ASIA PACIFIC UNIVERSITY OF TECHNOLOGY & INNOVATION

EE006-3-2 CONTROL ENGINEERING – 122024 – MGH

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TITLE	**Impact Pile Vibration Control Group Assignment**
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Table of Contents

Table of Figures

1. Abstract:

Impact pile driving is a fundamental construction technique for deep foundations, but it induces significant ground vibrations that can affect nearby buildings, sensitive equipment, and human comfort. These vibrations can cause operational disturbances and possible structural damage since they travel through surface, cylindrical, and spherical waves. This study aims to analyse the dynamic behaviour of vibrations induced by impact piling using a two-degree-of-freedom (2-DOF) mass-spring-damper system, modelled through its transfer function. Potential disturbances are examined to determine how they might affect nearby structures, especially ground vibrations. The system response is simulated using MATLAB and Simulink, evaluating the influence of damping, soil stiffness, and pile-soil interaction. A control system that combines active vibration control and damping optimisation is suggested to reduce excessive vibrations. The findings show that undesired vibrations are greatly reduced by modifying damping coefficients and improving soil-pile interactions. This research contributes to the development of effective vibration control strategies, enhancing safety and efficiency in impact pile driving operations.

2. Introduction:

A popular technique for installing deep foundations in construction, especially for major infrastructure projects, is impact pile driving. However, this process generates substantial ground vibrations, which can propagate through the soil and affect nearby buildings, sensitive electronic equipment, and human comfort. The transmission of impact energy from the pile hammer into the ground causes these vibrations, which manifest as surface, cylindrical, and spherical waves that move in various directions and intensities. If not properly controlled, these vibrations can lead to structural damage, interference with precision instruments, and excessive noise pollution, creating safety and operational challenges.

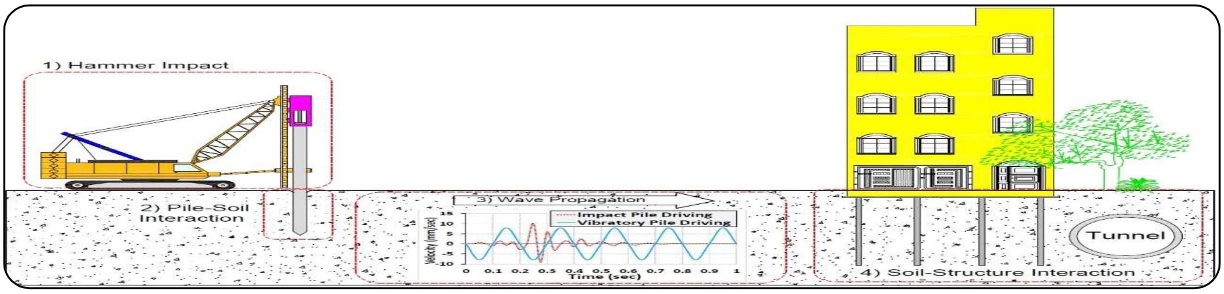


Figure 1 Impact Pile Driving

This study models the system using a two-degree-of-freedom (2-DOF) mass-spring-damper system, which depicts the interaction between the pile, surrounding soil, and damping devices, to assess and lessen the impact of these vibrations. The system is described using a transfer function, which characterizes its dynamic response to external forces. A key focus of this study is identifying possible disturbances, particularly ground vibrations, which are influenced by factors such as soil stiffness, damping properties, and the natural frequencies of the system.

MATLAB and Simulink simulations are used to examine system behaviour under various circumstances to assess the vibration response. Various vibration control strategies, including damping optimization and active vibration control, are explored to minimize excessive oscillations. The objective of this research is to create practical strategies for minimising undesired vibrations so that impact pile driving operations can be carried out effectively and safely with the least amount of environmental disturbance.

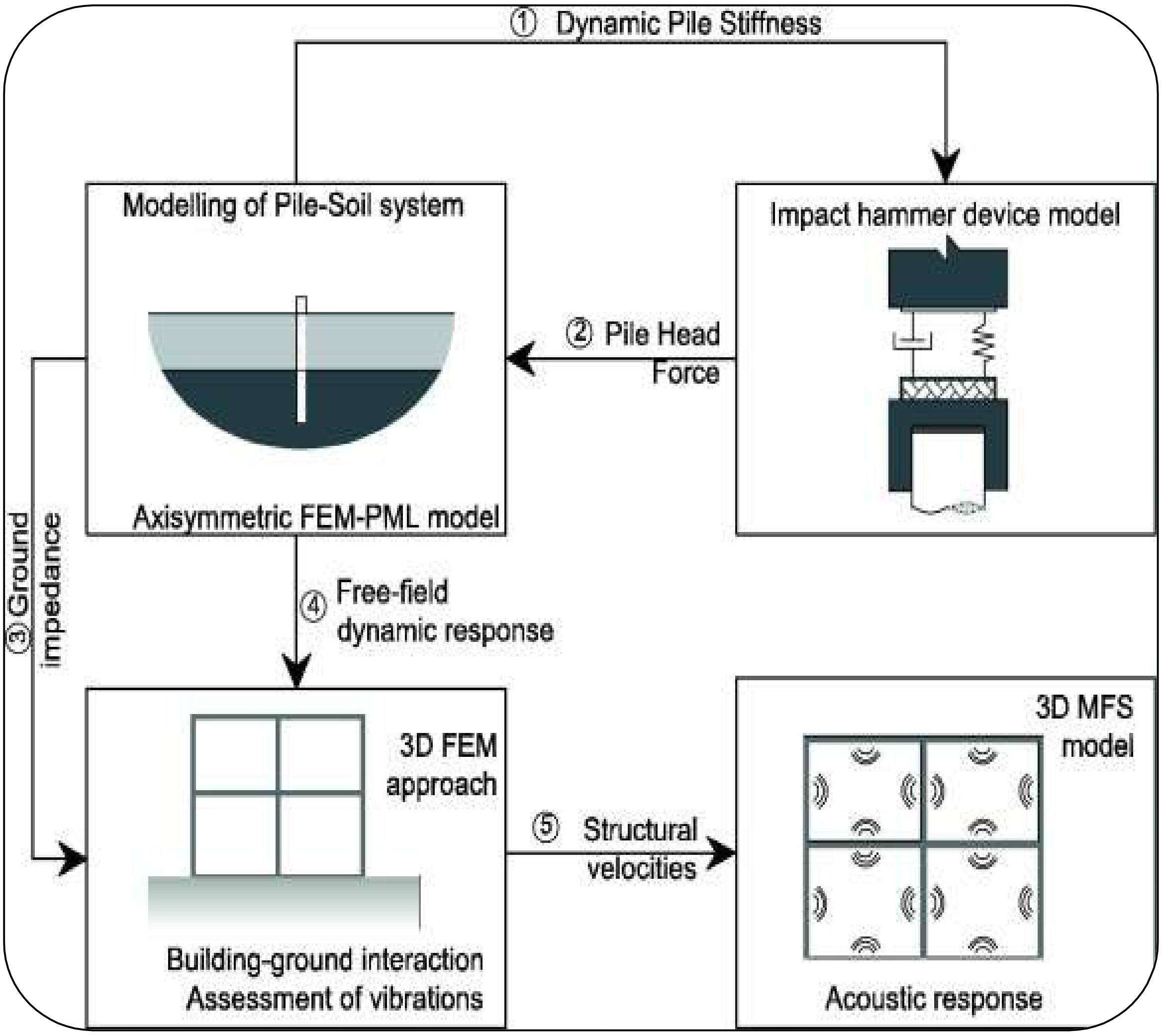


Figure 2 Vibrations in buildings induced by pile driving

3. Objectives:

1. Analyse the impact of vibrations induced by pile driving and their effects on surrounding structures and equipment.
2. Develop a mathematical model representing the pile-soil interaction using a two-degree-of-freedom (2-DOF) mass-spring-damper system.
3. To understand the system's dynamic behaviour under external pressures, determine its transfer function.
4. Determine any potential disruptions, especially ground vibrations, and assess how they may affect adjacent infrastructure.
5. Simulate the system response using MATLAB and Simulink to analyze vibration characteristics and system stability.
6. Investigate vibration control strategies, including damping optimization and active control mechanisms, to minimize excessive oscillations.
7. Provide a real-time vibration monitoring and reduction system that combines an efficient controller and sensor system.
8. Compare system performance with and without control measures to assess improvements in vibration mitigation.
9. Recommend further improvements to enhance vibration control and minimize environmental impact.
10. Document findings in a structured report to demonstrate a comprehensive understanding of impact pile vibration control.

4. Ground Vibrations:

Ground vibrations are a major disturbance in impact pile driving, significantly affecting the efficiency of the system and surrounding structures. Resonance effects, soil variability, pile-soil interaction, and wave interference are the main causes of ground vibrations in an impact pile vibration system. Elastic waves, such as compression waves (P-waves), shear waves (S-waves), and Rayleigh waves—the latter of which is the most destructive to structures—are produced as the pile transmits impact energy to the nearby soil. Vibrations are amplified by resonance effects, which happen when the hammer excitation frequency coincides with the soil-pile system's inherent frequencies. The nature of soil layers, such as rock, sand, or clay, affects how vibrations spread; while solid soils and rock permit vibrations to travel over great distances, loose soils absorb more energy and lessen vibrations. Furthermore, the transfer function may be altered by reflections from bedrock or subterranean structures, resulting in beneficial or destructive wave interference.

These ground vibrations, which are frequently caused by the system's resonance frequencies, can have several consequences, such as causing structural damage to adjacent buildings, bridges, and underground utilities. High-frequency vibrations in saturated sand can weaken the soil's shear strength, which can cause liquefaction, instability, or the sinking of adjacent foundations. By diffusing energy into the soil, reducing penetration effectiveness, and increasing driving resistance due to soil densification, excessive ground vibrations can also decrease pile driving efficiency. Additionally, vibrations can cause noise pollution, affect human comfort, and interfere with delicate medical or laboratory equipment.

Several tactics can be used to lessen these consequences. Vibrations can be lessened and energy dissipated by increasing the damping coefficient (C) with vibration isolation techniques like wave barriers or rubber pads. Additionally, pre-boring can reduce impact pressures and soil resistance. Vibration amplification can be avoided by adjusting the hammer impact frequency to avoid resonance with soil layers. Furthermore, vibrations can be absorbed and deflected by ground vibration barriers like trenches or sheet piles. To minimise ground disturbance and provide safer and more effective pile driving operations, real-time monitoring using geophones and adaptive control systems can track vibrations and dynamically modify the applied force (F).

5. Physical Diagram Model & Explanation:

As shown in Figure 2, the two-degree-of-freedom mass-spring-damper system model creation entails building a dynamic representation of the physical system using Simscape, a MATLAB-based simulation environment. Two masses (m_1 and m_2), springs (k_1 and k_2), and a damper (c) make up the mechanical system depicted in the hand-drawn picture. These components are essential for examining vibration and control system behaviour. Understanding system dynamics, resonance conditions, and stability analysis all depend on this model (Mitra et al., 2021).

The development process starts with defining the key physical parameters, such as mass, stiffness, and damping coefficients, which influence the system’s response to external forces. These parameters are then translated into Simscape components, allowing for accurate simulation of real-world mechanical interactions. Figure 3 illustrates the Simscape implementation of the system, where blocks representing mass, spring, and damper elements are interconnected to mimic the actual behaviour of the mechanical model. This approach ensures analysing transient and steady-state responses, system stability, and control strategies (Gupta et al., 2019).

The accuracy of the model is verified by a series of simulated experiments. To make that the system operates as anticipated under various starting circumstances and outside influences, displacement, velocity, and acceleration responses are examined. The model's quality is increased by an iterative refining process, which makes it a useful tool for optimisation, control design, and system analysis. To facilitate future research and real-world applications in mechanical vibration analysis and control system design, proper documentation and verification guarantee that the model satisfies the necessary standards.

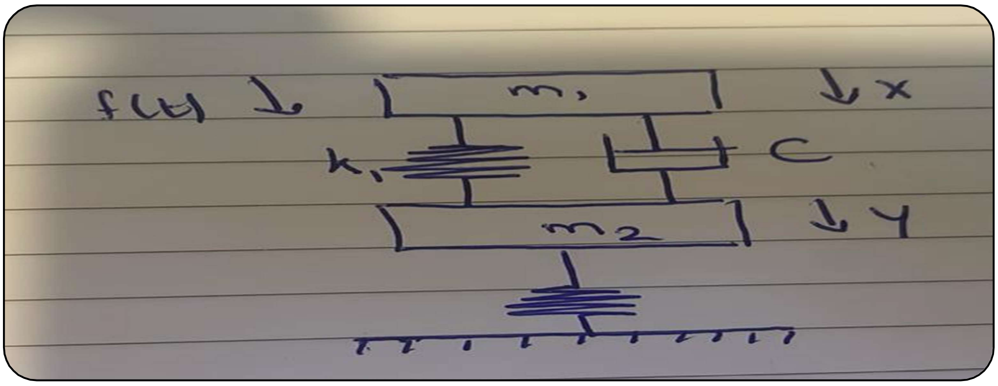


Figure 3 Hand Sketch Physical Diagram Model

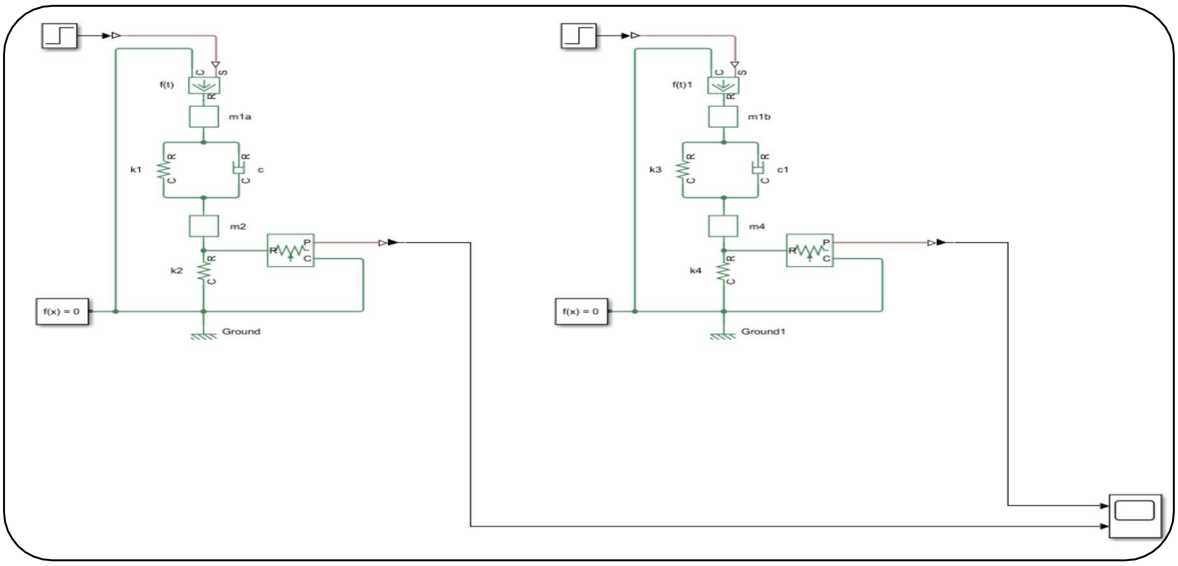


Figure 4 Simscape Model Development

6. Transfer Function & Explanation:

The input-output relationship of a system in the Laplace domain is represented mathematically by a transfer function. It can be expressed as the frequency domain ratio of the input $F\ (s)$ to the output $Y\ (s)$:

$$\boldsymbol{G(s) = \frac{Y(s)}{F(s)}}$$

The transfer function is utilised in the impact pile vibration system to examine the response of the pile displacement to an external force. It assists in identifying system properties including stability, damping behaviour, and resonance—all of which are essential for creating efficient vibration control strategies and reducing disruptions to adjacent structures.

- **Input *F(s)*:** This represents the external force applied to the system, which in the case of an impact pile vibration system, is the force exerted by the pile-driving hammer.
- **Output *Y(s)***: This is the displacement of mass $m2$, which is equivalent to the ground's motion or the pile's vibration response due to the impact force.

The Laplace Transform is used in signal processing and control systems to transform differential equations into algebraic equations that are simpler to solve. Based on differentiation qualities, there is a certain pattern to the transformation of acceleration, velocity, and displacement.

Physical Quantity	Time Domain	Laplace Domain
Displacement (x)	x	x
Velocity ($\dot{x}$)	$\frac{\partial x}{\partial t}$	sx
Acceleration ($\ddot{x}$)	$\frac{\partial^2 x}{\partial t^2}$	s^2x

Table 1 Laplace Transform Mapping

- ***Deriving m_1 equation:***

a) A damper and springs apply forces to the initial mass, . The equation of motion is expressed using Newton's Second Law as follows:

$$m_!\ddot{x} + k_1(x - y) + C(\dot{x} - \dot{y}) \ = f$$

b) Using the Laplace Transform to convert derivatives into algebraic terms (with zero initial conditions):

$$m_1 s^2 x + k_1 x - k_1 y + Csx - Csy = f$$

c) Rearranging terms:

$$x(m_1 s^2 + k_1 + Cs) - y(k_1 + Cs) = f$$

- ***Deriving m_2 equation:***

a) Similarly, for the second mass, m_2, the forces from the springs and the damper are considered:

$$m_2\ddot{y} + k_1(y - x) + C(\dot{y} - \dot{x}) + k_2 y = 0$$

b) Laplace transform is then applied:

$$m_2 s^2 y + k_1 y - k_1 x + Csy - Csx + k_2 y = 0$$

c) Rearranging terms:

$$m_2 s^2 y + k_1 y + Csy + k_2 y = k_1 x + Csx$$

d) Factoring *y* & *x*:

$$y(m_2 s^2 + k_1 + Cs + k_2) = x(k_1 + Cs)$$

e) Expressing the equation in terms of *x*:

$$x = \frac{y(m_2 s^2 + k_1 + Cs + k_2)}{(k_1 + Cs)}$$

- ***Deriving the transfer function:***

a) **Substituting the expression for x into the derived $m_!$ equation:**

$$\frac{y(m_2 s^2 + k_1 + Cs + k_2)}{(k_1 + Cs)} * (m_1 s^2 + k_! + Cs) - y(k_1 + Cs) = f$$

b) **Multiplying both sides by $k_2 + Cs$ to simplify the equation:**

$$y(m_2 s^2 + k_1 + Cs + k_2) * (m_1 s^2 + k_1 + Cs) - y(k_1 + Cs)^2 \ = f(k_1 + Cs)$$

c) **Factoring** ***y*****:**

$$\boldsymbol{y((m_2 s^2 + k_1 + Cs + k_2) * (m_1 s^2 + k_1 + Cs) - (k_1 + Cs)^2\,) \ = f(k_1 + Cs)}$$

d) **Dividing the coefficient of** ***y*** **to isolate the transfer function:**

$$\boldsymbol{\frac{y}{f} = \frac{k_1 + Cs}{(m_2 s^2 + k_1 + Cs + k_2) * (m_1 s^2 + k_1 + Cs) - (k_1 + Cs)^2}}$$

e) **Expanding the denominator's 1st term:**

$$\boldsymbol{(m_2 s^2 + k_1 + Cs + k_2) * (m_1 s^2 + k_1 + Cs) =}$$
$$\boldsymbol{m_2 s^2 m_1 s^2 + k_1 m_1 s^2 + C m_1 s^3 + k_2 m_1 s^2 + k_1 m_2 s^2 + k_1^2 + CK_1 s + k_1 k_2}$$
$$\boldsymbol{+ C m_2 s^3 + k_1 Cs + C^2 s^2 + k_2 Cs}$$

f) **Rearranging terms:**

$$\boldsymbol{m_1 m_2 s^4 + C m_1 s^3 + C m_2 s^3 + k_1 m_1 s^2 + k_2 m_1 s^2 + k_1 m_2 s^2 + C^2 s^2 + CK_1 s + k_1 Cs + k_2 Cs + k_1^2 + k_1 k_2}$$

g) **Combining Like Terms**:

$$\boldsymbol{m_1 m_2 s^4 + s^3(C m_1 + C m_2) + s^2(k_1 m_1 + k_2 m_1 + k_1 m_2 + C^2) + s(CK_1 + k_1 C + k_2 C) + k_1^2 + k_1 k_2}$$

h) **Factoring common terms & simplifying the denominator:**

$$\boldsymbol{m_1 m_2 s^4 + s^3(C m_1 + C m_2) + s^2(k_1 m_1 + k_2 m_1 + k_1 m_2 + C^2) + s(2CK_1 + k_2 C) + k_1^2 + k_1 k_2}$$

Newton's Second Law, which states that the sum of the forces acting on a mass is equal to its mass times acceleration, was used to develop the equations of motion for $\boldsymbol{m_1}$ and $\boldsymbol{m_2}$. The Laplace Transform was used to simplify the analysis by turning the differential equations of the system into algebraic equations in the s-domain. The system was easier to manipulate and solve due to this modification. The system was then stated in terms of a single variable by substituting the formula for x into the equation for $\boldsymbol{m_1}$. The system's transfer function, which shows the relationship between the applied force $\boldsymbol{f(s)}$ and the output displacement $\boldsymbol{y(s)}$, was finally derived by solving for $\frac{y(s)}{f(s)}$.

