ASIA PACIFIC UNIVERSITY OF TECHNOLOGY & INNOVATION

EE006-3-2- CONTROL ENGINEERING

TITLE	Washing Machine Control System
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We would like to express our deepest gratitude to our lecturer, Dr. Syed Mohd Bahrin, for their unwavering support and guidance throughout this module and this academic journey. Their expertise, encouragement, and commitment to our learning have been very important in shaping our understanding of the subject matter. In addition, I would like to extend my heartfelt appreciation to my fellow group members, whose collaborative efforts have made this learning experience not only educational but also enjoyable. Our shared insights, diverse perspectives, and collective teamwork have enriched my understanding of the module and contributed to the overall success of our project.

Abstract

This research project explores the application of control system using Simulink and MATLAB to decrease and control vibrations in washing machines. Vibrations during the washing cycle not only affect the machine's performance but also contribute to noise pollution and potential mechanical wear. The transfer function and equations were derived using data sheets of washing machine models. The study was conducted collaboratively by a team of four members who aimed to develop an effective vibration control system.

Introduction

In all our households, washing machines have become an important component, completely changing the way we handle laundry. However, with the benefits they bring, washing machines also pose challenges, particularly in managing the vibrations generated while they are operating. Uncontrolled vibrations can lead to noise disturbances and sometimes even structural damage. To address this issue, many techniques were created and used, mostly related to control systems. Control systems are engineering structures designed to regulate, or manipulate the behaviour of other systems or processes. These systems play a crucial role in maintaining desired conditions or performances by adjusting inputs based on feedback or predefined parameters. The primary components of a control system include sensors to gather information, as well as a processor to analyse data, and actuators to execute adjustments made. The figure below shows an example of the block diagram of a control system:

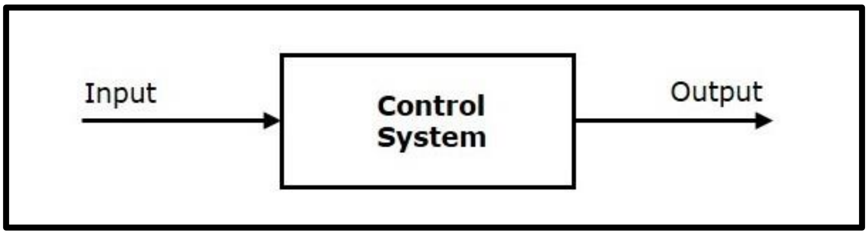


Figure 1: Block Diagram of Control System, (Control Systems - Quick Guide, n.d)

Control systems shape the behavior of dynamic systems through two main approaches: open loop and closed loop. Open loop systems offer straightforward instructions without real-time feedback, suitable for simple tasks. In contrast, closed-loop systems continuously monitor and adjust based on real-time feedback, often used in systems demanding accuracy and responsiveness. Transfer functions are mathematical representations that are used in control systems to describe the relationship between the input and output of a linear time-invariant system. They are particularly useful for analyzing and designing control systems, showing important information about system behavior and response. The transfer function is defined in the Laplace domain, it relates the Laplace transform of the output of the system, Y(s), to the Laplace transform of its input, X(s) under certain conditions.

$$H(s) = \frac{Y(s)}{X(s)}$$

Figure 2: Transfer Function General Form (Transfer Function, n.d.)

Controllers are often used to reduce vibration in different systems, including washing machines. These controllers continuously monitor vibrations and apply real-time adjustments to give a balance between stability and performance. Controllers for managing vibration come in different forms. PID (Proportional-Integral-Derivative) controllers for example provide a combination of proportional, integral, and derivative terms to finely tune the response into the desired state. Adaptive controllers dynamically adjust their parameters based on changing conditions, which helps control vibration. The figure below shows the working mechanism of a PID controller:

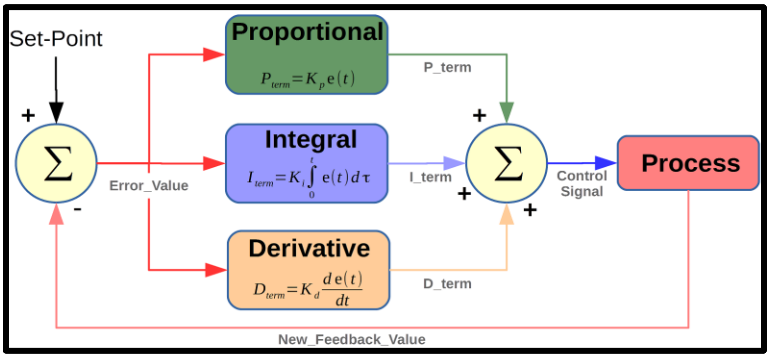


Figure 3: PID Controller Block Diagram (Concepts, 2018)

In the individual part of this assignment, a PID controller is added with an actuator (gain) to reduce the vibration or displacement in the system. The addition of the controller will help to detect irregularities and adjust the spin speed or redistribute the load for smoother and quieter operation. The figure below shows the block diagram for a closed loop system with a PID controller.

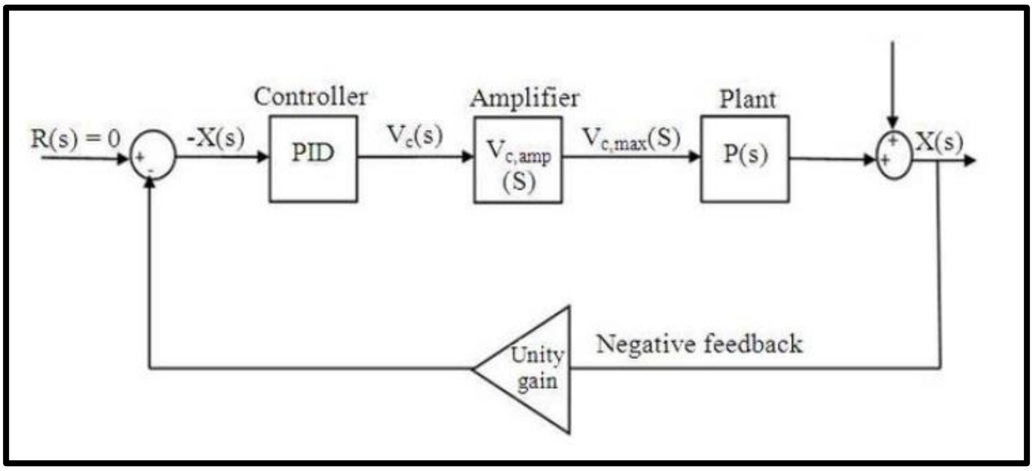


Figure 4: PID Controller Closed Loop Block Diagram, (Konadu et at, 2013)

Washing Machines As A Dynamic Model

Rotary mechanisms find applications in various sectors of today's industry, including mechanical engineering and computer technology. Frequently, these processes are required to function at elevated velocities. Hence, significant oscillations resulting from the shifting of the rotor's centre of gravity might pose a substantial concern and potentially result in mechanical harm. The issues of reducing vibration caused by rotating rotors and the frequency of the first rotor harmonic (rotor vibration) are of utmost significance in the design, production, and functioning of nearly all contemporary rotary devices. The reliability of these machines is primarily influenced by rotary vibration. These machines are characterized by high rotating speeds, relatively low structural rigidity, and critical modes that typically occur within the range of angular velocities during operation. The washing machine is a subject of particular interest in the study of dynamics and the reduction of vibrations and noise. This is because the machine constantly deals with randomly distributed and shifting imbalances caused by the laundry in the drum. Additionally, the machine's low requirements for the precision of its manufacturing and assembly of parts and components are crucial to keep costs down (Drach et al., Design principles of horizontal drum machines with low vibration 2021).

A variety of components with diverse functions can be found within a machine. However, the primary objective is to ensure that each component functions accurately, harmoniously, and securely. If a machine is imbalanced or experiencing excessive vibrations, it has the potential to cause damage not just to its internal components but also to the surface on which it is placed. Minimizing machine vibration mitigates potential damages to both the equipment and the surrounding region, while simultaneously optimizing operational efficiency (Narkhede & Dhande, Vibration Reduction of Top-Load Washing Machine Based on Suspension System 2009).

Washing machines are a significant class of household appliances that have been utilized for some years to automate manual duties and assist humans. Vibration issues might arise in the spin drum of a fully automatic washing machine when there is an imbalanced quantity of clothes. During the spinning cycle of a washing machine, the clothing inside it creates a rotational imbalance. During the spin-drying stage, the drum rotates at a high velocity, resulting in the clothes being forced against the inner wall of the drum and forming a substantial imbalanced mass until the stage ends. This exerts significant stress on the cabinet and emits noise. This commonly happens during the water extraction procedure when the drum initiates rotation, leading to substantial centrifugal imbalance forces and an uneven distribution of laundry mass rotation. Consequently, this causes vibration and shaking. Eliminating these vibrations enables the creation of quieter washing machines that can accommodate larger wash loads without increasing the size of the machine. Hence, it is essential to carefully design the suspension characteristics of the drum to restrict the transmission of vibrations and enhance the effectiveness of isolation. This study centers on the suspension system of a horizontal-axis drum-based washing machine, which connects the drum to the machine cabinet. The purpose of the suspension is to mitigate the transmission of vibrations from the drum to the chassis, hence preventing acoustic noise and potential damage to machine components (Narkhede & Dhande, Vibration Reduction of Top-Load Washing Machine Based on Suspension System 2009).

There are two methods for controlling the vibration of a washing machine. The initial strategy relies on regulating the tub balance, whereas the subsequent approach focuses on managing the suspension system. Another technique employed to mitigate vibration involves the utilisation of a hydraulic balancer, which incorporates salt water and is affixed to the upper extremity of the tub. S.Bea, et al. conducted a dynamic examination of a vertical axis automatic washing machine specifically during the spin-drying stage using this technique. The researchers developed a mathematical model of a hydraulic balancer under steady-state conditions, which was then verified using experimental data on centrifugal force. The experimental results obtained from the spin-drying step of the washing machine were compared with the simulated results. The study conducted a parametric analysis to examine the impact of vibration on several metrics. Through the parameter investigation, it was revealed that the vibration can be mitigated by increasing the mass and decreasing the volumetric ratio (BAE et al., Dynamic Analysis of an automatic washing machine with a hydraulic balancer 2002). In this study, however; the vibration of the washing machine will be controlled Based on second approach which is control of suspension system.

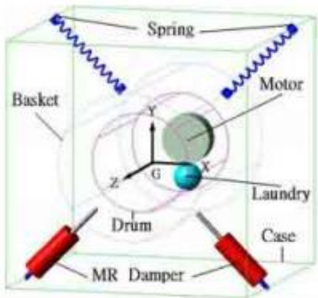


Figure 5: Washing Machine As A Dynamic System (Tyan & Chao, Modeling and Vibration Control of a Drum-Type Washing Machine via MR Fluid Dampers)

Figure 5 illustrates a basic dynamic model of a washing machine, which is crucial for analyzing techniques to reduce vibration. This model is frequently employed in academic and technical research to simulate and analyze the vibrational dynamics of washing machines. The central drum is upheld by a suspension system comprising of symmetrical springs and dampers.

The springs in this model exert a restoring force to counteract any displacement produced by imbalances during operation. They facilitate the oscillation of the drum around a stable position and assist in preserving the drum's alignment. The rigidity of these springs dictates the extent of the drum's mobility; more rigid springs minimize movement but enhance vibration transmission, while less rigid springs permit greater movement but absorb more vibration.

Dampers function by attenuating vibrational oscillation through the dissipation of energy from the system. As the drum rotates, the dampers provide a force in the opposite direction of the drum's velocity, transforming mechanical energy into heat and thereby decreasing the magnitude and strength of the vibrations. This force is essential in preventing the ongoing oscillation that would happen if springs were the only means of support, resulting in a more stable operation and decreased wear on the machine components.

The interaction between the springs and dampers determines the washing machine's dynamic reaction to vibrational forces. The springs determine the inherent frequency of the system, whereas the dampers specify the rate at which oscillations diminish. Collectively, they ascertain the resonance properties and the transient reaction of the system, which are crucial for the washing machine's functionality and longevity.

The dynamic model emphasizes the role of springs and dampers in the suspension system of a washing machine. When calibrated correctly, this suspension system may effectively minimize vibrations resulting from imbalances in the wash cycle, resulting in enhanced performance and less noise and structural strain.

TRANSFER FUNCTION

The transfer function is a fundamental key in control systems, and it can be

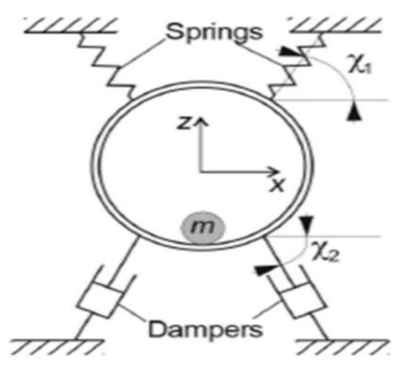


Fig. 4. Dynamical model of the washing machine

Table 1. Dynamic characteristics of the washing machine

Tub weight m_1, kg	48.2
Drum weight m_2, kg	12.5
Stiffness of each of the two suspension springs c, N/mm	6.0
Spring angle X_1	75°
Damping constant of each damper h, N·s/m	175
Damper tilt angle X_2	70°
Eccentricity e, mm	14.8
Drum length L_g, mm	190

Figure6: Dynamical Model and Dynamical Characteristic of the Washing Machine

implemented into any control system because, through the transfer function, we can describe or define the relationship between the input and the output of the system selected. Besides that, the simulation will take place where we will control the system more effectively. Moreover, it

is crucial to get the necessary information that we need which information in respect to our case is about the causes of vibrations in a washing machine. We have gathered some data and information on the parameters of the washing machine selected for this assignment which are the two masses (m1 and m2) where one is for the tub weight and the other is for the drum weight of the washing machine with values such as 48.2 kg and 12.5 kg, another parameter is the stiffness of the two suspension springs (k) which is 6.0 N/mm, another one is the damping constant (b) of each damper which is 175 N.s/m, then we have the angles coming from both spring and damper which are 75 and 70 degrees. The last two parameters

From the physical model, we can determine the transfer function of the washing machine but before that, we detected the parameters that characterized the washing machine selected and those parameters can be observed in the physical model as you may appreciate in the figure above.

- The first step that took place was to determine the transfer function by using the method of mass-spring-damper equation:

$$m\ddot{x} + b\dot{x} + kx = F$$

$\ddot{x}$ = acceleration

$\dot{x}$ = velocity

x = displacement

- Now the second step is to apply the Laplace transform method. One important point to notice is that the acceleration, velocity, and displacement in the Laplace transform are represented differently as you can observe in the next implementation:

$$ms^2X(s) + bsX(s) + kX = F$$

- Now we take a common factor which is X. We will control the displacement of the washing machine which is why we must factorize X as It represents the displacement:

$$X(ms^2 + bs + k = F)$$

- At the end we can get the transfer function for displacement which is:

$$\frac{X}{F} = \frac{1}{ms^2 + bs + k = F}$$

- Now, we must set the parameters used in the transfer function in the standard form:

Based on the table of values we have the spring value which is 6.0 N/mm, and it should be converted into N/mm so basically, we will have:

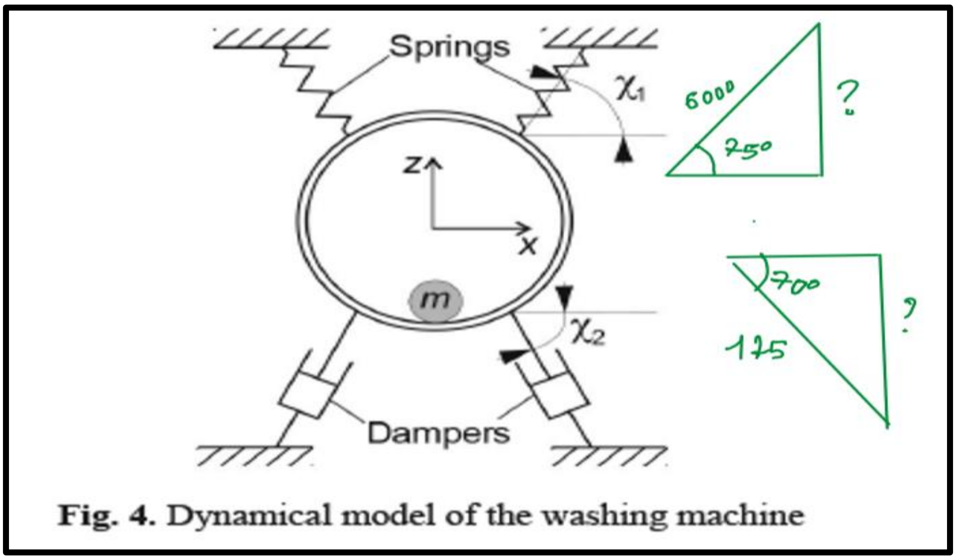


Figure 7: Dynamical Model With the Angles

6.0 N/mm to N/m is equal to 6000N/m so basically now we must look at the angle that is formed across the springs in the physical model:

- Now, we can calculate the value from the opposite side of the angle of the spring, so we should implement sine and we will have:

Sin 75 = $\frac{k}{6000}$, so now we will end up having the next value:

k = sin 75* 6000; k = 5795.66

- After that we can proceed to get the value for the damping which is b.

sin 70= $\frac{b}{175}$, we can get the value for the spring which is:

b = sin 70* 175; b= 164.44

- We have the values of the two masses that are 48.2 and 12.45:

M1 = 48.2; m2 = 12.5

Total mass = 48.2 + 12.5; Total mass = 60.7 kg

- Now after getting the angle and set all the parameters to standard form, we can substitute the values of the parameters in the transfer function for displacement:

$$\frac{X}{F} = \frac{1}{ms^2 + bs + k = F}$$

$$\frac{X}{F} = \frac{1}{\left(60.7s^2 + 164.54s + 5795.55\right)}$$

Finally, we have the transfer function for the displacement of the washing machine which is going to control, reduce, and regulate the vibrations inside the washing machine due to an unbalance load in the washing machine. By using this transfer function, we will be able to control the system through simulation.

