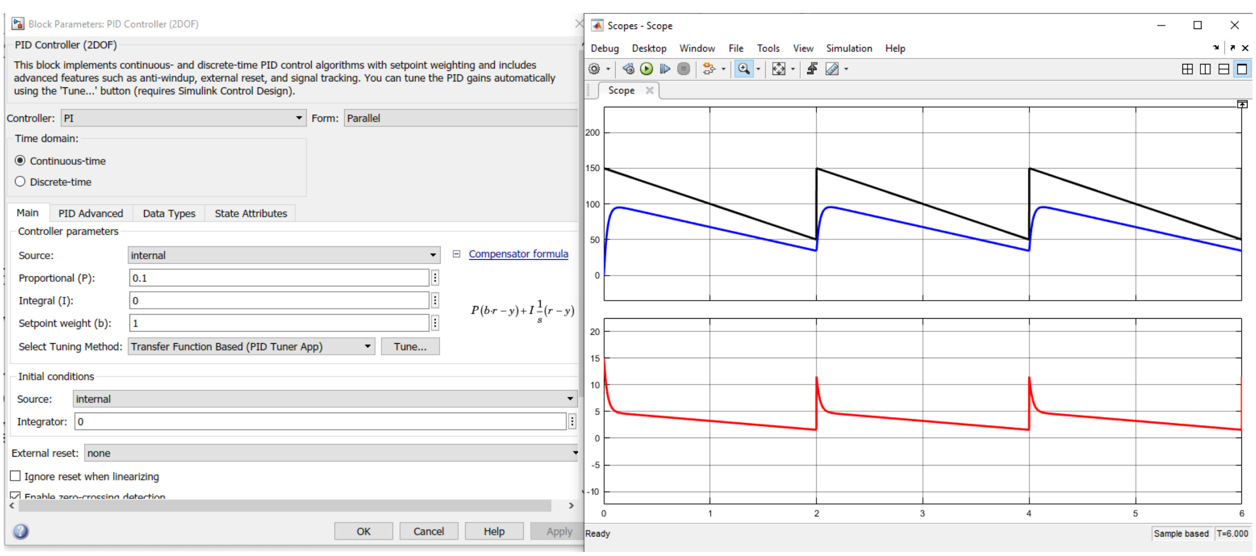
Follow this procedure:

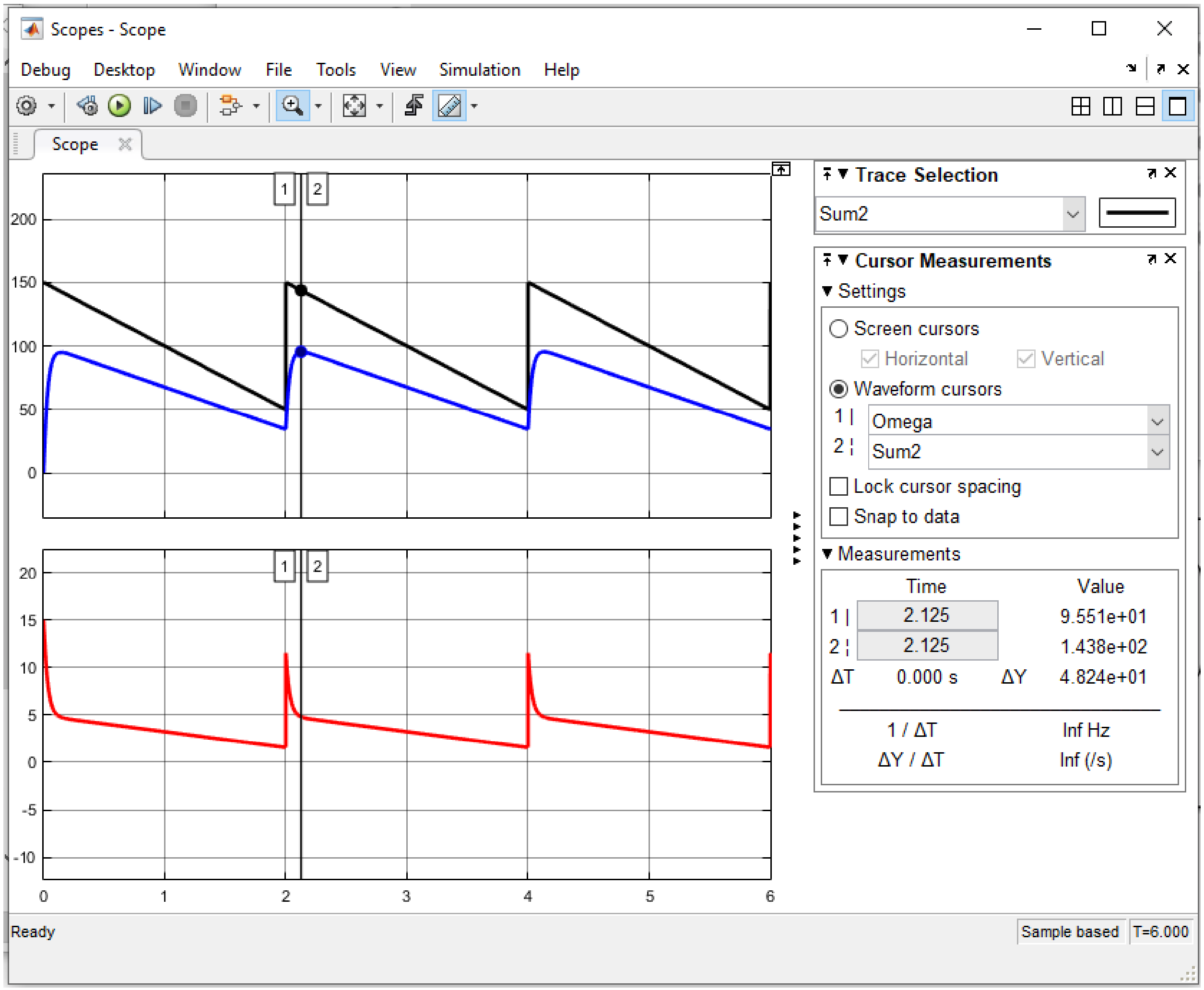
Step 1. Ensure the Simulink model is in a default state (noise and disturbance set to 0) and the following properties are set:

