

**An Evaluation of Tracking Performance of a Positioning Controller with
Feedforward on an XY Milling Table Ball-Screw Driven System**

Submitted By

Saeid Bin Hossain

200012116

Raham Binte Kamrul

200012122

Tahsin Muhammed Payel

200012128

Supervised By

Dr. Madihah Binti Haji Maharof

**A Thesis submitted in partial fulfillment of the requirement for the degree of
Bachelor of Science in Industrial and Production Engineering**



Department of Mechanical and Production Engineering (MPE)

Islamic University of Technology (IUT)

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Candidate's Declaration

This is to certify that the work presented in this thesis, titled, “**An Evaluation of Tracking Performance of a Positioning Controller with Feedforward on an XY Milling Table Ball-Screw Driven System**”, is the outcome of the investigation and research carried out by Saeid Bin Hossain (200012116), Raham Binte Kamrul (200012122), and Tahsin Muhammed Payel (200012128) under the supervision of Dr. Madihah Binti Haji Maharof, Assistant Professor, Department of Mechanical and Production Engineering, Islamic University of Technology (IUT).

It is also declared that neither this thesis nor any part of it has been submitted elsewhere for the award of any degree or diploma.

Saeid Bin Hossain
200012116

Raham Binte Kamrul
200012122

Tahsin Muhammed Payel
200012128

Recommendation of the Thesis Supervisors

The thesis titled “An Evaluation of Tracking Performance of a Positioning Controller with Feedforward on an XY Milling Table Ball-Screw Driven System” submitted by Saeid Bin Hossain (200012116), Raham Binte Kamrul (200012122), and Tahsin Muhammed Payel (200012128) has been accepted as satisfactory in partial fulfillment of the requirements for the degree of B.Sc. in Industrial and Production Engineering on 6th October, 2025.

Supervisor

Dr. Madihah Binti Haji Maharof

Assistant Professor

MPE Dept., IUT, Board Bazar, Gazipur-1704, Bangladesh.

CO-PO Mapping of ME 4800 -Thesis and Project

COs	Course Outcomes (CO) Statement	(PO)	Addressed by	
CO1	Discover and Locate research problems and illustrate them via figures/tables or projections/ideas through field visit and literature review and <u>determine/Setting</u> aim and objectives of the project/work/research in specific, measurable, achievable, realistic and timeframe manner.	PO2 Problem analysis	Thesis Book	
			Performance by research	
			Presentation and soft skill	
CO2	Design research solutions of the problems towards achieving the objectives and its application. Design systems, components or processes that meets related needs in the field of mechanical engineering	PO3 Design/development of solutions	Thesis Book	
			Performance by research	
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CO3	Review, debate, compare and contrast the relevant literature contents. Relevance of this research/study. Methods, tools, and techniques used by past researchers and justification of use of them in this work.	PO4 Investigation	Thesis Book	
			Performance by research	
			Presentation and soft skill	
CO4	Analyse data and exhibit results using tables, diagrams, graphs with their interpretation. Investigate the designed solutions to solve the problems through case study/survey study/experimentation/simulation using modern tools and techniques.	PO5 Modern tool usage	Thesis Book	
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			Presentation and soft skill	
CO5	Apply moral values and research/professional ethics throughout the work, and justify genuine referencing on sources, and demonstration of own contribution.	PO8 Ethics	Thesis Book	
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			Presentation and soft skill	
CO6	Perform own self and manage group activities from the beginning to the end of the research/work as a quality work.	PO9 Individual work and teamwork	Thesis Book	
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CO7	Compile and arrange the work outputs, write the report/thesis, a sample journal paper, and present the work to wider audience using modern communication tools and techniques.	PO10 Communication	Thesis Book	
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CO8	Recognize the necessity of life-long learning in career development in dynamic real-world situations from the experience of completing this project.	PO12 Life-long learning	Thesis Book	
			Performance by research	
			Presentation and soft skill	

Student Name /ID:

Signature of the Supervisor:

1. Saeid Bin Hossain, 200012116

Name of the Supervisor: Dr. Madihah Binti Haji Maharof

2. Raham Binte Kamrul, 200012122

3. Tahsin Muhammed Payel, 200012128

K-P-A Mapping of ME 4800 -Theis and Project

COs	POs	Related Ks								Related Ps							Related As				
		K1	K2	K3	K4	K5	K6	K7	K8	P1	P2	P3	P4	P5	P6	P7	A1	A2	A3	A4	A5
CO1	PO2	✓	✓	✓	✓					✓											
CO2	PO3					✓	✓		✓			✓				✓		✓	✓		
CO3	PO4						✓	✓	✓			✓	✓	✓			✓	✓			
CO4	PO5						✓	✓						✓				✓			
CO5	PO8			✓											✓						
CO6	PO9			✓	✓	✓										✓				✓	
CO7	PO10					✓	✓									✓	✓		✓	✓	
CO8	PO12								✓							✓				✓	

Student Name /ID:

Signature of the Supervisor:

1. Saeid Bin Hossain, 200012116

Name of the Supervisor: Dr. Madihah Binti Haji Maharof

2. Raham Binte Kamrul, 200012122

3. Tahsin Muhammed Payel, 200012128

List of Sustainable Development Goals (SDGs) Addressed in this Project

SDG No.	Goals	Targets	Relevance to the Thesis (put √ if valid)	Remarks
1	No Poverty	1.1 Eradicate extreme poverty (people living on less than \$1.25/day).		
		1.2 Reduce poverty in all its forms by at least half.		
		1.3 Implement nationally appropriate social protection systems.		
		1.4 Ensure equal rights to economic resources, services, property, inheritance, technology, and financial services.		
		1.5 Build resilience of the poor and reduce exposure to climate-related and other shocks.		
		1.a Mobilize resources to end poverty.		
		1.b Create pro-poor policy frameworks.		
2	Zero Hunger	2.1 End hunger and ensure access to safe, nutritious food year-round.		
		2.2 End all forms of malnutrition.		
		2.3 Double agricultural productivity and incomes of small-scale producers.		
		2.4 Ensure sustainable food production systems and resilient agricultural practices.		
		2.5 Maintain genetic diversity of seeds, plants, and animals.		
		2.a Increase investment in rural infrastructure, research, and technology.		
		2.b Correct and prevent trade restrictions/distortions in global food markets.		
		2.c Adopt measures to ensure proper functioning of food commodity markets.		
3	Good Health and Well-Being	3.1 Reduce global maternal mortality ratio.		
		3.2 End preventable deaths of newborns and under-5 children.		
		3.3 End epidemics of AIDS, tuberculosis, malaria, and neglected tropical diseases.		
		3.4 Reduce premature mortality from NCDs and promote mental health.		
		3.5 Strengthen prevention and treatment of substance abuse.		
		3.6 Halve global deaths/injuries from road traffic accidents.		
		3.7 Ensure universal access to sexual and reproductive healthcare.		

		3.8 Achieve universal health coverage.		
		3.9 Reduce deaths from hazardous chemicals, pollution, and contamination.		
		3.a Strengthen tobacco control (WHO FCTC).		
		3.b Support R&D of vaccines and medicines.		
		3.c Increase health financing and workforce.		
		3.d Strengthen capacity for early warning and risk management.		
4	Quality Education	4.1 Ensure all complete free, equitable, quality primary and secondary education.		
		4.2 Ensure access to quality early childhood development and pre-primary education.		
		4.3 Ensure equal access to affordable technical, vocational, and higher education.	√	Supports higher technical education through advanced control research
		4.4 Increase skills for employment and entrepreneurship.	√	Builds practical engineering and simulation skills
		4.5 Eliminate gender disparities in education.		
		4.6 Ensure literacy and numeracy for youth and adults.		
		4.7 Ensure learners acquire knowledge/skills for sustainable development.		
		4.a Build and upgrade education facilities that are inclusive and safe.		
		4.b Expand scholarships for developing countries.		
		4.c Increase supply of qualified teachers.		
5	Gender Equality	5.1 End all forms of discrimination against women and girls.		
		5.2 Eliminate violence against women and girls.		
		5.3 Eliminate harmful practices (child, early, forced marriage, FGM).		
		5.4 Recognize and value unpaid care and domestic work.		
		5.5 Ensure women's participation in leadership and decision-making.		
		5.6 Ensure universal access to reproductive health and rights.		
		5.a Undertake reforms to give women equal rights to resources.		
		5.b Enhance use of enabling technology to empower women.		
		5.c Adopt and strengthen policies and laws for gender equality.		

6	Clean Water and Sanitation	6.1 Achieve universal and equitable access to safe drinking water.		
		6.2 Achieve access to adequate sanitation and hygiene.		
		6.3 Improve water quality by reducing pollution.		
		6.4 Increase water-use efficiency and sustainable withdrawals.		
		6.5 Implement integrated water resources management.		
		6.6 Protect and restore water-related ecosystems.		
		6.a Expand international cooperation in water and sanitation.		
		6.b Support participation of local communities.		
7	Affordable and Clean Energy	7.1 Ensure universal access to affordable, reliable, modern energy services.		
		7.2 Increase substantially the share of renewable energy.		
		7.3 Double global rate of improvement in energy efficiency.	√	Improves energy efficiency in CNC operations.
		7.a Enhance international cooperation on clean energy research/technology.		
		7.b Expand infrastructure and upgrade technology for sustainable energy.	√	Upgrades industrial systems for sustainable use.
8	Decent Work and Economic Growth	8.1 Sustain per capita economic growth.		
		8.2 Achieve higher levels of productivity through diversification, tech, and innovation.	√	Boosts productivity through control innovation.
		8.3 Promote policies for decent job creation and entrepreneurship.	√	Encourages industrial innovation and efficiency.
		8.4 Improve resource efficiency in production and consumption.	√	Enhances resource efficiency in production
		8.5 Achieve full and productive employment for all.		
		8.6 Substantially reduce youth not in employment/education/training.		
		8.7 Eradicate forced labour, modern slavery, and child labour.		
		8.8 Protect labour rights and safe working environments.		
		8.9 Promote sustainable tourism.		
		8.a Increase aid for trade support.		
		8.b Develop a global youth employment strategy.		
9	Industry, Innovation, and	9.1 Develop quality, reliable, sustainable infrastructure.		
		9.2 Promote inclusive and sustainable industrialization.		