Control Design and Simulink

This will be talking about the configuration and the design for the block diagram which will represent the transfer function obtained for the washing machine. Firstly, lets recap what the variables in the transfer function we obtained are. The final function of the washing system is shown below.

$$\frac{1}{(60.7s^2 + 164.54s + 5795.55)}$$

Mass:

60.7 represents the total mass of the washing machine. The weight is split into two parts, the tub weight, and the drum weight.

Damping:

164.54 represents the vertical damping on the washing machine. Based on the calculation shown in the section which shows the derivation of the transfer function we obtained the value shown in the main equation.

Spring Constant:

5795.55 represents the vertical effects of the spring on the washing machine. Based on the calculation shown in the section which shows the derivation of the transfer function we obtained the value shown in the main equation.

Before proceeding to the configurations and design of the system, we would like to talk about the input for the transfer function. So, since the objective of the assignment is to see how displacements affect the vibrations in a washing machine, we will have to consider our input for the transfer function which gives us a balanced response. One of the factors that effects the vibration of the washing machine is the overloading of clothes. If the mass of the load exceeds the maximum weight, there will be disturbance in the response. so based of the datasheet the maximum load the washing machine can handle is 7 kg. So, the input will be total forces that will act on the washing machine when its running. These forces will be from the load as well as the centrifugal force when the tub starts spinning. The table below shows the values that will be used when calculating the forces for the mass as well as the force from the rotational speed of the tub.

Table 1: Washing Machine Datasheet

Full Load Capacity	7kg
Maximum Spin Speed	1400 rpm
Rated Power	2000 W
Cavity Width	600 mm
Radius	300 mm

Design:

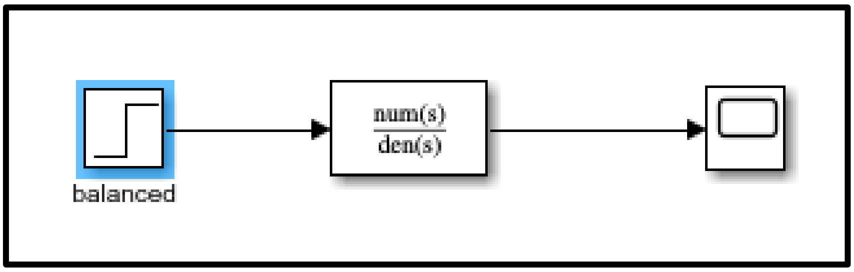


Figure 8: Balanced Group Component

The image above shows the general design on Simulink. The design consists of two major blocks which are the step input block and the transfer function block. The step input block is where we will instantiate the input values for the system, in our case it will be the total force acting on the washing machine when its running. Then you have the transfer function block which will have the variable which we talked about earlier. To show the response we have a scope attached at the end.

Configuration:

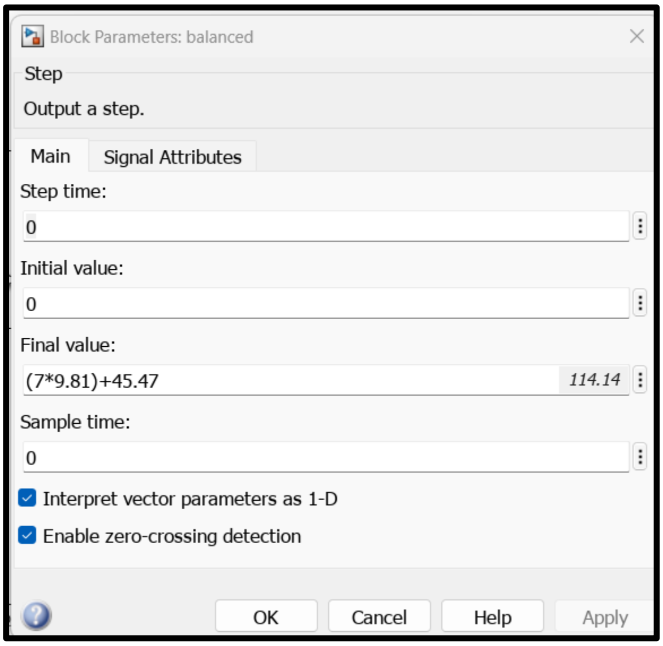


Figure 9: Parameters of Step Component

The image above shows the input values for the system. So, to get the force acting on the washing machine due to the load we must multiply the mass of the maximum load with the 9.81whcih helps give the values in Newtons.

$$\frac{F}{2\pi r N}$$

The equation shown is used in finding the force acting on the washing machine due to the spinning of the drums. The equation shows the relationship between the power of the washing machine, rotational speed, and the radius in the system. The power output is directly proportional to the product of the rotational speed and the radius of the rotational system.

2000/ [2pi (0.3) (1400/60)] = 45.47

The value obtained from the equation is 45.47.

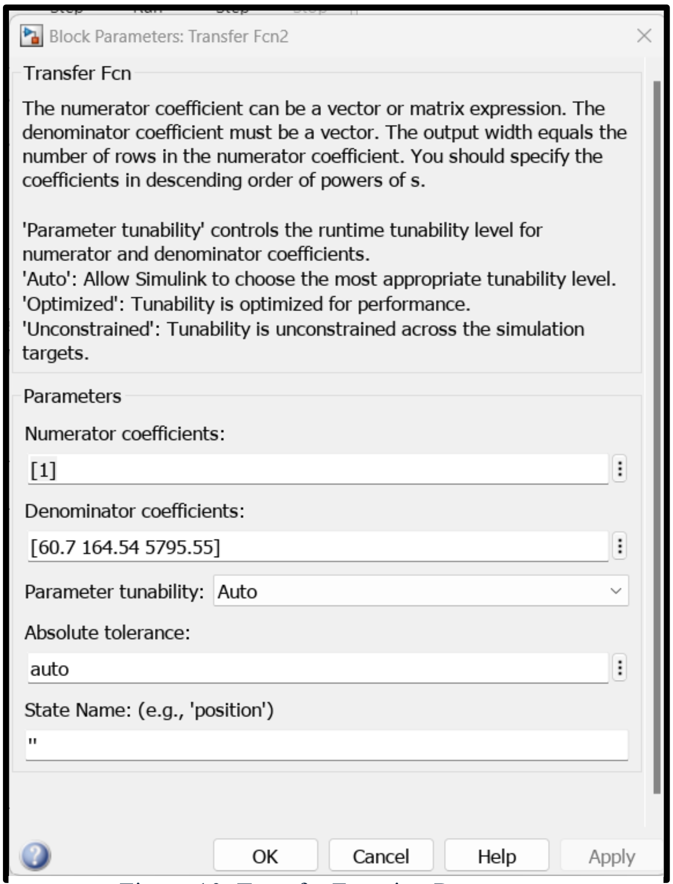


Figure 10: Transfer Function Parameters

We have configured the transfer function block with the values we obtained for the mass, damping and the spring stiffness. Time to show the simulation results.

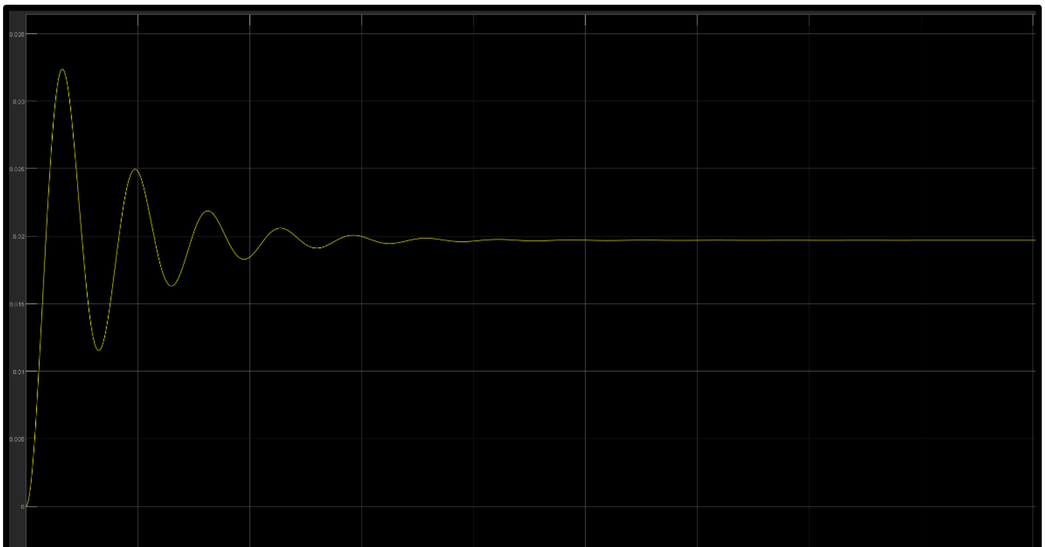


Figure 11: Response For Balanced System With No Disturbance

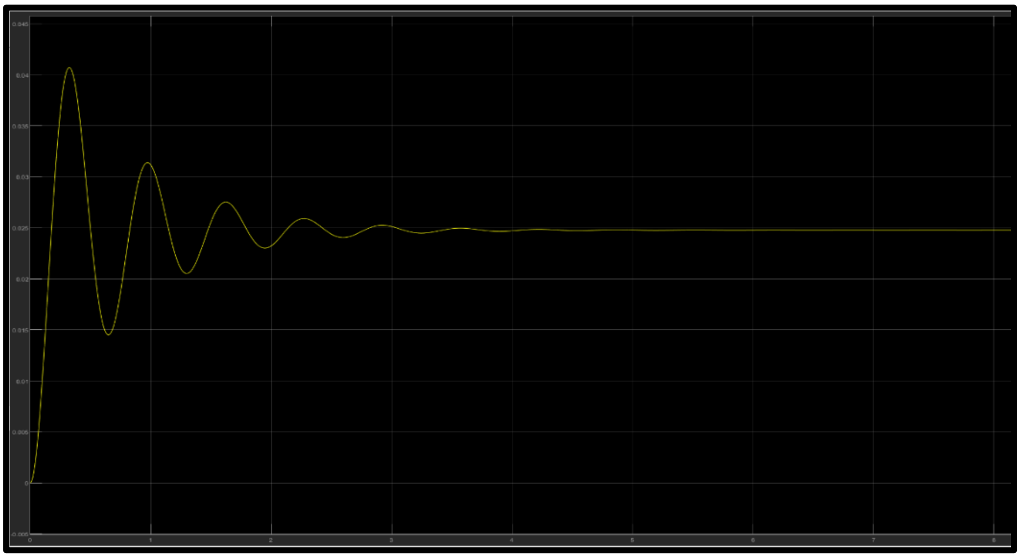


Figure 12: Response For Balanced System With DisturbanceFigure

Comparing Both Response:

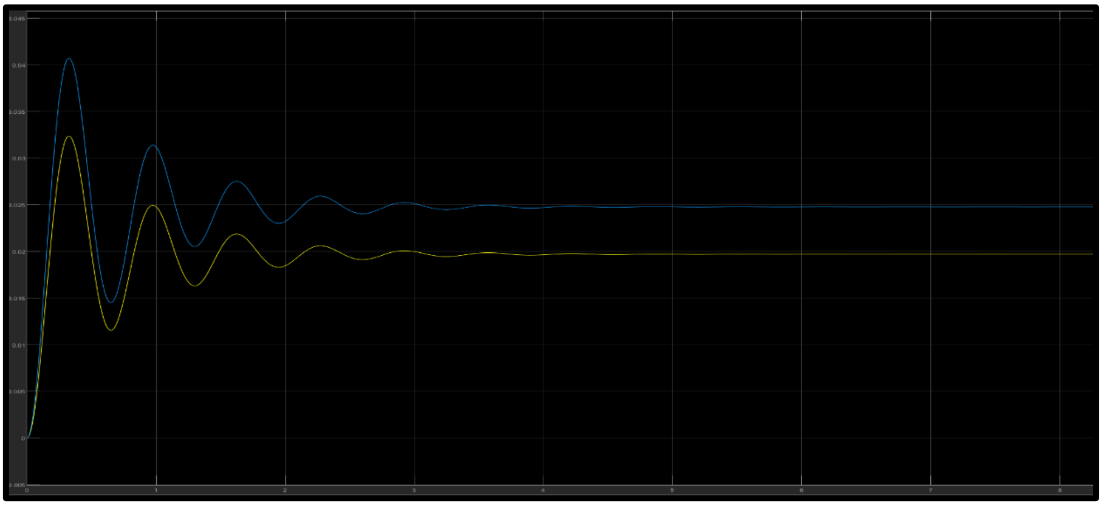


Figure 14: Responses With(blue) and Without Disturbances(yellow)

Note: The blue line is for the system with disturbance and the yellow line is for the balanced system with no disturbance.

Root Lucus:

To obtain the root locus the following mahlab code was used to generate the graph. The code makes use of the built mathlab function rlocus to find and generate the graph. The snippet of

```
% Define the numerator and denominator of the transfer function
num = [1]; % Replace with your numerator coefficients
den = [60.7, 164.544, 5795.55]; % Replace with your denominator coefficients

% Create the transfer function
sys = tf(num, den);

% Plot the root locus
figure;
rlocus(sys);

% Optionally, you can adjust plot properties
title('Root Locus of the Transfer Function');
xlabel('Real Axis');
ylabel('Imaginary Axis');
grid on;
```

Figure 16: Root Locus Matlab CodingFigure 17: Root Locus Matlab Coding

the code is shown below.

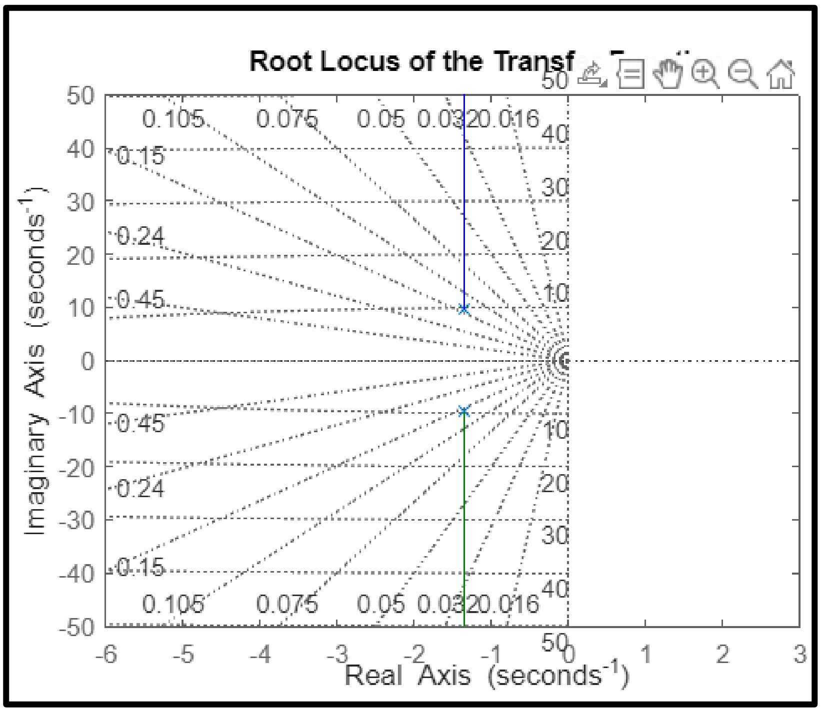


Figure 18: Root Locus RepresentationFigure 19: Root Locus Representation

INDIVIDUAL PEDRO FABIAN OWONO ONDO MANGUE (TP063251)

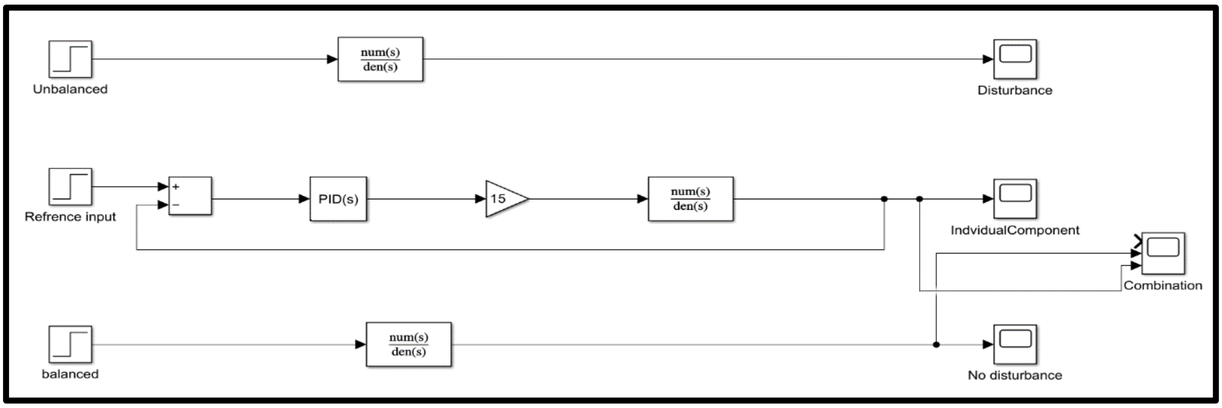


Figure 20: Design Simulink Circuit (Pedro)

Figure 21: Design Simulink Circuit (Pedro)

INTRODUCTION

The washing machine is having an unbalanced load that leads to its vibration which is a common issue in the washing machine system. An unbalanced load in the washing machine is caused due to an uneven distribution in the drum.