Waveform	**Amplitude**	**Frequency**	**Offset**	k_p	k_i	b_{sp}
Sawtooth	50 [rad/s]	0.5 [Hz]	100 [rad/s]	0	1	1



Step 2. Observe the pure integral control response. What is the maximum steady-state tracking error? How does this change if k_i is increased or decreased?





Step 3. Now observe the pure proportional control response by setting k_p to 0.1 and k_i to 0. What is the maximum steady-state tracking error? How does this change if k_p is increased or decreased?

Step 4. Introduce an integer term by setting k_i to 1. How is the response changed? What is the maximum steady-state tracking error? How does increasing or decreasing the gains affect the response?

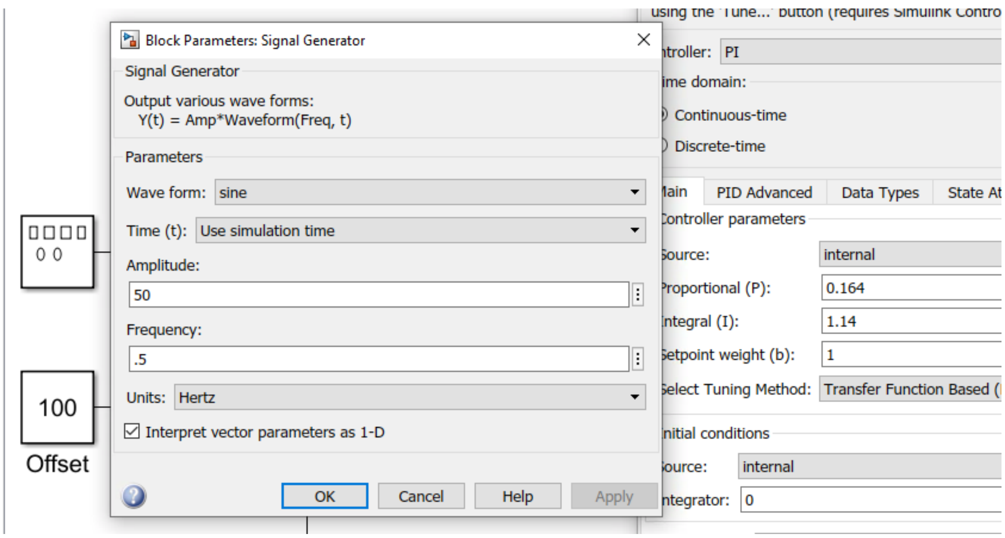
Step 5. Summarize your findings in your report. Make note of your observations and provide results to justify your claims.