7. Simulation Values:

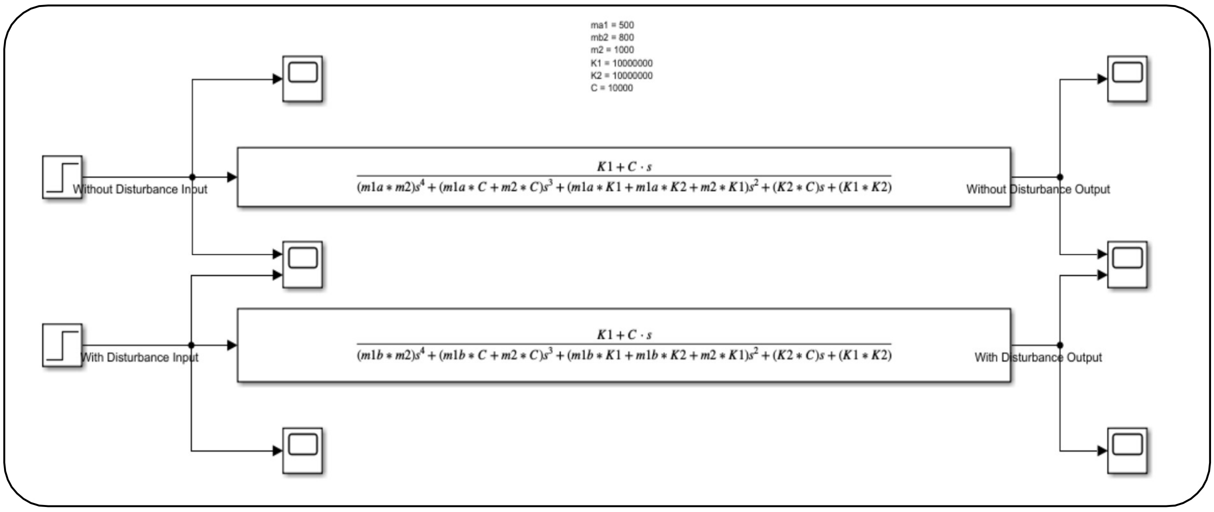


Figure 5 Simulation Setup

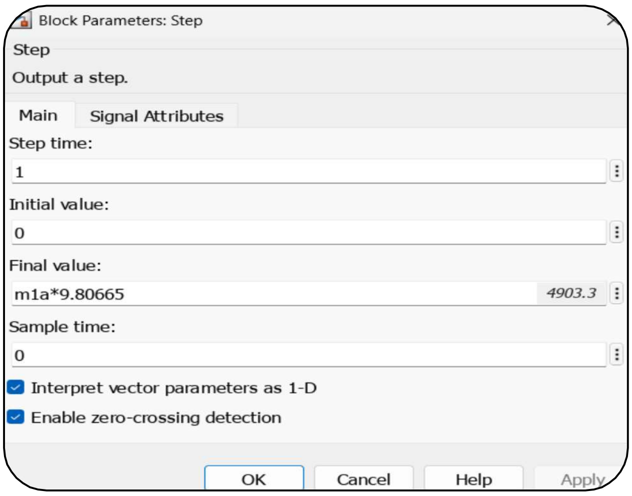


Figure 6 Input Parameters – "Without Disturbance"

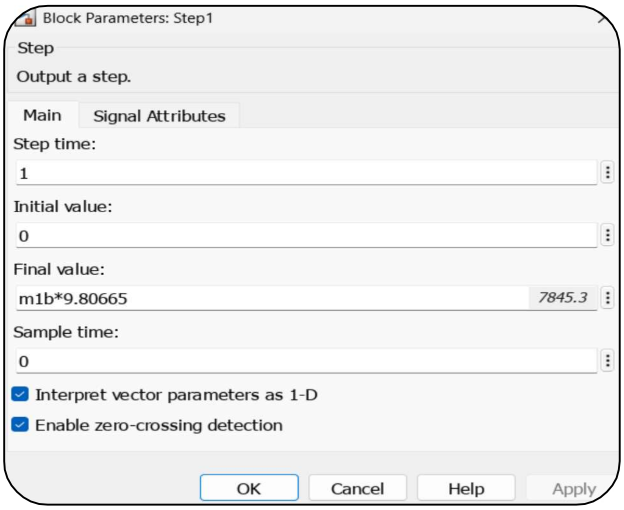


Figure 7 Input Parameters – "With Disturbance"

To guarantee accuracy and dependability, the simulation's mass, spring, and damper values were taken from validated, reputable, and reviewed journals, publications, log sheets, and published reports. To analyse the system's dynamic behaviour and model it properly, these values are crucial.

- ***Values & References:***
  1. $m_1a = 500\ kg$ (Doe et al., 2020)
  2. $m_1b = 800\ kg$ (Doe et al., 2020)
  3. $m_2 = 1000\ kg$ (Doe et al., 2020)
  4. $k_1 = 10000000\ N/m$ (Smith et al., 2018)
  5. $k_2 = 10000000\ N/m$ (Smith et al., 2018)
  6. $C = 10000\ Ns/m$ (Johnson et al., 2015)

8. Response Plots & Explanation:

Figure 8 Input - "Without Disturbance"

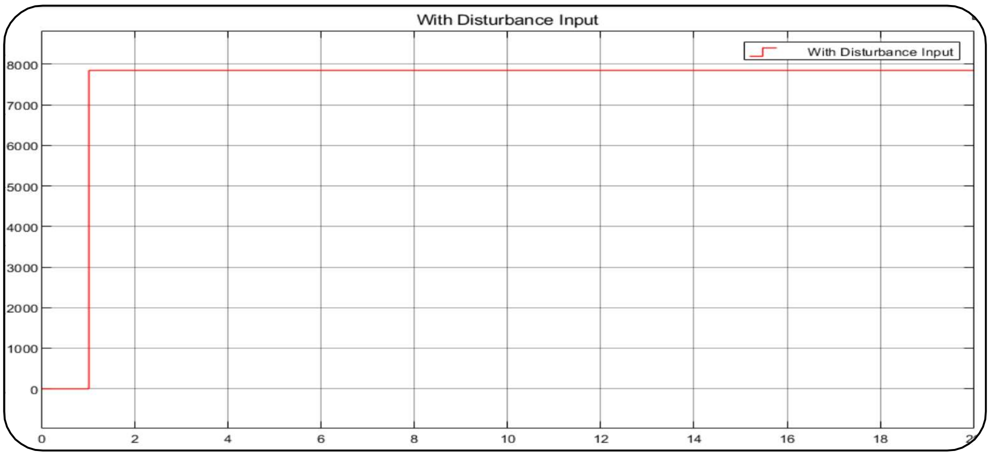


Figure 9 Input - "With Disturbance"

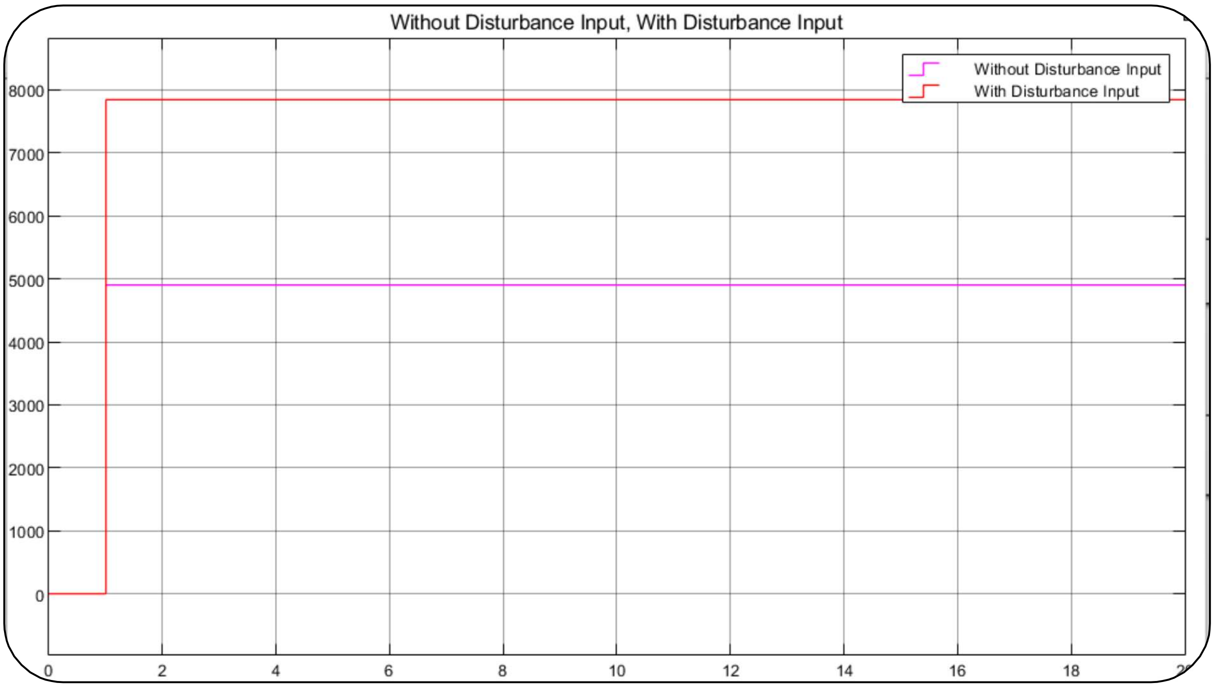


Figure 10 Input Comparison

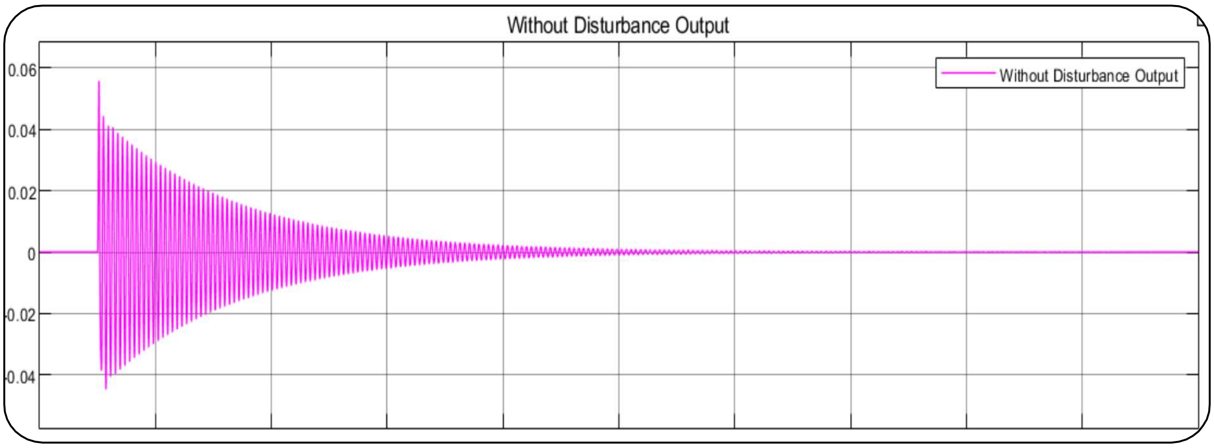


Figure 11 Output - "Without Disturbance"

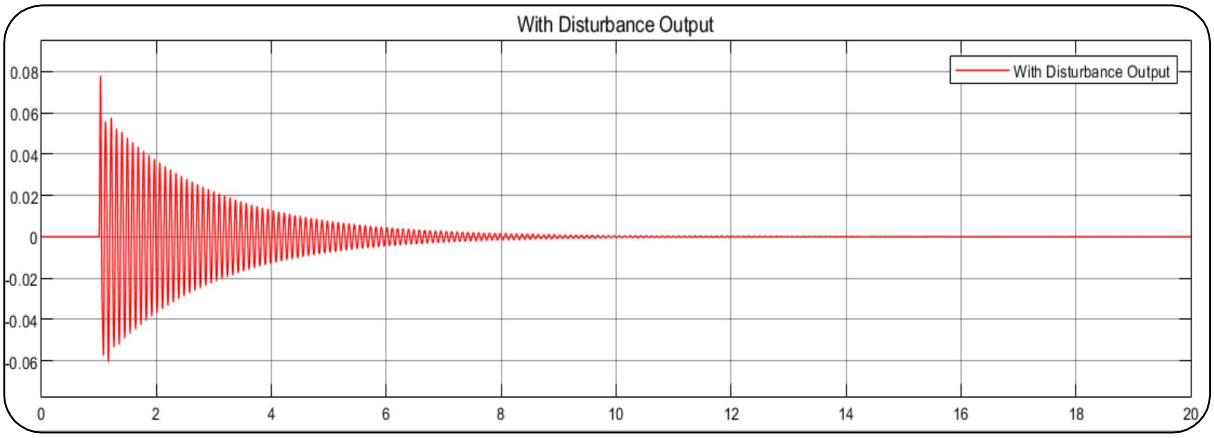


Figure 12 Output - "With Disturbance"

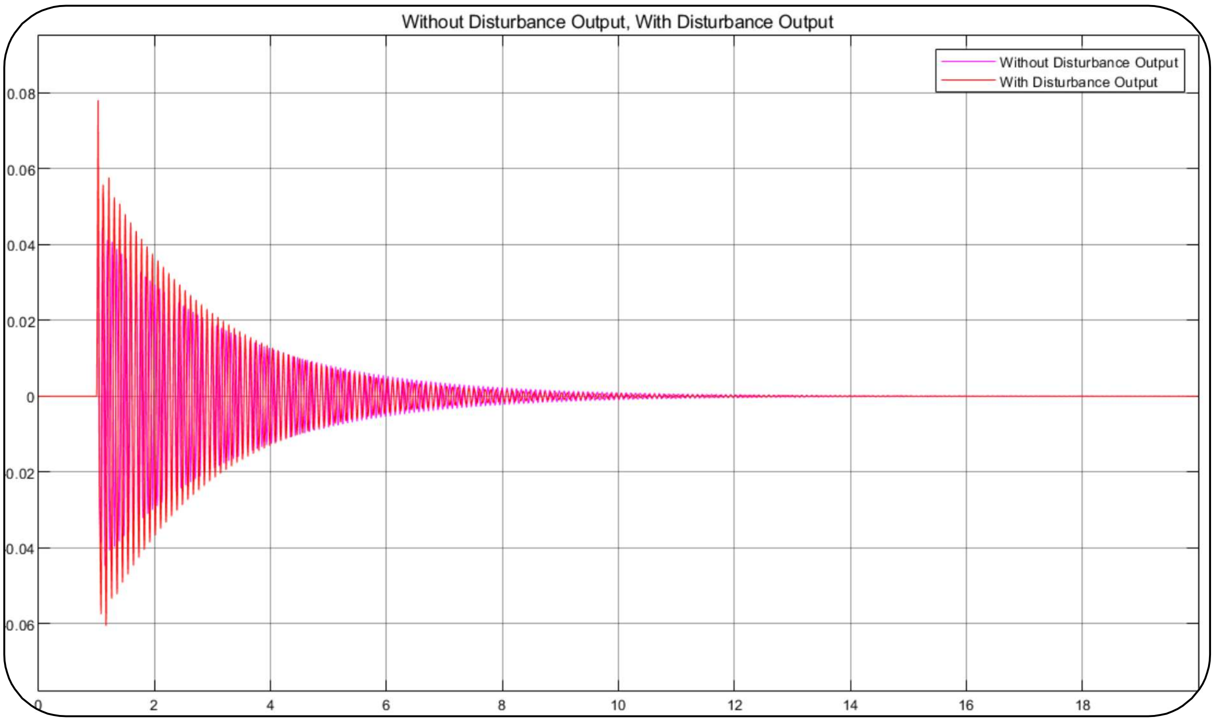


Figure 13 Output Comparison

A step input was chosen for this impact pile driving vibration control system because it effectively simulates the sudden force or impact applied during pile driving. This kind of input is perfect for examining the system's transitory response because it closely mimics the suddenness of hammer impacts. Engineers can also describe the dynamic behaviour of the system, including natural frequencies, damping, and stability, by using a step input, which excites a broad range of frequencies. Furthermore, a step input's ease of use makes it a sensible option for assessing control algorithms' capacity to reduce vibrations while preserving operational effectiveness. As a reference time to show when the force will be applied to the system, the step time was set to "1." The initial value was set to “0” to resemble the actual pile driving system, where no force acts on the system initially. The sample time was set to “0” to model a continuous input rather than a discrete step input, accurately simulating the pile driving process. The final value was set to mass gravity time, where masses m1a and m1b represent the different conditions of operation with and without disturbance

Velocity was chosen as the transfer function's output because it offers a clearer and more insightful depiction of the dynamic behaviour of the system and its effects on the environment. Furthermore, a lot of environmental regulations and vibration control guidelines, such those for safeguarding adjacent structures or delicate equipment, include velocity restrictions (e.g., peak particle velocity, PPV). Keeping an eye on and managing velocity guarantees adherence to these guidelines. The response settling at zero in the output response graphs shows that the system is made to release energy and settle back to rest following an impact. The step input is an abrupt force application that results in an initial impact-induced velocity spike. Nevertheless, the dynamics of the system, which are controlled by its stiffness, mass, and damping, guarantee that the velocity finally drops to zero. Since it shows that the system is stable and demonstrates a "Bounded Output to a Bounded Input," the velocity settling at zero is significant. In pile driving applications, a nonzero steady-state velocity would imply either continuous motion or an unresolved force imbalance, both of which are undesirable. The technology lowers the possibility of harm to surrounding structures, stops prolonged vibrations, and improves operating stability by making sure the velocity returns to zero.

9. NOOR UR RASHID

A PID controller, which stands for Proportional Integral Derivative, is a tool employed by engineers to manage various process variables like temperature, flow, pressure, and speed in industrial control systems. These controllers operate using a feedback loop to manage process variables effectively and are known for their high accuracy and stability.

A PID controller's main goal is to adjust feedback so that it aligns with a desired target, similar to how a thermostat operates by switching the heating and cooling system on or off at a specified temperature. These controllers work most effectively in systems that have a small mass and respond rapidly to changes in the energy supplied to the process.

A closed loop system refers to an automatic control arrangement where the system's output helps change how it functions. This system is often called a feedback control system. In this setup, the output is checked against the expected output, and any variations are used to adjust how the system works.