In my design model, I implemented a transfer function for displacement which is the same as the one used in the group component.

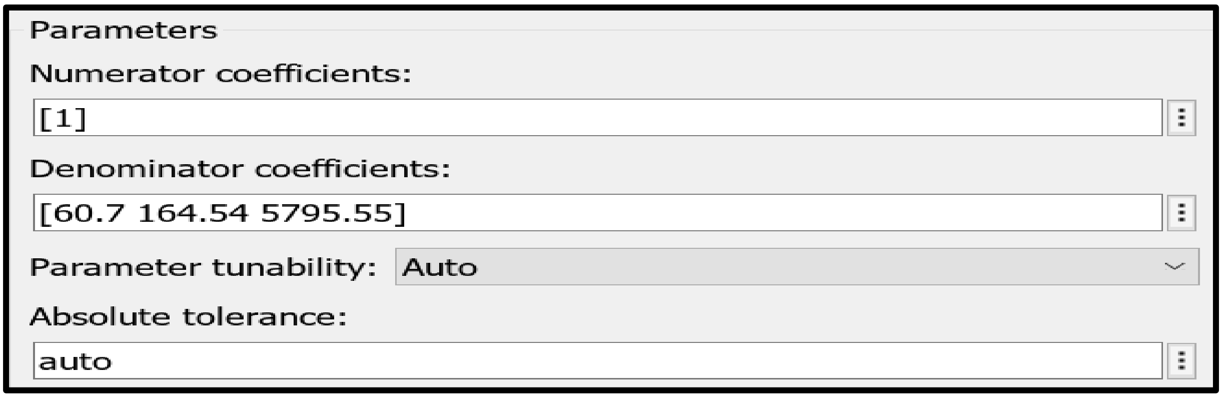


Figure 22: Transfer Function Block (Pedro)

My washing machine control system is considered as a closed-loop system because it can monitor the operation of the washing machine based on feedback.

The PID controller was integrated into my system to control and reduce any effect that may be happening to the washing machine based on any unbalanced load.

The PID parameters are three:

The parameter “P” is essentially the one responsible for counteracting the vibrations through a force, so it will bring the system closer to zero displacement which means that it will avoid any percentage error between the expected and the current displacement.

The parameter “I” is going to contribute to eliminating any steady-state errors which means that it will make sure that there is no significant error in the response before the settling time.

parameter “D” will help to regulate a suitable overshoot and oscillation by applying a mechanism that can detect any change in the speed of the displacement error.

In my system, I implemented the step block where I used an input of 0.01969 as the final value because that is how the signal will start vibrating and get to the point where it will stop vibrating and will be aligned with the response obtained in the group component.

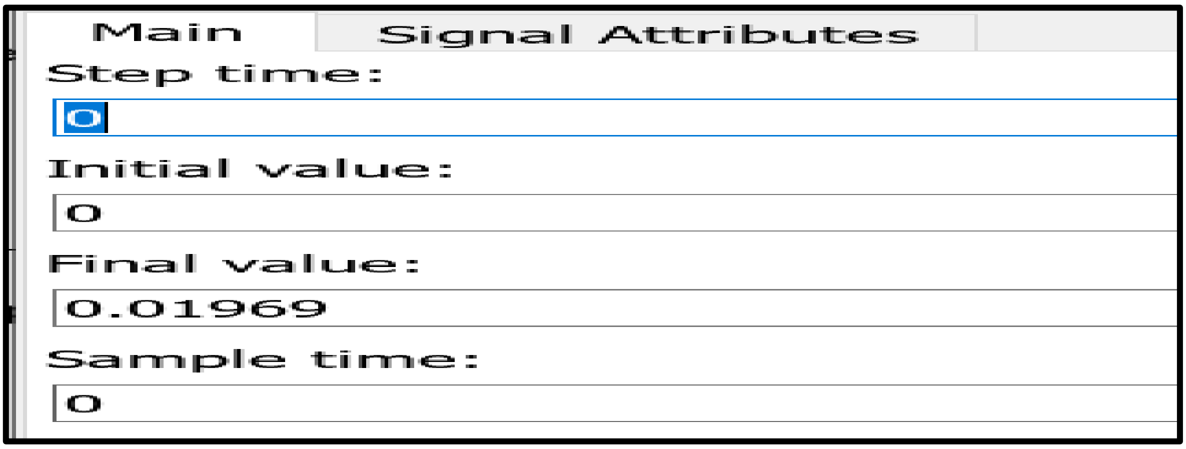


Figure 23: Parameters Of The Step Block (Pedro)

I implemented a proper tuning method of the PID controller where I got the PID parameters of my control system, and this is where a gain takes place because after getting the parameters of the PID we will have to adjust the value of the gain which has been set to 15 as it helped to get the desired overshoot.

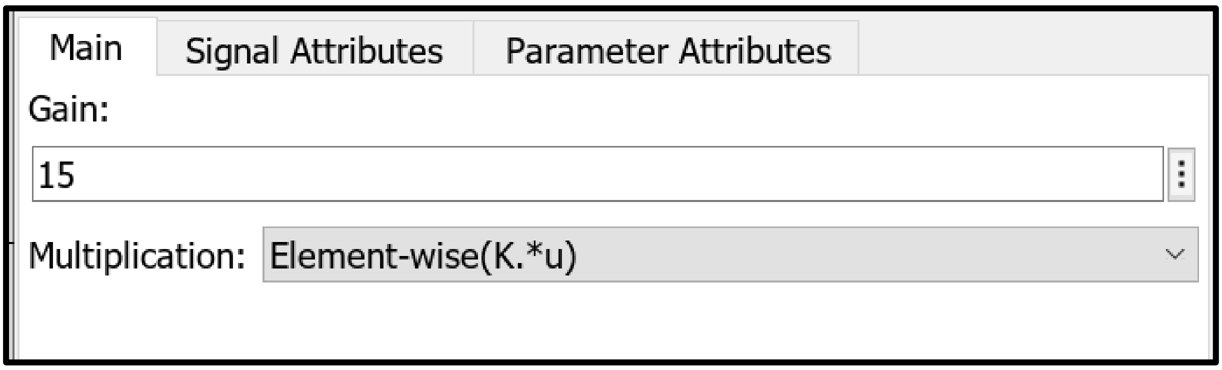


Figure 24: Gain_Actuator (Pedro)

A PID controller has been implemented into the washing machine control system and I decided to go for the PID controller because it is a key controller that we used to control the steady and transient response of the washing machine through simulation. The PID controller helps us to maintain and control essential parameters in the washing machine which can be for instance the temperature, water level, agitation, etc. so we can end up getting the expected or the desired performance of the washing machine. Besides that, in a PID controller we will have a reference input or setpoint which might help us to fulfill the objective of what we are trying to control in the washing machine:

I chose the PID controller for my system which I placed after the subtractor block that represents the negative feedback in the system and after the PID component I introduced an actuator which is a linear actuator that was added to the system to control the signal generated by the PID controller that influences the system being controlled. We have one function of the actuator which is:

Control Loop Feedback: The actuator in control loop feedback works together with sensors and controllers to adjust the output of the system based on the feedback that might be coming from the sensor. In MATLAB simulation, the actuator is represented as a gain block.

In the end, the summation block is an indication that represents the closed-loped system.

The three parameters in the controller are P. I, and D which we have got through the next MATLAB coding are shown in the figure below:

```
% Define the transfer function of the system
s = tf('s');
G = 1 / (60.7*s^2 + 164.54*s + 5795.55);

% Define the design requirements
overshoot = 40; % Percent overshoot
Ts = 0.8; % Settling time

% Convert percent overshoot to damping ratio (zeta)
zeta = -log(overshoot/100) / sqrt(pi^2 + log(overshoot/100)^2);

% Convert settling time (Ts) to natural frequency (wn)
wn = 4 / (zeta * Ts);

% Define the desired closed-loop bandwidth (approximate)
bw = wn;

% Calculate phase margin from damping ratio
pm = atan(2*zeta/sqrt(sqrt(1 + 4*zeta^4) - 2*zeta^2));

% Convert phase margin to degrees
pm = pm * (180/pi);

% Create options set for pidtune
options = pidtuneOptions('PhaseMargin', pm);

% Tune the PID controller
[controller, info] = pidtune(G, 'PID', options);

% Display the PID gains
Kp = controller.Kp;
Ki = controller.Ki;
Kd = controller.Kd;
fprintf('Kp: %f\nKi: %f\nKd: %f\n', Kp, Ki, Kd);
```

Figure 25: Matlab Coding Implementation (Pedro)

In the MATLAB coding, we have implemented a tuning method to get the respective PID parameters which are represented in the MATLAB coding method such as Kp, Ki, and Kd.

I have defined the selected transfer function obtained through the mathematical model which is a second-order system. That transfer function represents the behavior of the system in the Laplace domain, that is why we implemented the command “tf”. After that, I have selected my objectives for the washing machine by selecting its overshoot and settling time which are 40% and 0.8 seconds which I will justify in the next section accordingly. Besides that, you may realize that I implemented the formula for zeta which converts the percent overshoot to the damping parameter then through the “wn” we are trying to get the value for the natural frequency. It is important to get the value for the damping ratio and the natural frequency because we need those parameters to control the second-order system of our control system. After that, we should define the close loop bandwidth and calculate the phase margin which is what I did by using the “pm” variable in the coding. In the end, we used the PID Tune function to get the values for the PID parameters.

Now, I will display the parameters of the PID controller that were obtained through the MATLAB coding:

For the N or filter coefficient I have assigned a value of 50 to achieve the expected overshoot value which is 40.141. I did not get the value for the settling time in the block parameter, so I decided to implement the PID tuner where I adjusted the system to take an overshoot of 40.141 and I got a value for the settling time which is 0.612 through the PID tune method.

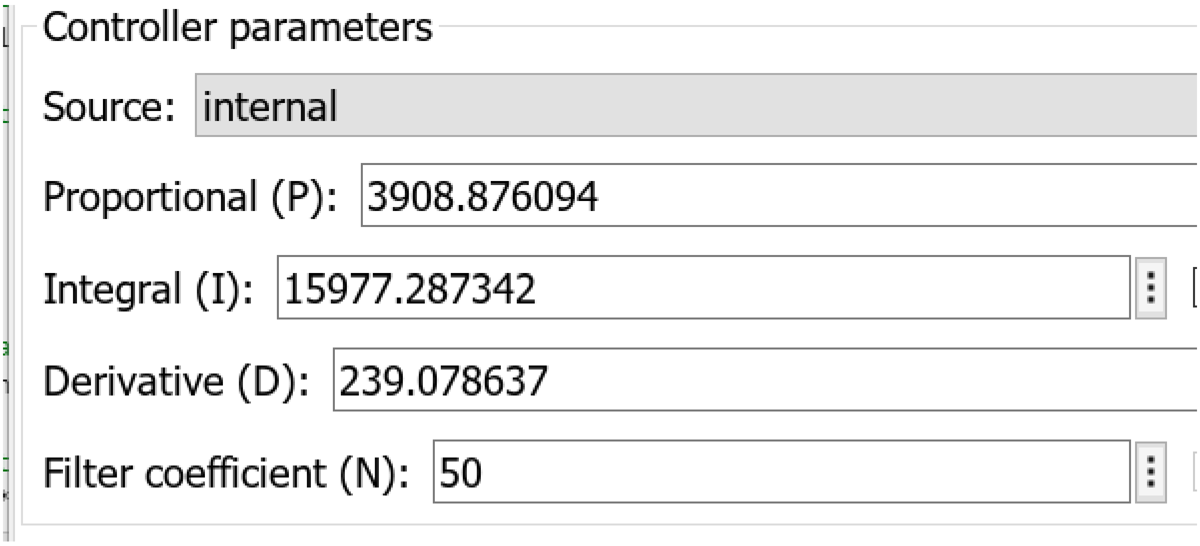


Figure 27: Parameters Of PID Controller (Pedro)

RESULTS

I implemented a closed loop system by referencing the negative feedback into the system and the use of a PID controller and an actuator as well the use of the transfer function of the system and you can observe the response of the system in the next figure.

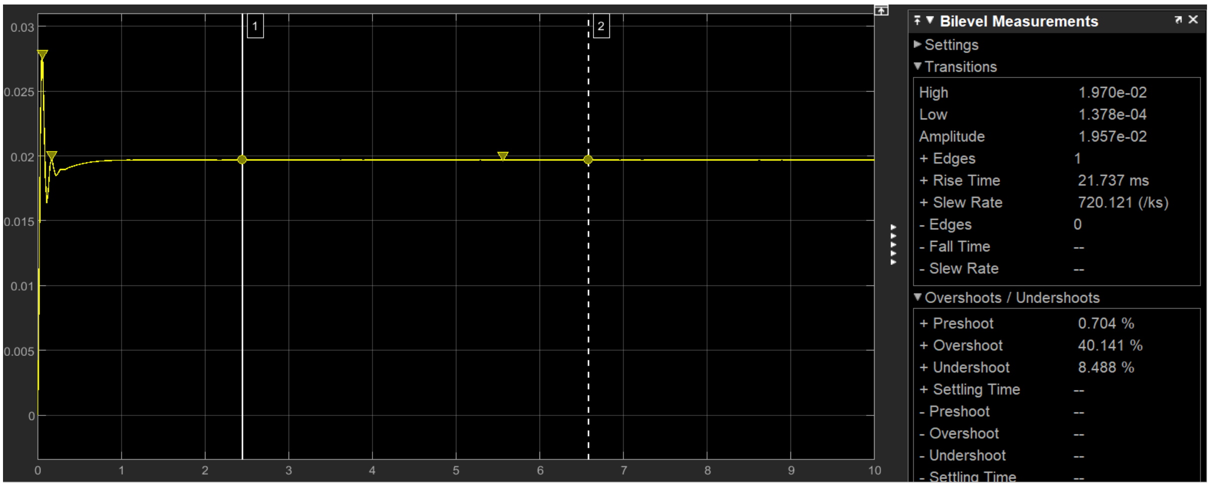


Figure 28: Response Of My System (Pedro)

Figure 29: Response Of My System (Pedro)

In the analysis of the response for the control system with the actuator, the PID control was tested for a duration of 10 seconds to observe the behavior of the system. The vibrations for the response start oscillating until they become stable which is because we are studying the vibrations of the washing machine under normal conditions or balanced conditions. When the washing machine is under normal conditions, we can get its maximum overshoot which is shown in the group component section where we got an overshoot of 65%. So basically, I decided to reduce the overshoot of the washing machine to 40% to get a better performance of the system under normal conditions.

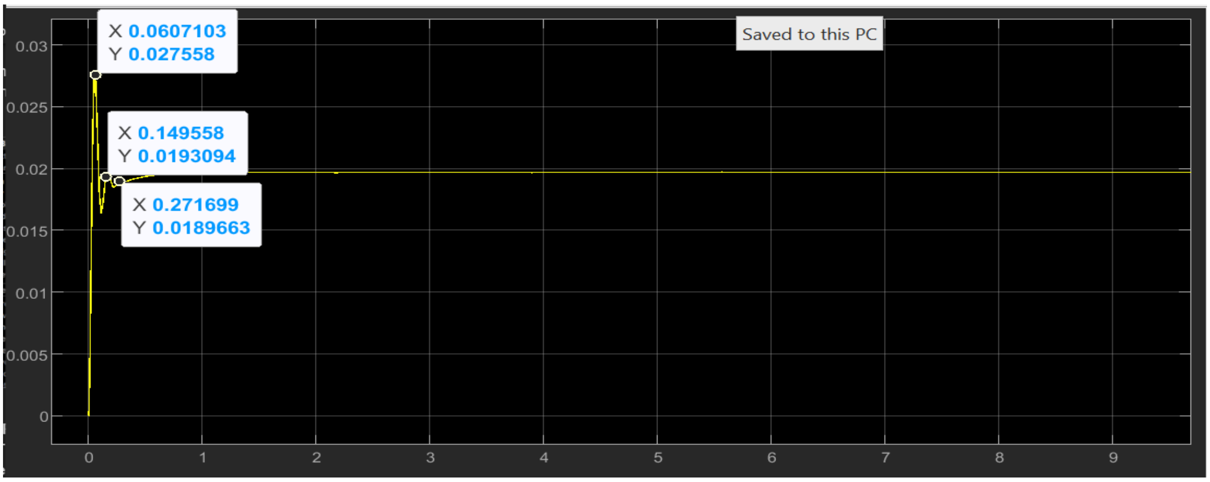


Figure 30: Response Parameters Of My System (Pedro)

Figure 31: Response Parameters Of My System (Pedro)

The maximum peak of the system is 0.027558 at 0.0607103 seconds and the rising time is 21.737 ms. Then you can observe that the amplitude decreases or drops to 0.0193094 at 0.149558 seconds and after that, the response drops to an amplitude of 0.0189663 at 0.271699. Then the signal remains constant accordingly which means that the vibration starts reducing until it disappears from the washing machine.

The maximum peak of the system is 0.027558 at 0.0607103 seconds and the rising time is 21.737 ms. Then you can observe that the amplitude decreases or drops to 0.0193094 at 0.149558 seconds and after that, the response drops to an amplitude of 0.0189663 at 0.271699. Then the signal remains constant accordingly which means that the vibration starts reducing until it disappears from the washing machine.

In the next scenario, I will explore and analyze the presence of the graph with and without disturbance.