		9.3 Increase access of SMEs to financial services and integration into value chains.		
		9.4 Upgrade infrastructure for sustainability and resource efficiency.	√	Modernizes CNC systems for higher efficiency.
		9.5 Enhance scientific research and technology development.	√	Advances research in control and automation.
		9.a Facilitate sustainable infrastructure in developing countries.		
		9.b Support domestic tech development and value addition.		
		9.c Increase access to ICT and internet.		
10	Reduced Inequalities	10.1 Achieve income growth of bottom 40%.		
		10.2 Empower and promote inclusion regardless of status.		
		10.3 Ensure equal opportunity and reduce inequalities of outcome.		
		10.4 Adopt policies for fiscal, wage, and social protection equality.		
		10.5 Improve regulation of global financial markets.		
		10.6 Ensure enhanced representation in global institutions.		
		10.7 Facilitate safe, regular, and responsible migration.		
		10.a Implement special treatment for developing countries.		
		10.b Encourage development assistance and investment in least developed areas.		
		10.c Reduce remittance costs.		
11	Sustainable Cities and Communities	11.1 Ensure access to adequate, safe, and affordable housing.		
		11.2 Provide sustainable transport systems.		
		11.3 Enhance inclusive urbanization and capacity for planning.		
		11.4 Protect cultural and natural heritage.		
		11.5 Reduce disaster impact and losses.		
		11.6 Reduce environmental impact of cities (air quality, waste).		
		11.7 Provide access to safe, inclusive green/public spaces.		
		11.a Support positive links between urban, peri-urban, rural.		
		11.b Increase disaster risk reduction strategies.		
		11.c Support least developed countries in sustainable building.		
12	Responsible	12.1 Implement 10-Year Framework on sustainable consumption/production.		

		12.2 Achieve sustainable management and use of resources.	√	Improves resource and material utilization.
		12.3 Halve per capita global food waste.		
		12.4 Manage chemicals and waste sustainably.		
		12.5 Substantially reduce waste generation.	√	Reduces waste through precise machining.
		12.6 Encourage companies to adopt sustainable practices.		
		12.7 Promote sustainable public procurement.		
		12.8 Ensure people have relevant information for sustainable development.		
		12.a Support developing countries' scientific and technological capacity.		
		12.b Develop tools to monitor sustainable tourism impacts.		
		12.c Rationalize inefficient fossil-fuel subsidies.		
13	Climate Action	13.1 Strengthen resilience and adaptive capacity to climate-related hazards.		
		13.2 Integrate climate measures into national policies.		
		13.3 Improve education and awareness on climate change.	√	Encourages energy-efficient industrial design.
		13.a Implement UNFCCC commitments (mobilize \$100 billion annually).		
		13.b Promote mechanisms for capacity-building in least developed countries.		
14	Life Below Water	14.1 Reduce marine pollution.		
		14.2 Sustainably manage and protect marine ecosystems.		
		14.3 Minimize and address ocean acidification.		
		14.4 Regulate harvesting and end overfishing.		
		14.5 Conserve at least 10% of coastal and marine areas.		
		14.6 Prohibit harmful fisheries subsidies.		
		14.7 Increase economic benefits from sustainable marine resources.		
		14.a Increase scientific knowledge and marine technology transfer.		
		14.b Provide access for small-scale artisanal fishers.		
		14.c Implement international law for oceans.		
15	Life on Land	15.1 Conserve terrestrial and freshwater ecosystems.		
		15.2 Promote sustainable management of forests.		

		15.3 Combat desertification and restore degraded land.		
		15.4 Ensure conservation of mountain ecosystems.		
		15.5 Take urgent action to reduce biodiversity loss.		
		15.6 Promote fair benefit-sharing from genetic resources.		
		15.7 End poaching and trafficking of protected species.		
		15.8 Prevent introduction of invasive alien species.		
		15.9 Integrate ecosystem values into policies/planning.		
		15.a Mobilize resources for biodiversity.		
		15.b Finance sustainable forest management.		
		15.c Support local communities for forest and wildlife.		
16	Peace, Justice and Strong Institutions	16.1 Reduce violence and related death rates.		
		16.2 End abuse, trafficking, and violence against children.		
		16.3 Promote rules of law and equal access to justice.		
		16.4 Reduce illicit financial/arms flows, organized crime.		
		16.5 Reduce corruption and bribery.		
		16.6 Develop effective, accountable institutions.		
		16.7 Ensure inclusive, participatory decision-making.		
		16.8 Broaden participation of developing countries in global governance.		
		16.9 Provide legal identity for all (including birth registration).		
		16.10 Ensure access to information and protect freedoms.		
		16.a Strengthen national institutions for prevention of violence.		
		16.b Promote/enforce non-discriminatory laws and policies.		
17	Partnerships for the Goals	17.1 Strengthen domestic resource mobilization.		
		17.2 Developed countries to implement ODA commitments.		
		17.3 Mobilize additional financial resources.		
		17.4 Assist developing countries with debt sustainability.		
		17.5 Invest in least developed countries.		

	17.6 Enhance access to science, technology, innovation.	√	Uses modern research tools for innovation.
	17.7 Promote environmentally sound technologies.		
	17.8 Fully operationalize technology bank for LDCs.		
	17.9 Enhance international support for capacity-building.		
	17.10 Promote a universal, rules-based trading system (WTO).		
	17.11 Increase exports of developing countries.		
	17.12 Timely implementation of duty-free, quota-free market access.		
	17.13 Enhance global macroeconomic stability.		
	17.14 Enhance policy coherence for sustainable development.		
	17.15 Respect national policy space.		
	17.16 Enhance global partnerships.		
	17.17 Encourage multi-stakeholder partnerships.		
	17.18 Enhance data capacity of developing countries.		
	17.19 Support capacity-building for sustainable development indicators.		

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Abstract

This study evaluates the tracking performance of various positioning controllers for an XY milling table ball-screw driven system under dynamic cutting force disturbances. The objective was to determine the effectiveness of augmenting traditional feedback controllers with Feedforward (FF) compensation to improve precision. Four control strategies were designed and simulated in MATLAB/Simulink: a standalone PID controller, a PID with Feedforward (PID plus FF), a Cascade P/PID controller, and a Cascade P/PID with Feedforward (Cascade plus FF). Performance was assessed using Maximum Tracking Error (MTE), Root Mean Square Error (RMSE), and Fast Fourier Transform (FFT) analysis. Results demonstrated that the Cascade P/PID controller significantly outperformed the standalone PID, reducing RMSE by over 55%. The most effective strategy was the Cascade plus Feedforward controller, which achieved the lowest errors, reducing RMSE by 57.3% compared to the baseline PID and attenuating the dominant 26 Hz disturbance harmonic by 59.1%. The study concludes that the synergistic combination of cascade control and feedforward compensation provides superior tracking performance and disturbance rejection, making it the recommended strategy for high-precision CNC machining applications.

Summary

Modern industries like aerospace, automotive, and medical devices rely heavily on CNC milling machines to make precise parts. These devices move their cutting instruments along precise routes on an XY table. Defective items can result from even small mistakes. However, powerful and fluctuating forces disrupt the table's motion when cutting materials, making it more difficult for conventional controllers to maintain precision. This study examined various control strategies to determine which one maintains the table's accuracy in these circumstances. A simple PID, a PID with feedforward, a cascade controller, and a cascade with feedforward were the four controllers that were examined. Real cutting force data from milling operations was used to conduct computer simulations. According to the data, introducing feedforward had a significant impact even if the fundamental controllers still functioned fairly well. It made it possible for the system to predict motion requirements and minimize errors to a few micrometers. To test them fairly, the controllers were simulated using real cutting force data from milling operations at different spindle speeds. The performance was measured with key indicators: Maximum Tracking Error (MTE), Root Mean Square Error (RMSE), frequency analysis using Fast Fourier Transform (FFT) which show how closely the table followed its intended path. The results were clear. Under severe disruption, the simple PID and cascade controllers still displayed observable errors even if they offered respectable accuracy. The Cascade P/PID + feedforward controller, on the other hand, greatly decreased average and peak errors. By anticipating the necessary movement instead of only responding after it happened, feedforward assisted the system. It was better able to manage dynamic cutting forces according to its predictive capability, which kept errors to a few microns. Benefits include cheaper production costs, less rework, fewer material waste, and better product quality. This study concludes that feedforward enhanced control systems can increase the efficiency and dependability of CNC machines. They open the door to fast manufacturing and higher quality goods without requiring significant additional funding by reducing disruptions.