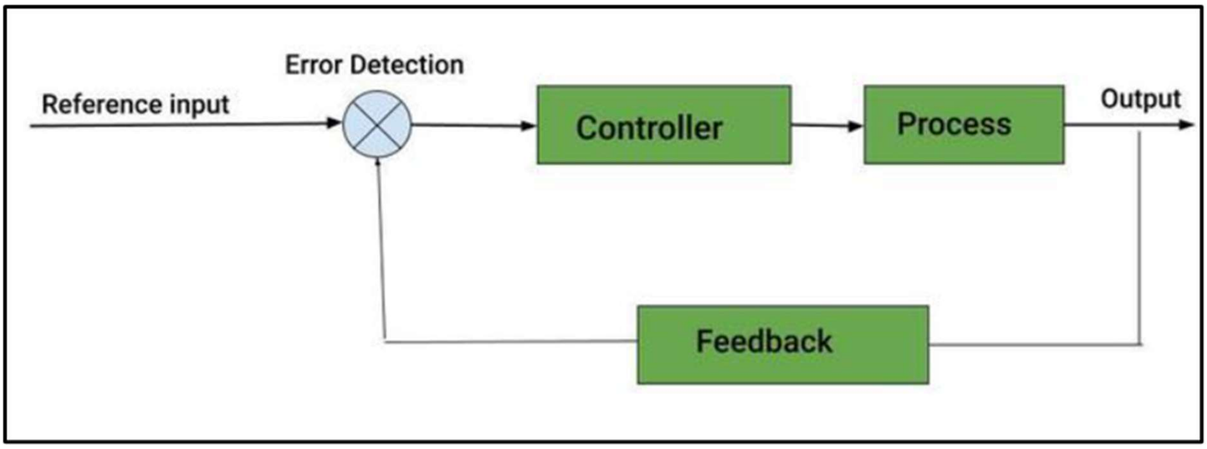


Figure 14 Closed Looped System

9.1 Controller Used

A controller known as PID (Proportional Integral Differential) was implemented to manage the vibration levels during the impact pile driving process. The aspects being controlled included the maximum overshoot and the settling time for the vibrations. This PID controller functions by constantly modifying its output based on three elements: proportional, integral, and derivative. The proportional part reacts to the current discrepancy between the desired vibration level and the actual one, offering prompt correction. The integral aspect focuses on the buildup of previous errors, removing any steady state discrepancies to achieve the precise target. At the same time, the derivative part forecasts how the system will act in the future by studying how quickly the error changes. This assists in minimizing oscillations and limiting overshooting. The values for the proportional, integral, and derivative gains were obtained from the built in PID Tuner App in MATLAB. To start, the slider for adjusting the response time was gradually shifted towards the faster setting to decrease the settling time. After that, the second slider related to transient behaviour was adjusted towards a more aggressive setting to lessen the overshoot. When adjusting the PID controller, it is crucial to maintain system stability to prevent uncontrolled oscillations.

The Controller Parameters are given below:

Proportional (P): 100

Integral (I): 0

Derivative (D): 10

Filter Cofficient (N): 100

A PID controller was utilized to control vibration levels during the process of driving piles into the ground. The parts of the controller—proportional, integral, and derivative—change the output according to the current error, previous errors, and how quickly the error is changing. The settings were adjusted with the help of MATLAB's PID Tuner App, aiming to reduce any overshoot and quicken the settling time while ensuring everything remains stable.

9.2 Actuator Used

The method of impact pile driving used an electric actuator to follow the commands given by the PID controller, which efficiently controlled the vibration levels. Electric actuators are recognized for their precision and reliability, providing smooth and steady movement, which makes them ideal for this use. By transforming electrical signals from the PID controller into physical motion, the actuator guaranteed that vibrations in the system were adjusted continuously based on immediate feedback. This active control enabled the actuator to keep the intended level of vibration while lessening overshoot and shortening the time needed to settle.

One significant benefit of electrical actuators is how quickly they respond, which is essential for making immediate changes during the pile driving procedure. Their excellent accuracy guarantees that vibrations stay at safe levels, protecting surrounding structures from harm and minimizing the impact on the environment. The transfer function of the actuator was established following studies from the literature on impact pile driving, particularly citing the research done by Klotz and Taylor in 2001. The resulting transfer function is shown below:

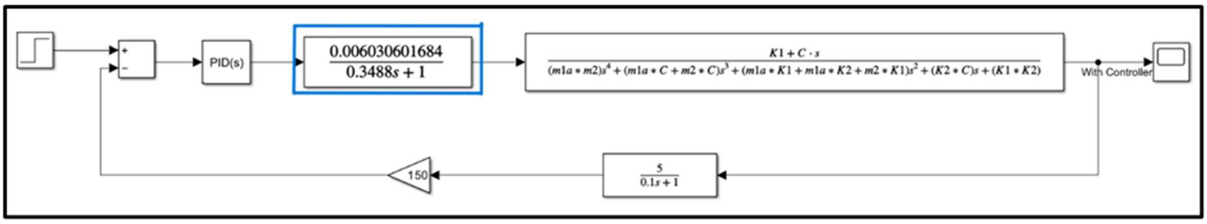


Figure 15 Electrical Actuator Transfer Function

$G_{\text{actuator}} = \frac{K}{\tau S + 1}$

$\varsigma = 0.7$

$Wn = 4.0960012$

$\tau = \frac{1}{\varsigma Wn} = 0.3487$

$Ts = \frac{4}{(0.7) \times (4.096001282)} = 1.395$

$\text{Value} = 2.957 \times 10^{-2}$

$\text{Sensitivity, } K = \frac{(2.957 \times 10^{-2})}{500 \times 9.80665} = 0.006030601 \times 10^{-3}$

$G_{\text{actuator}} = \frac{(0.006030601 \times 10^{-3})}{0.3487S + 1}$

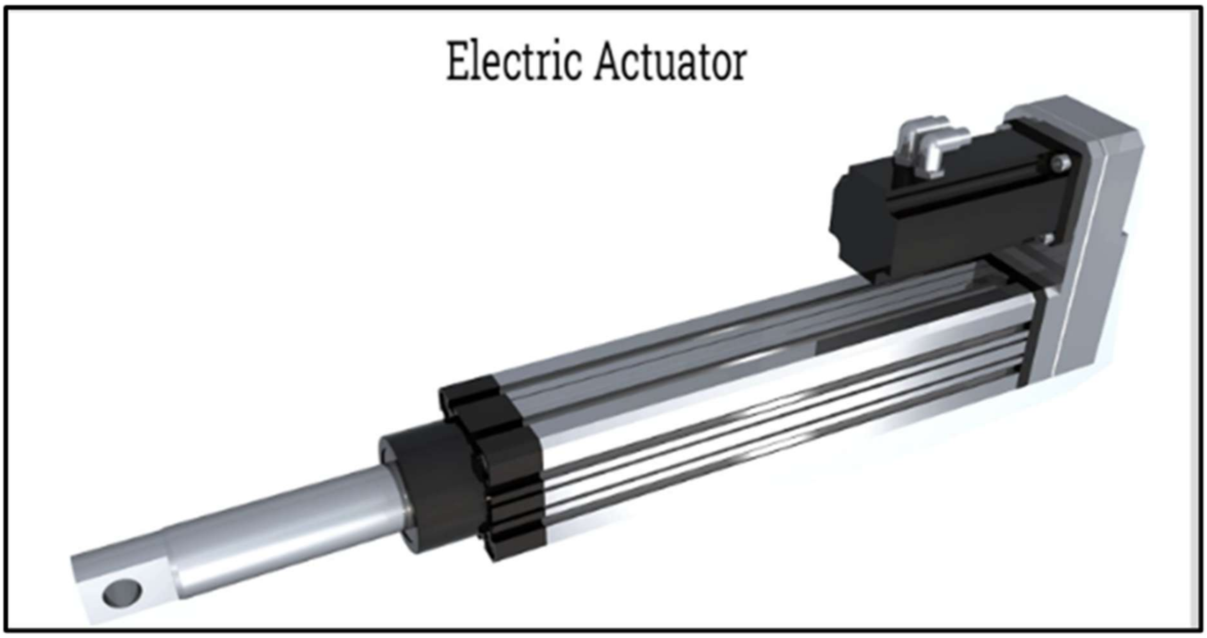


Figure 16 Electric Actuator

9.3 Signal Conversion and Feedback Loop Design

$G_{sensor} = \frac{K}{\tau S + 1}$

Strain gauge sensor was used:

$G_{actuator} = \frac{5}{0.1S + 1}$

The sensor data sheet was used to modify the values.

$F_{feedback} = K * v(t)$

$F_{feedback}$ Feedback Force (N)

K: Proportional Gain N/(m/s)

v(t): Velocity measured by the sensor (m/s).

The proportional gain, represented by K, is expressed in N/(m/s) and is essential for the feedback control of the system. A K value of 150 was chosen after evaluating the system's behavior and the needed feedback force. This particular figure was selected to make sure the correcting force is powerful enough to effectively address system errors while avoiding too much shaking or instability. As the force sensor gives output in the correct units, there is no need for extra conversion before sending it back into the system. The complete feedback force is then calculated using this formula:

$F_{\text{total feedback}} = F_{\text{force sensor}} + K * v(t)$

The error signal is created by subtracting the input force from this combined feedback force:

$F_{\text{error}} = F_{\text{input}} + F_{\text{total feedback}}$

9.4 Sensor Used

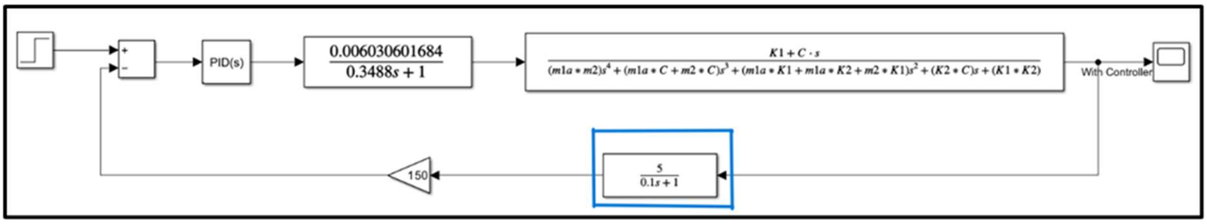


Figure 17 Sensor

In mechanical testing and measurement, it is important to understand how an item reacts to various forces. Strain indicates how much a material changes shape when a force is applied. It is calculated by comparing the change in length of a material to its original, unchanged length, as shown in Figure 1. Strain can be either positive, known as tensile strain which happens when something stretches, or negative, referred to as compressive strain when something gets shorter. When a material is pressed in one direction, it usually expands in the two other directions that are perpendicular to the force applied; this is referred to as the Poisson effect (Measuring Strain with Strain Gages, 2025). The measurement related to this effect is called Poisson's ratio (v), which is defined as the negative ratio of the strain measured sideways compared to the strain measured along the length. Although strain does not have specific units, it is sometimes represented in units like in. /in. or mm/mm. Since the amount of strain measured is typically very small, it is frequently shown as macrostrain (uε), which is equal to ε multiplied by 10^-6. The transfer function $\frac{5}{0.1S + 1}$, the response of the strain gauge or the related signal conditioning circuit plays a crucial role in providing reliable and precise feedback for the functioning of the closed loop system.

9.5 Results

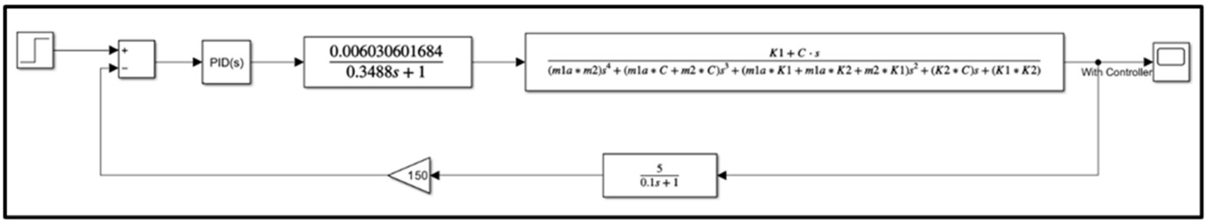


Figure 18 Controlled Block Diagram

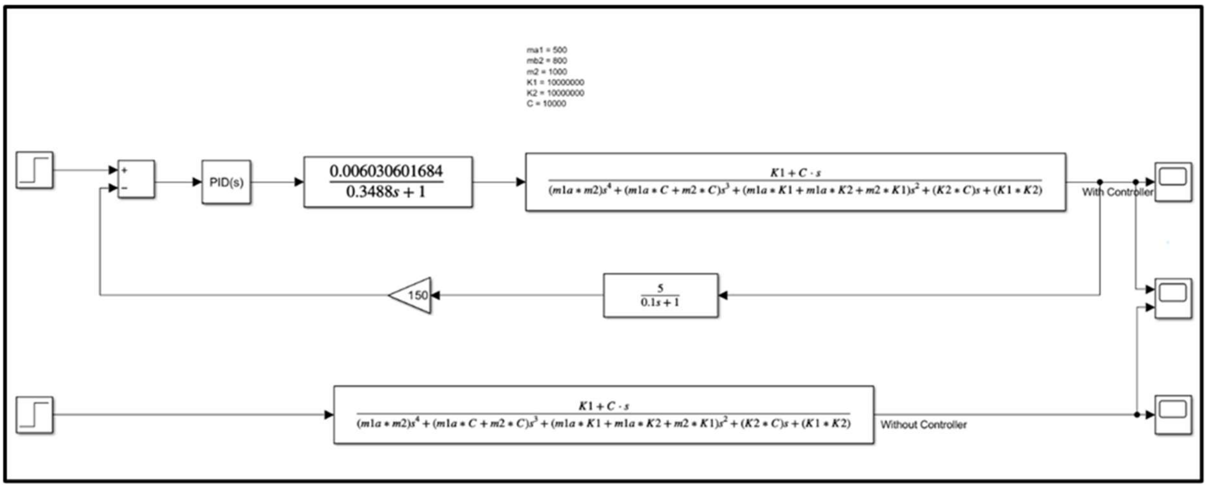


Figure 19 Block Diagram Comparison

The error signal is calculated using the sum block, and it represents the distinction between the input signal and the output signal.

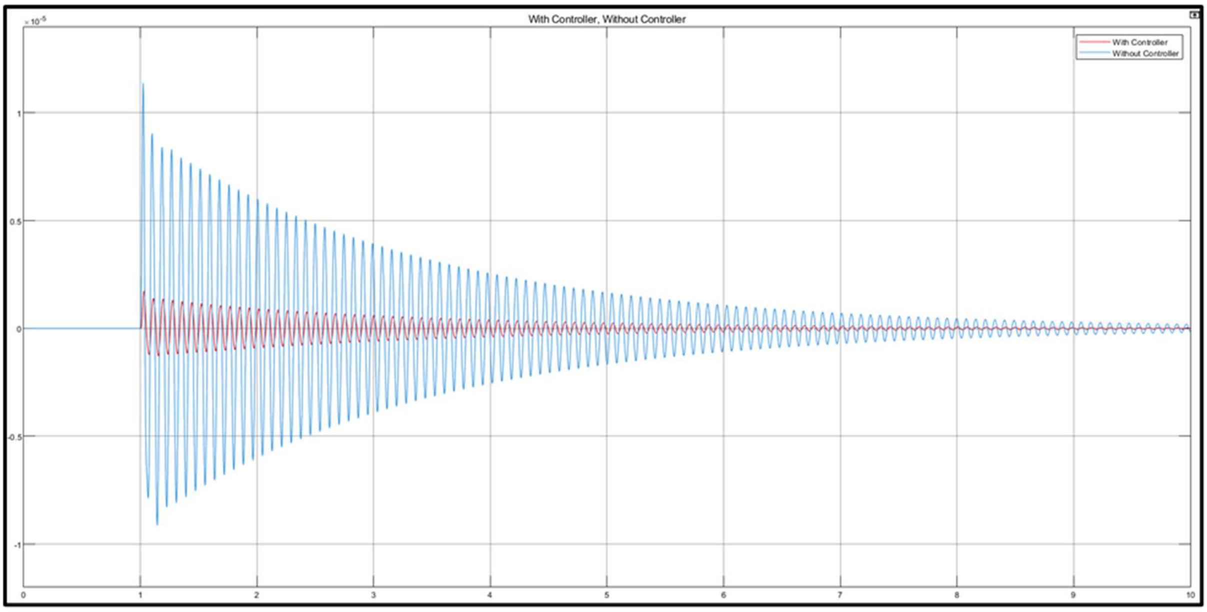


Figure 20 Output Results

The graph shows a comparison of how the system vibrates with and without the PID controller. The response with the controller is shown by the red line, and the blue line indicates the response when the controller is absent.

9.6 Discussion

In this research, the influence of the pile vibration control system was examined with and without a PID controller to evaluate how well it reduces strong vibrations. The main goal was to lower the overshoot and time it takes for vibrations to stabilize using a closed loop control mechanism.

Without Controller

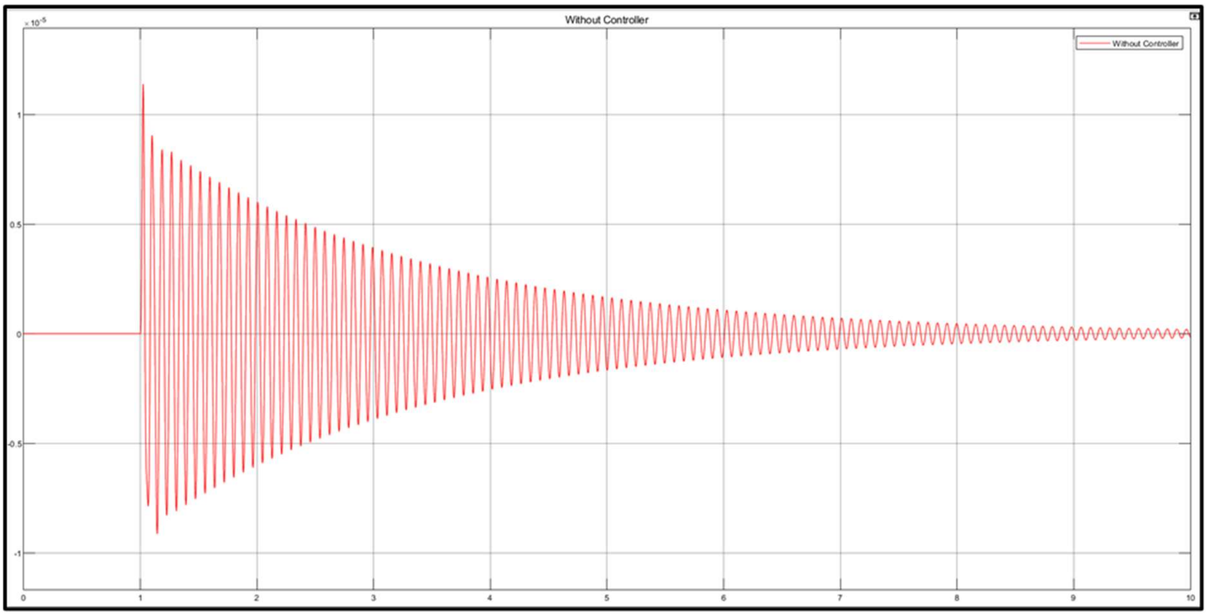


Figure 21 Without Controller

When the system functions without a controller, the vibrations show wild movements, resulting in a longer time to settle and too much overshoot. The system depends only on the natural dampening features of the structure, which often do not work well enough to control the strength and length of the vibrations effectively. As a result, the vibrations last for a long time, which could lead to harm to the structure and problems in pile driving tasks. The lack of feedback systems causes a slow or poor reaction to outside disruptions, making the system unstable and hard to predict.