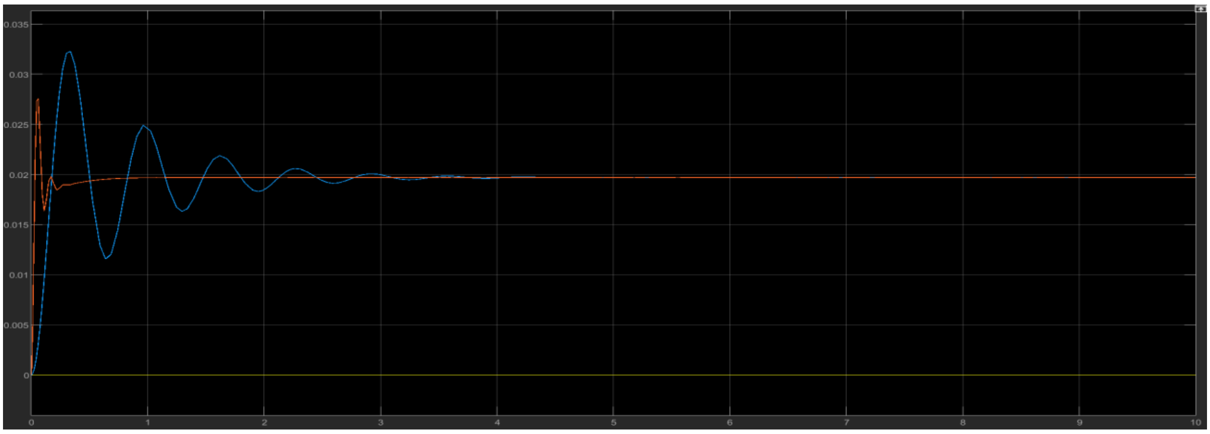


Figure 32: Response Without Disturbance And Group Component (Pedro)

Figure 33: Response Without Disturbance And Group Component (Pedro)

In this scenario where we have the response for the system under normal conditions or without disturbance (blue color) we can observe that the amplitude of the response without disturbance In the next figure 26 you can appreciate that we got the parameters for the overshoot and the settling time that was fixed to 40.1% and 0.612 seconds. I also implemented the PID tune method to get all the parameters required to get the expected output. The PID parameters are also fixed.

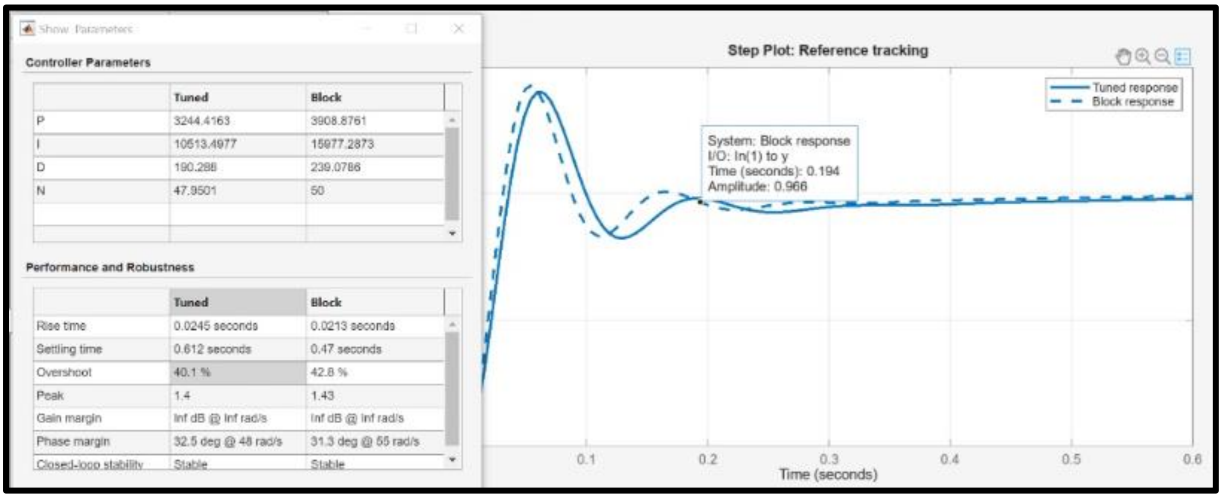


Figure 34: PID Tuning Method (Pedro)

Figure 35: PID Tuning Method (Pedro)

DISCUSSION:

In the discussion section, we will go through an analysis of the graphs obtained in the assignment.

Let us start by calculating the parameters that control the 2nd order system of the washing machine based on the transfer function:

Table 2: Objectives

	Group parameters	My objective
Overshoot	65%	40%
Settling time	2.95	0.612

As you can see in the table, I set my objective based on what I want to achieve in the system. The first objective is that the overshoot should be reduced to 40% and the settling time should be around 0.652 seconds which I got by using the tuned method. Now I will proceed to get the damping and the natural frequency.

overshoot = 40% ; $T_s = 0.612$ seconds

$$M_p = \frac{-\pi\zeta}{e^{\sqrt{1-\zeta^2}}}$$

$$0.4 = \frac{-\pi\zeta}{e^{\sqrt{1-\zeta^2}}}$$

$$\ln(0.4) = \frac{-\pi\zeta}{e^{\sqrt{1-\zeta^2}}}$$

$$(-0.9163)^2 = \left(-\frac{\pi\zeta}{e^{\sqrt{1-\zeta^2}}}\right)^2$$

$$\zeta = \sqrt{\frac{0.8396}{\pi^2 + 0.8396}}$$

$$\boxed{\zeta = 0.28}$$

$$T_s = \frac{4}{\zeta W_n}$$

$$W_n = \frac{4}{0.28 \cdot 0.612}$$

$$\boxed{W_n = 23.34\ rad/s}$$

I could get the parameters of natural frequency and damping which are 0.28 and 23.34 rad/s. which are: $\zeta = 0.28$ and the $W_n = 23.34$ rad/s After calculating the two parameters we can refer to the root dominant of my component which is going to be:

$Sd = -6.54 \pm 22.41$

Justification of the reduction of my overshoot

Overshoot = 40%

I reduced the overshoot of my system for the next reasons:

Figure 36: Damping and Natural Frequency For Individual Part (Pedro)

Figure 37: Damping and Natural Frequency For Individual Part (Pedro)

Increase the durability and reliability of the system:

When the overshoot in a washing machine is higher, it can lead to issues in the mechanical components, so basically by reducing the overshoot, I will be able to minimize any small percentage of damage in the motor, drum, etc.

To improve the performance of the system: If we reduce the overshoot that will help to reach the expected state of the washing machine more easily and accurately.

Safety and Stability: In this case, if we can maintain or keep the overshoot within a suitable range that will minimize any risk, and the washing machine will be safe.

One of the observations of the graphs from the section results is that we can notice that the oscillations of the response with the PID controller become less while the response for the group component without disturbance is higher. This means that the more we increase the damping, the lesser oscillations we will get from the response because for the control system with PID controller and the presence of an actuator, we don't have as many oscillations as in the group component response and it is also due to the reduction of the overshoot from the response with the PID controller.

The response to disturbance is not under normal conditions which means that the washing machine is not operating effectively due to a disturbance that was introduced into the system by increasing or modifying the full load capacity of the washing machine.

There are ways I can improve the control system of the washing machine and they are:

The first way can be through optimization of the washing machine where I could adjust the transfer function that was used in the group component to get a reduced and reliable overshoot. Another way to improve the washing machine would be through the integration of a sensor for feedback control. For example, it would have been better if I included a sensor in the system, so I could provide much better feedback to the system. It can be any sensor like a sensor to control or respond to the drum speed or water level. The last way that I could improve the washing machine control system is by load balancing where we can come up with suitable alternatives and mechanisms that can help in detecting when the load is not distributed properly, then we can pause the cycle, so the washing machine can distribute again the load automatically.

CONCLUSION

In conclusion, I have been able to enhance the system of the washing machine where I implemented two approaches which are through MATLAB coding where I got the PID parameters and eventually the overshoot, and on the other side, I implemented the PID tuning method to get the settling time of the washing machine control system. By optimizing the transfer function selected and focusing on load balancing, and vibration of the washing machine the performance of the washing machine has been improved because I have taken into account the fact that the response that I got with the PID controller and the actuator does not exceed the amplitude of the response with disturbance otherwise the washing machine won't be performing as expected because of the disturbance occurring into the system.

INDIVIDUAL MOHAMED ASIM KHIDIR WEDATALLA (TP065603)

Justification of chosen Controller

The PID controller was chosen for my part to reduce the vibration/displacement caused by the washing machine due to several factors:

- The PID controller, unlike the PI and P controllers offers improved damping and stability since the derivative term (D) in the PID controller helps in introducing damping to the system. Damping is crucial for reducing oscillations and ensuring that the system settles quickly with less overshooting. The derivative term also helps the PID controller to respond faster to changes in the systems, such as external disturbances similar to the ones found in our washing machine model, and changes in setpoint. This fast response helps reduce the impact of the disturbance found in the system.
- The integral term (I) helps in eliminating steady-state errors by integrating the increasing error over time. This is particularly important in vibration control, since maintaining a steady state is crucial for both system stability and comfort.
- The combination of proportional, integral, and derivative terms allows the PID controllers to adapt to a wide range of different system dynamics. This is important in vibration control applications where the characteristics of the system may change over time.

- One of the most important factors that lead to choosing PID controllers is the tuning flexibility. The three parameters (Proportional, Integral, and Derivative) can be adjusted to achieve the desired control performance, which results in a decrease of control error (Dombrosky & Dombrosky, 2023).
- The derivative term also helps in reducing both the settling time and overshoot, which is important in controlling vibration to reduce the time taken for the system to reach a stable state and avoid excessive oscillations.

The PID controller was chosen since it combines the advantages of both integral and derivative actions (PI & PD). This combination allows PID controllers to offer better stability and faster response compared to PI and PD controllers.

Discussion/ Results and Analysis

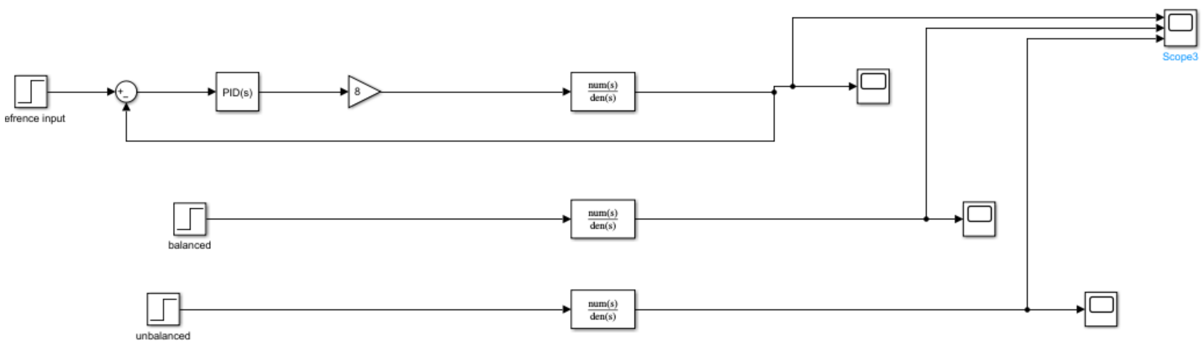


Figure 38: Block Diagram using PID and Without PID (Mohamed Asim)

The block diagram above shows the use of the PID controller along with an actuator represented by a gain of 8, connected to the transfer function in a closed loop system. The block diagram below it is for the balanced system, and the bottom block diagram is for the unbalanced system with disturbance. The parameters for the PID controller in Simulink were generated using two methods: MATLAB calculations and PID tuner. Both values generated for Kp, Ki, and Kd had some differences, yet they both had the same overshoot desired.

Method 1: MATLAB Calculations

```
% Define system's transfer function
s = tf('s');
G = 1 / (60.7*s^2 + 59.75*s + 1552.8);

% requirements
overshoot = 20; % Percent overshoot
Ts = 1.5; % Settling time
zeta = -log(overshoot/100) / sqrt(pi^2 + log(overshoot/100)^2);
% Convert settling time (Ts) to natural frequency (wn)
wn = 4 / (zeta * Ts);
bw = wn;
pm = atan(2*zeta/sqrt(sqrt(1 + 4*zeta^4) - 2*zeta^2));
% Convert phase margin to degrees
pm = pm * (180/pi);
% Create options set for pidtune
options = pidtuneOptions('PhaseMargin', pm);
% Tune the PID controller
[controller, info] = pidtune(G, 'PID', options);
% Display the PID gains
Kp = controller.Kp;
Ki = controller.Ki;
Kd = controller.Kd;
fprintf('Kp: %f\nKi: %f\nKd: %f\n',Kp,Ki,Kd);
```

Figure 39: Calculating PID Parameters Using MATLAB (Mohamed Asim)

The figure above shows the calculations that were used to derive the parameters for the PID controller. It can be seen from the figure above that the desired overshoot is set to 20% and the settling time is set to 1.5 seconds. The parameters generated using these inputs can be shown in the figure below:

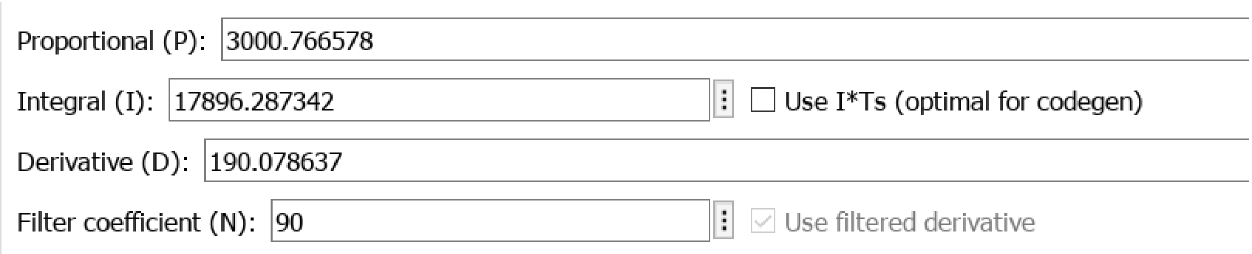


Figure 40: PID Parameters Using MATLAB (Mohamed Asim)

The figure above shows the parameters calculated by MATLAB to get an overshoot of approximately 20%. The filter coefficient was set to 90 to get the overshoot of 20%.

Method 2: PID Tuner

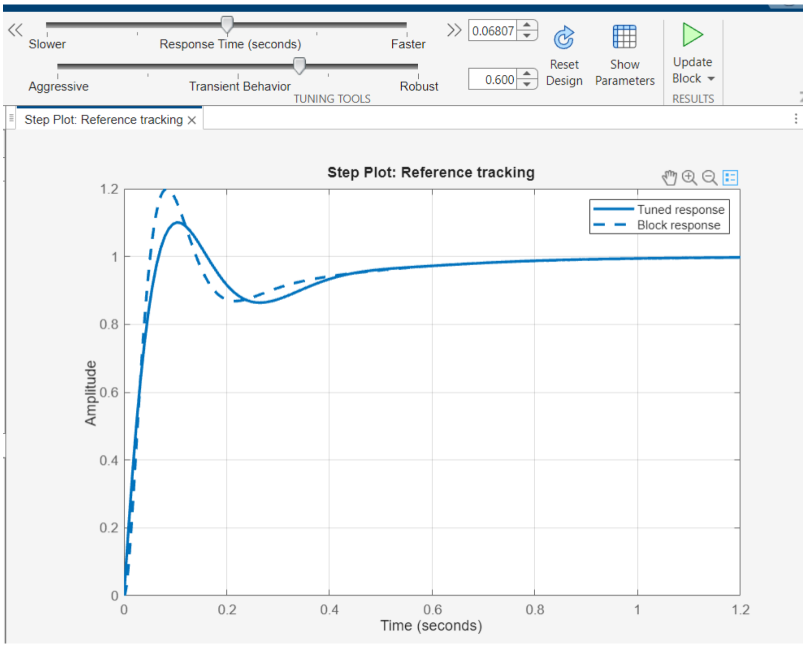
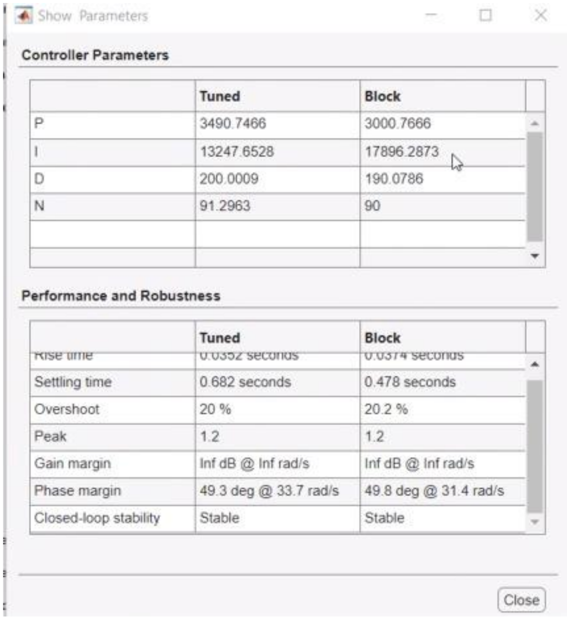


Figure 41: Tuning Method (Mohamed Asim)

Another way to get the PID parameters is by using the PID tuning feature, by adjusting the response time and transient behaviour shown at the top of the figure above until the desired value is generated.



Show Parameters

Controller Parameters

	Tuned	Block
P	3490.7466	3000.7666
I	13247.6528	17896.2873
D	200.0009	190.0786
N	91.2963	90

Performance and Robustness

	Tuned	Block
Rise time	0.0352 seconds	0.0374 seconds
Settling time	0.682 seconds	0.478 seconds
Overshoot	20 %	20.2 %
Peak	1.2	1.2
Gain margin	Inf dB @ Inf rad/s	Inf dB @ Inf rad/s
Phase margin	49.3 deg @ 33.7 rad/s	49.8 deg @ 31.4 rad/s
Closed-loop stability	Stable	Stable

Close

Figure 42: Tuned Parameters For PID (Mohamed Asim)

The figure above shows the tuned parameters for the PID controller. The overshoot value was set to exactly 20% using the PID tuner method. However, the settling time increased from 0.478 seconds to 0.682 seconds with the same peak values and some changes in the values of Kp, Ki, and Kd. The difference in the PID parameters of both methods are shown in the table below.