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Nomenclatures

Abbreviations	Meaning
PID	Proportional-Integral-Derivative
FF	Feedforward
CNC	Computer Numerical Control
MTE	Maximum Tracking Error
RMSE	Root Mean Square Error
FFT	Fast Fourier Transform
RPM	Revolutions Per Minute
2-DOF	Two-Degrees-of-Freedom
GM	Gain Margin
PM	Phase Margin
ADC	Analog-to-Digital Converter
DAC	Digital-to-Analog Converter
PLC	Programmable Logic Controller
PAC	Programmable Automation Controller
ILC	Iterative Learning Control
CV	Computer Vision
CNN	Convolutional Neural Network
NRE	Non-Recurring Engineering
ROI	Return on Investment

List of Symbols

Symbols	Meaning
$G(s)$	Plant transfer function (continuous-time)
$G_m(s)$	Specific plant model
$Y(s)$	System output (position, in laplace domain)
$U(s)$	Control input (motor command, in laplace domain)
s	Laplace variable
A, B, C	Coefficients of the second-order transfer function
T_d	Time delay
ω_n	Natural frequency
$G_c(s)$	Controller transfer function
$G_{PID}(s)$	PID controller transfer function
K_p	Proportional gain
K_i	Integral gain
K_d	Derivative gain
N	Derivative filter coefficient
$L(s)$	Open-loop transfer function
$T(s)$	Closed-loop transfer function
$H(s)$	Notch filter transfer function (continuous-time)
$H(z)$	Notch filter transfer function (discrete-time)
f_n	Notch frequency (26 hz)
Q	Quality factor (of the notch filter, ≈ 30)
T_s	Sampling period (0.001 s)
z	Z-transform variable
$u_{plant}[k]$	Plant input at discrete time step kk
$u_{PID}[k]$	PID controller output at discrete time step kk
$d[k]$	Disturbance input at discrete time step kk
$V_{ol}(s)$	Velocity open-loop transfer function
$P_{ol}(s)$	Position open-loop transfer function
K_v	Proportional gain for the outer position loop (408.07)
$\omega_{gc,v}$	Gain crossover frequency of the velocity loop (408 rad/s)
$\omega_{gc,p}$	Gain crossover frequency of the position loop (340 rad/s)
$e_p(t)$	Position tracking error

List of Units

Units	Meaning
mm	Millimeter
Hz	Hertz
rad/s	Radians per second
N	Newton (Unit of force)
dB	Decibel

CHAPTER 1

INTRODUCTION

1.1 Introduction

Machining precision is a fundamental requirement in CNC milling machines and other automated assemblies, especially in the high-stakes industries of the aerospace, automotive, and medical device sectors. A common design choice for achieving accurate linear motion involves using an XY axis milling table with ball screw drives. These elegant mechanisms convert the rotary motion of an electric motor into linear movement of the table, all while keeping backlash very low and maintaining high stiffness. For CNC systems, the X (and Y) drive must follow position commands very accurately to ensure that the cutting tool performs exactly as specified. While the high stiffness and low backlash of ball screws help maintain accuracy even under load, some tracking challenges do arise at high speeds. These disturbances stem from cutting forces during the machining process and the inertial reactions that occur with rapid changes in motion, potentially leading to position errors and compromising the geometrical accuracy of the machined parts.

The demand for greater productivity in the manufacturing arena is pushing cutting speeds and feed rates higher. This means that acceleration and deceleration forces acting on the moving table mass are larger, which can magnify any structural weaknesses. And of course, during the cutting operation, the interaction between the tool and the workpiece produces time-varying forces on the table. Cutting forces in milling are not only large but also exhibit a periodic or harmonic nature that is tied to the rotation of the spindle and the number of cutting teeth. Each time a tooth strikes the material, it generates a force pulse, resulting in force components that operate at the tooth-pass frequency and its harmonics. The input disturbances caused by the interaction of the tool and workpiece obviously affect the dynamics of the table. If your cutting conditions aren't ideal, or if your tools have the wrong geometry, the resultant forces will not only be large but also very non-ideal in terms of doing the job without inducing imprecision in the table's movements.

Traditional control approaches for positioning, such as single-loop PID feedback controllers, often struggle to maintain performance under these challenging conditions. Well-tuned PIDs

can handle slow or steady disturbances and eliminate static errors, but they have limitations in dealing with rapid or periodic force disturbances. For instance, a basic PID controller primarily reacts to position errors, and when it comes to predictable, frequency-specific disturbances introduced by cutting forces, a PID may not compensate effectively. This is particularly the case at higher spindle speeds or with multi-tooth cutters, where the disturbance frequency rises, and the loop may not respond quickly enough to cancel out these oscillatory errors. This can result in persistent periodic tracking errors at the disturbance frequency, which leads to poor machining accuracy. Cascade control architectures (e.g., a position loop with an inner velocity loop) improve disturbance rejection by handling motor dynamics more directly in the inner loop, but even they may be insufficient when facing strong harmonic disturbances without additional help. In summary, as cutting speeds increase and dynamic disturbances become significant, traditional feedback-only controllers are not quite up to the task. That is what motivates the present work.

1.2 Problem Statements

Identify the challenges in tracking performance in ball screw-driven systems. Several specific challenges degrade the tracking accuracy of ball screw-driven systems at high speeds and under variable cutting conditions:

- i. **Dynamic Limitations:** A PID controller cannot keep pace with large commanded position changes, particularly during acceleration and deceleration phases. The inertia associated with the moving table results in the need for considerable torque just to keep up with estimates. It is a well-known fact that a table's moving inertia is quite large, and a simple PID controller that a practitioner implements is likely to be tuned to ensure stability. Such a controller likely will not supply sufficient control effort to prevent stalling or overshooting during transients. Therefore, due to control effort inadequacy, the system experiences lag or overshoot in tracking both position and velocity.
- ii. **Load Variations:** Finishing passes, varying cutting depths, and changes in feed direction can reduce the effective bandwidth of the X-axis spindle controller. These variations introduce load changes that occur unpredictably based on the tool's engagement and cutting conditions. These vary every time the spindle rotational

speed or feed per minute is varied, so there's no set cutting force disturbance. As the revolution speed of the spindle or feed rate changes, the amount and frequency of cutting force disturbance shift correspondingly. These load disturbances invariably change. Relying solely on reactive control based on cutting force errors often compromises positional accuracy, especially when the system lacks anticipatory mechanisms to handle sudden force fluctuations. Lack of robust preemptive capabilities exposes the controller to unanticipated surges or drops in cutting force position.

- iii. **Vibration and Harmonic Disturbances:** At high feed speeds, the system is more prone to excite structural resonances or oscillatory modes. The ball screw, couplings, and machine frame have natural frequencies; if the disturbance (such as the periodic cutting force or motion-induced vibration) contains frequency components near these, it can cause amplified oscillations. These high-frequency oscillations not only deteriorate tracking precision but can also affect the surface finish of the machined part. Cutting forces with harmonic content (from multi-tooth cutters or imbalance) introduce repetitive errors that a simple controller may struggle to attenuate, leading to visible waviness or dimensional errors on the workpiece.

Traditional PID and other cascade P/PI types of controllers admittedly offer no such means to look ahead and allow a PID to correct errors after they happen. This absence of anticipatory (Feedforward) action in the controller leaves it consistently behind in its attempts to "catch up" with disturbances or set point changes, as opposed to avoiding errors. It is thus undesirable to use ordinary controllers to track references in view of the challenges. These problems are further exacerbated along the X-axis of the milling table where the cutting forces are generally greatest as a result of the cutting tool's motion and workpiece orientation.

To address these problems, this study proposes to augment the traditional control strategy with feedback and to evaluate advanced control configurations. By simplifying the analysis to a single axis (the X-axis) and neglecting friction effects, we isolate the primary sources of error namely, cutting-force disturbances and inertial loads due to high-speed motion. This focused approach allows a clearer investigation of how improved control schemes can mitigate the dynamic limitations, load variations, and vibration issues outlined above.

1.3 Objectives

The main goal is to evaluate the effectiveness of a Feedforward controller in improving tracking performance and reducing errors in an XY milling table. Considering the necessity for further refinement of disturbance rejection and tracking precision, this research aims to determine the impact brought about by adding Feedforward control to existing feedback controllers in a ball-screw-driven milling table positioning system. The goals include the following:

- i. **To design and implementation of controllers:** Develop four distinct control configurations for the X-axis of the XY milling table – namely:
 - a) a standalone PID position controller,
 - b) a PID controller with Feedforward compensation (PID plus FF),
 - c) a cascade controller with a proportional position outer loop and PI velocity inner loop (Cascade P/PI), and
 - d) a cascade controller augmented with Feedforward (Cascade plus FF). Each controller should be tuned to stabilize the system and provide good baseline performance in the absence of disturbances.

- ii. **To evaluate performance under disturbances:** Evaluate and compare the tracking precision obtained with the control strategies just described, across several different simulated test environments. Focus on how effectively the controllers perform when the system is subjected to "cutting force" disturbances. When reference tracking is disturbed in this manner, model the disturbances as harmonic force or torque inputs at various frequencies:
 - a) The frequencies should correspond to typical cutting conditions (realistic cutting conditions) that would affect the controller's performance, such as varying cutting speeds.
 - b) Also consider conditions representative of non-cutting operations, such as when the system tracks a reference composed of a linear combination of sinusoidal inputs ranging from 0.1 Hz to 1000 Hz.

- iii. **To identify the best control strategy:** For high-speed operation of the ball-screw drive, determine configurations that give the optimal positioning precision and disturbance rejection features. The criteria involve determining how much each approach offers error alleviation under changing disturbance conditions, along with how robust each approach is to variation in disturbance frequency or amplitude. The result will demonstrate the most suitable control strategy for precision CNC positioning under dynamic cutting interference disturbances, which will assist in the design of machine tool automation controls among the various control techniques tested, including PID, PID plus FF, Cascade, and Cascade plus FF.

1.4 Scopes

The scopes of this research are:

- i. **Focus on X-Axis Only:** All modeling, controller design, and experiments concentrate on the X-axis of the XY milling table. While the machine has two axes, the X-axis is selected because it generally experiences the largest forces during typical milling operations (for example, when cutting in the X direction, or due to the weight of the moving Y-axis assembly on it). By focusing on one axis, we simplify the system dynamics and avoid complications from multi-axis interactions such as cross-coupling or contour error. The Y-axis is held fixed and its effects are not considered in this study.
- ii. **Neglecting Friction Nonlinearities:** The control design and analysis do not include a detailed friction model. We assume that friction in the ball screw and guideways is low and mostly manifested as a constant or velocity-proportional damping (thanks to lubrication and the use of high-quality linear guide bearings). No explicit friction compensation (such as Coulomb or stick-slip friction modeling) is implemented. This simplification is made to focus on the impact of cutting force disturbances and inertial effects. It is assumed that any minor friction present is mitigated by proper lubrication and remains small relative to the disturbance forces of interest.
- iii. **Semi-Closed-Loop Control:** The positioning system is operated in a semi-closed-loop configuration, meaning the feedback sensor is the motor's rotary encoder rather than a direct linear scale on the table. This is a common industry practice in CNC machines due to cost and simplicity, but it implies that any flexibility or backlash

between the motor and the table can introduce slight discrepancies between the motor encoder reading and the actual table position. In our setup, the ball screw is preloaded to minimize backlash, and any compliance is relatively small. However, the semi-closed-loop nature is acknowledged in the analysis and small deflections in the drive may not be directly measured, potentially causing minor steady-state errors. The controller is designed with this in mind, but direct measurement of table position is outside the scope.