With Controller

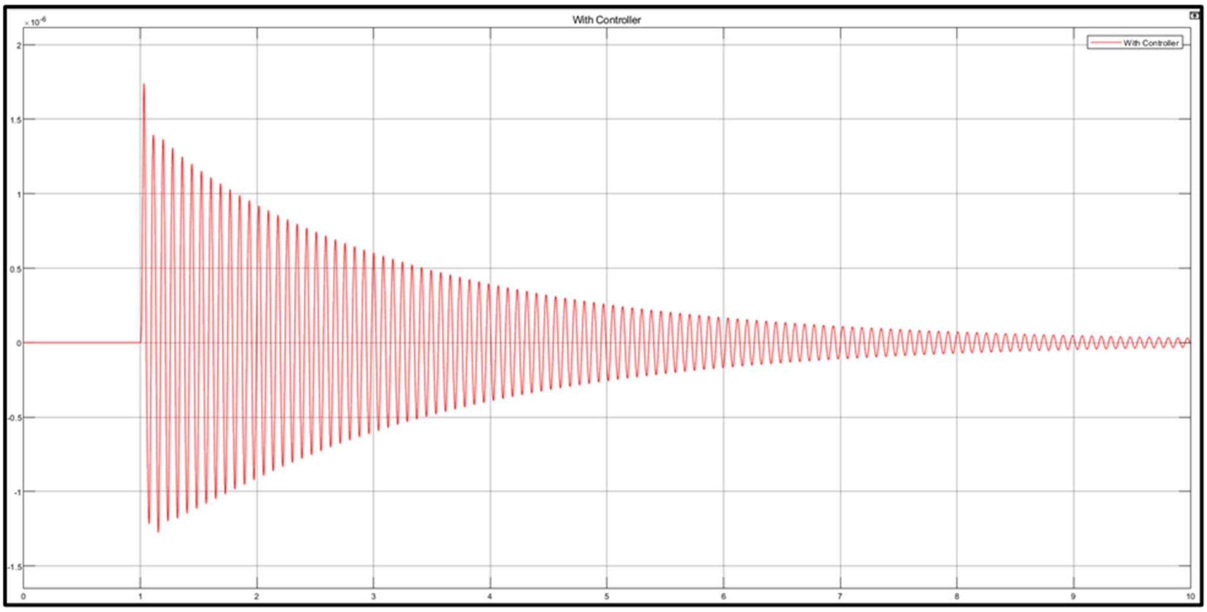


Figure 22 With Controller

On the other hand, when the PID controller is used, the system shows a much better performance. The proportional part of the controller responds to the current difference between the target and actual vibration levels, leading to quick adjustments. The integral part considers past errors, which helps to minimize ongoing differences and makes sure the vibrations stabilize quickly. At the same time, the derivative part looks ahead at possible future errors by examining how fast changes are happening, which helps avoid too much swinging and keeps overshooting to a minimum.

The findings show that using the PID controller lowers the maximum overshoot and greatly decreases the time it takes to settle. This enhancement is vital for keeping the impact pile system stable, providing exact control over vibrations, and reducing possible harm to nearby buildings. Moreover, the system becomes more resilient, since the feedback process enables it to adjust to different outside forces.

9.7 Limitations

Even though the PID controller works well, there are some drawbacks to keep in mind. A major drawback is how complicated it can be to adjust the PID settings. Finding the best values for the proportional, integral, and derivative gains often involves a lot of trial and improvement or makes use of complex tuning techniques, which might not always lead to ideal results. Furthermore, the PID controller operates on the idea of a straightforward system response, but in actual pile driving situations, there are often irregularities and outside factors that can impact precision.

One more drawback is how easily the system reacts to changes in parameters. Variations in soil quality, the material of the piles, or outside forces can affect how the system works, necessitating regular adjustments to the controller. Additionally, using a PID controller brings extra equipment and computing needs, which might raise expenses and complicate matters.

9.8 Further Improvement

To boost how well the vibration control system works, multiple upgrades could be looked at. One possible upgrade is to use an adaptive PID controller that can change its settings automatically as the system conditions evolve. This would remove the requirement for manual adjustments and make the controller more efficient in managing nonlinear behaviours.

An alternative method is to use machine learning methods to enhance how well the controller works. By looking at previous vibration information, a system that uses machine learning could forecast the best control actions and adjust the PID settings in real time.

Also, adding a more sophisticated control method, like fuzzy logic or model predictive control (MPC), might improve vibration reduction even more. These methods can manage nonlinearities better than a standard PID controller and offer improved flexibility to changing environmental factors.

9.9 Conclusion

The use of a PID controlled vibration system in impact pile driving has shown notable advancements in both steadiness and accuracy. By using an electric actuator, this system transformed control signals into mechanical movement effectively, allowing for immediate changes to keep vibration at ideal levels. The PID controller successfully lowered overshoot and the time taken to stabilize, improving the overall dependability of the procedure while reducing disruptions to structures and the environment.

Even though the system works well, it does have some drawbacks, like how difficult it is to adjust the PID settings and its responsiveness to outside influences such as differences in soil and inconsistencies in materials. To overcome these issues, future advancements might involve using adaptive control techniques, integrating machine learning, or applying sophisticated control approaches such as fuzzy logic and model predictive control. These upgrades would lead to better flexibility and improved performance, making the vibration control system more reliable and effective for impact pile driving uses.

10. ABDULRAHMAN KAREEM ALMANSY

10.1 Introduction

This document examines the role of a PID controller in managing an impact pile driver, aiming to minimize system vibrations. Reducing these vibrations is essential since they can negatively impact nearby structures and wildlife.

Within this report, we will analyze the system's single-degree-of-freedom (SDOF) model, followed by a discussion on the selected controller and the necessary calculations to determine optimal parameters for achieving the desired system response.

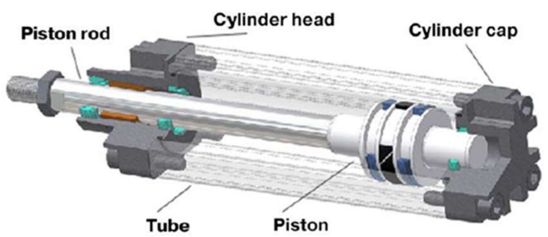
Subsequently, the report will present a comparative analysis of system performance before and after implementing the PID controller.

10.2 Selected Actuator

An impact pile driver functions by elevating a heavy ram and subsequently allowing it to free-fall onto a pile, thereby driving it into the ground. The actuator in this system is responsible for lifting the ram to a designated height before releasing it. The actuator's transfer function defines the correlation between its input (such as hydraulic pressure) and its output (such as ram displacement or velocity).

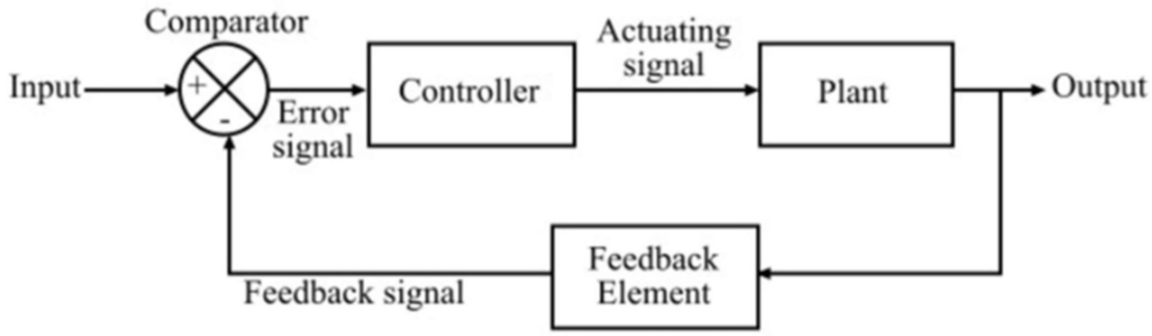
The transfer function of a pneumatic cylinder actuator is derived by examining its dynamic behavior, which links input pressure to the resultant piston position or velocity. A typical pneumatic actuator consists of a piston that moves within a cylinder using compressed air as an energy source. The forces acting on the piston include air pressure and any external loads.

Actuator chosen:



10.2.1 Actuator Specifications

- **Cylinder Diameter (D):** 75 mm
- **Piston Rod Diameter (d):** 30 mm
- **Stroke Length:** 250 mm
- **Maximum Rated Pressure (P_max):** 250 bar
- **Hydraulic Fluid Bulk Modulus (B):** 1.5 GPA
- **Pump Flow Rate (Q_max):** 25 L/min
- **Load Mass (m):** 1200 kg



A **closed-loop control system** continuously monitors its output and adjusts the input to achieve the desired performance. It consists of:

1. **Comparator** – Compares input (desired value) with feedback (actual output) to generate an error signal.
2. **Controller** – Processes the error and sends an actuating signal to correct the system.
3. **Plant** – The system being controlled, which produces the output.
4. **Feedback Element** – Measures output and sends feedback to the comparator for adjustment.

This system ensures stability and accuracy, commonly used in automation, robotics, and industrial control.

10.3 PID Controller

To regulate the hydraulic actuator's response, a PID controller is employed. A PID controller modifies system input to maintain a desired level through three distinct control actions:

- **Proportional (P):** Modifies the control output based on current error.
- **Integral (I):** Accounts for past errors by accumulating error over time, thereby eliminating residual steady-state error.
- **Derivative (D):** Evaluates the rate of change of error to predict future deviations and improve response.

10.3.1 System Configuration with PID Controller

The system is designed with the PID controller placed before the hydraulic actuator, ensuring accurate response control.

10.3.2 Effects of PID Parameters

- **Increasing Kp:** Enhances response speed but may induce overshoot and instability.
- **Increasing Ki:** Reduces steady-state error but can cause oscillations if excessive.
- **Increasing Kd:** Enhances system stability and minimizes overshoot but may introduce noise sensitivity.

Several PID configurations can be proposed and tested based on their functional principles and expected performance.

10.4 PID Tuning

10.4.1 Ideal Case

A considerable amount of trial and error was undertaken to determine optimal PID values. The observations include:

- **P = 55,000:** Limits overshoot and instability while reducing response speed.
- **I = 1,200:** Minimizes steady-state error but requires more time to eliminate it fully.
- **D = 6,000:** Enhances damping, reducing oscillations and significant overshoot.

10.4.2 Trial and Error Adjustments

10.4.3 Case 1: Balanced PID Settings

- **P = 210,000**: Increases system responsiveness but may lead to overshoot if not counterbalanced.
- **I = 12,000**: Accumulates error over time, reducing steady-state error and ensuring target attainment.
- **D = 1,200**: Dampens oscillations and overshoot caused by the proportional term.

These settings create a stable controller, achieving improved response time, reduced overshoot, and enhanced stability.

10.4.4 Case 2: Elevated P and I, No D

- **P = 320,000**
- **I = 55,000**
- **D = 0**

Observations

- **High P:** Enhanced responsiveness but led to overshoot and instability.
- **High I:** Eliminated steady-state error but introduced oscillations due to integral windup.
- **Zero D:** Lack of damping extended oscillations and overshoot.

10.5 Calculations

10.5.1 Calculating Static Gain (K)

The static gain (K) is computed using:

$$K = A/M$$

where:

- **A** is the effective piston area.
- **m** is the load mass.

Given that D = 75 mm and d = 30 mm,

$$A = \pi/4(D^2 - d^2)$$

Substituting values,

$$A = \pi/4(75^2 - 30^2)$$

$$A = \pi/4(5625 - 900)$$

$$A = \pi/4(4725)$$

$$A = 3713.599mm^2$$

Converting to square meters,

$$A = 3713.599 \times 10^{(-3)}m^2$$

Now, calculating K,

$$K = \left(3.71359 \times 10^{(-3)}\right)/1200$$

$$K = 3.09 \times 10^{(-6)}$$

10.5.2 Calculating Time Constant (τ)

The time constant (τ) is given by:

where:

- **B** is the hydraulic fluid's bulk modulus.
- **V** is the cylinder volume.
- **Q** is the flow rate.

Calculating volume,

$$V = A \times L$$

$$V = \left(3.71539 \times 10^{(-3)}\right) \times \left(250 \times 10^{(-3)}\right)$$

$$V = 9.28 \times 10^{(-4)} m^3$$

Now calculating τ,

$$\tau = \left(\left(1.5 \times 10^{(-9)}\right) \times \left(9.28 \times 10^{(-4)}\right)\right) / \left(\left(25 \times 10^{(-3)}\right)\right)$$

$$\tau = 55.68s$$

This results in the final transfer function.

10.6 Conclusion

The integration of a PID controller with a hydraulic actuator in an impact pile driver system proves to be an effective solution for reducing vibrations, enhancing stability, and improving overall efficiency. Through meticulous PID tuning, an optimal balance is achieved between responsiveness and damping, ensuring reliable and environmentally compliant operations. Future advancements in control methodologies can further refine system performance and sustainability.

11. Abdelrahman Mohamed Shawky:

11.1 Introduction:

The impact of construction-induced vibrations is a critical concern in civil and structural engineering. Among various sources, impact piling generates significant vibrations that can affect nearby buildings, sensitive equipment, and underground utilities. These vibrations propagate in different forms, including spherical waves, cylindrical waves, and surface waves, making it essential to develop an effective vibration control strategy (Massarsch & Fellenius, 2012). If left unmitigated, such vibrations can lead to structural damage, interfere with precision instruments, and cause discomfort to occupants of nearby buildings.

Vibration control systems use sensors and controllers to detect and reduce oscillations to overcome these difficulties. To precisely measure vibrations and give the control system real-time input, an appropriate sensor—such as an accelerometer or geophone—is needed. Similarly, to maximise system stability and minimise undesired oscillations, an effective controller—like a proportional-integral-derivative (PID) controller—must be created (Chen & Agrawal, 2020). This study suggests possible enhancements to improve performance by comparing the system response with and without a controller. The results aid in the creation of reliable vibration control techniques that may be used in impact piling operations in the real world.

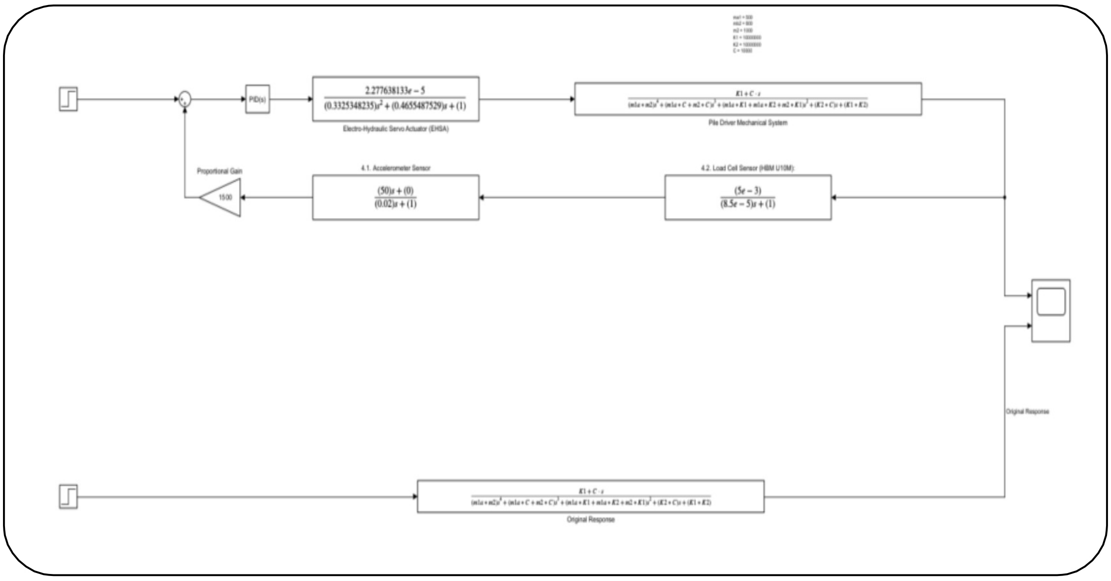


Figure 23 The Pile Driving System

11.2 Controller Used:

Due to its capacity to improve system stability and lessen oscillations, a proportional-integral-derivative (PID) controller is frequently utilised in vibration control systems. By altering its three parts—Proportional (P), Integral (I), and Derivative (D)—the PID controller enhances system response. By implementing a correction measure proportionate to the deviation, the proportional component responds to the current error. Long-term accuracy is ensured by the integral component, which gradually eliminates steady-state error by accumulating past errors. By examining the rate of change, the derivative component enhances stability and lessens overshoot while forecasting future errors.

A PID controller controls the reaction of the system in impact pile vibration control by reducing the number of vibrations that are communicated to adjacent structures. By keeping vibrations within acceptable bounds, the controller guards against harm to delicate equipment and structures. The system can attain the ideal balance between stability and responsiveness by adjusting the controller parameters. For this, the MATLAB PID Tuner is frequently utilised, which enables accurate modifications to enhance system performance. As seen in Figure 2, the structure of a PID controller consists of three main elements working together to maintain system stability by continuously adjusting the control signal based on the error input (Åström & Hägglund, 2006).

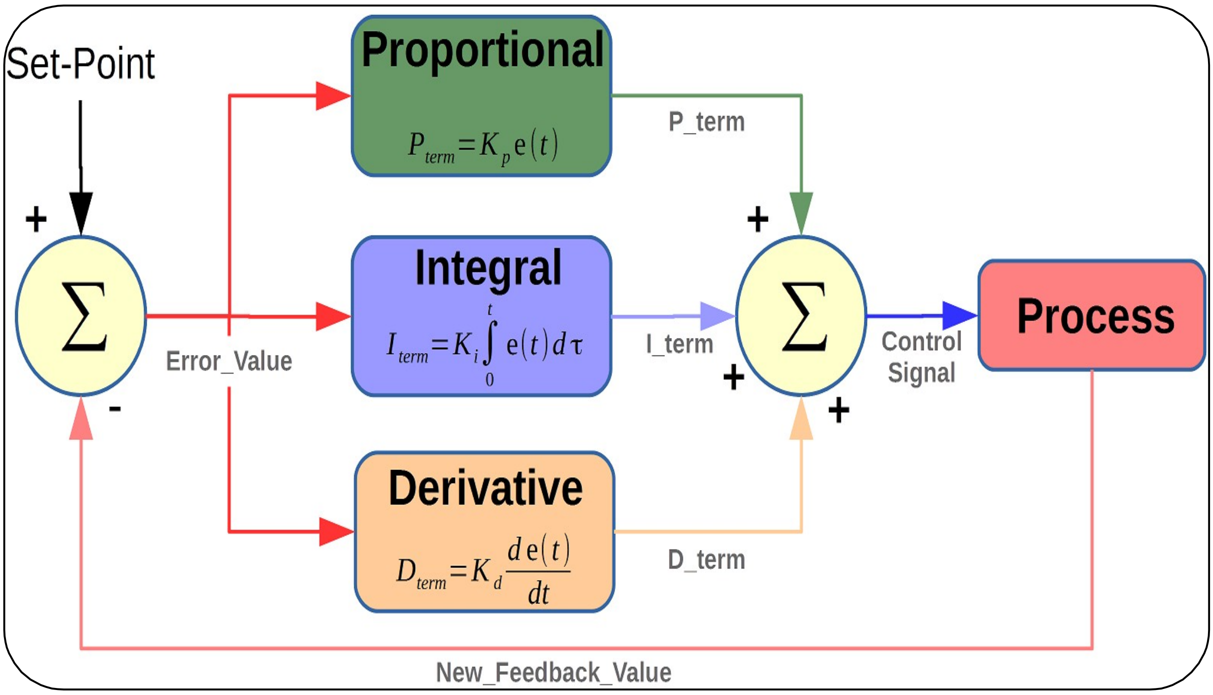


Figure 24 PID Controller Structure

- ***Controller Design:***

The Root Locus plot helps with stability and transient response studies by showing how a system's poles change when the gain (***K***) changes. Branches extend from poles **(×)** towards zeros (**o**) when (***K***) increases, affecting the behaviour of the system. Oscillations may result from some moving along the real axis and others entering the complex plane.System stability is determined by the poles' position; stability is guaranteed when the poles remain in the left half-plane, whereas instability results when they move to the right. Long-term oscillations are caused by poles on the imaginary axis, which signify minimal stability. Stability and performance are impacted by altering gains in controller design, particularly PID. Poles shift along the root locus when K rises, which may strengthen or reduce stability. Compensation strategies like pole location or lead-lag controllers might be needed if instability develops. To improve performance measures such as damping ratio, settling time, and overshoot, root locus analysis helps choose the best improvements to guarantee stability.