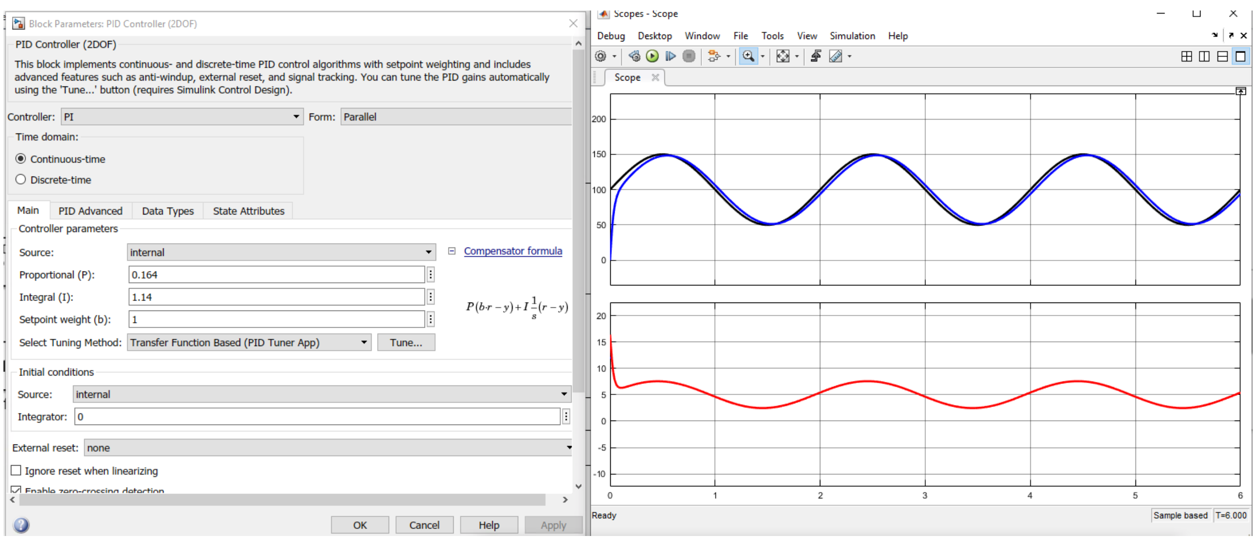
5.2 Tracking a Sine Wave

Analyze phase shift... compare to the theoretical phase shift of closed-loop TF at .5 Hz

Step 1. Ensure the Simulink model is in a default state (noise and disturbance set to 0) and the following properties are set. Set the gains to those used in Section 4.2:

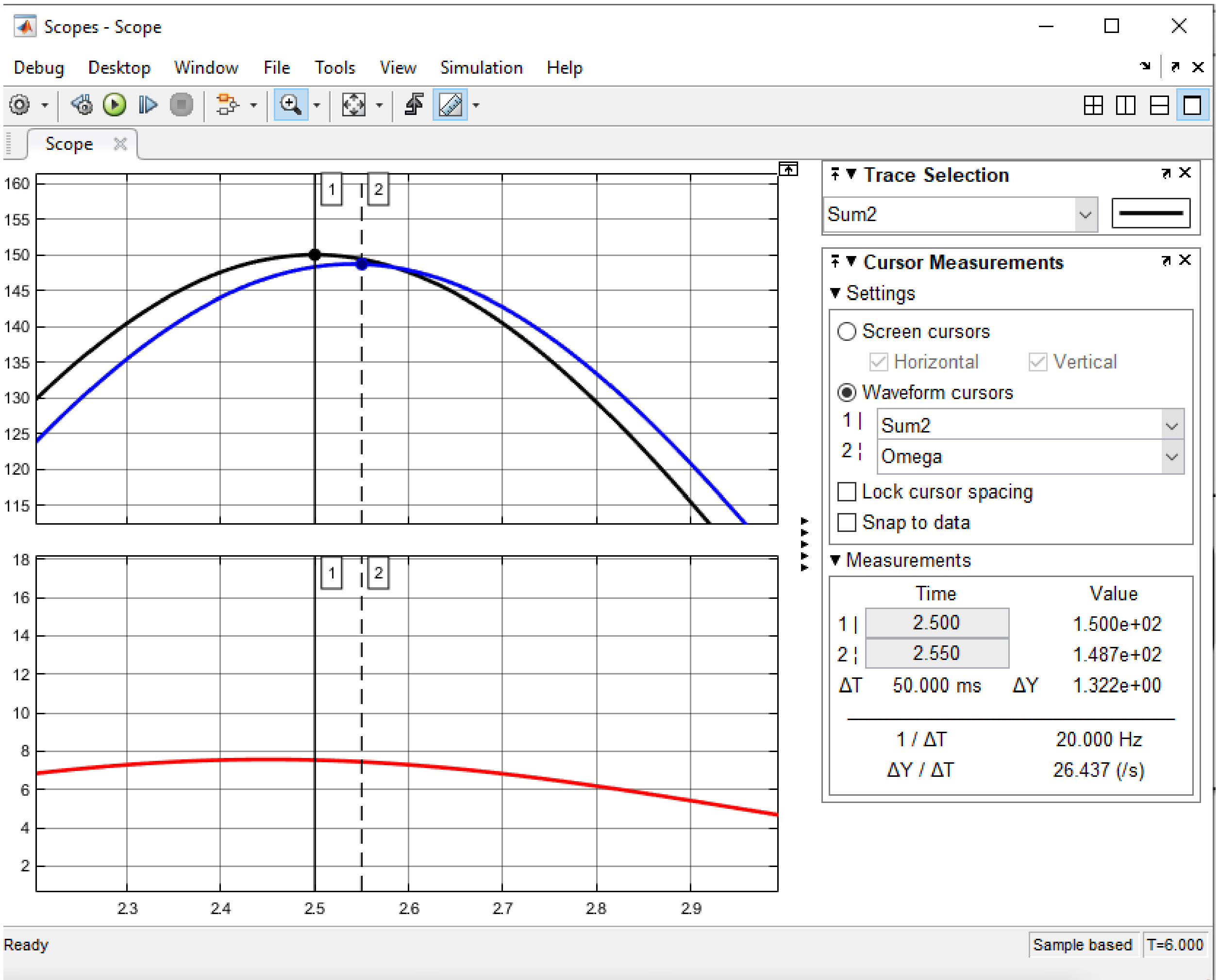
Waveform	**Amplitude**	**Frequency**	**Offset**	k_p	k_i	b_{sp}
Sine Wave	50 [rad/s]	0.5 [Hz]	100 [rad/s]	k_p	k_i	1





Step 2. Observe the response and calculate the phase shift of the output by measuring the time difference between the two peaks and using (12). How does increasing and decreasing k_p affect the phase shift? How does increasing and decreasing k_i affect the phase shift?

$$\phi = (\Delta t)(2\pi f) \tag{12}$$



Step 3. Summarize your findings in your report. Make note of your observations and provide results to justify your claims.

6 Response to Disturbances

Section about disturbance response...