- iv. **Numerical validation:** The evaluation of controller performance is carried out through numerical simulations.

- v. **Performance Metrics:** The scope of performance analysis is centered on the defined metrics (MTE, RMSE, FFT of error). These metrics are chosen to give a comprehensive view of controller performance in the time domain (maximum and average error) and the frequency domain (error spectrum). Other effects like long-term thermal drift, spindle-induced vibrations, or tool wear are beyond the scope of this work. By constraining the problem to the immediate tracking error under controlled sinusoidal motion and known disturbances, we can clearly attribute any improvements in performance to the control strategy itself. Broader machining outcome measures (such as surface roughness or part dimension accuracy over long periods) are not directly measured; instead, we assume that reducing real-time tracking error directly correlates with improved machining accuracy.

By defining the scope in this way, the study isolates the impact of advanced control strategies on high-speed tracking performance. The simplifications (single-axis focus, no friction, simulated disturbances) remove confounding factors and allow a transparent evaluation of how Feedforward and cascade control contribute to disturbance rejection. While this means the results are obtained in a somewhat idealized setting, they provide valuable insight that can later be applied to more complex multi-axis systems or extended to include friction and other nonlinearities in future work. The findings will specifically inform controller design for precision ball screw drives in scenarios where cutting-force disturbances are a dominant concern.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction of Positioning Control Systems

A positioning control system is an advanced closed-loop control architecture designed to achieve and maintain precise spatial alignment of a mechanical or electromechanical system by regulating actuator outputs based on real-time feedback signals, thereby ensuring accurate tracking of reference trajectories and robust disturbance rejection under dynamic and uncertain operating conditions. Positioning control systems are essential for applications that demand precise control of motion and location, i.e. robotics, CNC machines, 3D printers, and aerospace systems. The purpose is to precisely position an object or system with minimal error, zero overshoot, ensuring smooth operation and minimum settling time. Several control strategies are used in positioning systems, such as PID, Cascade P/PI control etc. Astrom and Hagglund (2011) noted that despite the availability of many advanced control methods, PID controllers remain dominant in industry because they offer a favorable balance between performance, robustness, and simplicity. Sorensen, Sagatun, and Fossen (1996) created a model-based dynamic positioning system that enables reliable marine vessel tracking and station-keeping by combining model reference feedforward control, Kalman filter estimation, and a modified LQG feedback controller. By presenting a robust dynamic positioning control system for ships, Katebi et al. (2001) showed through tank tests and simulations that the method offers better robustness, less thruster modulation, and superior low-frequency disturbance rejection when compared to traditional techniques.

2.1.1 PID Control (Proportional-Integral-Derivative)

PID is the most widely used feedback control strategy due to its simplicity and effectiveness. PID regulators are widely employed in industrial applications due to their simple structure, despite the fact that improved PID controllers have been created in recent years to govern nonlinear systems. A PID controller which is combined with a Feedforward controller accelerates dynamic response.

The fundamental downside of the PID approach is that it results in a slower set-point response in exchange for reducing overshoot. For addressing this issue, an inverse model-based feedforward action is commonly used (Visioli, 2004). Since the proportional, integral, and derivative (PID) controller is widely used in the process industries, there has been significant resistance to incorporating other control approaches in practical scenarios. The primary reasons are the simplicity, robustness, and efficiency of PID based control mechanisms (Lee, Park, Lee, & Brosilow, 1998). The fundamental downside of the PID approach is that it results in a slower set point response in exchange for reducing overshoot. To address this issue, an inverse model-based feedforward action is commonly used (Visioli, 2004).

Well-tuned PID-based controls continue to be the industry standard due to their simplicity and resilience (Ang et al., 2005). Skoczowski et al. (2005) proposed a robust PID control approach that can be readily implemented using standard industrial hardware such as PLCs and PACs. The development of practical PID control can be traced back to 1939, when the Taylor Instrument Companies and the Foxboro Instrument Company introduced controllers that incorporated proportional, integral, and derivative actions. Three primary control effects are identified by the PID controller. While I and D controllers aid to lower steadystate error and enhance the system's transient response, respectively, the P controller contributes to the total control action proportionate to the error signal (Koren and Lo, 1992; Koren, 1997; Li et al., 2006).

Ang, Chong, and Li (2005) emphasized that PID controllers remain the dominant choice in industry, with over 90% of control loops still relying on them due to their simplicity and effectiveness. In an ongoing research, Li, Ang, and Chong (2006) highlighted persistent tuning challenges, noting that the derivative term, though designed to improve transient response can actually reduce stability when transport delays are present. Borase et al. (2020) reviewed the evolution of PID tuning, showing how research has advanced from classical rules such as Ziegler–Nichols to modern optimization and intelligent control methods for complex systems. Similarly, Knospe (2006) pointed out that PID's intuitive structure and long history have made it not only a practical industrial tool but also a standard component of undergraduate control education.

2.1.2 Cascade Control

Cascade control enhances performance by employing multiple control loops, with the output of one loop i.e. the outer loop serving as the reference for another. The Cascade P/PI controller belongs to the conventional group of controllers and this control structure is widely applied in most machine control algorithms. The cascade P/PI control consists of a PI controlled inner velocity loop with a P controller in the outer position loop (Abdullah et al., 2015). According to Seborg et al. (2011) and Jeng and Lee (2012), this control structure is well known for improving the control performance of several systems with disturbances. Due to its greater bandwidth than the outer loop, this inner loop can reject disturbances more quickly and effectively (Sarkar, 2015; Smeur et al., 2018).

Modern CNC milling machines use precise positioning control systems to achieve excellent tool motion accuracy. These systems often employ closed-loop feedback controllers with a cascaded topology that includes an inner velocity loop and an outer position loop (Altintas et al., 2011a). In a cascade control system, Lee et al. (1998) proposed tuning the inner and outer loop controllers using the Internal Model Controller (IMC) principles. A feedback controller only responds to mistakes after they occur, therefore any lag or phase delay might result in tracking problems when command trajectories or disturbances contain significant high-frequency content (Tomizuka, 1987; Altintas et al., 2011). The cascaded P-PI control, which combines a proportional position controller and a PI velocity regulator, is an effective arrangement for feed drive servos that provides appropriate bandwidth for most applications (Stojanovic & Nedic, 2016).

In order to achieve better disturbance rejection and set-point tracking than traditional cascade approaches, Kaya, Tan, and Atherton (2007) suggested an enhanced cascade control structure that incorporates a PI-PD Smith predictor in the outer loop and internal model control in the inner loop.

2.2 Ball Screw-Driven Systems

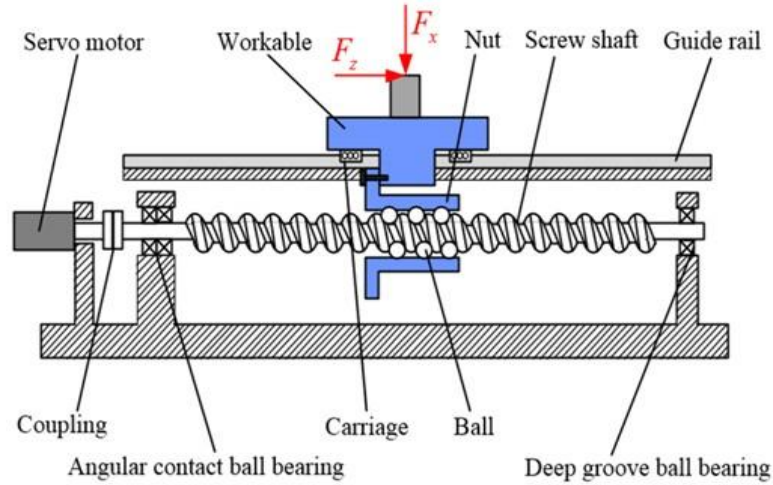


Figure 2.1: Ball-screw driven system

The modelling and control of ball screw feed-drive systems were critically reviewed by Huang et al. (2022), who discussed both conventional and cutting-edge approaches, including artificial intelligence, learning control, and data-driven techniques, while highlighting issues like vibration, friction, thermal error, and uncertainties. Ball screw-driven systems are among the most employed feed drive mechanisms in machine tool applications and broader electromechanical systems. Their popularity stems from advantages such as relatively low cost, high structural stiffness, and long operational life without stick-slip effects (Altintas et al., 2011b; Okwudire & Altintas, 2009). Structurally, these systems utilize a recirculating ball screw, also referred to as a ball bearing screw, which is composed of a screw, nut, and a series of balls that roll between the surfaces, reducing friction and enhancing service life (Chiew, 2013).

The principal function of the ball screw mechanism is to convert rotary motion from a motor into linear motion with high precision, efficiency, and reversibility. This mechanism is well-suited for integration into machines of varying sizes, feed rates, and force capacities (Altintas et al., 2011a; Pritschow & Philipp, 1990). Compared to other conventional mechanical drive systems, ball screws offer superior efficiency, typically operating at a minimum of 90%, making them ideal for applications requiring accurate linear motion and cost-effective performance (Hanifzadegan & Nagamune, 2014; Kamalzadeh & Erkorkmaz, 2007; Yamada & Kakinuma, 2016).

From a mechanical transmission standpoint, ball screw systems enable precise linear displacement by means of a threaded spindle and a spindle nut, between which ball chains circulate. These chains include spring elements that exert continuous pressure on the balls, ensuring stable contact and consistent force transmission. Importantly, the design ensures that at least one spring element is always engaged in the deflection zone of the ball channel, thereby maintaining preload and reducing backlash (Mayer et al., 2003).