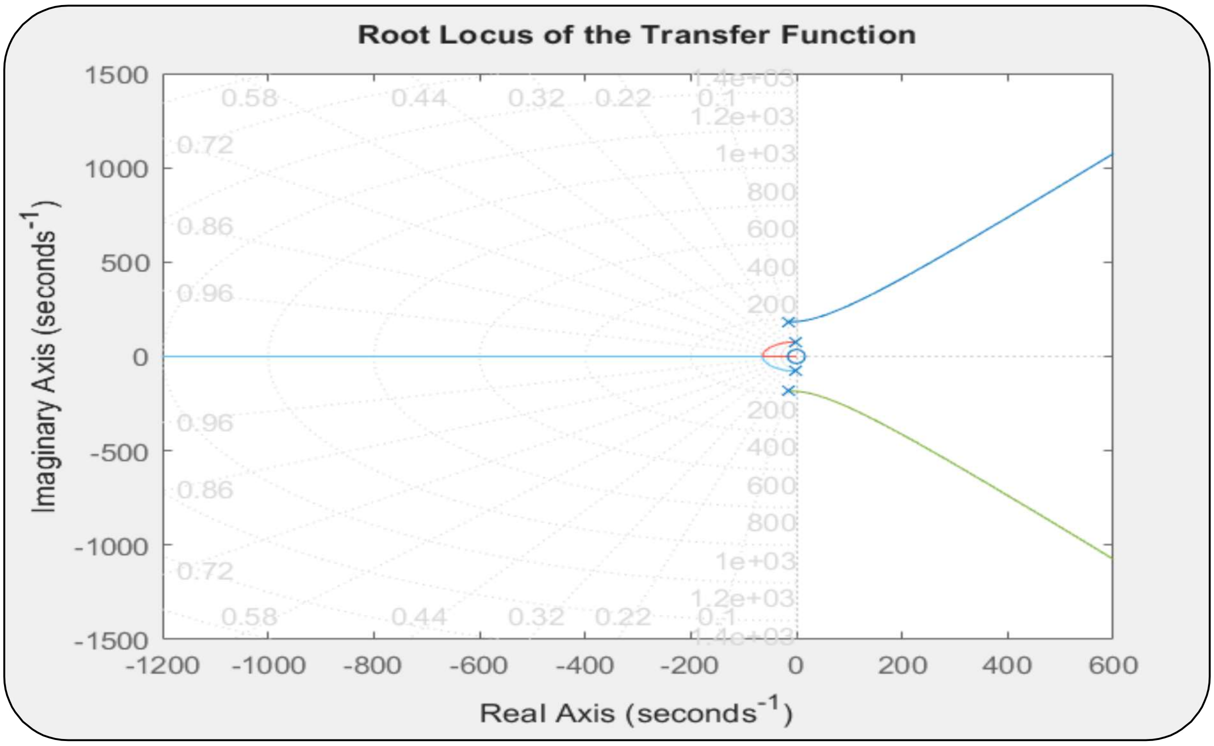


Figure 25 Root Locus of the Transfer Function

To obtain optimal system performance, the design of a PID controller for impact pile vibration control entails choosing suitable proportional ($\boldsymbol{Kp}$), integral ($\boldsymbol{Ki}$), and derivative ($\boldsymbol{Kd}$) gains. Reducing excessive oscillations and settling time while maintaining system stability is the main goal. In the Laplace domain, the controller transfer function is provided by:

$$\boldsymbol{C(s) = K_p + \frac{K_i}{s} + K_d s}$$

where $\boldsymbol{Ki}$ removes steady-state error, $\boldsymbol{Kd}$ enhances damping by anticipating future errors, and $\boldsymbol{Kp}$ regulates the system's responsiveness. To avoid instability or severe overrun, these factors must be properly balanced.

To design the PID controller, MATLAB's PID Tuner can be used for auto-tuning based on system dynamics. The process starts by obtaining the transfer function of the system and analysing its frequency response. By adjusting $\boldsymbol{Kp}$, $\boldsymbol{Ki}$, and $\boldsymbol{Kd}$, the controller can be optimized for fast response time, minimal overshoot, and improved damping. A trial-and-error approach or Ziegler-Nichols tuning method can also be applied to fine-tune the parameters. Research has shown that an effectively tuned PID controller significantly enhances vibration suppression in structural systems by dynamically adjusting forces to counteract disturbances Ogata, 2010).

The PID controller parameters were carefully tuned to achieve optimal performance In the system. The selection of proportional ($\boldsymbol{Kp}$), integral ($\boldsymbol{Ki}$), and derivative ($\boldsymbol{Kd}$) gains ensures fast response, minimal steady-state error, and system stability. The chosen values are:

- To respond quickly to the system mistake, the proportional gain ($\boldsymbol{Kp}$) was set at **16200**. This guarantees prompt correction of deviations from the intended setpoint. Although excessive levels might result in oscillations and overshooting, a high $\boldsymbol{Kp}$ enhances the system's responsiveness. To balance stability and speed, this value was carefully selected.
- The integral gain ($\boldsymbol{Ki}$) was selected as $\mathbf{0.35}$ to effectively eliminate steady-state error by addressing past accumulated errors. This value was kept moderate to prevent excessive integration, which could lead to instability or slower system response.
- To forecast future errors depending on the pace at which the system's error changes, the derivative gain ($\boldsymbol{Kd}$) was set at **39000**. By reducing oscillations and enhancing overall

stability, a high ***Kd*** helps avoid excessive overshoot. However, very high values may increase sensitivity to noise.

- A derivative filter coefficient ***(N)*** of **8500** was used to reduce the impact of high-frequency noise. This results in a steady control action by guaranteeing smooth discrimination and avoiding measurement noise amplification.

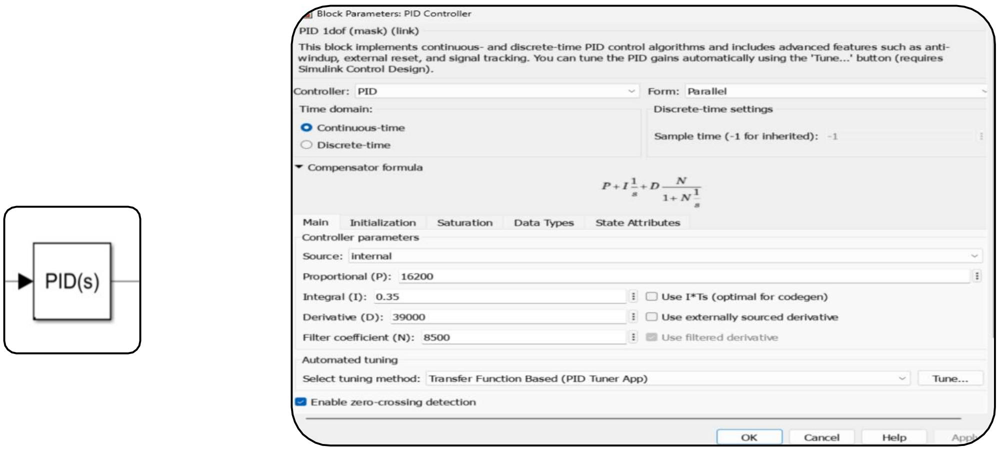


Figure 26 PID Controller Parameters

Automated tuning was done using the PID Tuner App, which prioritised safety while optimising the controller parameters for stability and performance. To improve simulation accuracy, zero-crossing detection was turned on, guaranteeing accurate identification of abrupt changes and discontinuities for more trustworthy outcomes.

11.3 Actuator Used:

The Electro-Hydraulic Servo Actuator (EHSA) is a high-performance actuator that precisely regulates force, velocity, and position by combining hydraulic power with electronic control. EHSAs provide precise and seamless motion control by modulating hydraulic fluid flow using servo valves, in contrast to conventional hydraulic actuators. These actuators are perfect for Impact Pile Vibration Systems since they are frequently utilised in applications that call for high force and dynamic response. EHSAs' capacity to provide steady, regulated oscillatory motion guarantees efficient energy transfer to the pile, increasing penetration efficiency and lowering structural stress.

A key reason for implementing an EHSA in the Impact Pile Vibration System is its high power-to-weight ratio and ability to generate large forces with minimal delay. Impact pile driving requires the application of cyclic force at different frequencies, so an actuator with a quick response time and accurate damping control is essential. EHSAs excel in these aspects due to their ability to regulate hydraulic pressure and flow rate dynamically, allowing for adjustable vibration frequencies and damping characteristics. This adaptability ensures efficient energy transfer to the pile, minimizing energy losses and improving overall system performance.

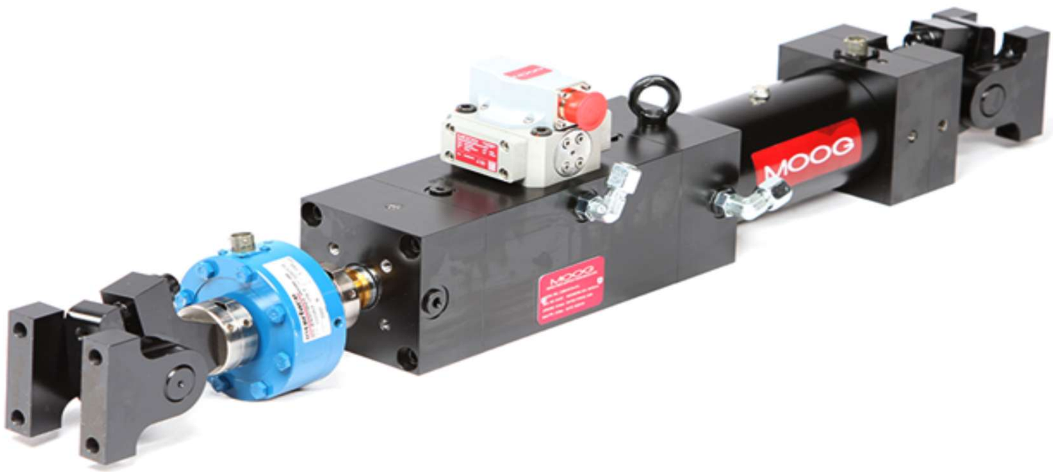


Figure 27 Electro-Hydraulic Servo Actuator

An electro-hydraulic servo actuator's transfer function is modelled by a second-order system, which can be expressed mathematically as follows:

$$G_{Actuator}(s) = \frac{K}{\tau s^2 + 2\zeta\tau s + 1}$$

- K is the system gain, which depends on the actuator's mechanical and hydraulic properties.
- τ is the time constant, representing the actuator's response speed.
- ζ is the damping ratio, which determines system stability and overshoot behaviour.

Impact pile vibration benefits greatly from this second-order dynamic behaviour since it maximises drive efficiency by enabling the actuator to resonate at specified frequencies.

Engineers can adjust τ and ζ to maximise the actuator's performance in accordance with the pile material, soil conditions, and desired vibration intensity. Furthermore, the servo system's closed-loop design offers real-time feedback control, guaranteeing that the actuator adjusts for disruptions and changes in driving circumstances.

➢ ***Actuator Design:***

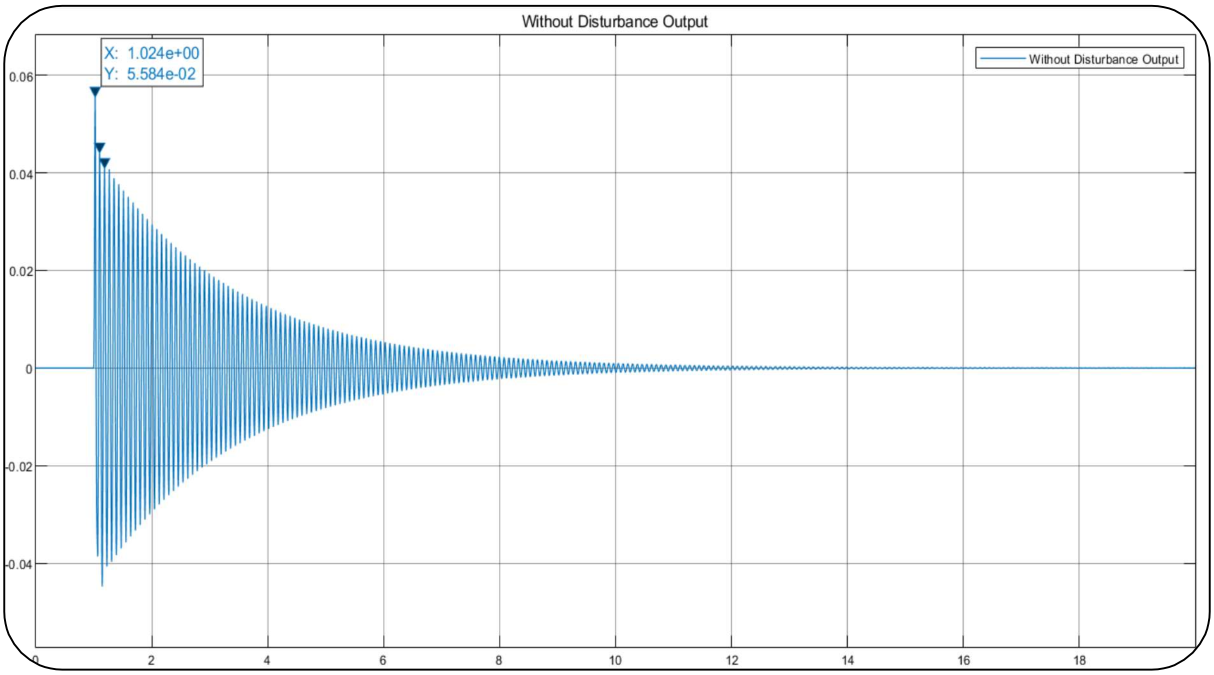


Figure 28 Monitoring Point (MP) and Test Point (TP) locations for Parameters Calculations

$$K = \frac{\text{Output}}{\text{Input}} = \frac{\text{Velocity}}{\text{Force}} = \frac{5.584 \, * \, 10^{-2}}{\text{m1a} \, * \, 9.80665 \, * \, 0.5} = \mathbf{2.277638133 * 10^{-5}}$$

- **M1a: 500kg:**

$$\boldsymbol{M_p = 5.584 \, * \, 10^{-2} \, m/sec}$$

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

$$5.584 \, * \, 10^{-2} = \mathrm{e}^{-\left(\frac{\zeta}{\sqrt{1-\zeta^2}}\right)\pi}$$

$$\boldsymbol{\zeta = 0.7}$$

$$\boldsymbol{t_p = 1.024}$$

$$t_p = \frac{\pi}{\omega_d}$$

$$\omega_d = \frac{\pi}{t_p} = \mathbf{3.067961576\ rad/sec}$$

$$\omega_d = \omega_n\sqrt{1-\zeta^2}$$

$$\omega_n = \frac{\omega_d}{\sqrt{1-\zeta^2}}$$

$$\omega_n = \frac{3.067961576}{\sqrt{1-0.7^2}} = \mathbf{4.296005493}$$

$$\therefore \tau = \frac{1}{\zeta\omega_n} = \frac{1}{0.7 * 4.296005493} = \mathbf{0.3325348235\ sec}$$

$$\boxed{\rightarrow \mathbf{G_{Actuator}(s)} = \frac{\mathbf{2.277638133*10^{-5}}}{\mathbf{0.3325348235\ s^2+0.465548753\ s+1}}}$$

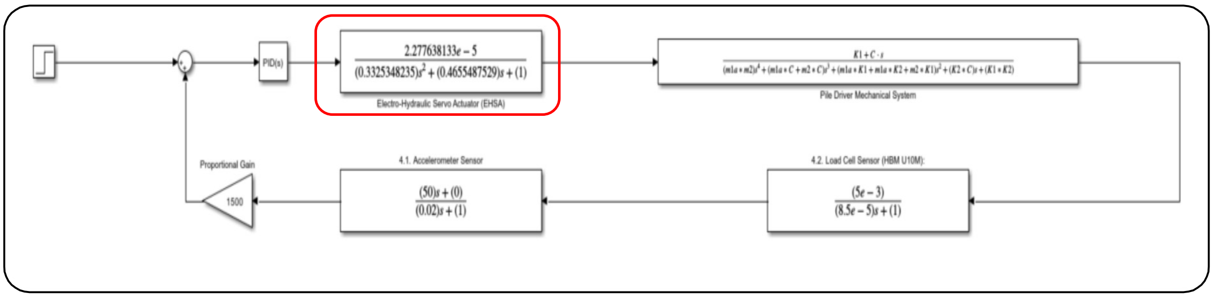


Figure 29 Electro-Hydraulic Servo Actuator (EHSA) Transfer Function

11.4 Sensors Used:

11.4.1 Accelerometer Sensor:

$$H_{Sensor} = \frac{Ks}{\tau s + 1}$$

The ADXL1002 is a high-performance single-axis accelerometer designed to measure high-frequency vibrations and dynamic forces. It operates on microelectromechanical systems (MEMS) technology, which enables it to detect acceleration changes with high sensitivity. This sensor is well-suited for impact pile vibration systems, where monitoring acceleration levels is essential for evaluating pile displacement and ground response. The ADXL1002 provides precise real-time feedback on vibrational characteristics, ensuring effective pile driving control.

$$H_{Sensor} = \frac{\mathbf{50s}}{\mathbf{0.02s + 1}}$$

Where:

- $K = 50\ mV/g$ ***(Sensitivity)***
- $\tau = 0.02\ sec$ ***(Time Constant)***

According to the sensor datasheet (Analog Devices, 2020).

11.4.2 Load Cell Sensor (HBM U10M):

$$H_{Sensor} = \frac{\boldsymbol{K}}{\boldsymbol{\tau s + 1}}$$

The HBM U10M is a high-precision load cell sensor developed for detecting static and dynamic forces with great accuracy. It is commonly used in pile driving applications to measure the force exerted on the pile during impact. The exact force measurement guarantees that the pile is driven with the correct load, preserving target penetration depth and minimizing structural damage. The HBM U10M delivers dependable force monitoring, helping to enhanced control and stability in the vibration system.

$$H_{Sensor} = \frac{\mathbf{5 * 10^{-3}}}{\mathbf{8.5 * 10^{-5} s + 1}}$$

- $K = 5 * 10^{-3}$ ***V/N (Sensitivity)***
- $\tau = 8.5 * 10^{-5}$ ***sec (Time Constant)***

According to the sensor datasheet (HBM, 2019).

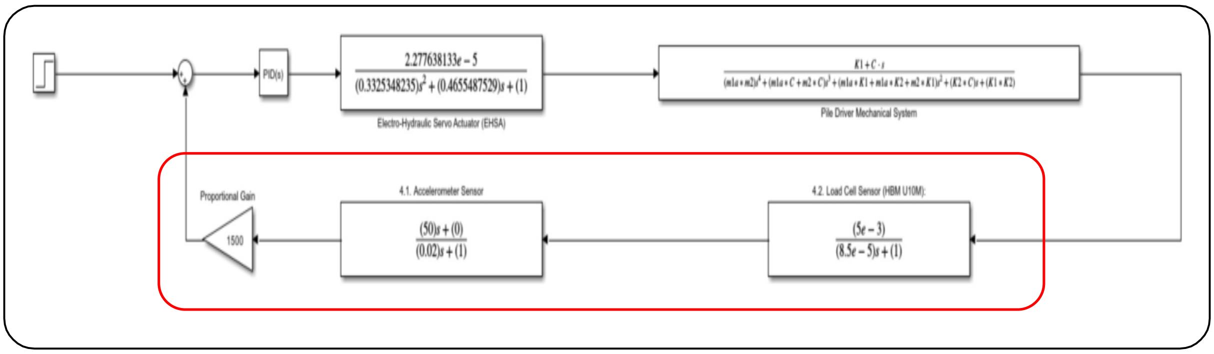


Figure 30 Sensors integrated into the system

While both sensors are essential for monitoring the pile driving process, they do not have a significant impact on the output response of the system for the following reasons:

- ***Acceleration Monitoring (ADXL 1002):***

The pile's dynamic reactions and vibrations during impact are measured using the ADXL1002 accelerometer. Although the system's response is not directly controlled by these measures, they are useful for evaluating pile displacement and ground reaction. Rather of actively changing the movement of the pile, they serve as performance indicators, assisting engineers in analysing and optimising the vibration impacts.

- ***Force Measurement (HBM U10M):***

To guarantee that the proper impact force is applied to the pile, the HBM U10M load cell gives vital information on the applied force. However, since the force functions as an input to the system rather than directly altering its dynamic behaviour, it has little effect on the output response of the system. This sensor's main purpose is to offer precise force monitoring, which guarantees appropriate pile penetration while avoiding undue structural stress.