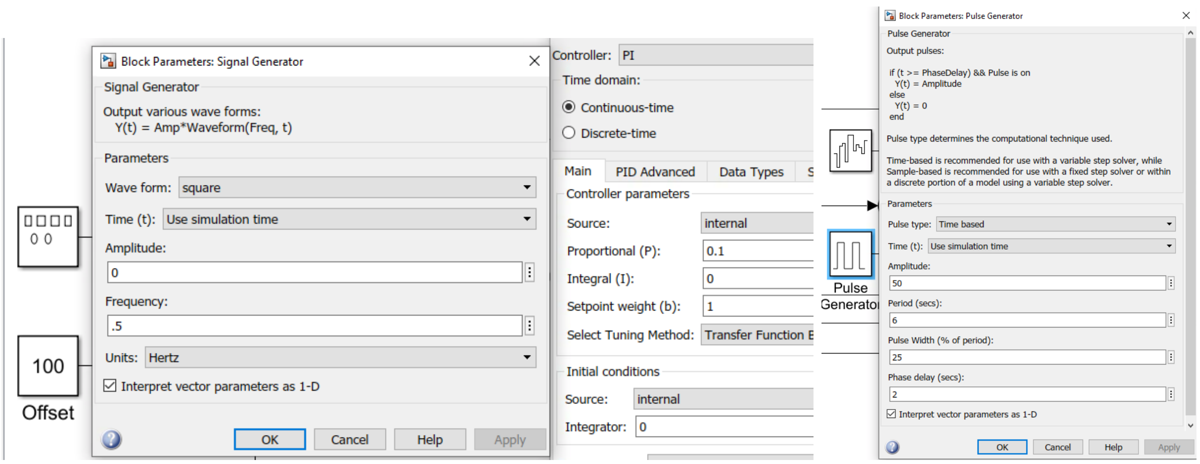
6.1 Pure Proportional Control

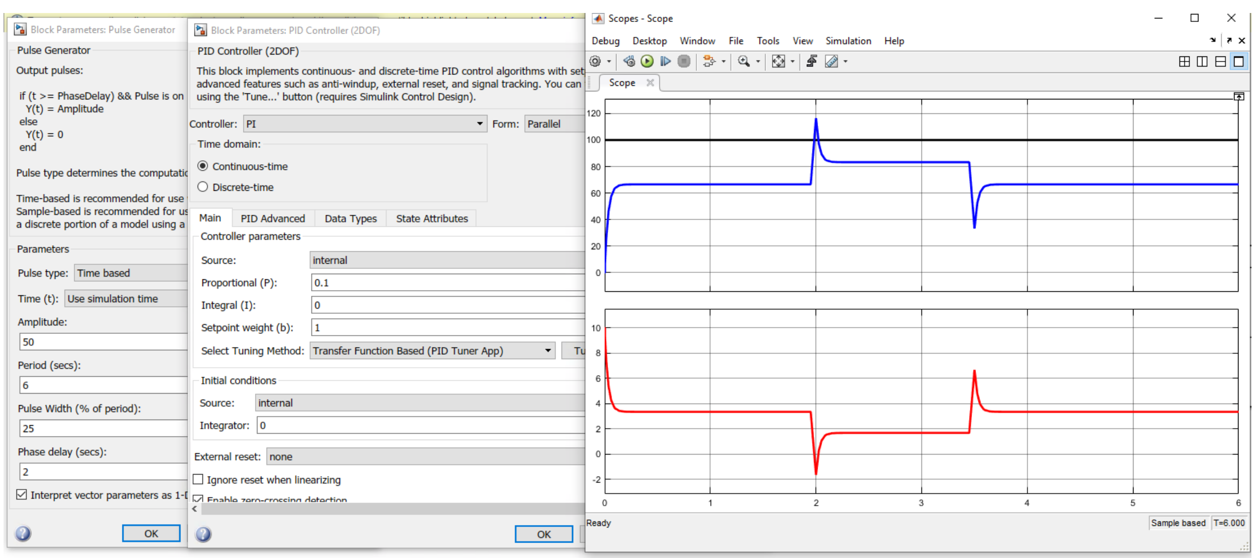
Explore the ability for a pure P controller at responding to disturbances by following this procedure:

Step 1. Reconfigure the Simulink model to test disturbance response by setting the following parameters:

Waveform	**Amplitude**	**Frequency**	**Offset**	k_p	k_i	b_{sp}
Square Wave	0 [rad/s]	0.5 [Hz]	100 [rad/s]	0.1	0	1

Step 2. Set the magnitude of the disturbance pulse generator (Fig. 4) to 50. How does the system react to the disturbance?





Step 3. Modify the proportional gain, k_p, from 0 to k_{pc}. How does the response change depending on the proportional gain?