An important dynamic aspect of ball screw systems involves the torque generated during axial thrust transmission between the screw and the nut. Accurately predicting the system's resonant frequencies and stiffness requires dynamic models that incorporate not only preload mechanisms but also torque transmission effects. Advanced models that capture these dynamics have demonstrated better agreement with experimental results compared to traditional models, making them essential tools for optimizing system performance (Li et al., 2017).

Mechanical tracking errors, caused by inertial, frictional, and external forces, can lead to axial elongation and compression, reducing tracking accuracy. Feed-forward compensation methods based on dynamic models that include torque transmission and friction parameters can effectively eliminate most tracking errors, improving the overall accuracy of ball screw drives (Li et al., 2018).

2.3 Feedforward Control

Feedforward control is a proactive control approach used in engineering and automation to enhance system performance by predicting disturbances before they impact the process. Feedforward control works by detecting disturbances before they enter the system and taking corrective action to mitigate their effects. The basic idea is to use a process model to predict how disturbances will impact the output and then alter the control signal accordingly.

Industrial feedforward control technologies were thoroughly reviewed by Liu et al. (2018), who also described typical algorithms for reference tracking and disturbance rejection, their application domains, and implementation, robustness, and stability issues. Feedforward control uses a system model or input information to directly apply a compensatory control action as it is opposed to feedback which reacts to error. In a positioning system, feedforward often implies sending an additional instruction to the servo motor based on the desired

trajectory so that it can achieve motion without the need for error-driven correction. The feedforward channel also handles the predictable part of the control effort, while feedback addresses the unmodeled or unpredictable parts (Ang et al., 2005; Liu et al., 2019). Feedforward has two key applications in servo systems i.e. reference tracking and disturbance rejection. The primary drawback of the PID technique is that, in exchange for less overshoot, it causes a delayed set-point reaction. A feedforward action based on an inverse model is frequently employed to address this problem (Visioli, A., 2004).

The use of feedforward design requires caution because residual errors are directly impacted by model flaws. The feedback loop may have to correct for overcompensation or under compensation if the feedforward model is too basic, such as assuming a constant mass and no friction. Even defective Feedforward, as long as it is appropriately calibrated, can be beneficial because it relieves the feedback controller of labor. It essentially converts the control system to a two-degrees-of-freedom (2-DOF) system, with one DOF i.e. Feedforward path shaping the reference response and the other feedback path molding the disturbance response and assuring stability (Ang et al., 2005). This separation is beneficial as it allows for better tracking without compromising disturbance rejection capacity and vice versa. For example, increasing acceleration Feedforward gain might reduce following error on quick moves without increasing the feedback loop's aggressiveness which could destabilize the system. The end result is faster rise times and smaller latency, while feedback stability margins remain the same (Liu et al., 2019).

2.4 Research Gaps

Extensive research has been conducted on positioning control for machine tools, with particular focus on improving tracking performance in the presence of disturbances like friction, cutting force, thermal effects etc. This section summarizes key findings and gaps from previous studies, focusing on controllers similar to those evaluated in this research: PID controllers, Feedforward compensation, cascade structures, and their combinations. Guzmán and Hägglund (2021) examined feedforward control tuning rules in conjunction with PID controllers, covering its historical evolution, resolving implementation issues such as delay inversion, and outlining current developments that enhance load disturbance rejection and control performance. Chen and Lee (1999) performed an early example on a modified milling machine by using direct velocity and acceleration Feedforward along with a PID feedback loop.

Stojanovic and Nedic (2016) provided a direct comparison of Feedforward and no-Feedforward in a cascaded loop in a different domain like hydraulic parallel robot platform in which they found that including Feedforward considerably improved tracking, thus they developed an optimization-based tweaking method for the Feedforward benefits. Though their solution is hydraulic, the outcome is consistent with what we expect from electromechanical drives i.e. Feedforward offers a significant tracking advantage. Similarly, in case of robotics, Kempf and Kobayashi (1999) demonstrated in hard disc drive servos in which disturbance Feedforward i.e. using a disturbance observer to estimate repetitive runout and feeding forward a cancelling signal significantly improved disc read/write head tracking. This is similar to machine tool drives in which repetitive disturbances for example, cutting force harmonics can be controlled by Feedforward action.

However, there is still inadequate validation for its direct application to machining settings with complex, non-repetitive disturbances. Zhu et al. (2023) suggested an integral sliding mode controller with an extended state observer for a flexible ball-screw-driven system which can handle both matched and mismatched disturbances. While their approach is more sophisticated than classical PID, it has an intrinsic Feedforward-like component which produces very low tracking errors under varied loads. They also demonstrated increased robustness to disturbances. This suggests that even with advanced nonlinear controllers, the idea of anticipating the required control action i.e. Feedforward is critical to optimal performance. Returning to CNC machines, Gordon and Erkorkmaz (2013) completed an important work on a ball-screw drive that closely paralleled the objectives of this thesis. They compared a standard cascade controller to an advanced controller that used pole-placement design, feedforward, and a trajectory prefilter. Feedforward control has also been tested in conjunction with other methods. For example, several studies combine feedforward with repetitive control or learning control to address both repetitive and non-repetitive components of error. Zhang and Yao (2004) included feedforward terms into an adaptive robust control framework for a ball-screw drive in which their controller included a model-based feedforward to manage nominal dynamics and an adaptive component to deal with uncertainties. Previous studies have consistently demonstrated that adding feedforward to a positioning controller reduces the size of tracking errors. This reduction is especially noticeable during periods of rapid acceleration and when compared to periodic or reference-following jobs.

CHAPTER 3

METHODOLOGY

3.1 Introduction

This chapter outlines the systematic approach employed to evaluate the tracking performance of various positioning control strategies with Feedforward on the X-axis of an XY milling table driven by a ball-screw mechanism. The methodology is divided into three main phases: understanding the research problem and developing a system model, designing and simulating controllers, and analyzing the resulting performance. Each phase is structured to ensure that the influence of cutting force disturbances on positioning accuracy is rigorously modeled and assessed. The methodology integrates theoretical modeling, MATLAB/Simulink-based simulations, and performance evaluation using key tracking metrics such as Maximum Tracking Error (MTE), Root Mean Square Error (RMSE), and Fast Fourier Transform (FFT) analysis. This structured approach ensures that the findings are both valid and relevant for improving precision in milling operations under real-world disturbance conditions. Below, the overall research methodology is shown through a flowchart with brief descriptions.

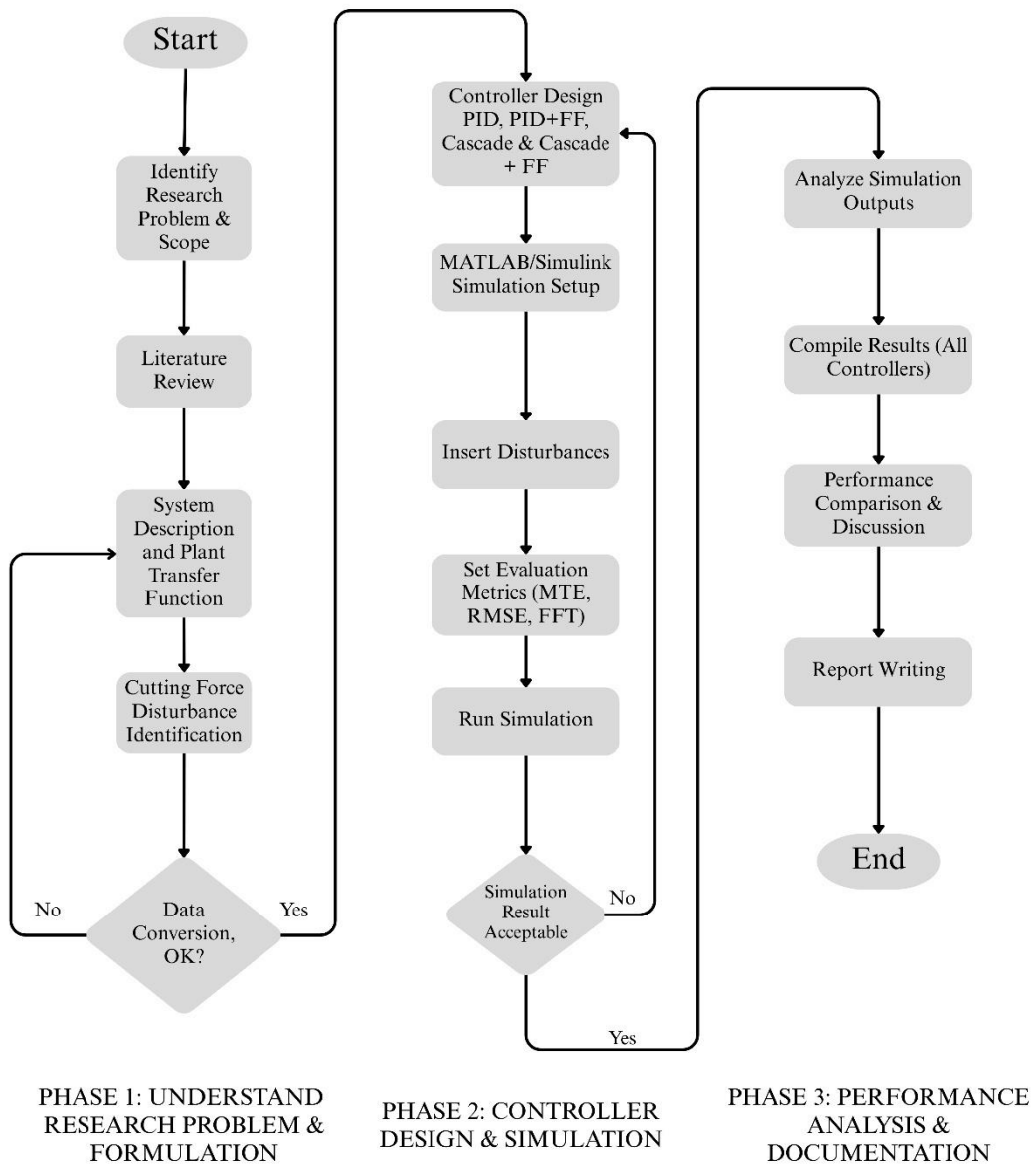


Figure 3.1: Methodology flowchart

3.2 Phase 1: Understand Research Problem and Modelling

i. Identify Research Problem, Objective and Scope

This step defines the research issue: improving positioning accuracy and cutting force disturbance rejection of an X-axis motion system in a milling machine. The objective is to evaluate various control strategies (e.g., PID, PID plus FF, Cascade, Cascade plus FF) under realistic disturbances, especially cutting forces. The scope is limited to one axis (X-direction) and considers only cutting force as a disturbance.