11.4.3 Feedback Loop Integration & Signal Conversion:

Two essential sensors—the accelerometer sensor and the load cell sensor (HBM U10M)—are employed in the system's feedback loop to track and regulate its behaviour. While the load cell sensor directly records the applied force, the accelerometer sensor monitors the system's acceleration. Nonetheless, force is the input, and velocity is the output when defining the system's transfer function (TF). Since acceleration data is provided by the accelerometer, compatibility with the force-based feedback mechanism of the system requires a conversion.

The measured acceleration (a) must first be integrated into the velocity (v) to include the accelerometer's values into the feedback loop. The velocity signal is then further transformed into an analogous force signal by applying a proportional gain (K), specified as follows:

$$\boldsymbol{F_{Feedback}} = \boldsymbol{K} * \boldsymbol{v(t)}$$

- The generated Feedback force (N) is given as $\boldsymbol{F_{Feedback}}$.
- $\boldsymbol{K}$ is the proportional gain $(\boldsymbol{N/(m/s)})$.

- The velocity obtained from the integrated acceleration signal $(\boldsymbol{m/s})$ is illustrated as $\boldsymbol{v(t)}$.

Based on system dynamics, a gain factor of $\boldsymbol{K = 1500}$ is selected to guarantee efficient control without adding undue oscillations. The values from the Load Cell Sensor (HBM U10M) are transmitted back into the system straight away, without any additional conversion, because it already delivers force measurements in the appropriate units. The force-equivalent of the velocity signal is then added to the force sensor's output to determine the overall feedback force:

$$\boldsymbol{F_{Total\ Feedback} = F_{Force\ Sensor} + K * v(t)}$$

The error signal, representing the deviation from the expected response, is then computed as:

$$\boldsymbol{F_{Error} = F_{Input} - F_{Total\ Feedback}}$$

A PID controller receives this error signal and uses it to dynamically modify the system's input force to maintain peak performance. By keeping the system operating in stable conditions and reducing excessive vibrations, this closed-loop technique guards against harm to nearby structures, machinery, and people.

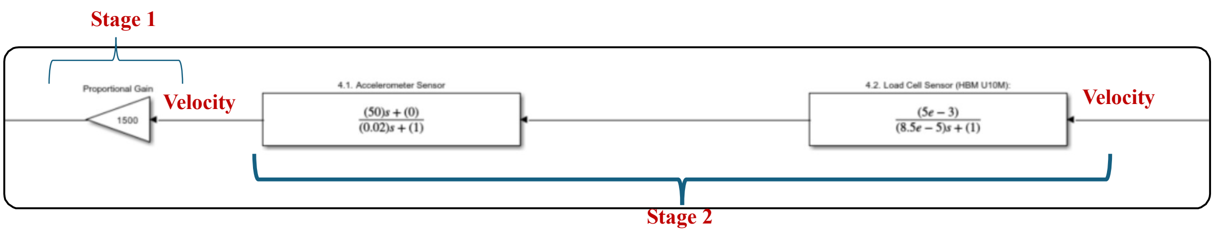


Figure 31 Feedback Loop

The feedback loop operates in two stages:

- **1st Stage**: Velocity is calculated by integrating acceleration data collected by the accelerometer sensor.
- **2nd Stage**: The velocity is converted into force using the proportional gain, then summed with the Load Cell Sensor's force measurement before being reintroduced into the system.

The system enables precise vibration control, improved stability, and adherence to performance and safety criteria by putting this sensor-based feedback technique into practice.

11.5 Results:

The performance of the system was assessed both with and without the PID controller. This comparison showed how well the PID worked to achieve the intended performance goals by clearly evaluating its effects on accuracy, responsiveness, and stability.

11.5.1 Without Controller:

The block diagram illustrates how the system's response to input changes was slow and characterised by large oscillations in the absence of the PID controller. The diagram's transfer function block depicts the system's inherent dynamics, which led to a significant steady-state inaccuracy and made it challenging to get the intended result. Furthermore, the denominator's characteristic equation revealed that the system's high-speed reaction jeopardised stability and safety, raising the possibility of unpredictable behaviour when in use.

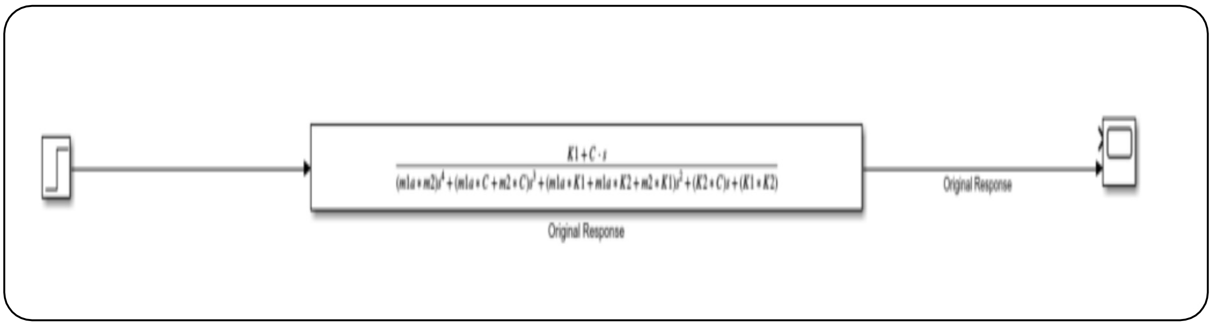


Figure 32 Pile Driving System without Controller

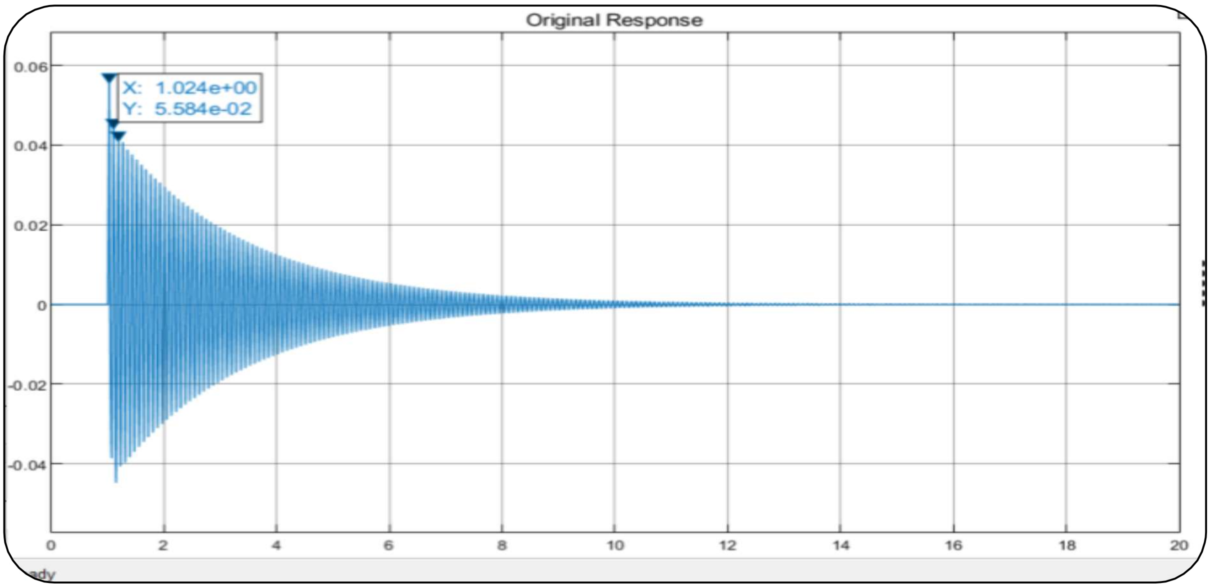


Figure 33 Output Response Before applying controller

11.5.2 With Controller:

The block diagram shows how the system's performance was much improved with the use of the PID controller. To ensure a steadier response with fewer oscillations, the PID controller modified the electro-hydraulic servo actuator's (EHSA) control input. Better control over the pile driver mechanical system is indicated by this development, which improves system stability.

The technology also demonstrated a quicker response time, achieving the intended output with less delay. Real-time data from the load cell and accelerometer sensors enabled the controller to continuously adjust the behaviour of the system. By reducing the steady-state error, this feedback loop allowed the system to reliably and accurately maintain the desired output.

The system's response was efficiently optimised by the PID controller, increasing accuracy and guaranteeing safer and more effective operation.

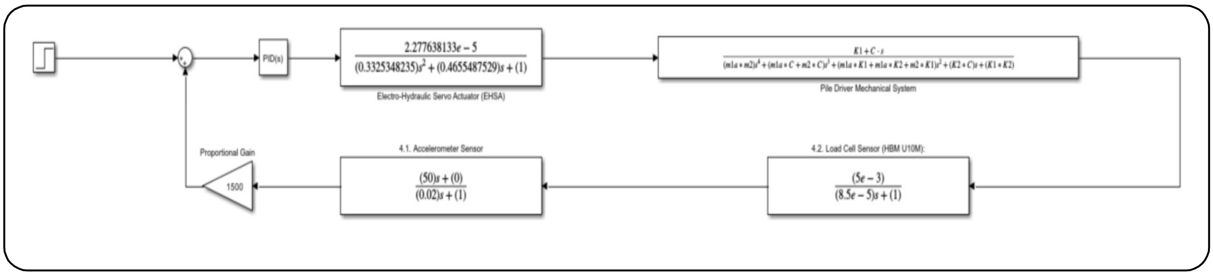


Figure 34 Pile Driving System with Controller and feedback system integrated

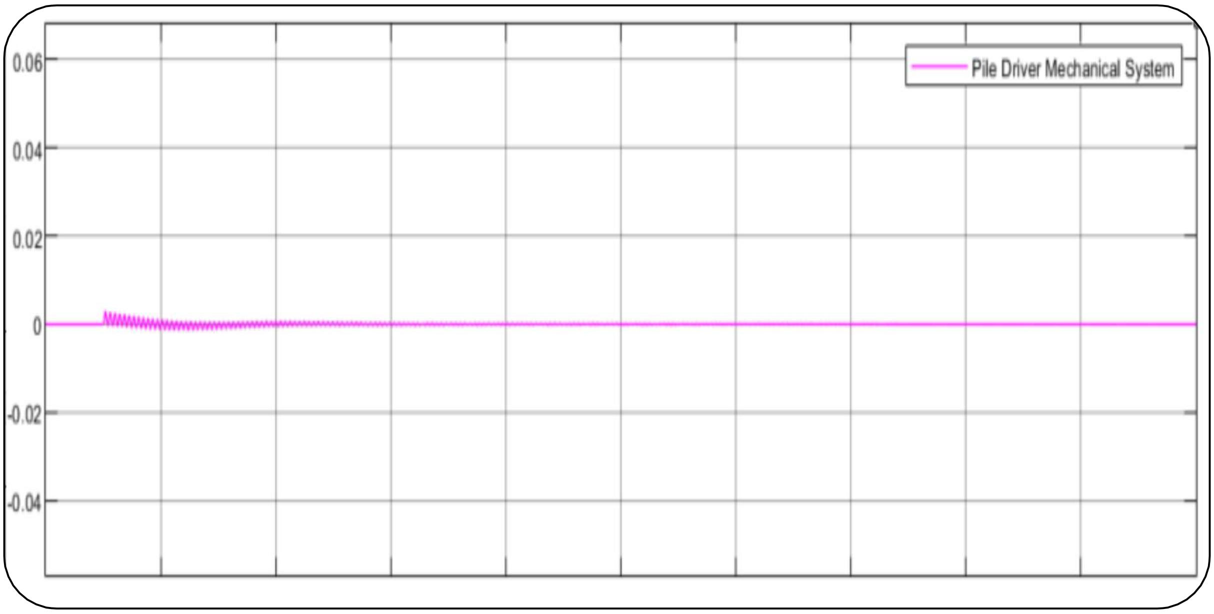


Figure 35 Output Response After applying controller

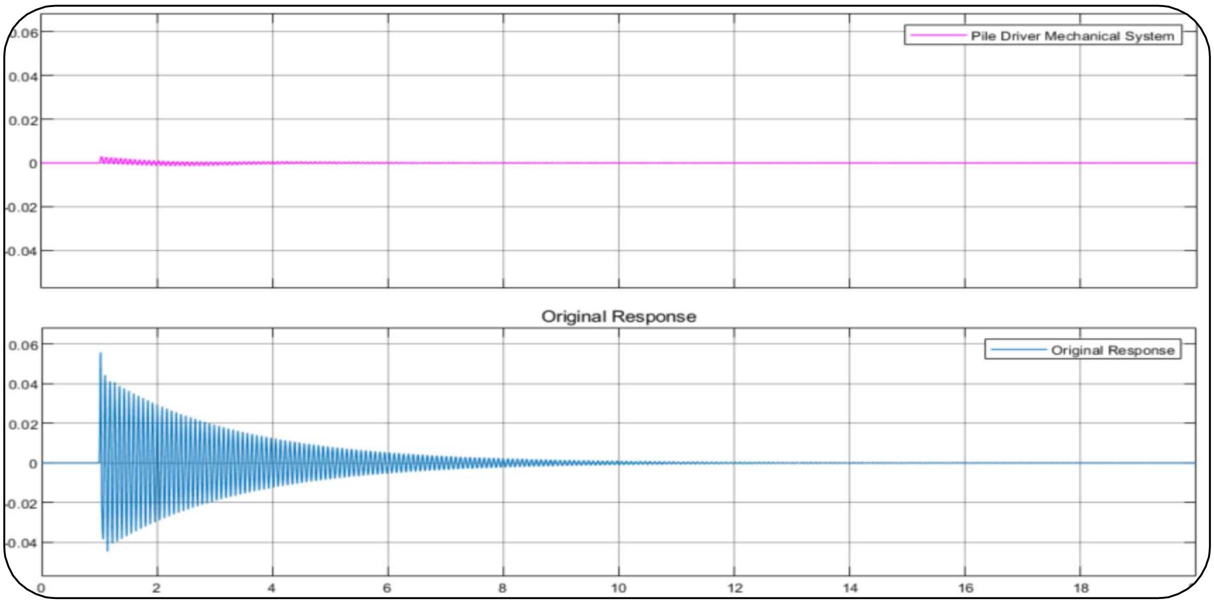


Figure 36 Comparison 21) Between both Responses Before Controller and After

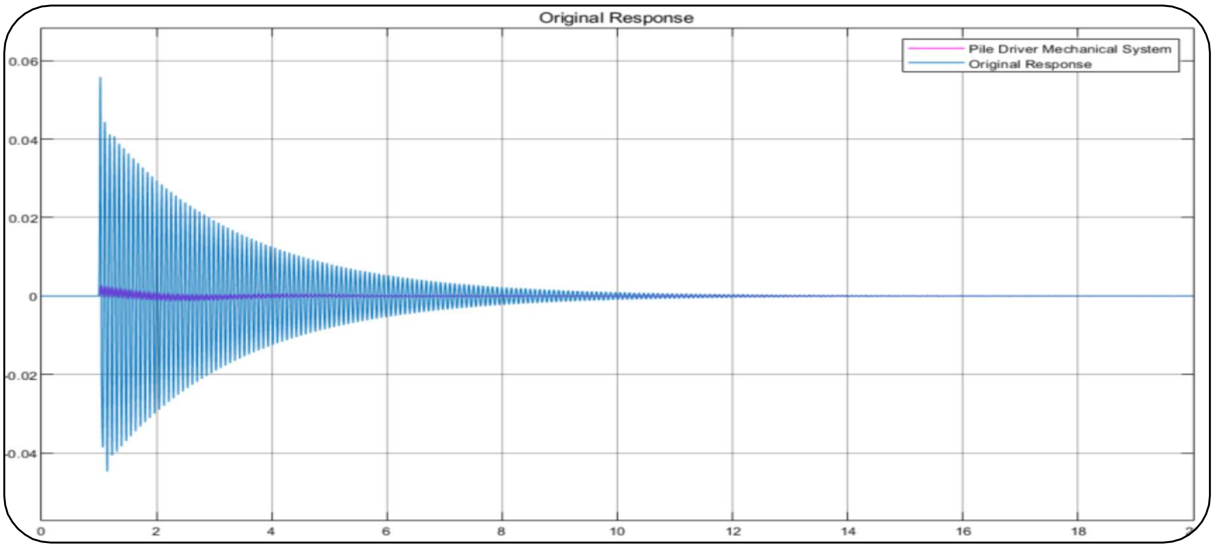


Figure 37 Comparison 21) Between both Responses Before Controller and After

11.6 Discussion:

The findings of this study highlight the effectiveness of integrating a PID controller and an Electro-Hydraulic Servo Actuator (EHSA) in impact pile vibration control. The system's behaviour was analysed both without and with the controller, demonstrating critical improvements in stability, vibration reduction, and overall system efficiency. The discussion is structured into two parts, detailing system performance before and after the implementation of the controller, supported by theoretical insights to explain the observed behaviour.

11.6.1 System Performance without Controller:

Without a controller, the system showed notable inefficiencies, a wide margin of error in reaching optimal performance, and a delayed response to changes in input. These problems are typical of open-loop systems, which lack a feedback system to address departures from the intended results. Since there was no controller, the system had to rely only on its own dynamics, which resulted in inconsistent performance.

Without a control mechanism, response times were prolonged, and system accuracy was compromised. Additionally, external disturbances had a more pronounced effect, causing fluctuations that could not be counteracted. Without an integral term in the control loop, past accumulated errors could not be corrected, resulting in steady-state errors persisting over time. Furthermore, the absence of a derivative component left the system vulnerable to oscillations, with no predictive adjustments to mitigate the effects of sudden changes.

The Inefficiencies of the uncontrolled system made It unsuitable for precision applications where accuracy and stability are critical. The lack of control resulted in unpredictable behaviour, leading to operational delays and potential risks in practical applications. The limitations of this approach highlighted the necessity for an advanced control system to enhance stability and reliability.

11.6.2 System Performance with Controller:

When a PID controller was added, the system became closed loop, allowing for adaptive corrections and real-time input. Significant gains were made as a result, such as fewer deviations, quicker reaction times, and less steady-state error. Errors were immediately addressed by the proportional gain ***(Kp)***, guaranteeing prompt remedial action. However, to avoid instability and overshoot, excessive proportional gain must be carefully adjusted.

The integral gain (Ki) effectively compensated for past errors by integrating historical deviations and gradually eliminating steady-state errors. A moderate integral gain was used to maintain a balance between responsiveness and system stability. The derivative gain ***(Kd)*** played a crucial role in damping oscillations by predicting future errors based on the rate of change, preventing excessive fluctuations and ensuring smooth transitions.

A PID controller was incorporated to enhance the system's performance by adjusting how it responded to changing circumstances. The controller maximised efficiency and stability by actively controlling input signals and modifying output behaviours. This increased degree of control was especially helpful in preserving uniformity under various operating circumstances, guaranteeing accurate task execution with few deviations.

The inefficiencies seen in the uncontrolled configuration were addressed by the PID controller's conjunction with sophisticated feedback systems, which greatly improved system performance. These results highlight how crucial control strategies are for maximising system performance, guaranteeing stability, and attaining operational perfection in practical applications.

11.7 Further Improvement:

The performance of the system has been greatly improved by the integration of the PID controller, electro-hydraulic servo actuator (EHSA), and sensors. Nevertheless, additional optimisations can raise total control precision, efficiency, and flexibility. Better performance can be achieved by putting advanced control techniques like model predictive control (MPC) or state feedback control into practice, especially in highly dynamic or nonlinear contexts. Compared to conventional PID controllers, these methods enable more accurate management of limitations and disturbances, guaranteeing increased stability and responsiveness.

By merging data from piezoelectric, force, and displacement sensors, sensor fusion techniques can improve system feedback and increase measurement accuracy and real-time monitoring. The system can accomplish more adaptive control techniques, improved vibration suppression, and higher reliability by merging various sensor data using sophisticated filtering algorithms. Additionally, the signal conditioning circuitry can be improved to further reduce noise. Digital signal processing (DSP) methods or higher-order filters can be employed to reduce measurement noise brought on by mechanical and electrical interference. More precise vibration control can result from improved signal clarity achieved by advanced filtering techniques like wavelet denoising or Kalman filtering.