Table 3: PID Parameters Methods Comparison

Parameters	MATLAB calculations	PID tuning
Kp	3000.7666	3490.7466
Ki	17896.2873	13247.6528
Kd	190.0786	200.0009
N (filter coefficient)	90	91.2963

Choosing Actuator

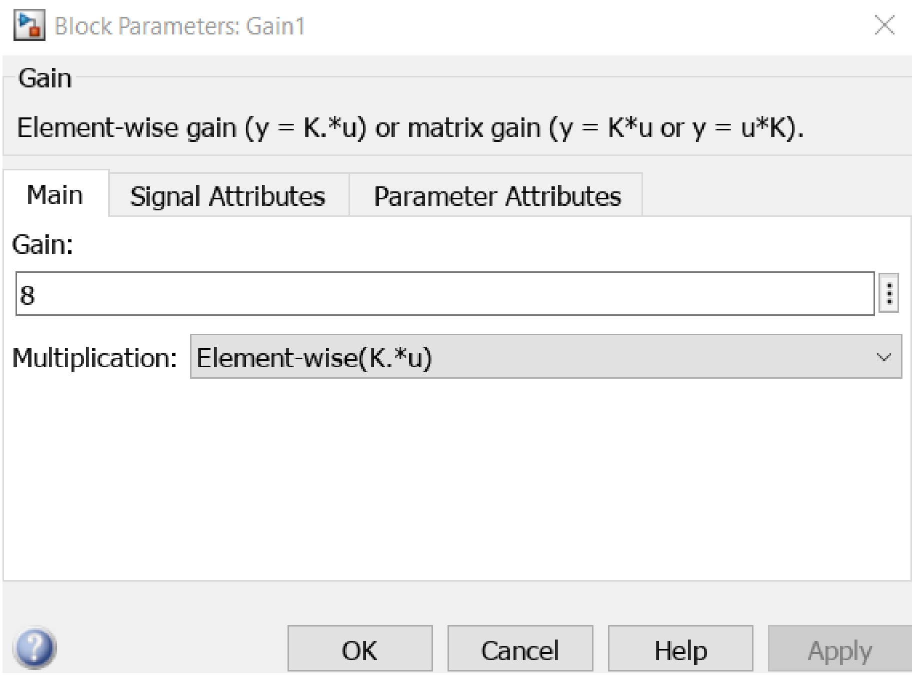


Figure 43: Value Of Actuator and Gain (Mohamed Asim)

The actuator is used in the system as a gain block, since the actuator is used to power up the system and provide enhancement by being multiplied with the transfer function of the system. Instead of adding a transfer function for the actuator, a gain was assumed since it is easily controlled. Using a higher gain for the system could lead to a faster response, however, it could also result in instability which causes an in increase in overshoot. Therefore, some systems could tolerate a high gain value for an actuator to maintain stability while other systems could require a lower gain value for an actuator to maintain stability. The system was experimented with different gain values, and 8 was found to be the ideal value for the actuator since it provided the desired settling time and overshoot. The choice of the gain value was considered with relating the use of the PID controller as well.

System Response

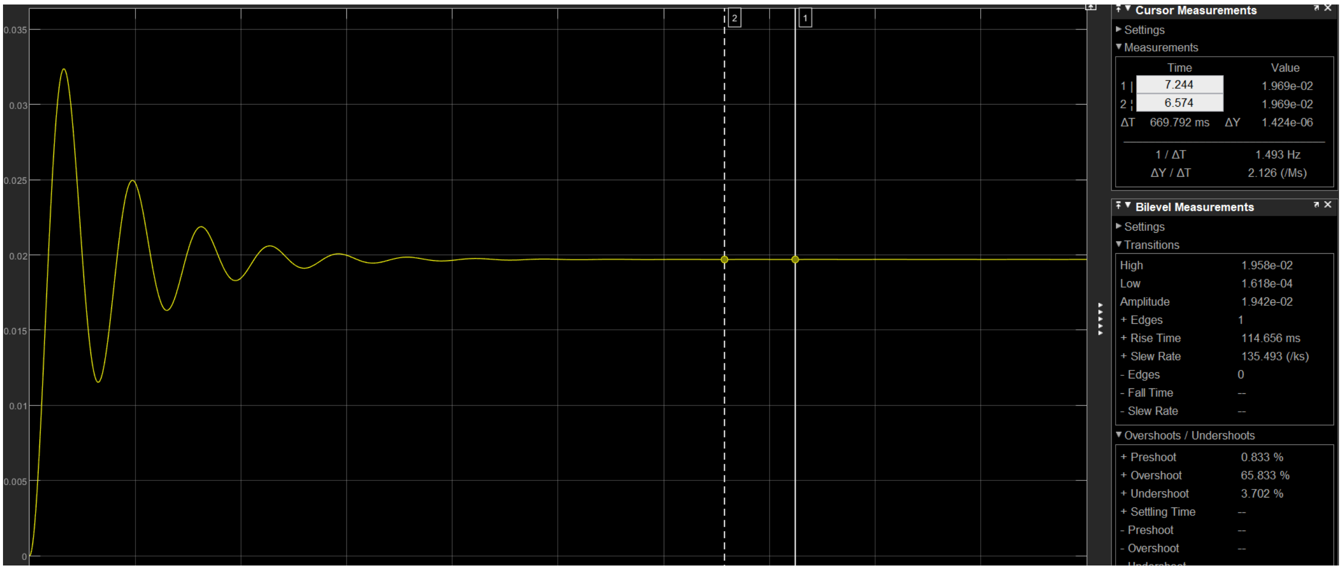


Figure 44: Response Of Balanced System Without PID Controller (Mohamed Asim)

The figure above shows the response of the balanced system without the PID controller and the actuator. The settling time is around 5 seconds, and the overshoot of the system is 65.833% which is considered a very high overshoot value that can lead to complications and instability. The peaks of the system must also be reduced to avoid damage. The output of this component is shown using the cursor measurement feature to be 0.01969 which is used as the input of the system with the PID controller with a sample time of 0.01 as shown in the figure below.

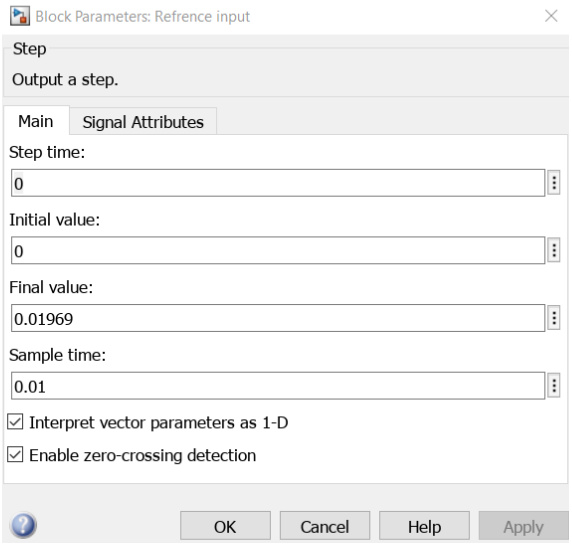


Figure 45: Input Of System With PID Controller (Mohamed Asim)

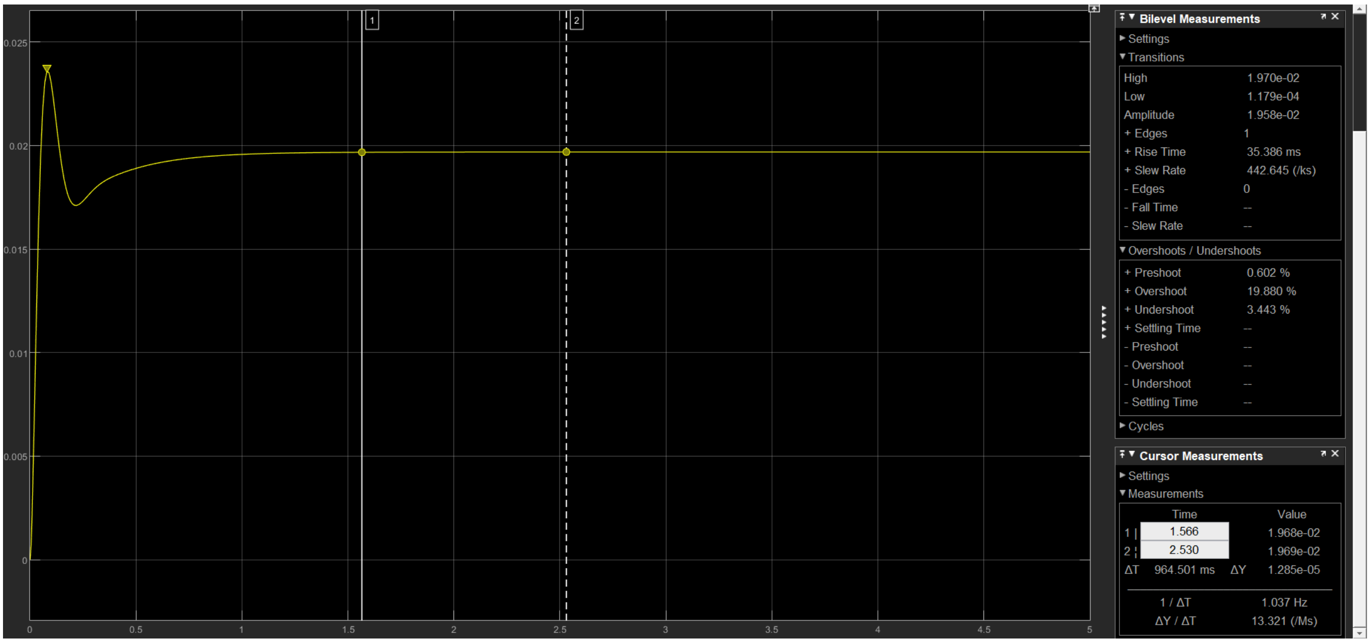


Figure 46: Response Of System With PID Controller (Mohamed Asim)

The figure above shows how the PID controller affects the balanced system of the washing machine positively, The PID parameters MATLAB calculation method was chosen since it had a shorter settling time. The overshoot is shown to decrease until 19.880% and the settling time is also decreased to 1.5 seconds which are the desired values set for the system. The integration of the PID controller and the actuator is shown to have reduced the noise and disturbances hugely. The new response showed very different results from the system without the controller and actuator, for example, the peak amplitude is reduced as well as the rise time, and a faster settling time compared to the previous system. According to the values from both responses, the system without the controller is shown to have a rise time of 114.658ms, while the system with the controller is shown to have a faster rise time of 35.386ms. The overshoot is also shown to decrease from 65.833% in the original system to 19.880% in the improved system.

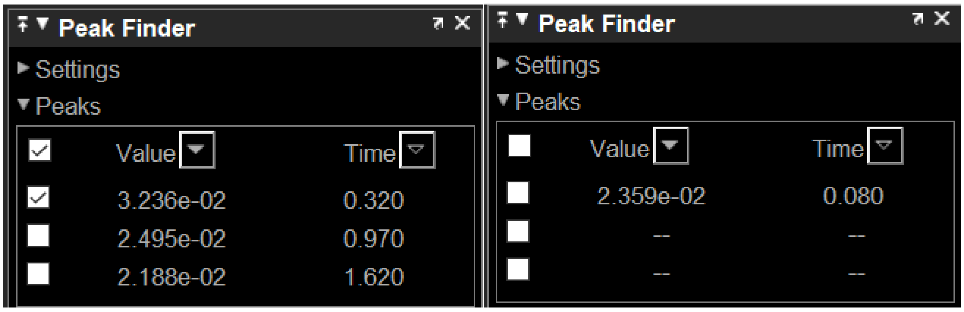


Figure 47: Peak Of System's Response Without and With PID Respectively (Mohamed Asim)

The figure above shows the original system peak amplitude at 0.03236cm in 0.320 seconds, and the system with the PID controller which is much quicker at an amplitude of 0.02359cm at 0.080 seconds. The system with the controller also has lesser oscillations as shown above.

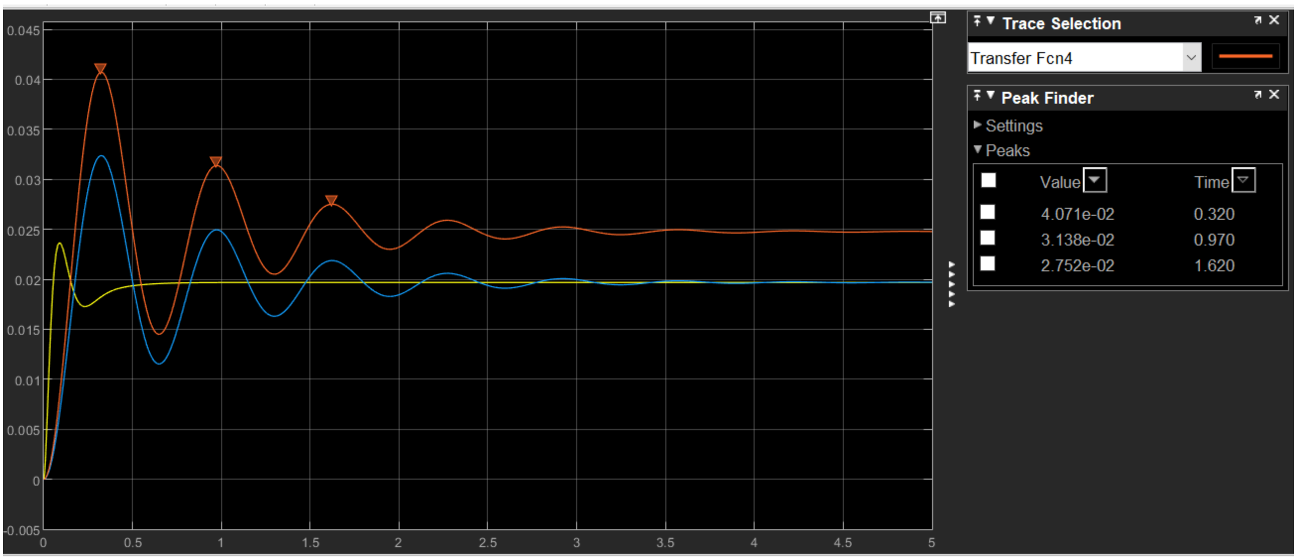


Figure 48: Response Comparison (Mohamed Asim)

The figure above shows the overlapping of all the responses of the system. The red response being the system with disturbance (high load), and the system in blue being the balanced original system, and the system in yellow which is the PID controller with the actuator. The response of the system with disturbance shows a huge increase in amplitude at 0.04071 at 0.320 seconds which is the same time as the balanced system. The overlapping of all responses shows the huge difference between the system with the PID controller and both the other systems, where the system with the PID controller and the actuator is very much smoother with lower disturbance and faster settling time.

Further improvements

The system is successfully running, and the implementation of PID controllers and actuators resulted in a very huge reduction in noise and disturbance. However, several improvements can still be made such as:

- The addition of adaptive control algorithms that can automatically adjust PID parameters based on changes in the system or operating conditions. This can enhance the controller's performance under different circumstances.
- Consider more advanced control strategies instead of PID, such as model predictive control (MPC) or fuzzy logic control. These strategies offer improved performance in handling complex and nonlinear systems. The MPC controller is also capable of handling different constraints in comparison with PID controllers which cannot. (*Model Predictive Control Vs. Proportional, Integral, Derivative Control*, n.d.)
- The addition of sensors, such as position sensors and accelerometers, to the closed loop system. This can improve the feedback since sensors give real-time feedback on the current state of the system, this can help the PID controller to adjust the control signal based on the error, this can also maintain stability and help preventing overshooting.
- The addition of filters and signal processing techniques to pre-process sensor data. Filtering can help remove noise and unwanted frequencies, providing a cleaner input to the controller.
- The addition of an error detection and diagnosis system to identify and address any issues in real-time happening to the system. This can enhance the reliability of the vibration control system.
- The use of a piezoelectric actuator along with the PID controller. These actuators are known for high precision, fast response time and lack of mechanical wear. The usage of these actuators along with the PID can improve the performance of the system.

Conclusion

In conclusion, the introduction of a PID controller into a balanced system of a washing machine resulted in a large decrease in noise and disturbance, as well as a faster settling time, which is the time taken by the system to go into a steady, balanced state after disturbance. The system with the PID controller also had a quicker time compared to the balanced system as well as a lower percentage for the overshoot. The vibration and disturbance found in the system was due to an unbalanced loading to the washing machine. An actuator was also used along with the PID controller and was depicted as a gain value of 8 which is multiplied to the transfer function. Two methods can be used to choose the parameters for the PID controller, by using calculations and by using the PID tuner. The calculations method was analysed since it provided a faster settling time value. Furthermore, some improvements can still be made by the addition of a piezoelectric actuator, or sensors such as accelerometer, or filters to ensure stability and comfort in the system.

Aravind Soundirarajan Individual Component (TP066273)

So, this my individual component. Firstly, before we start let's recap on what we did in the group component and what is required of my individual component. Vibration is a very important factor in a washing machine. Having high vibration in the washing machine can cause internal as well structural damages to a washing machine. Some of the common factors that can cause vibrations are:

- Overloading the machine with extra load will throw the washing machine of balance thus causing vibrations.
- Another factor can be that the structural build of the washing machine is not balanced causing vibrations and disturbance as well.