ii. Literature Review

A critical review of existing work in precision control of CNC and milling machines, focusing on:

- Ball-screw-driven systems.
- Disturbance sources (e.g., cutting forces).
- Control strategies include PID, Feedforward, and cascade systems.
- Use of MATLAB/Simulink for modeling and simulation.

iii. System Description and Plant Transfer Function

Transfer function derivation position response to input torque or voltage.

$$G_m(s) = \frac{78020}{s^2 + 163s + 193.3}$$

iv. Cutting Force Disturbance Identification

Defines and models the disturbance input acting on the system, based on machining dynamics. This includes

- Direction and nature of force (only in the X-direction).
- Magnitude based on machining operation.
- Representation in simulation as an external input force/disturbance.

v. Data Conversion

Verifies whether the collected data (e.g., experimental, literature-based) can be used directly or needs transformation (e.g., unit conversion, signal conditioning). If it is not acceptable, then refinement is needed.

3.3 Phase 2: Controller Design and Simulation

- i. Designs the four control architectures (PID, PID plus FF, Cascade, Cascade plus FF)
 - **PID**: Standard feedback control to track reference and reject disturbances.
 - **PID plus FF**: Adds Feedforward from reference input for improved tracking.
 - **Cascade**: Secondary inner loop (e.g., velocity) for faster disturbance rejection.
 - **Cascade plus FF**: Combines inner-loop and Feedforward for enhanced performance.

- ii. **MATLAB/Simulink Simulation Setup**

Implements the plant and controller models in Simulink. Includes:

 - Importing transfer function.
 - Configuring simulation blocks (e.g., controller, summation points, scope, etc.)

- iii. **Insert Disturbance Inputs**

Applies identified cutting force disturbance as an external input during simulation to evaluate how controllers manage the real-world scenario.

- vi. **Set Evaluation Metrics (MTE, RMSE, FFT)**

Defines performance metrics for comparison:

 - **MTE (Maximum Tracking Error)**: Worst-case deviation from reference.
 - **RMSE (Root Mean Square Error)**: Overall tracking accuracy.
 - **FFT (Fast Fourier Transform)**: Frequency-domain analysis of response (to evaluate resonance, noise sensitivity, etc.).

- v. **Run Simulation**

Executes simulations under identical test conditions (reference signal plus disturbance) for each controller.

- vi. **Simulation Results Acceptable?**

Checks if the system meets the performance criteria. If not, tuning is repeated.

3.4 Phase 3: Performance Analysis and Documentation

- i. **Analyze Simulation Outputs:** Examines simulation results to assess
 - Tracking accuracy.
 - Disturbance rejection.
 - Controller stability.

- ii. **Compile Results (All Controllers)**

Gathers results from each controller configuration into a comparative dataset/table for analysis.

- iii. **Performance Comparison and Discussion**

Discusses which controller performs best under cutting force disturbance and why, considering

 - Response time.
 - Overshoot.
 - Robustness to disturbance.

- vi. **Report Writing**

Compiles all findings, designs, simulations, and analyses into a structured thesis document.

3.5 System Description

The system under study is the X-axis of a precision XY milling table driven by a ball-screw mechanism. This axis is driven by a rotary servo motor that drives a ball-screw to translate the table in the X-direction. The motor's rotary motion is converted into linear motion of the table through the ball-screw, which has high stiffness and minimal backlash to ensure precise positioning. The control input to the system is the motor drive command (voltage or equivalent current command), and the output is the table's linear position along the X-axis. A high-resolution encoder is typically attached to the motor or table to provide feedback on the position. In the context of this simulation study, we model the X-axis drive system as a linear time-invariant system, capturing the dominant dynamics of the motor and ball-screw assembly while simplifying or neglecting higher-order effects. Friction and other nonlinear effects (such as backlash or stick-slip) are excluded from the model to focus solely on the

influence of cutting force disturbances. This means that in simulation, the only external disturbance acting on the axis is the cutting force, and any frictional forces are assumed to be either negligible or already compensated, allowing us to isolate the disturbance rejection capabilities of the controllers.

3.6 Dynamics of the X-axis

Based on prior system identification work (from experimental frequency response analysis of the milling table), the X-axis can be approximated by a second-order dynamic model with a time delay. The open-loop transfer function of the table X-axis (position output per drive input) behaves like a lightly damped second-order system. This second-order behavior arises from the motor inertia and the mechanical compliance of the ball-screw and table. The time delay (on the order of a millisecond) represents computational and transport delays in the drive and measurement. For simulation purposes, these dynamics are represented by a continuous transfer function of the form:

$$G(s) = \frac{A}{s^2 + Bs + C} e^{-T_d s}$$

Where,

A: DC gain of the system (overall magnitude of output per input).

B: Damping coefficient (controls how fast the oscillations die out).

C: Square of the natural frequency ω_n^2 , which determines how fast the system responds.

T_d: the small delay.

Here

$$Y(s) = G(s)U(s)$$

Where:

$U(s)$ = control signal (what you send to the motor),

$Y(s)$ = actual position of the table.

Denotes the Laplace-domain relation between the output position $Y(s)$ and the control input $U(s)$. In this notation, $Y(s)$ corresponds to the table X-axis position output, and $U(s)$ is the controller output or motor command input. The system has one fast pole associated with the electrical drive and motor, and one slower pole associated with the mechanical motion of the table. For example, an identified model for a similar ball-screw drive showed a dominant

low-frequency pole (mechanical mode) around a few hertz and a high-frequency pole (motor dynamics) above 20 Hz, with an overall DC gain on the order of a few hundred (mm movement per volt command) when expressed in appropriate units. The damping of the mechanical mode is moderate, ensuring stability but allowing some oscillatory response if excited. In the context of a position control loop, this second-order plant model provides the basis for controller design and simulation. The controller must stabilize this plant and ensure accurate tracking despite disturbances.

3.7 Spectral Analysis of Cutting Force

To assess the frequency characteristics of the cutting force disturbance, we perform Fast Fourier Transform (FFT) on the time-domain disturbance signal. This analysis helps identify the dominant frequency components and their harmonics, which influence the system's response. The time-domain cutting force (top plot) shows the fluctuations in the force applied to the milling table. The FFT plot (bottom plot) represents the frequency content of this disturbance. The dominant peak at 26 Hz corresponds to the fundamental frequency of the disturbance, and the harmonics (e.g., 52 Hz, 78 Hz) are related to the tooth pass frequency and the tool's interaction with the material.

- P1: The first frequency peak at 0.26 Hz corresponds to the fundamental oscillation at low frequencies.
- P2: The second peak at 26.0 Hz (with an amplitude of 7.97 N) is the primary disturbance frequency induced by the tool's rotation.
- P3: The third peak at 104 Hz (with a force of 2 N) represents higher-order harmonics of the system.

This spectral information is crucial for designing controllers that can handle these oscillations efficiently. The FFT analysis helps in understanding how the disturbance will affect the system at different frequencies and how well each control strategy can reject these disturbances.

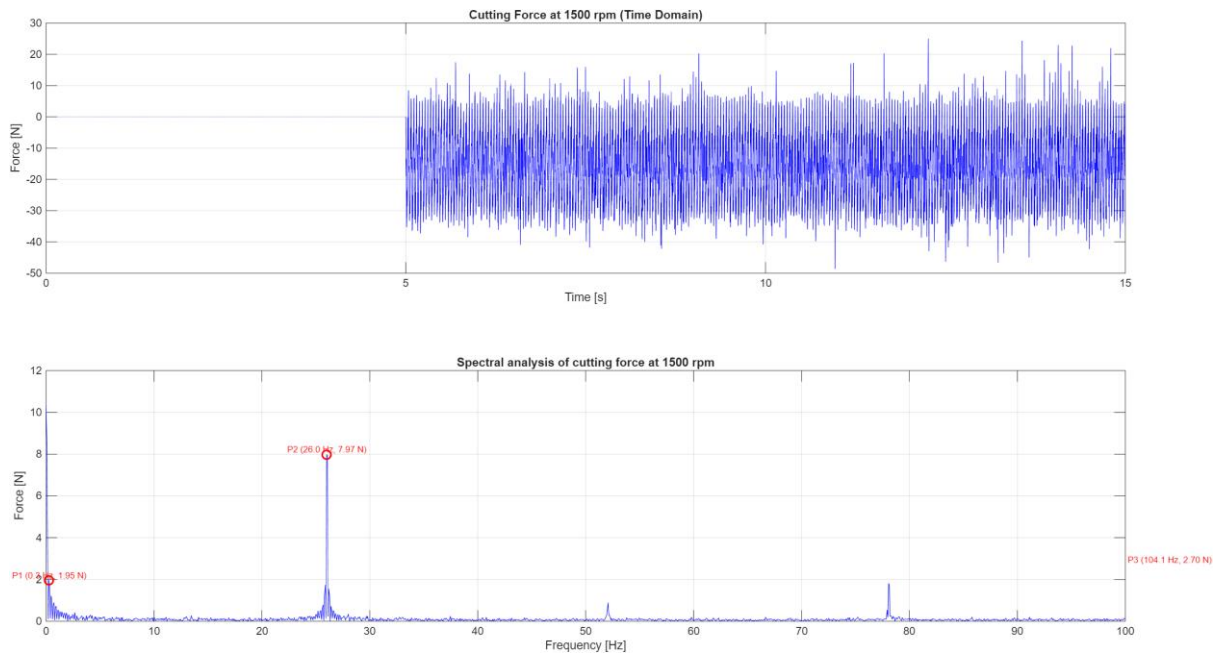


Figure 1.2: Time-domain and frequency-domain analysis of cutting force disturbance at 1500 RPM

The above graph shows the time-domain cutting force disturbance (top) and its corresponding spectral analysis (bottom) after applying the Fast Fourier Transform (FFT). The time-domain plot shows the oscillatory nature of the force applied by the tool. The spectral analysis reveals the primary disturbance frequency at 26.0 Hz along with its harmonics (e.g., 52 Hz and 78 Hz). The primary peak corresponds to the fundamental frequency due to tool rotation, while the harmonics are influenced by the number of cutting teeth and the tool-material interaction.