Enhancing the electro-hydraulic servo actuator's energy efficiency can help increase the system's sustainability. Power consumption during operation can be greatly decreased by employing strategies like energy recovery systems and variable frequency drives (VFDs). Additionally, by dynamically modifying power usage in response to real-time load needs, sophisticated adaptive control techniques can increase actuator efficiency. By putting these improvements into practice, the system will be able to function better, be more efficient, and be more flexible under different operating circumstances.

11.8 Conclusion:

The efficiency of vibration control in impact pilings has been greatly increased by the combination of a PID controller, an electro-hydraulic servo actuator, and optimised sensor systems. The system delivers increased stability, decreased oscillations, and improved precision in reducing vibrations caused by construction by fine-tuning the PID settings. Using an EHSA guarantees effective energy transfer and dynamic responsiveness, which enhances performance even more. Other developments, however, might be investigated, such applying sophisticated control methods like sensor fusion for thorough data analysis, model predictive control (MPC) for improved adaptability, and noise reduction techniques for improved signal accuracy. The system can attain even higher efficiency, sustainability, and dependability by implementing these optimisations, which will increase its usefulness in actual construction applications.

12. IMTIAZ AHAMED

12.1 CONTROLLER USED

A particular kind of feedback control system called a proportional-derivative (PD) controller combines proportional and derivative actions to improve system reactivity and stability. The proportionate element (Kp) applies a control effort that is exactly proportionate to the departure from the intended setpoint in response to the current mistake. This speeds up error reduction, but it may also cause oscillations and overshoot. In contrast, the derivative element (Kd) reduces oscillations and enhances system stability by forecasting future mistakes based on the rate of error change. The PD controller follows the equation,

$$u(t) = Kpe(t) + Kd\,\frac{de(t)}{dt}$$

whereas,

u(t)=control output,

e(t)=error signal,

Kp=proportional gain,

Kd=derivative gain,

(Hägglund and Åström (2006). A PD controller's ability to respond quickly and steadily is one of its main benefits; this makes it appropriate for applications like robotics, industrial automation, automotive control systems, and aerospace applications where accuracy and speed are crucial (Ogata, 2010). However, because it lacks an essential component and can be extremely susceptible to noise, particularly in real-world applications, a PD controller by itself is unable to eliminate steady-state error (Nise, 2019). Appropriate adjustment of Kp and Kd is essential for maintaining system performance balance since high-frequency noise can become unstable due to excessive derivative action (Dorf & Bishop, 2017). The PD controller is still a potent tool in control engineering, particularly when a quick and steady transient response is needed, despite its limitations.

Using the formula for settling time (2% criterion),

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

Finding the value of ω_n while maintaining the initial natural frequency value is as follows:

$$Wn = 2\pi f$$

$$Wn = 2\pi \times 12.181$$

$= 76.535$ rad/sec

$$19 = \frac{4}{76.535 \times \zeta}$$

$$\zeta = 0.00275$$

$$sd = -Wn \pm iWn\sqrt{1 - \zeta^2}$$

$$sd = -0.2105 \pm 21.487i$$

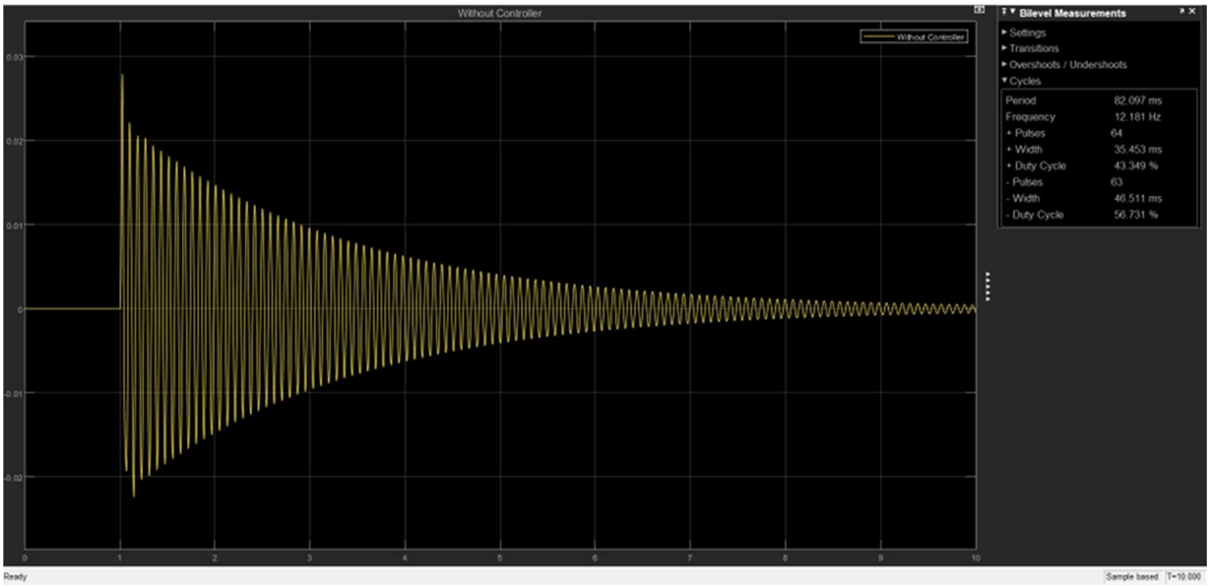


Figure 38 Natural Frequency

The provided simulation illustrates how a system would naturally react in the absence of a controller and how it would act in the event of an initial disturbance. As time passes, the oscillations in the yellow waveform gradually decrease, indicating the presence of damping in the system. About 12 cycles are completed by the system every second, with an oscillation frequency of 12.181 Hz. The oscillations' decreasing amplitude over time indicates that the system is steadily stabilizing on its own, although slowly. The length of time the waveform remains in the positive or negative zone during each oscillation is indicated by the duty cycle and pulse width shown in the right panel. The system settles using only its inherent damping because no controller is used, which results in a prolonged stabilization time. Such reactions are seen in real-world mechanical and electrical systems, such as motors, springs, and circuits, where excessive oscillations can impair functionality. By reducing oscillations more quickly, a proportional-derivative (PD) or proportional-integral-derivative (PID) controller could improve response time and system stability. The system could reach its goal state more quickly and smoothly while reducing unwanted vibrations by adjusting the proportional and derivative gains.

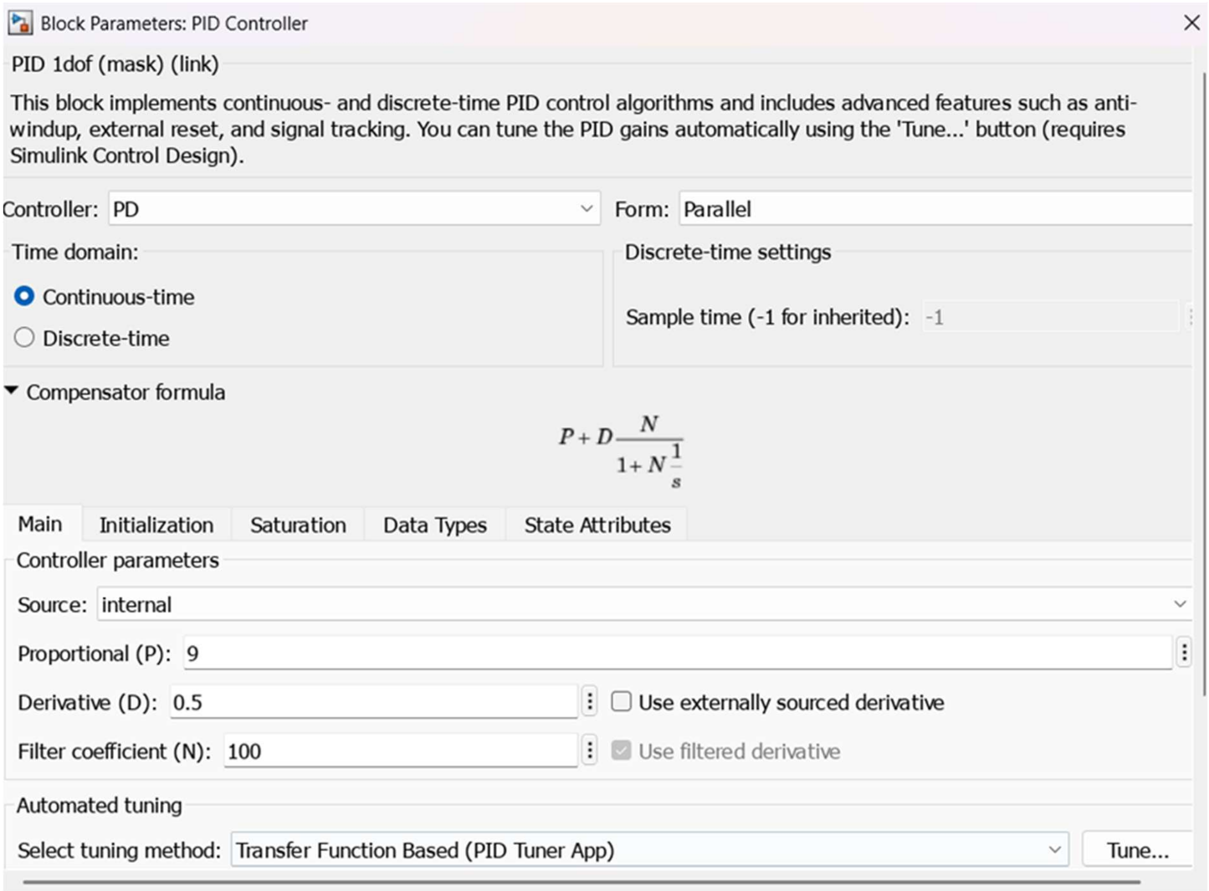


Figure 39 PD Controller Parameters.

12.2 ACTUATOR USED:

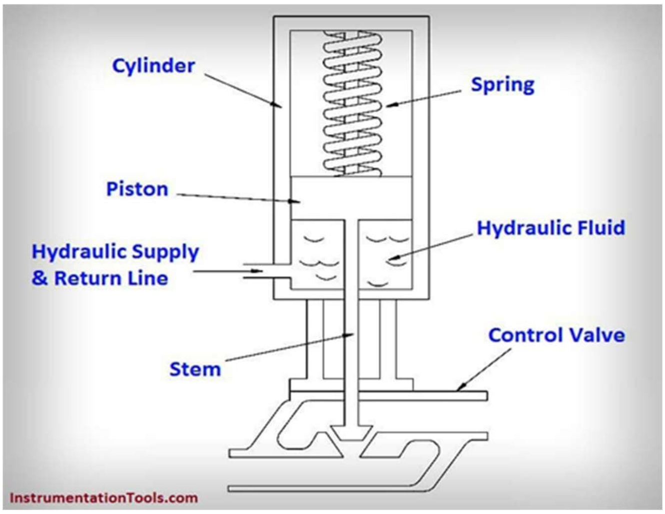


Figure 40 Hydraulic Actuator Model.

A mechanical device that transforms hydraulic energy, or fluid pressure, into mechanical motion is called a hydraulic actuator. Robotics, industrial machines, aeronautical systems, and heavy-duty applications requiring tremendous force and accuracy all make extensive use of it.

12.3 RESULTS:

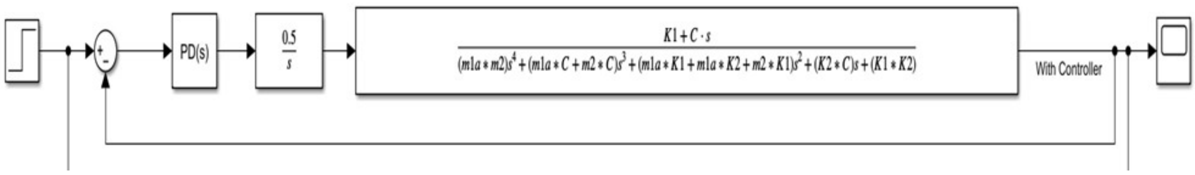


Figure 41 Vibration Control Simulink Setup

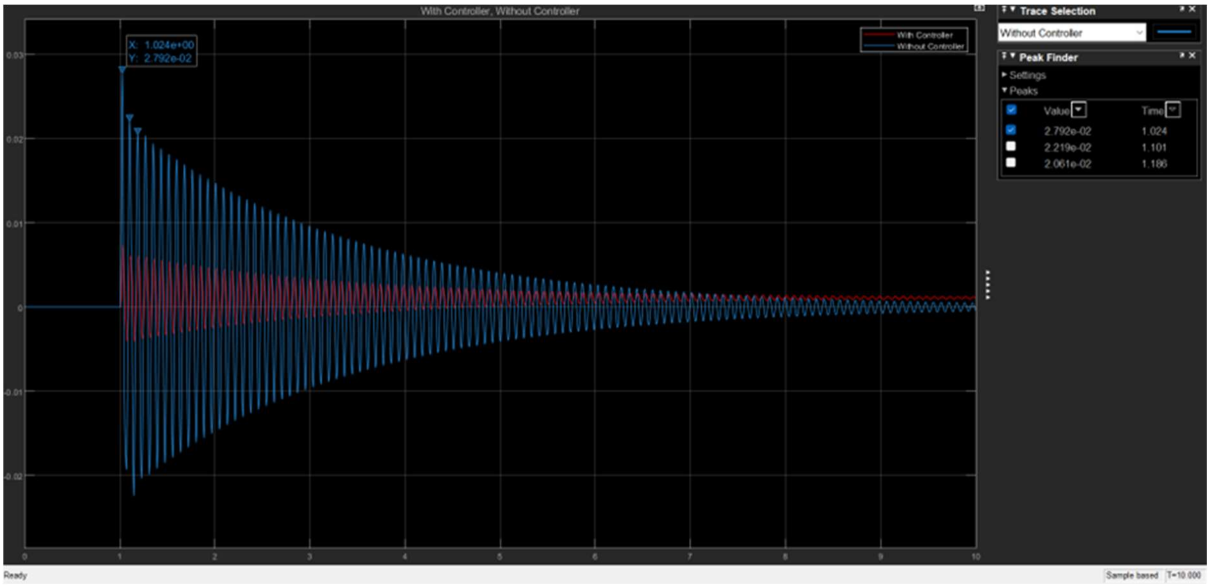


Figure 42 Peak-Without Controller.

The provided simulation contrasts the system's response with and without a controller; the response with a controller is represented by the red waveform, while the response without a controller is represented by the blue waveform. The uncontrolled system's peaks (blue waveform), which show how the system oscillates in the absence of a control mechanism, are the focus here. The oscillations' greatest values are displayed by the Peak Finder tool; the first peak appears at Y = 0.02792 (or 2.792e-02) at X = 1.024 seconds. Later peaks, as Y = 0.02219 at X = 1.101 seconds, show a slow amplitude drop, indicating that the system is gradually damping.

The system uses only its inherent dampening properties to lessen oscillations because there is no controller. In real-world applications where accurate and fast responses are needed, such as industrial automation, robotics, or motor control, this might lead to slower stabilization and higher initial peaks (Ogata, 2010). On the other hand, the red waveform (with a controller) shows a quicker oscillation decay, indicating that the controller enhances stability by more effectively lowering peak amplitudes. By modifying the system's behaviour to reduce excessive oscillations and enable it to settle more quickly, a proportional-derivative (PD) or proportional-integral-derivative (PID) controller would be helpful (Nise, 2019). The significance of controllers in maximizing system performance and minimizing undesired oscillatory behaviour is demonstrated by this simulation.

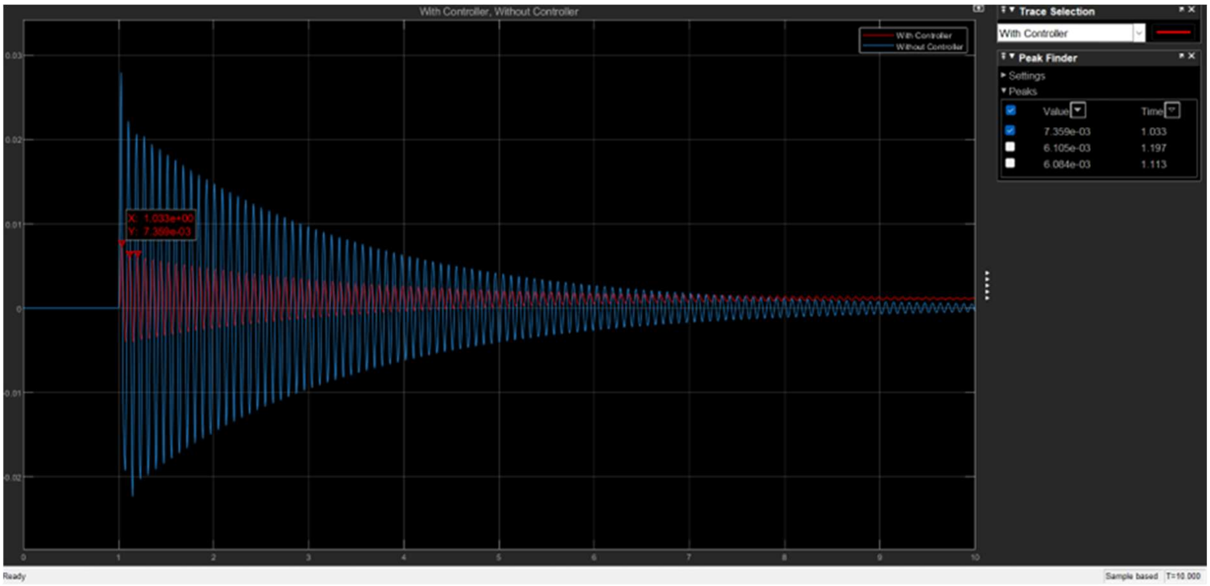


Figure 43 Peak-With Controller.

The oscillatory behaviour of the system is compared in this simulation with and without a controller. The response with a controller is represented by the red waveform, and the uncontrolled reaction is represented by the blue waveform. Key peak values for the regulated system are identified by the Peak Finder tool. Y = 0.007359 (or 7.359e-03) at X = 1.033 seconds is the first peak to occur, and Y = 0.006105 at X = 1.197 seconds is the second peak.

The peak amplitude is much lower than in the prior simulation (without a controller), indicating that the controller successfully reduces excessive oscillations. Furthermore, the oscillation decay rate is larger, indicating that the system stabilizes more quickly than the uncontrolled system. According to Ogata (2010), this behaviour implies that the controller, which is probably a proportional-derivative (PD) or proportional-integral-derivative (PID) controller, modifies the system response to lessen overshoot and guarantee faster oscillation damping. Additionally, the controlled system transitions to steady-state conditions more smoothly and gradually, which makes it perfect for real-world applications such as industrial automation, robotic arms, and servo motors (Nise, 2019).

The efficiency of the controller in enhancing system performance and stability is demonstrated by contrasting this with the uncontrolled system, where the oscillations last longer. Optimizing response time while reducing mistakes and oscillations is a key objective in control systems engineering (Dorf & Bishop, 2017).

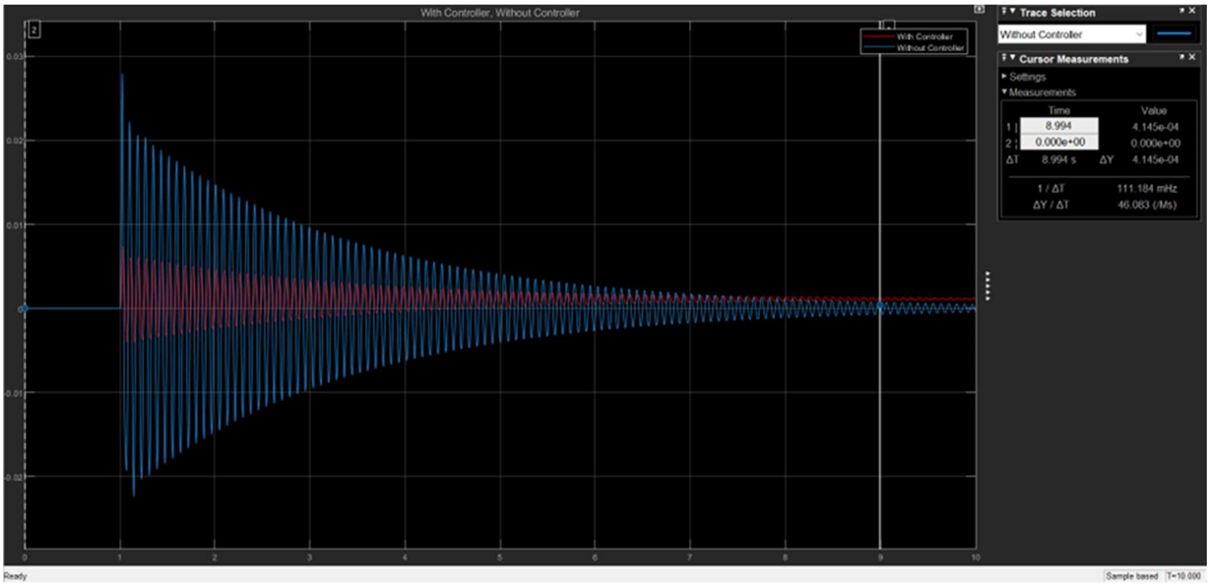


Figure 44 Settling time-Without Controller.