These are some factors that can affect the dynamics of the washing machine. So, for the assignment we chose to see how displacement can affect the vibrations due to overloading by mass. So, my objective is to create a system that can handle the desired displacement value and make sure that there is minimal overshoot. So, my system needs to be able to handle a range of displacements and make sure that the washing machine will have minimal vibrations/overshoot and will have a quick settling time. To achieve this, I will have to introduce two components which are a controller as well as a actuator.

Controller Type

So, before I talk about the controller, I used in my assignment let's talk briefly on what controller is. Controllers are an important aspect in the space of control systems. Controllers function is to be able to minimize the differences that might present between the actual value and the desired value of the system. Controllers have many important a few are stated below:

- Helps in reducing steady state error and helps in improving the accuracy of the system.
- Helps to make the system ore stable.
- Reduces unwanted offsets in a system.
- Helps to minimize the overshoot in a system.
- Helps reduce the settling time as well as helps to boost or speed up the slow response due to damping.

There are few advantages in using a controller in the system. In control systems fours types of controllers can be used which are Proportional controllers (P), proportional integral controller (PI), proportional derivative controllers (PD) and proportional integral and derivative controller (PID).

So, for my system I have decided to choose PID controller. I will now explain my reasoning to choosing this type of controllers. The PID controller helps in providing greater accuracy, efficiency and helps provides better stability to the system. The PID controller consists of three variables which are proportional, integral, and derivative.

Using PID controller in washing machine system helps to provide many advantages. Firstly, the PID controller ensures greater accuracy then other on/off controllers. The logic of the PID controller provides efficiency and does not impose heavy duty work on the physical hardware. Since PID controller is a combination of all the other three controllers it has good system tracking.

So, when using a PID controller or any controller for that matter we must include a closed loop system or in other words a feedback loop. In a control system the output is compared with he desired output we want. Closed loop system is very useful in our system because it helps to constantly monitor the system and helps to ensure that the performance of the system is consistent and accurate.

The PID controller has been chosen s the controller for my system.it was selected because of its simplicity, accuracy, and the ability to adapt to the system. The reason I said simplicity is because the PID controller offers a very balanced combination between the proportional, integral, and derivative control actions. It is very easy to debug and very straight forward to implement in the system. The PID controller helps to align perfectly with robust structure of the washing machine system which involves optimizing the load forces as well as the centrifugal forces acting on the washing machine when its running.

Washing machine system output will always vary depending on the conditions which could be the overloading of clothes, structural balances etc. this condition could cause disturbance to the system and vibration to the washing machine. So, another reason why I chose PID controller is the fact it’s able to counteract the disturbance in the system and helps in proving the accuracy of the system. This helps to make sure that the washing machine will be handle higher load which would cause maximum displacement.

Actuator

Actuator is a mechanical component in the space of control systems. For actuators to generate mechanical motion, they need both an energy source and a control signal. Actuators use a control signal, which can be manual, automated electronic, fixed mechanical, software-run, robotic, or powered by compressed air, electricity, or hydraulic pressure. For my approach I decided to use a gain block to represent the actuator instead.

One of the reasons I used a gain to represent an actuator id due to simplification. Having actuator block can have complicated dynamics and in certain situations these dynamics can affect the overall system performance. After trying out a different actuator we finally decided to use a gain. Using a gain helps for a simple linear relationship between the input and the output. The point of the actuator is to help create a linear and proportional relationship between the input and the output. The gain value represents the proportionality constant of the actuator.

Design

Now I will start showing my design of my system with the PID controller.

Overall Design:

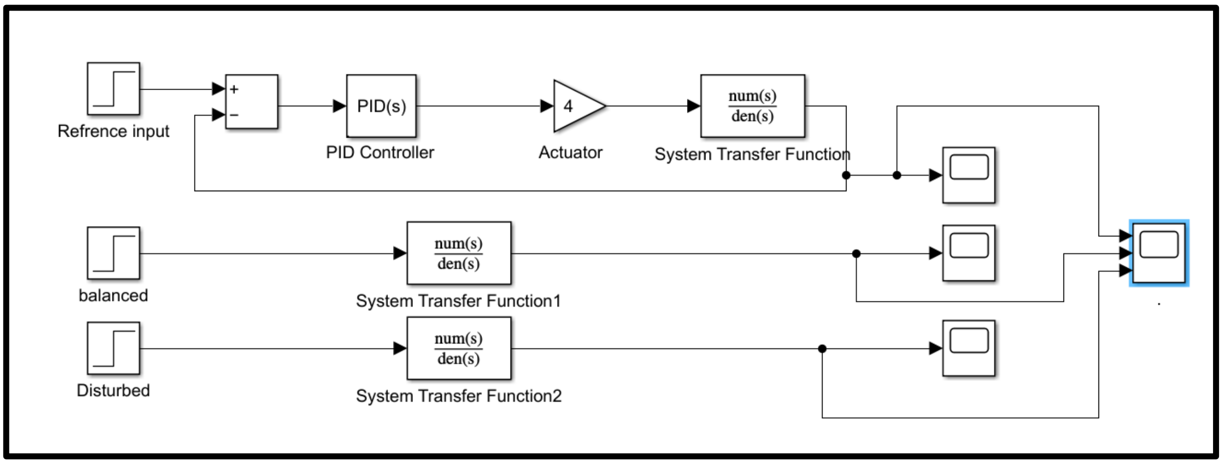


Figure 49: Design Simulink Circuit (Aravind)

The image above shows the Simulink design of my individual component. My individual component consists of system with the PID controller as well as the original group component that shows the balanced as well as the disturbed response of the washing machine system. Some of the components that I used are transfer function block, scope, step time block, gain and etc. I have individual scopes for each response and one main scope to show all the response which i will use in the discussion. Now I will explain my design part by part and show the results at the end.

Reference Input:

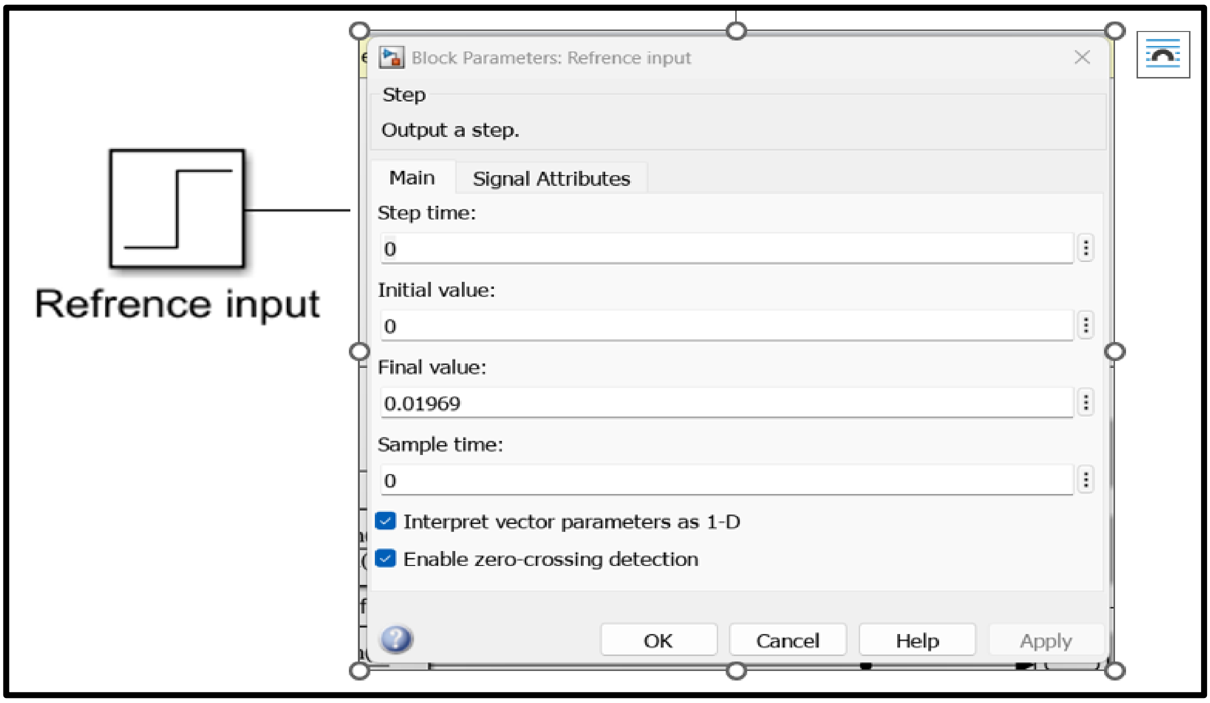


Figure 50: Reference Input Parameters (Aravind)

So, this is the step block component in here is where I will add my reference input. The reference input will be based on balanced response of the washing machine. So, value in the step block will be my displacement of the response. The displacement value ii chose was 0.01969. this is the desired response that I would want to see in the result.

PID Controller/configuration:

```
% Define the transfer function of the system
s = tf('s');
G = 1 / (60.7*s^2 + 164.54*s + 5795.55);

% Define the design requirements
overshoot = 10; % Percent overshoot
Ts = 2; % Settling time

% Convert percent overshoot to damping ratio (zeta)
zeta = -log(overshoot/100) / sqrt(pi^2 + log(overshoot/100)^2);

% Convert settling time (Ts) to natural frequency (wn)
wn = 4 / (zeta * Ts);

% Define the desired closed-loop bandwidth (approximate)
bw = wn;

% Calculate phase margin from damping ratio
pm = atan(2*zeta/sqrt(sqrt(1 + 4*zeta^4) - 2*zeta^2));

% Convert phase margin to degrees
pm = pm * (180/pi);

% Create options set for pidtune
options = pidtuneOptions('PhaseMargin', pm);

% Tune the PID controller
[controller, info] = pidtune(G, 'PID', options);

% Display the PID gains
Kp = controller.Kp;
Ki = controller.Ki;
```

Figure 51: MATLAB Coding Implementation (Aravind)

```
Kp: 1752.783444
Ki: 10111.193857
Kd: 75.961599
```

This is the code that I used to derive the PID controller values. So firstly, I declared the transfer function of my washing machine system. So, one of the first steps when getting the controller values is firstly you will state your objective. In my case my desired response I want the input values to have a 10 percent overshoot and a settling time of 1.5 to 2 seconds.

To get damping and the natural frequency I set a separate instantiation in my code. So based of the damping and the natural frequency values the values of the PID controller can be found. By using the ins-built function in mathlab called pidtune I can tune the pid controller to get the values. So based on the mathlab code I derived the following PID controller values shown above.

This is the controller block and the values I have set inside is the values I got from the mathlab code. From the block you can see I have set the controller I have set it to PID. The snippet of the block is shown below. This is the controller block and the values I have set inside is the values I got from the mathlab code. From the block you can see I have set the controller I have set it to PID. The snippet of the block is shown below.

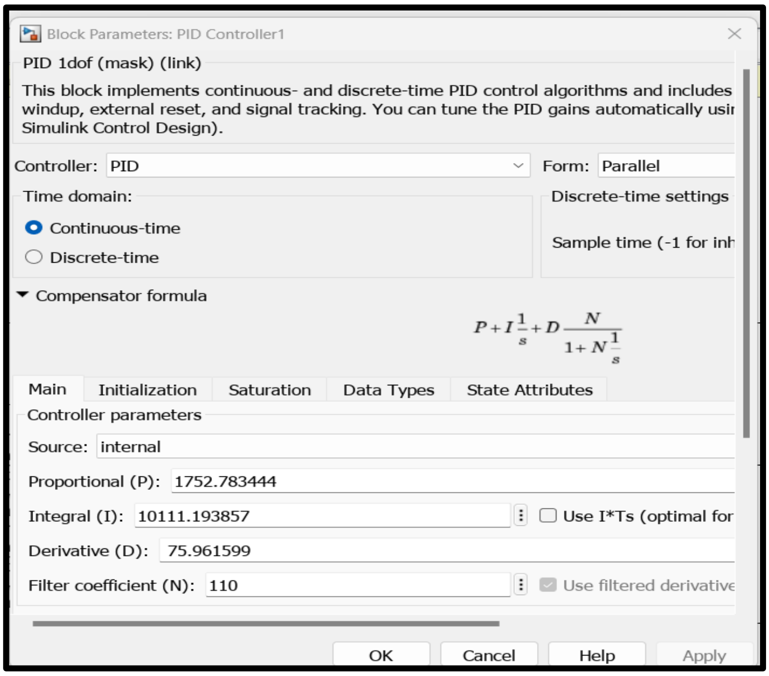


Figure 52: Parameters of PID Controller (Aravind)

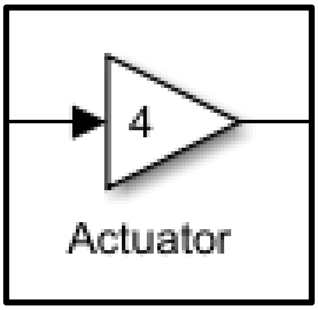


Figure 53: Gain Actuator (Aravind)

Actuator:

As stated, before I have used gain instead of the actual actuator since gain can be easy to create the system. So, I have chosen the values of 4 as that was the value that gave me a very close overshoot and the desired settling time. The output of this is the transfer function of the washing system.

Transfer Function Block:

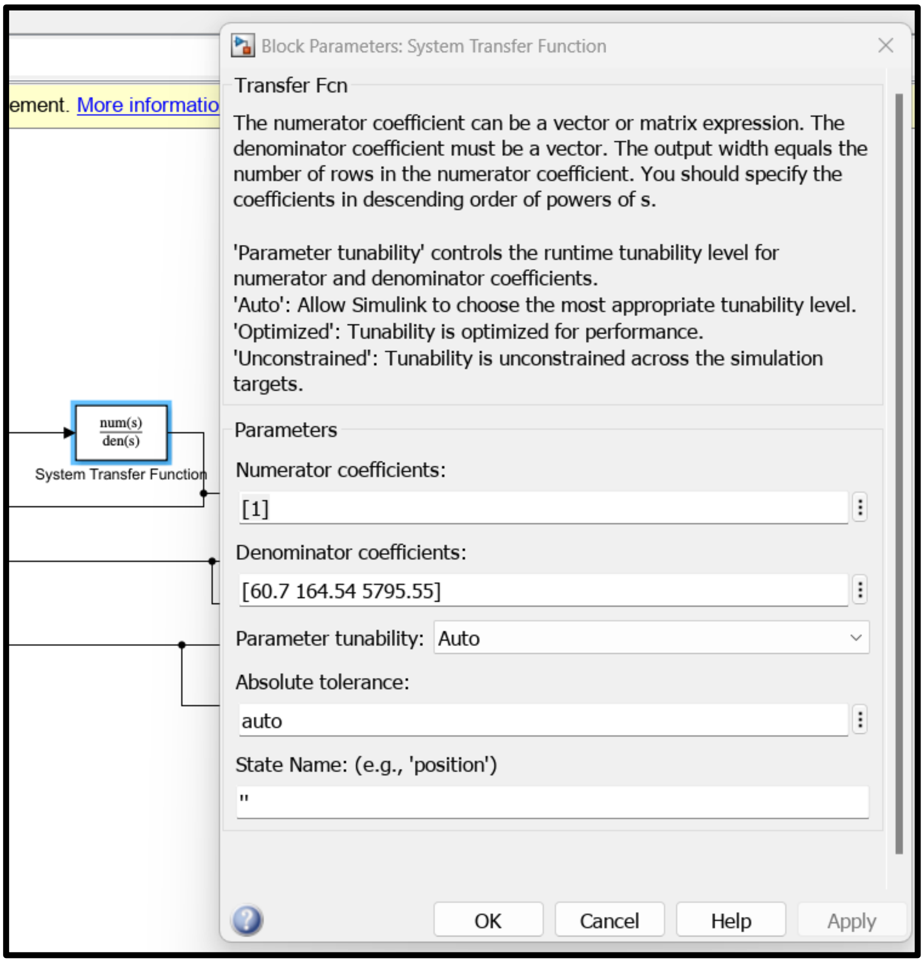


Figure 54: Transfer Function Parameters (Aravind)

The figure above shows the values I used in my transfer function block. These values were obtained in the group part of the assignment. So, the variables of the function consist of the total mass of the washing machine, vertical damping on the washing machine and the vertical spring effect on the washing machine. the transfer function and the variables were obtained based on dynamic model and the datasheet which we used as reference. For more information related to the derivation of the transfer function of the system please refer to the group report which is at the start of this documentation.

Results:

So, in this section I will provide the results obtained when the Simulink simulation started.

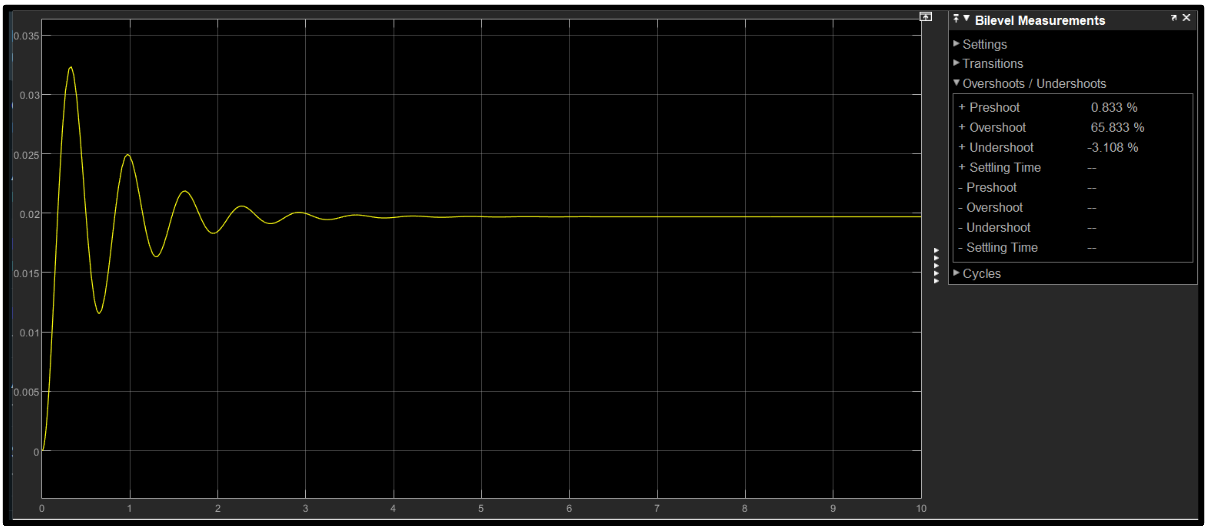


Figure 55: Balanced Response (Aravind)

The figure shows the balanced response of the washing machine system without the pid controller and actuator.