3.8 Experimental Setup

The experimental setup comprises interconnected software components configured for real-time control and data analysis:

i. Software

- **MATLAB/Simulink:** Used for system identification, controller and observer design, numerical simulations, and generating real-time code for the dSPACE board via Real-Time Workshop (RTW) or Simulink Coder.
- **dSPACE ControlDesk:** Software providing the user interface for experiments. It allows users to interact with the real-time application running on the DS1104

board, change parameters, start/stop experiments, and log data from the system (e.g., encoder position, control signals, estimated values).

- **Kistler Dynaware:** (Used for cutting force characterization). Software used with the Kistler dynamometer system for acquiring, visualizing, and analyzing the measured cutting force data.

ii. **Data Acquisition and Signal Flow:**

- **Position Feedback:** Incremental encoders on the motors send digital pulse signals to the DS1104 board encoder inputs. The board decodes these pulses to determine the axis position.
- **Control Output:** The control algorithm running on the DS1104 board calculates the required motor voltage. This digital value is converted to an analog voltage signal by the board's DAC.
- **Amplification:** The analog voltage signal from the DAC is sent to the servo amplifier, which drives the corresponding AC servo motor.
- **Data Logging:** ControlDesk logs desired variables (reference position, actual position, error, control signals, observer estimates, etc.) from the real-time application at the specified sampling rate (e.g., 2000 Hz) for offline analysis.

iii. **Cutting Force Measurement (for characterization):**

The Kistler dynamometer outputs charge signals proportional to force components. These are converted to voltage by a charge amplifier, acquired (potentially via the DS1104 ADC or a separate DAQ system), and processed using Dynaware.

CHAPTER 4

DESIGN OF CONTROLLER

4.1 PID Controller

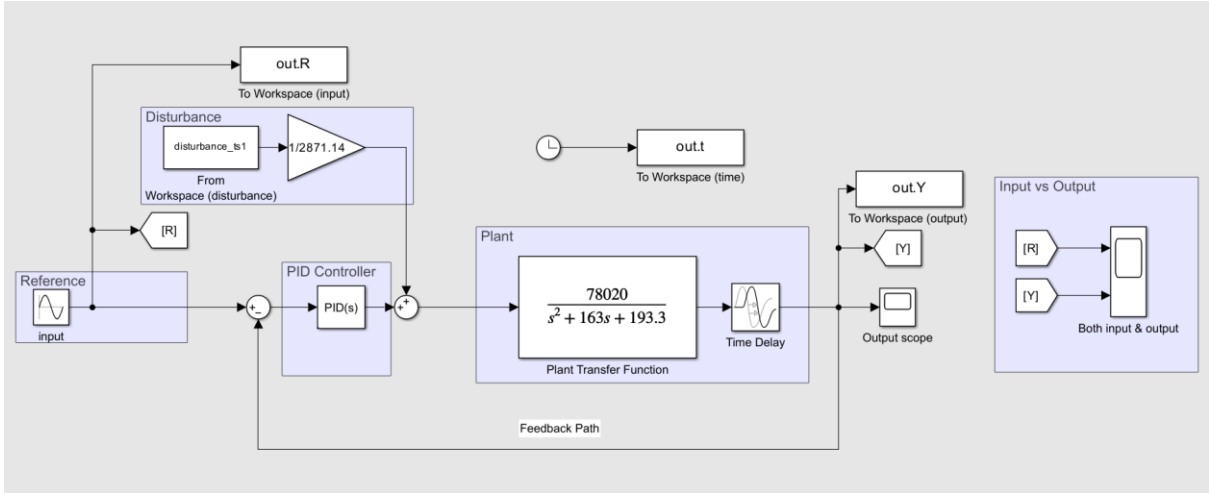


Figure 2.1: PID Controller

The Proportional-Integral-Derivative (PID) controller is one of the earliest and most widely applied control strategies in industrial applications due to its simple structure and effective performance across a broad range of systems (Ogata, 1997; Åström and Wittenmark, 2013). A standard PID controller consists of three terms: proportional (P), integral (I), and derivative (D). The proportional term produces an output proportional to the error, the integral term eliminates steady-state error by accumulating the past error, and the derivative term predicts future error trends to improve transient response. The general transfer function of the ideal PID controller is given as:

$$G_{PID}(s) = k_p + \frac{k_i}{s} + k_d s$$

where k_p , k_i , and k_d denote the proportional, integral, and derivative gains respectively. Each parameter influences the closed-loop response differently: increasing k_p reduces rise time but may increase overshoot, k_i eliminates steady-state error but slows settling, and k_d improves damping and reduces overshoot at the cost of sensitivity to noise (Koren, 1992; Li et al., 2006). In this study, the PID controller is employed to regulate the position of the

milling table system. The block diagram in figure, illustrates the control loop, where the reference input is compared with the system output, and the error signal drives the PID controller. The controller output is applied to the plant transfer function:

$$G_m(s) = \frac{78020}{s^2 + 163s + 193.3}$$

A small transport delay is also considered in the plant dynamics. In addition, an external disturbance input (1500RPM, 2500RPM, 3500RPM) is introduced to evaluate the disturbance rejection capability of the control system. The open-loop transfer function of the system is expressed as:

$$L(s) = G_c(s)G_m(s)$$

where $G_c(s)$ is the controller transfer function. The corresponding closed-loop transfer function is:

$$T(s) = \frac{G_c(s)G_m(s)}{1 + G_c(s)G_m(s)}$$

characterizes the ability of the system to suppress disturbances and measurement noise. Tuning of the PID parameters was performed with the objective of achieving a balance between tracking accuracy, disturbance rejection, and robustness. In practice, loop shaping in the frequency domain is a common approach to ensure satisfactory gain margin and phase margin, with typical design targets of at least 6 dB and 40° respectively (Skogestad and Postlethwaite, 2010). These ensure adequate robustness while maintaining acceptable transient response. The implemented controller thus provides a compromise between speed of response, overshoot, and robustness against disturbances, making it a suitable choice for the positioning control of the milling table system under study.

4.1.1 PID Tuning

The PID controller was tuned to achieve a balance between fast response, disturbance rejection, and robust stability. The controller was implemented in the parallel form:

$$G_c(s) = K_p + \frac{K_i}{s} + \frac{K_d s}{1 + \frac{s}{N}}$$

where K_p , K_i , and K_d represent the proportional, integral, and derivative gains, respectively, and N denotes the derivative filter coefficient used to limit high-frequency noise amplification. Table 4.1 summarizes the final tuning parameters obtained using MATLAB's PID tuning toolbox. Two equivalent sets of values are listed; normalized gains (K_p , K_i , K_d) and the corresponding absolute scaling used in the actual implementation. The controller gains were selected to ensure

- **Adequate phase margin** for robust stability.
- **Integral action** to remove steady-state error in tracking tasks.
- **Derivative action** to improve transient response and reduce overshoot.
- **Filter coefficient** to mitigate derivative noise sensitivity.

Table 4.1: Tuning Values of PID controller

Controller	k_p	k_i	k_d	Filter coefficient
PID	0.957	0.369	0.005	48017.982

Table 4.2: GM & PM of PID

Gain margin	Phase margin
9.46 dB at 1280 rad/s	58.4 deg at 434 rad/s

The tuning criteria for the PID demanded a Gain Margin (GM) of at least 6 dB and a Phase Margin (PM) of at least 40° as listed in table 4.2 above. These conditions ensure the system robustness, allowing it to withstand disturbances and maintain stable transient response performance.

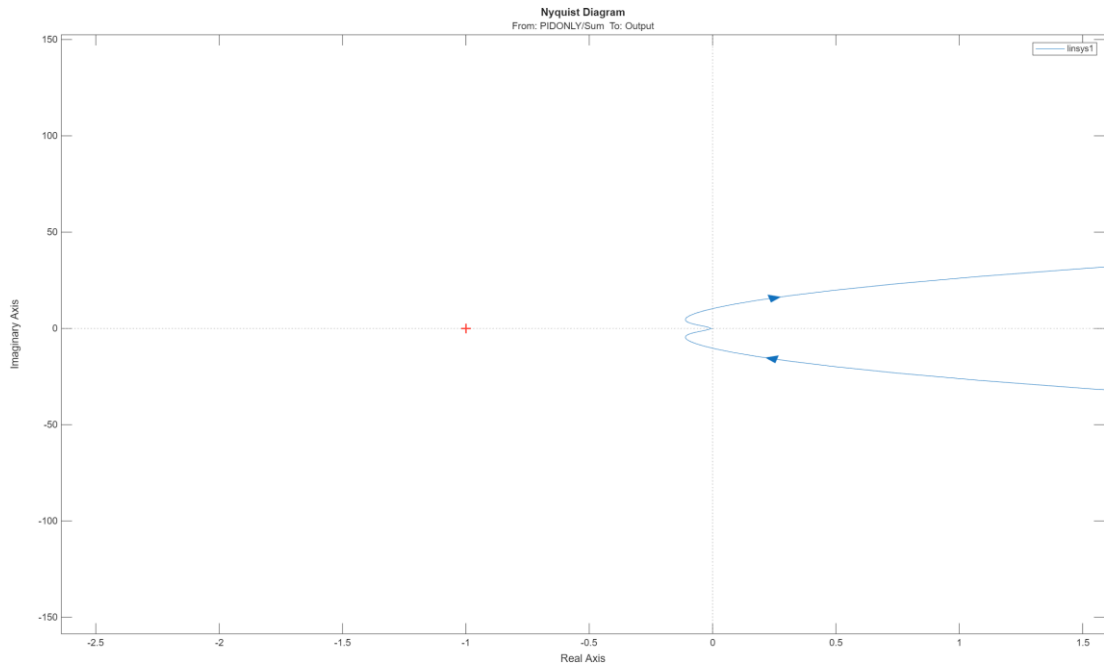


Figure 4.2: Nyquist Plot for PID

The closed-loop stability of the resulting design was confirmed by the Nyquist plot. The plot shows that the open-loop frequency response does not encircle the $(-1,0)$ point, which verifies that the closed-loop system remains stable under the chosen PID parameters.