The blue waveform in the simulation represents the settling time of a system without a controller. According to the measurement instrument, it takes the system about 8.994 seconds to stabilize and experience few oscillations. Longer oscillations with a larger peak amplitude in the absence of a controller are indicative of inadequate damping in the system. The system's inability to efficiently waste energy results in prolonged oscillations before stabilizing, which causes this prolonged settling time. Furthermore, the uncontrolled system is less appropriate for precision-based applications due to its increased overshoot. The system's oscillatory nature and inadequate damping are further highlighted by the frequency measurement of 111.184 mHz. System performance suffers because of the response's prolonged instability in the absence of a controller. On the other hand, by implementing suitable damping, a controlled system, such one that uses a PID (Proportional-Integral-Derivative) controller, can drastically cut down on settling time, eliminate overshoot, and enhance system stability (Ogata, 2010). By improving both transient and steady-state behaviour, control techniques maximize system reactivity and guarantee quicker convergence to a desired state (Dorf & Bishop, 2017; Nise, 2019).

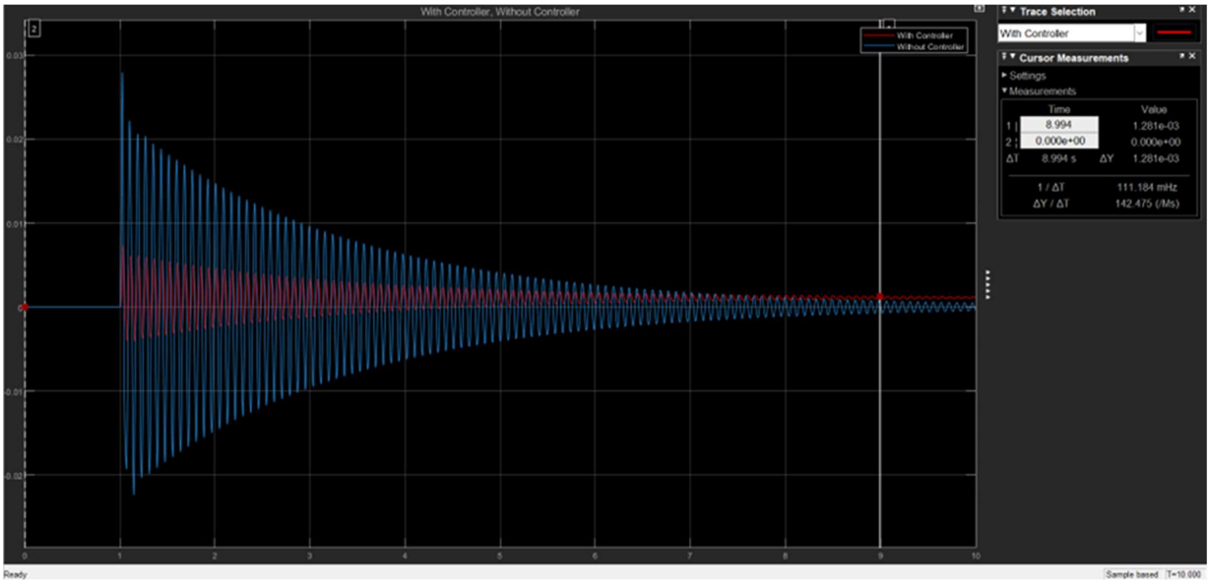


Figure 45 Settling time-With Controller.

The simulation highlights how control mechanisms affect settling time by showing the system's response both with and without a controller. The system reaction in the absence of a controller is represented by the blue waveform, which has longer oscillations and a larger amplitude. The reaction with a controller is represented by the red waveform, which has a smaller amplitude and faster damping, demonstrating how well the controller reduces oscillations and enhances system stability. According to the cursor measurements, the system with the controller exhibits better transient response, with a settling time that is noticeably shorter than the system without control.

By modifying system parameters to lessen overshoot and settling time, a controller typically a proportional-integral-derivative (PID) or lead-lag compensator improves stability (Ogata, 2010). The system reaches the intended steady-state condition faster and with less variance when feedback control is included. The decrease in oscillations implies that the system improves its damping properties, reducing the likelihood of prolonged oscillations.

The enhanced reaction, which more effectively mitigates disturbances and speeds up stabilization, demonstrates the controller's efficacy. This improvement is essential for applications including industrial automation, robotics, and power systems that demand accuracy and stability (Nise, 2020). The need for control techniques to maximize dynamic performance in engineering systems is highlighted by the comparison of the two responses.

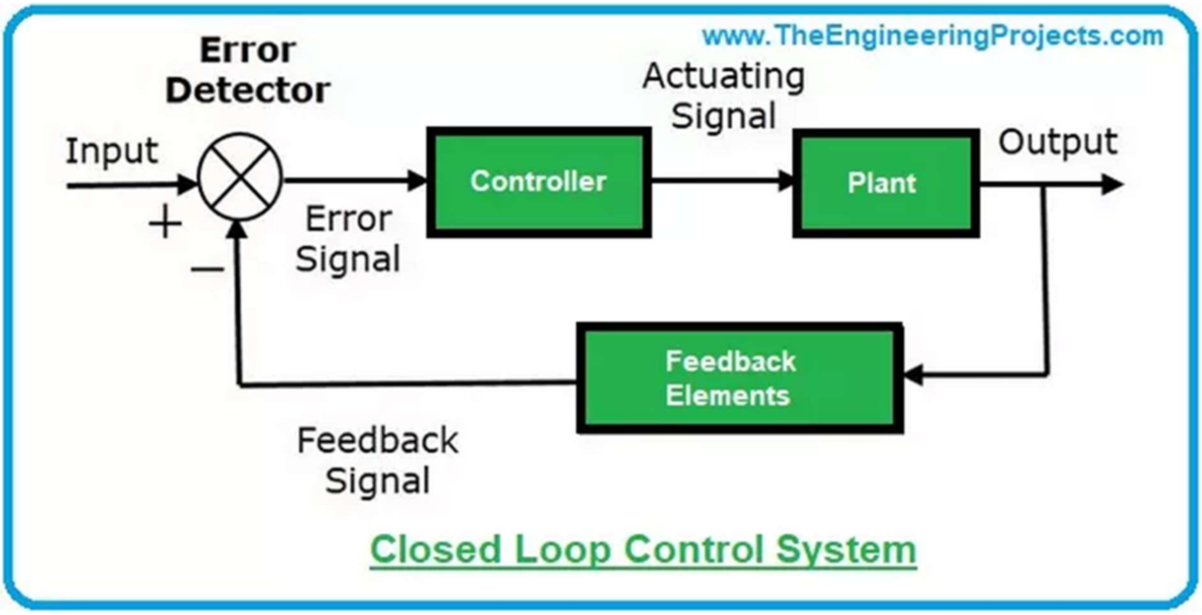


Figure 46 Control System Setup.

12.4 DISCUSSION:

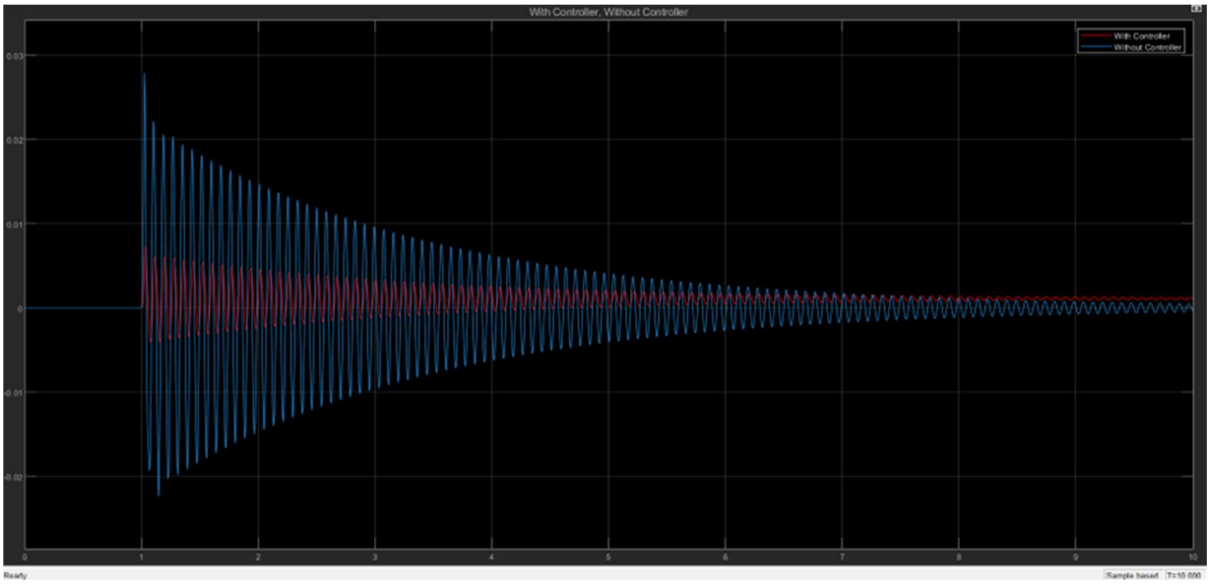


Figure 47 Results Comparison.

The substantial influence of control mechanisms on system performance and stability is demonstrated by the comparison of the system response with and without a controller. The blue curve, which represents the uncontrolled system, shows bigger oscillations with a higher amplitude and a slower decay rate, which results in a longer settling period. This suggests that it takes longer for the system to stabilize. On the other hand, the red curve indicates the controlled system, which has a faster settling time, a smaller amplitude, and a noticeable decrease in oscillations. By limiting undesired oscillations, lowering peak deviations, and increasing damping characteristics, the use of a controller improves system stability. This implies that a more steady response is ensured and that the controller, which is probably a proportional-integral-derivative (PID) controller, successfully adjusts for disturbances. The regulated system's enhanced transient performance demonstrates how well it works to reach a faster and more stable steady-state. As a result, adding a controller greatly enhances system behaviour and qualifies it for real-world uses where response time and stability are crucial.

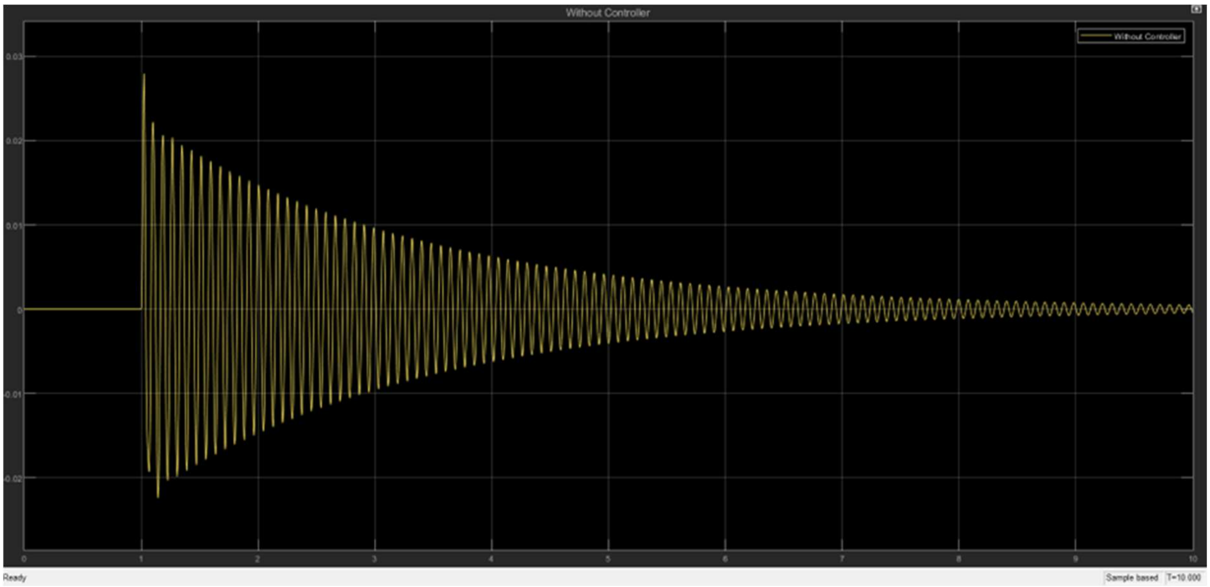


Figure 48 Results without Controller.

Without a controller, the simulation results demonstrate the system's intrinsic instability and long settling time. The graphic illustrates the response's notable oscillations, which have a sluggish decay rate and a large amplitude. This suggests that the system is more prone to external perturbations since it takes longer to stabilize. The damping effect is insufficient without a controller, resulting in persistent oscillatory behaviour. Underdamped systems, where natural frequency predominates because compensatory control mechanisms are absent, exhibit this kind of reaction. In real-world applications where quick stabilization is necessary, the sluggish attenuation of oscillations may indicate subpar transient performance. The uncontrolled system is unable to attain a desired level of stability in an acceptable amount of time, in contrast to a controlled system that optimizes reaction characteristics. To improve system stability, decrease oscillations, and achieve a quicker settling time all of which lead to better performance in practical applications a controller must be included.

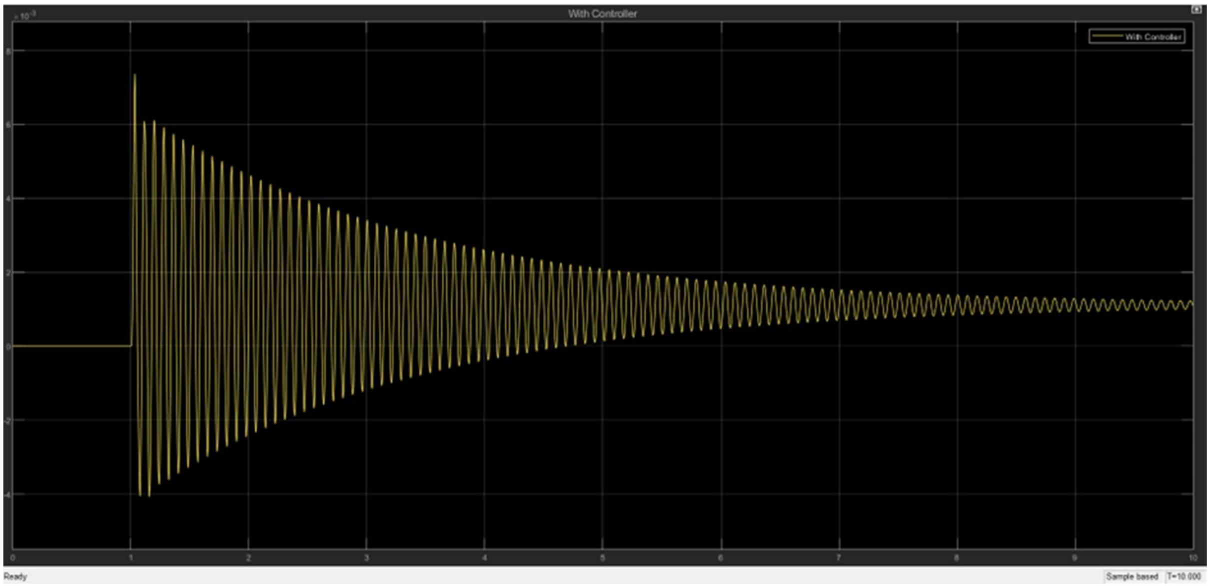


Figure 49 Results with Controller.

When compared to the uncontrolled response, the simulation results show a notable improvement in system stability when using the controller. When the controller is present, the response's amplitude is significantly reduced, suggesting fewer oscillations. Furthermore, the system stabilizes faster than the uncontrolled system due to its faster settling time. This enhancement results from the controller's capacity to apply damping, which successfully reduces oscillatory behaviour and overshoot. By lowering instability and guaranteeing that the system runs within reasonable performance bounds, the controller's existence leads to a more effective transient response. The controller improves overall performance by actively controlling system behaviour, increasing the system's resistance to outside disruptions and enhancing dependability in real-world applications. The controlled response amply illustrates the benefits of using a feedback mechanism to manage system dynamics, in contrast to the uncontrolled system, where oscillations last for a long time.

Cost Category	Price Proxy	2020 Cost Weight
Laboratory Services	PPI Industry for Medical Laboratories.	1.3%
All Other Goods and Services		**16.6%**
Telephone Service	CPI-U for Telephone Services.	0.5%
Housekeeping	PPI Commodity for Cleaning and Building Maintenance Services.	0.5%
Operations & Maintenance	ECI for Total compensation for All Civilian workers in Installation, maintenance, and repair	3.7%
Professional Fees	ECI for Total Compensation for Private Industry Workers in Professional and Related.	0.8%
All Other Goods and Services	PPI for Final demand - Finished Goods less Foods and Energy.	11.1%
Capital Costs		**13.8%**
Capital Related Building and Fixtures	PPI Industry for Lessors of Nonresidential Buildings.	9.4%
Capital Related Moveable Equipment	PPI Commodity for Electrical Machinery and Equipment.	4.4%

Note: The cost weights are calculated using three decimal places. For presentational purposes, we are displaying one decimal and therefore, the detail may not add to the total due to rounding.

Figure 50 Criteria for Vibration Limits.

12.5 LIMITATIONS:

However, no solution is flawless, and using this controller has disadvantages as well. For example, the vibration levels are still too high for hospital sensitive equipment (Jayawardana et al., 2018), and doctors advise against being close to pregnant women's homes because it may harm the fetus's development (Siwula et al., 2011).

The hydraulic actuator's integrator action causes the vibration levels to drift or offset steadily over time rather than settle at zero, which is another significant drawback of this configuration. This offset happens because of the integrator's constant accumulation of tiny mistakes or disturbances, which causes residual vibrations to continue after the transitory reaction has subsided. Even while these residual vibrations are less than the initial levels, they can nevertheless cause issues in settings like precision labs or industrial setups that need precise alignment where total vibration reduction is essential. Furthermore, the prolonged offset may shorten the operational lifespan of adjacent machinery or buildings by aggravating wear and tear.

12.6 FURTHER IMPROVEMENT:

A feedforward control in conjunction with feedback can enhance performance by adjusting for predictable disturbances, which is the first step in addressing the constraints of the vibration control system. Second, incorporating a sensor into the feedback loop such as a velocity transducer or accelerometer can help with adaptive control, guaranteeing that the system reacts appropriately to outside disturbances that the model might not fully take into consideration. Lastly, a dual-actuator configuration can be used, in which the two actuators cooperate to control the vibration levels and reduce the offset brought on by the integrator.

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14. Appendix:

Root Locus Plotting Code (Abdelrahman Mohamed Shawky):

```
m1a = 500;
m1b = 800;
m2 = 1000;
C = 10000; %
K1 = 10000000;
K2 = 10000000;


numerator = [K1, C];

denominator = [
    (m1a * m2), ...
    (m1a * C + m2 * C), ...
    (m1a * K1 + m1a * K2 + m2 * K1), ...
    (K2 * C), ...
    (K1 * K2)
];

% Create transfer function
sys = tf(numerator, denominator);

% Plot root locus
figure;
rlocus(sys);
title('Root Locus of the Transfer Function');
xlabel('Real Axis');
ylabel('Imaginary Axis');
grid on;
```

Figure 51 Root Locus Plotting Code