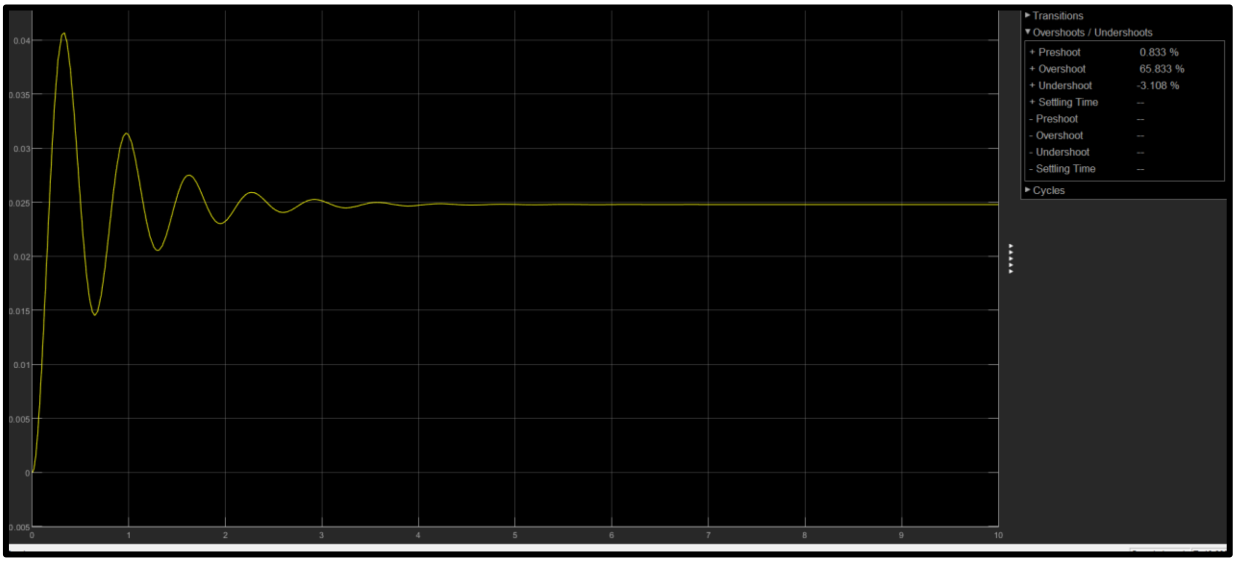


Figure 56: Disturbed Response (Aravind)

The figure above shows the disturbed response of the washing machine system when the load of the washing machine is overloaded.

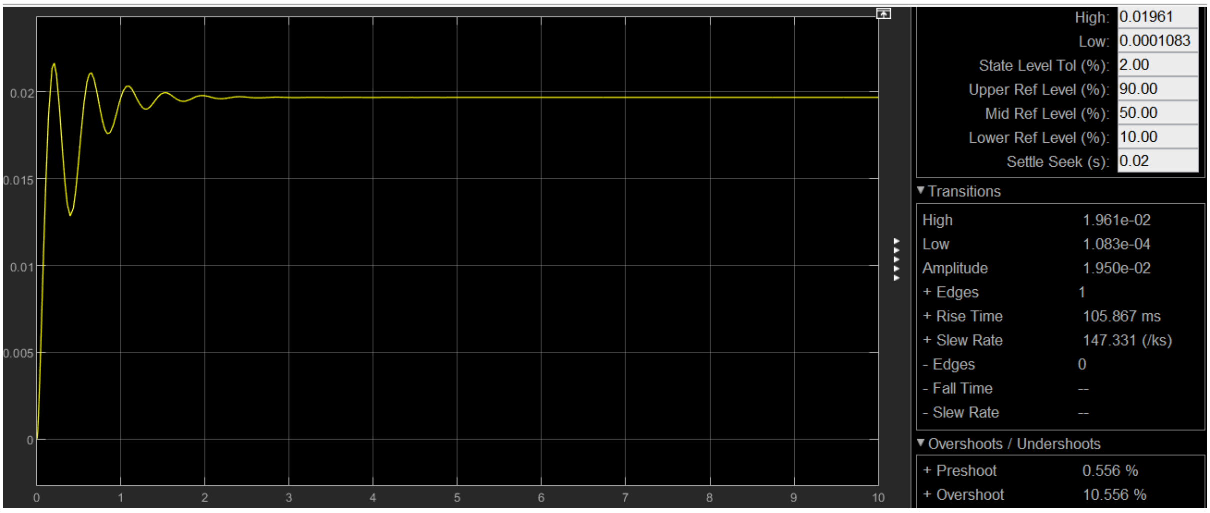


Figure 57: PID Controller Response (Aravind)

This response I obtained with use of the Pid controller as well as the actuator.

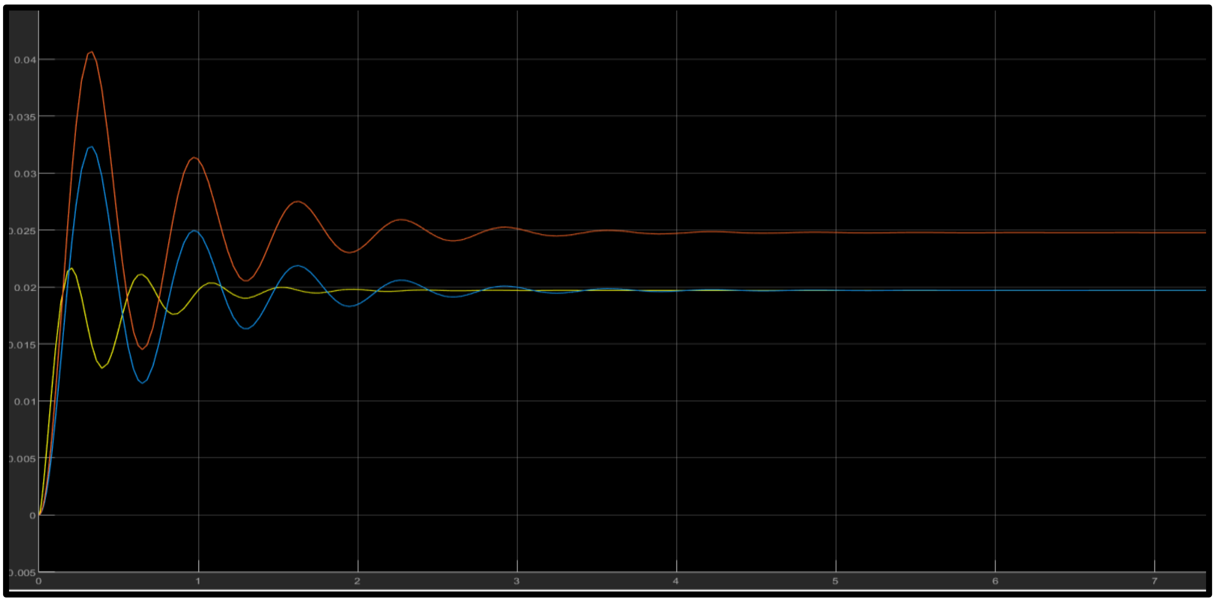


Figure 4858: All The Responses (Aravind)

The graph above shows all the responses in one graph. The red line is the response when there are disturbances, the blue line is when the system is balanced and has no disturbances, and the yellow line shows the response with implementation of the PID controller.

Discussion

Now before I explain the results obtained firstly, I will talk about briefly about the response obtained without the PID controller. Firstly, based on figure for the balanced response from the scope we can state that the response has a overshoot of 65 percent and I am able to prove this with the calculations shown below.

$$\frac{1}{(60.7s^2 + 164.54s + 5795.55)}$$

The equation above shows the transfer function of the system. From this equation we will derive the standard equation form which is shown below.

$$\frac{(60.7s^2 + 164.54s + 5795.55)}{60.7} = (s^2 + 2.7107s + 95.4785)$$

Divide the denominator by 60.7. this helps to simplify the equation more making it easier to calculate the damping and the natural frequency.

$$(s^2 + 2\zeta \text{Wns} + Wn^2 s)$$

Using the equation shown above we must deduce the values for the damping and the natural frequency.

$$Wn^2 = 95.4785$$

$$Wn = \sqrt{95.4785}$$

$$Wn = 9.7713$$

so now with the values obtained above we can find the damping of the system.

$$2\zeta \text{Wns} = 2.7107$$

$$2\zeta = \frac{2.7107}{9.7713}$$

$$\zeta = 0.1386$$

Now that I have calculated the damping and the natural frequency of the system, I can now calculate the overshoot and the settling time of the balanced system.

$$Ts = \frac{4}{(0.1386)(9.7713)}$$

$$Ts = 2.95$$

$$Mp = \frac{-\pi(0.1386)}{e^{\sqrt{1-(0.1386)^2}}}$$

$$Mp = 63.1\%$$

As you can see the value I obtained for the overshoot and the settling time was very close to the value in the response. The overshoot we got in the response with simulation was 65 percent. I got a similar overshoot also when calculating the overshoot for the disturbed response.

Now for my response with PID controller as well as well as the actuator my objective was to get a 10 percent overshoot and to have a settling time of 1.5 seconds. Since the maximum overshoot was 65 percent as per the calculation.

With the 10 percent overshoot the value or the maximum displacement wont cross over the maximum overshoot of the balanced system.

So, with the PID values I obtained from the mathlab code I was able to get the desired response. As you can see that my system stabilizes faster in comparison to the balanced response. We can make this conclusion from the settling time, meaning my system will be handle the displacement values within the given range, the washing machine will have small initial overshoot of 10 percent before settling and stabilizing.

Another thing we can note is the rising time of the peak of the displacement of the response with the controller. Compared to the balanced system response my system happens to have a quicker rising time which indicates that when the washing starts the displacement will rise quickly and start which then settles much faster.

Now if you refer to the final figure that shows the response for all the systems, we can see clear comparisons between each response. Firstly, we can notice the settling time of each response. Once again, the yellow line is the response with the controller, the blue line is balance, and the red is the disturbed system. You can notice that the red and blue line settle around 2 to 3 seconds whereas the yellow like settles at around 1.5 seconds. So, we can state that my system is able to handle the vibrations and is able to quickly stabilize.

Then we can look at the state error of the responses. The state error between the disturbed response and the balanced response is high whereas the state error between the controller response is nearly zero. This indicates that the actual state of the system and the desired state is small. This means that the system is operating very close to its desired state. So, we able to achieve accurate and precise control of the system. So this is an overall comparison between the PID controller response and the balanced and disturbed response.

Ok before I talk about the limitation, I want to show how I can further tune the controller to give pinpoint values and a shorter settling time. I will use this by using the inbuilt method in mathlab called PID tuner. The steps are shown below.

o)Figure 59:Figure 60: tune buttonFigure 61:Figure 62: tune button

- Firstly, go to the PID controller block and press the tune feature which start automatically tune my system.

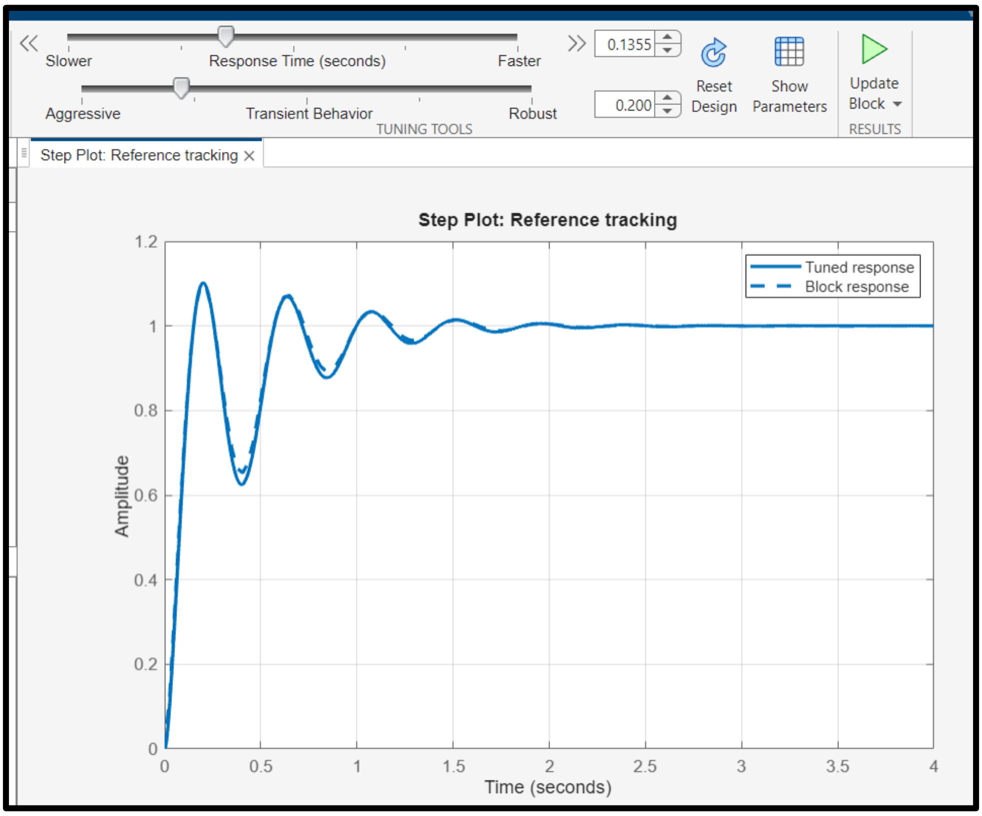


Figure 63:Figure 64: tuned waveformFiFigure 65:Figure 66: tuned waveform

- You come to this tab which allows to manually tune the PID tuner with the help of the sliders.

	Tuned	Block
P	1736.9414	1752.7834
I	9182.6685	10111.1939
D	69.4193	75.9616
N	80.5014	110

Performance and Robustness

	Tuned	Block
Rise time	0.105 seconds	0.107 seconds
Settling time	1.38 seconds	1.37 seconds
Overshoot	10.1 %	10.2 %
Peak	1.1	1.1
Gain margin	Inf dB @ Inf rad/s	Inf dB @ Inf rad/s
Phase margin	29 deg @ 14.8 rad/s	30.5 deg @ 14.7 rad/s
Closed-loop stability	Stable	Stable

Figure 67: tuned block parameters

- So, after tuning the controller the figure above shows the tuned values compared to the block values. From the figure we can see the new improved controller values and the overshoot has slightly improved.

Limitations

Given that my PID controlled system was able to reduce and minimalize the vibration and the displacements of course there will be limitation sin my system. So below are a few limitations of my system.

- Non- Linear Behaviour: washing machines have nonlinear dynamics and the PID controller is linear controller so a lot of pf parameters or factors can change drastically during a wash cycle. PID controller may struggle to adapt to these non-linearities.
- Response time: the Pid controller at instance would not be able to respond efficiently to a sudden change in washing machine process. Example if the machine detects an unbalanced load, it may need a faster response to redistribute the laundry effectively.

- Model Uncertainty: pid controllers depend on a accurate model of a control system to get a optimal performance, so in our case can be difficult due to the complexity of the system.

Improvements

• Including additional sensors, including accelerometers and position sensors, in the closed loop system. Because sensors offer real-time information about the system's current condition, they can help the PID controller adjust the control signal in response to an error, preserving stability and reducing overshooting.

• Filters and signal processing techniques are used to pre-process sensor data. Filtering can help offer a cleaner input to the controller by eliminating unwanted frequencies and noise.

• The implementation of an error detection and diagnosis system to swiftly detect and resolve any system faults. This may increase the dependability of the vibration control system.

• A piezoelectric actuator is employed in combination with the PID controller. These actuators are known for their excellent precision, rapid response, and lack of mechanical wear. These actuators can improve system performance when utilised in combination with the PID.

conclusions

Finally, the addition of a PID controller to a balanced system of a washing machine resulted in a significant reduction in noise and disturbance, as well as a shorter settling time, which is the time it takes for the system to return to a stable, balanced condition following disturbance. The system with the PID controller also ran faster than the balanced system and had a lower proportion of overshoot. The system's vibration and disturbance were caused by an uneven load on the washing machine. Along with the PID controller, an actuator was employed, which was represented as a gain value of 4 multiplied by the transfer function. The settings for the PID controller may be selected using two methods: computations and the PID tuner. The technique of computation was examined since it produced a faster settling time value. In conclusion I was successfully able to complete the assignment.

INDIVIDUAL Khaled Abdelkarim Mahmoud Abdelkarim **(TP06**6548)

The suspension system of a washing machine is an essential element as it ensures the appliance's equilibrium and steadiness, particularly during high-speed spinning or when washing loads that are unevenly distributed. The first suspension system underwent modifications to optimize its performance and establish a more efficient and dependable mechanism. In order to compare the original and improved replies, the input circumstances were maintained at a constant level, with the sole emphasis on examining alterations in the output. The closed-loop transfer function was altered by incorporating a PID controller and a linear actuator. The aim of this redesign was to provide a more effective and durable suspension system for the washing machine, guaranteeing smoother functioning and decreased vibrations.