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

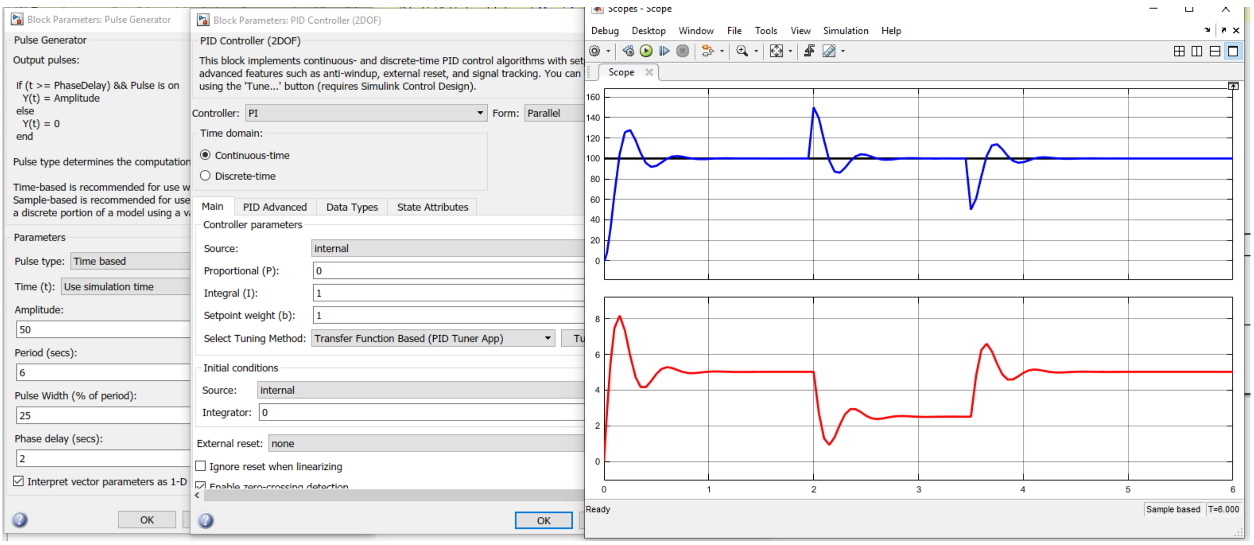
6.2 Pure Integral Control

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

Step 1. Ensure the Simulink model is configured to test disturbance response by setting the following parameters:

Waveform	**Amplitude**	**Frequency**	**Offset**	k_p	k_i	b_{sp}
Square Wave	0 [rad/s]	0.5 [Hz]	100 [rad/s]	0	1	1

Step 2. Set the magnitude of the disturbance pulse generator (Fig. 4) to 50. How does the system react to the disturbance?



Step 3. Modify the integral gain, k_i, from 0 to k_ic. How does the response change depending on the proportional gain?

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

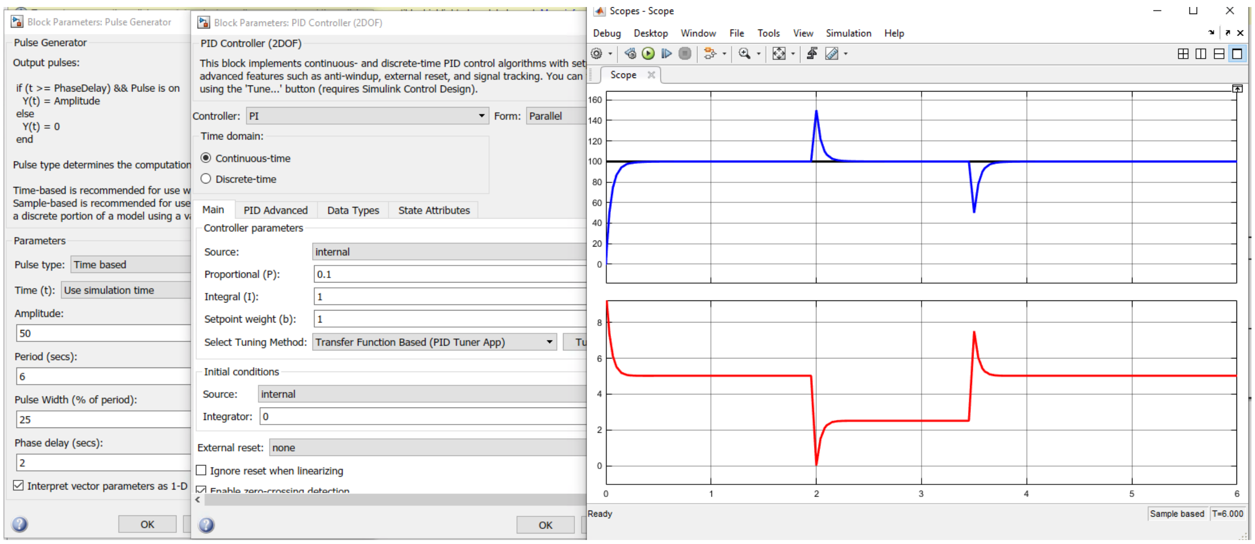
6.3 Proportional and Integral Control

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

Step 1. Ensure the Simulink model is configured to test disturbance response by setting the following parameters:

Waveform	**Amplitude**	**Frequency**	**Offset**	k_p	k_i	b_{sp}
Square Wave	0 [rad/s]	0.5 [Hz]	100 [rad/s]	0.1	1	1

Step 2. Set the magnitude of the disturbance pulse generator (Fig. 4) to 50. How does the system react to the disturbance?



Step 3. Keep k_p constant at the default state (Step 1) and adjust k_i from 0 to $k_i c$. Observe how the error and control signal are affected.

Step 4. Keep k_i constant at the default state (Step 1) and adjust k_p from 0 to $k_p c$. Observe how the error and control signal are affected.

Step 5. Test the response of the system with the gains k_p and k_i obtained from the Ziegler-Nichols method in Section 3.2. Are these gains a good choice for a PI controller dealing with load disturbances?

Step 6. Test the response of the system with the gains k_p, k_i, and b_{sp} calculated in the pre-lab and tuned in Section 4.1 and 4.2.

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