A PID (Proportional Integral Derivative) controller is a sophisticated control system mechanism that utilizes a feedback loop to constantly monitor and regulate the process variables, guaranteeing that the system maintains a desired set point or level despite any disturbances or alterations within the plant (Omega Engineering, 2022). This controller is widely used in diverse industrial applications to regulate important variables such as temperature, speed, pressure, and flow.

The effectiveness of the PID controller relies on its capacity to calculate the output by considering the measured deviation from the set point (error) and the predetermined controller gains, namely the Proportional gain (Kp), Integral gain (Ki), and Derivative gain (Kd) (Cornell ECE, n.d.). The gains regulate the controller's response to the error in distinct manners: Kp governs the reaction to the present error, Ki influences the accumulation of previous errors, and Kd affects the anticipation of future errors. The ultimate result of the controller, which is the action implemented to bring the process variable closer to the set point, can be mathematically represented as a function of these three parameters. The output is typically expressed using a mathematical formula:

$$\text{Output} = Kp \times \text{Error} + Ki \times \int \text{Error}dt + Kd \times \frac{d(\text{Error})}{dt}$$

Here, the symbol ∫Error dt denotes the integral of the error with respect to time, which reflects the cumulative error. On the other hand, d(Error)/dt represents the derivative of the error, indicating the pace at which the error is changing. The PID controller achieves a refined equilibrium that enables it to adjust to the system's dynamics, hence offering accurate control throughout a broad spectrum of operating situations.

The PID controller utilizes a closed-loop feedback mechanism to assess the feedback value against a predetermined set point, generating an error signal. The system's output is constantly adjusted in response to the error signal until the error is eliminated or the feedback variable reaches the fixed point. Figure 52 displays the block diagram of a PID controller (Jain, Types of controllers: Proportional integral and derivative controllers 2021).

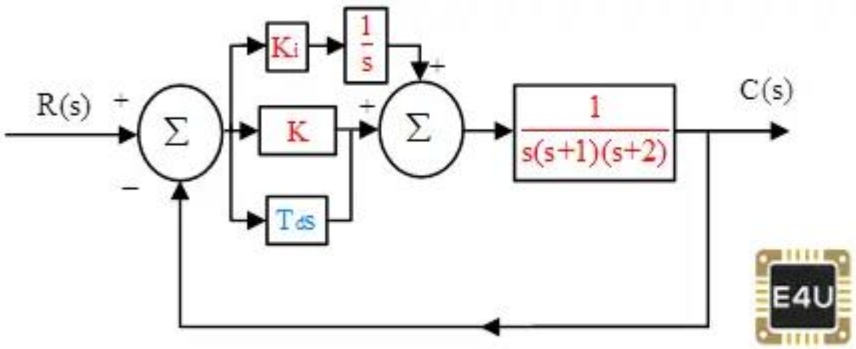


Figure 5268: PID Controller Implementation (Khaled Abdelkarim)

Various approaches can be employed to adjust a PID controller, such as trial and error and the Ziegler-Nichols tuning procedures.

A linear actuator was incorporated into the closed-loop circuit to enhance the output responsiveness of the original simulation. Actuators, devices that convert energy sources into mechanical force, can be categorized into three distinct types: hydraulic, electric, and pneumatic. The intended hydraulic actuator in this simulation is commonly employed for demanding applications and possesses a greater force capacity. By installing this actuator, the passive automotive suspension system is converted into an active system that employs automatic additional force to reduce vibrations caused by unbalanced load. In the MATLAB simulation, the representation of this is a gain block that amplifies the force to counterbalance the vibrations. PID controllers are employed for the automated regulation of actuator motion. The PID control is executed in MATLAB by utilizing the "PID controller" function from the "controller" toolbox, with the provided parameter values. The simulation results are plotted, and the model's performance is evaluated after its execution.

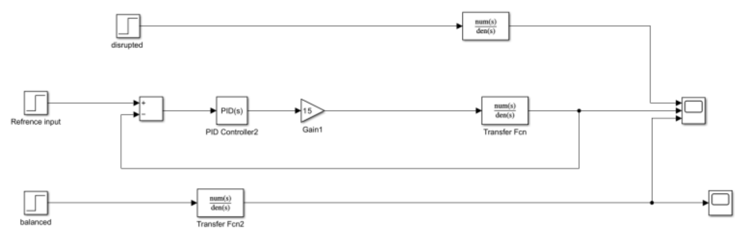


Figure 5369: Simulink Design Circuit (Khaled Abdelkarim)

The active suspension system and the passive suspension system are interconnected to the initial input to form the block diagram. Except for the active suspension system, two blocks were introduced: the "PID controller" block and the actuator, which was represented by a gain block. The active suspension system utilizes the identical transfer function as the passive suspension system.

The system was specifically intended to produce an underdamped response, characterized by a maximum Overshoot of 13% and a settling time of 0.8 s. To get the intended undamped response, the PID controller is adjusted by modifying the reaction time and transient characteristics. The response time and transient behavior variables were manipulated using the PID tuner app, as depicted in Figure 54.

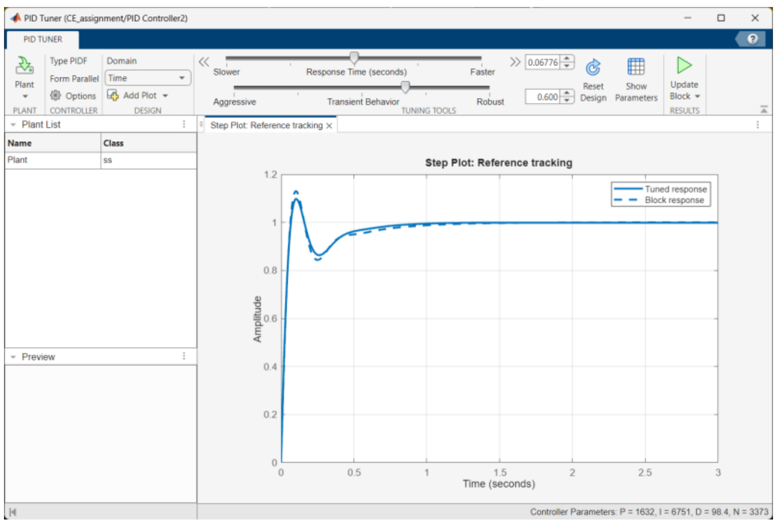


Figure 5470: PID Tuning Method (Khaled Abdelkarim)

The values for the P, I and D gains were automatically adjusted by the tuner and are given as shown in Figure 55.

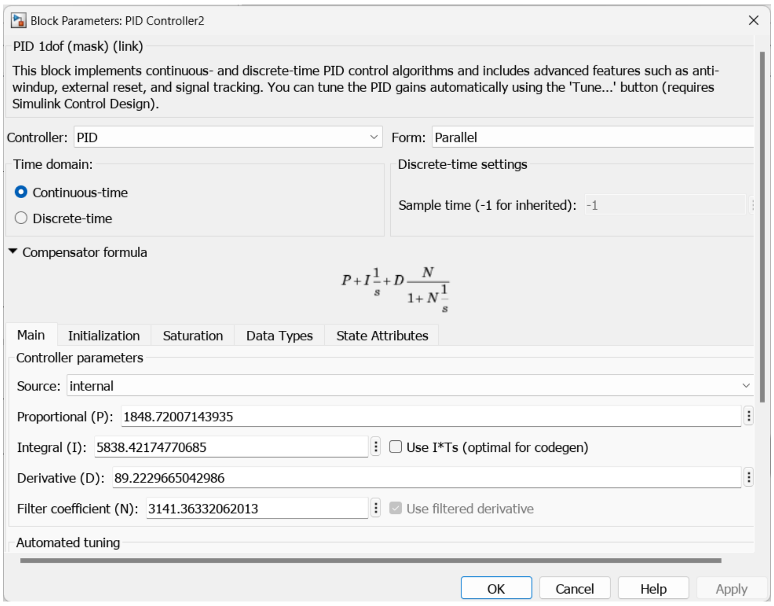


Figure 5571: PID Parameters (Khaled Abdelkarim)

Figure 18 shows the graph for the response without controller and actuator and Figure 19 illustrates the graph for the response of the transfer function.

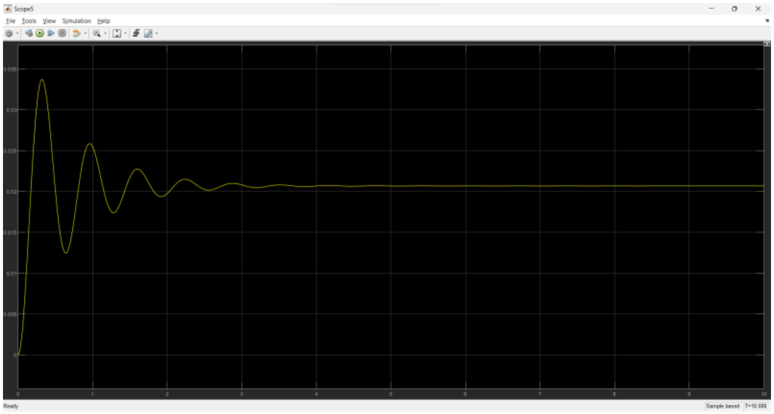


Figure 5672: Response With Disturbance (Khaled Abdelkarim)

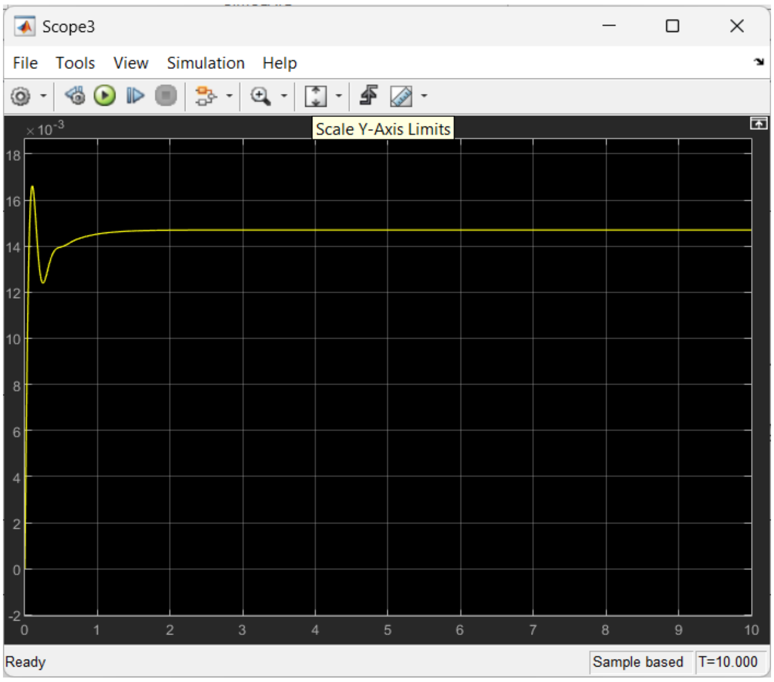


Figure 5773: Response with PID Controller and Actuator (Khaled Abdelkarim)

The study involved testing the active suspension system equipped with a PID controller and an actuator for 10 seconds to evaluate the performance of the suspension system. The results of the test of active system showed that the rising time of the system is 0.0484 seconds in which the amplitude was 0.01249 m. At 0.8 seconds, the system's amplitude reduced to 0.0147 m, which indicates that it has reached the settling time. The integration of the PID controller facilitated the quantification and assessment of the suspension system's functionality and the subsequent data obtained.

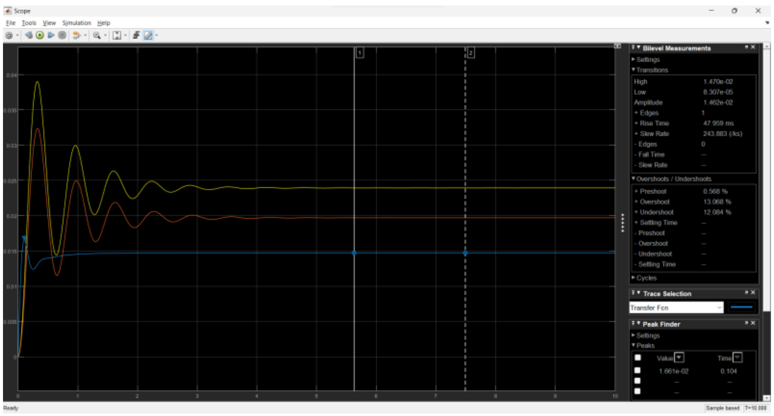


Figure 5874: Combination Of All Responses (Khaled Abdelkarim)

Figure 58 depicts a visual representation of the initial response of the suspension system compared to the enhanced response achieved by integrating a controller and an actuator. By superimposing the two responses, the inclusion of external aid had a substantial impact on the system's performance. The controller and actuator collaborate to dynamically modify the suspension's output, resulting in a response that can deviate substantially from the initial response. For instance, the enhanced reaction may demonstrate a shorter time to reach its maximum value, a reduced magnitude, or a faster time to stabilize in comparison to the original response. Utilizing external help provides enhanced authority and manipulation over the suspension system, facilitating the fine-tuning of its performance for certain uses.

Discussion

As observed in the above figures , The yellow graph depicts the displacement of the washing machine when subjected to an uneven load and without a controller to alleviate the vibrations. This scenario certainly reflects the most extreme instance in terms of the degree of vibrations. The peaks on the yellow graph represent pronounced oscillations, which correlate to vigorous vibrations experienced during the washing machine's operation. These factors may result in mechanical deterioration, audible disturbances, and potential displacement of the machine from its initial location. The washing machine lacking a controller is incapable of compensating for the unbalanced load, leading to greater displacements.

When a PID (Proportional-Integral-Derivative) controller and an actuator are added to the system, as represented by the blue graph, the displacement due to vibrations is significantly reduced. The PID controller works by continuously calculating an error value as the difference between a desired setpoint and a measured process variable, and applying a correction based on proportional, integral, and derivative terms. This feedback mechanism helps in damping the vibrations and bringing the system to a steady state more quickly. The blue graph shows smaller amplitudes and quicker settling time, indicating that the controller is effective in managing the displacement caused by an unbalanced load.

The upgraded system has a settling time of 0.848 seconds as opposed to the earlier method's 2.95 seconds. There was a 71.25% decrease in settling time between the two control methods. The settling time refers to the duration required for a system to reach a stable state. The shorter the settling time, which implies remarkable stability, the better the system is for most devices, including washing machine’s suspension systems. The peak time of a system refers to the duration it takes for the system to reach its initial overshoot, which is the highest departure from the steady state value. Put simply, it refers to the duration required for the system to reach its maximum point and subsequently return to its stable condition. The overshoot is the largest difference between the peak value and the steady state value, and it can be used to assess how much the system has "overshot" the desired steady state. Analyzing the performance and stability of a system can benefit from understanding its peak time and overshoot. These parameters offer valuable insights on the system's responsiveness to changes and its capacity to maintain a steady state. The active system in this simulation has a peak length of 0.104 seconds and a maximum amplitude of 0.01661 m. The passive system, on the other hand, has a maximum amplitude of 0.03903 m and a peak duration of 0.320 seconds.

A reference input of 0.014 m with an Overshoot of 13% was chosen for these system as 17 mm is the maximum displacement a washing machine can vibrate to without causing any damage to its internal component or the surroundings (Narkhede & Dhande, Vibration Reduction of Top-Load Washing Machine Based on Suspension System 2009). It can also be observed that the Steady-State error has been reduced to 0% which is due to the use of a PID controller which affects both the transient response as well as the steady-state response. The system's reaction has been greatly enhanced by utilizing a controller and an actuator, as depicted in Figure 19. The PID controller's various gains have been adjusted to get the intended outcomes.

Despite the enhancements, the controller does has certain restrictions. These phenomena are evident in the blue graph, where the displacement does not reach zero and there may be a lingering oscillation. The possible reasons for this could include delays in the actuator's reaction, constraints in the controller's calibration, or non-linearities in the system that the PID controller is unable to completely offset. Moreover, in the event that the uneven distribution of weight alters continuously throughout the process of washing, the PID controller may encounter difficulties in adapting to these changes, resulting in a diminished ability to effectively reduce vibrations.

The PID controller gains can be accurately adjusted to create a more acceptable response, characterized by a faster settling time and smaller Overshoot. Furthermore, the utilization of an enhanced actuator or the addition of a supplementary actuator can be employed to enhance the outcomes.

To enhance the system even further Precise measurement of displacement can be achieved by utilizing a Position Sensitive Detector. The latter refers to an optical sensor that generates a laser beam and detects the reflected beam in order to measure the inter-story.

Conclusion

Ultimately, examining the displacement graphs of a washing machine under different settings yields useful insights into the system's behavior and the effectiveness of control mechanisms. The unregulated reaction, as depicted by the yellow graph, illustrates the substantial influence of an imbalanced load on the stability of the system and the subsequent requirement for a control mechanism. The implementation of a PID controller and actuator, depicted by the blue graph, demonstrates a significant enhancement in regulating the displacements caused by vibrations, emphasizing the controller's function in reducing the negative impacts of the imbalance.

Nevertheless, the limitations of the controller are apparent, as indicated by the presence of residual vibrations, which implies the necessity for more improvement. Possible future enhancements may include implementing adaptive control systems, employing more sophisticated dampening techniques, and integrating machine learning algorithms to proactively address unbalanced conditions. These improvements have the capacity to optimize the efficiency of washing machines, enhancing their dependability, prolonging their lifespan, and enhancing customer satisfaction. This conversation highlights the ongoing interaction between identifying problems, applying technology, and developing solutions in engineering to fulfil the changing needs of consumer products.

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