4.2 PID plus Feedforward Controller

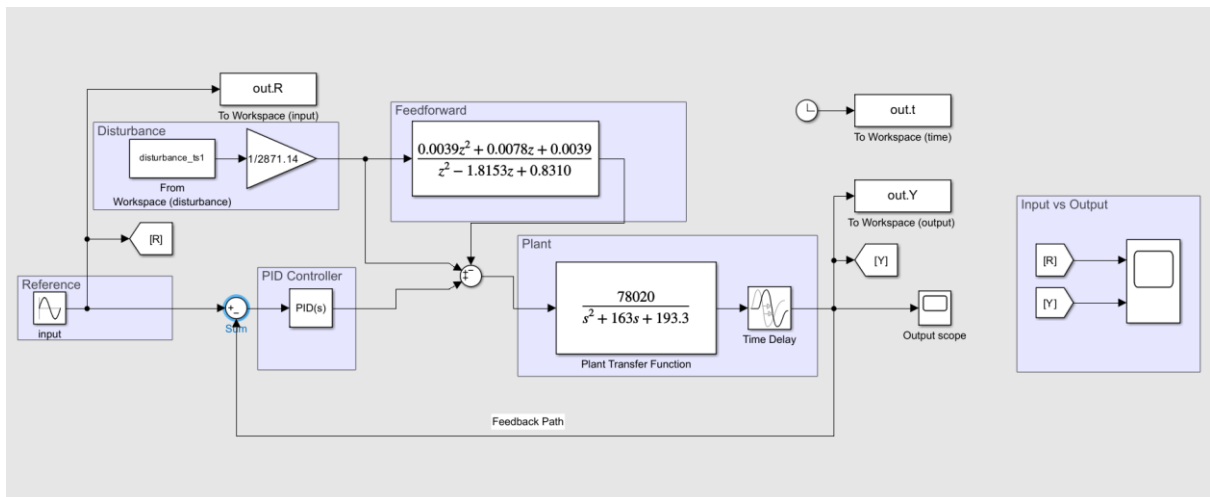


Figure 4.3: PID plus Feedforward Controller

4.2.1 Motivation for Feedforward Compensation

While the PID controller provides reliable feedback-based regulation, its ability to reject disturbances is inherently constrained by loop bandwidth and stability margins.

Disturbances that act directly on the plant input are particularly difficult to suppress rapidly using feedback alone, since corrective action only occurs after the disturbance has propagated to the output. To address this limitation, a feedforward compensation path was introduced. The purpose of the feedforward path is to process a measured disturbance signal and inject an opposing control action directly at the plant input, thereby reducing the effect of the disturbance before it propagates through the system dynamics.

4.2.2 Disturbance Characterization

The disturbance signal was recorded during the cutting process and analyzed in the frequency domain using the Fast Fourier Transform (FFT). The spectrum revealed a dominant narrowband component centered at 26 Hz. This frequency was identified as the principal contributor to the oscillatory disturbance observed in the plant output. Since the disturbance is concentrated at a single frequency, a notch filter was chosen as the feedforward compensator to selectively attenuate this component without significantly affecting the rest of the spectrum.

4.2.3 Notch Filter Design in Continuous Time

A standard second-order notch filter can be expressed as:

$$H(s) = \frac{s^2 + \omega_n^2}{s^2 + \frac{\omega_n}{Q}s + \omega_n^2}$$

where $\omega_n = 2\pi f_n$ is the notch frequency in rad/s, with $f_n = 26$ Hz, and Q is the quality factor. A value of $Q \approx 30$ was selected to ensure that the notch is narrow and does not significantly affect neighboring frequencies. Substituting the design parameters gives:

$$H(s) = \frac{s^2 + (2\pi \cdot 26)^2}{s^2 + \frac{2\pi \cdot 26}{30}s + (2\pi \cdot 26)^2}$$

This transfer function attenuates the 26 Hz disturbance component while leaving most of the frequency spectrum unaffected.

4.2.4 Discrete - Time Implementation

The system operates at a sampling frequency of 1000 Hz, corresponding to a sampling period

of:

$$T_s = \frac{1}{1000} = 0.001 \text{ s}$$

To implement the notch filter in discrete time, the bilinear transform (Tustin approximation) was applied:

$$s = \frac{2}{T_s} \cdot \frac{1 - z^{-1}}{1 + z^{-1}}$$

Substituting this into the continuous transfer function yields a rational discrete transfer function of the form:

$$H(z) = \frac{b_0 + b_1 z^{-1} + b_2 z^{-2}}{1 + a_1 z^{-1} + a_2 z^{-2}}$$

The coefficients (b_i, a_i) were computed numerically and implemented directly in Simulink using the Discrete Transfer Function block. The resulting implementation is shown in Figure.

4.2.5 Feedforward Path Integration

The feedforward compensation path consists of two main stages:

- i. **Notch Filter:** The measured disturbance is processed through the discrete-time notch filter $H(z)$, which selectively attenuates the 26 Hz frequency component.
- ii. **Summation with Negative Sign:** The filtered signal is inverted and added to the plant input alongside the PID controller output. The plant input can be expressed as:

$$u_{\text{plant}}[k] = u_{\text{PID}}[k] + d[k] - H(z)d[k]$$

where $u_{\text{plant}}[k]$ is the output of the PID controller and $d[k]$ is the measured disturbance.

This configuration ensures that the dominant 26 Hz disturbance is suppressed before entering the plant. The PID controller continues to regulate the tracking performance and compensate for residual disturbances and model uncertainties. As a result, the PID plus feedforward control strategy achieves improved disturbance rejection, reduced oscillations, and enhanced closed-loop performance, while maintaining the robustness of the feedback loop.

4.3 Cascade P/PID Controller

The Cascade P/PID architecture is chosen as the primary feedback structure because it provides enhanced disturbance rejection capabilities compared to a single-loop PID controller. This is made possible by dividing the control tasks into nested loops, allowing for better control of different dynamics within the system. This design approach leverages the loop shaping technique in the frequency domain, which is known for its reliability. This method focuses on maximizing the system's bandwidth while maintaining robust stability margins. By prioritizing these factors, the architecture ensures both efficient performance and stability even in the presence of disturbances.

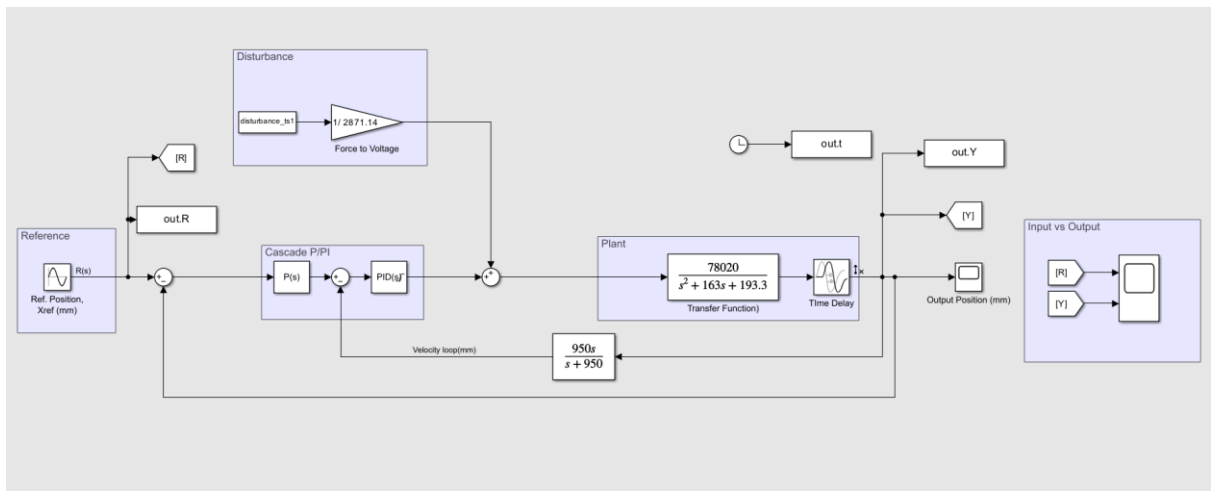


Figure 4.4: Cascade P/PID Controller

4.3.1 Inner Velocity Loop (PI) Design

The design process begins with the inner velocity loop, as its closed-loop dynamics define the environment for the outer position loop.

The main objective of tuning the velocity loop was to achieve high bandwidth while ensuring the stability of the system. The velocity open-loop transfer function, denoted as $V_{ol}(s)$, which is defined as:

$$V_{ol}(s) = PID(s) \times G(s) \times Vest(s)$$

The tuning criteria for the velocity loop demanded a Gain Margin (GM) of at least 6 dB and a Phase Margin (PM) of at least 40°. These conditions ensure the system's robustness, allowing it to withstand disturbances and maintain stable transient response performance.

Table 4.3: Lists the PI controller parameters for the x-axis of the XY positioning system

Loop	k_p	k_i	k_d	Filter coefficient
Velocity	0.00563	0.76358	0.00001	46750.991

Table 2.4: Gain margin and phase margin of the velocity open loop

Gain margin	Phase margin
7.18 dB (at 1540 rad/s)	82.8 (at 409 rad/s)

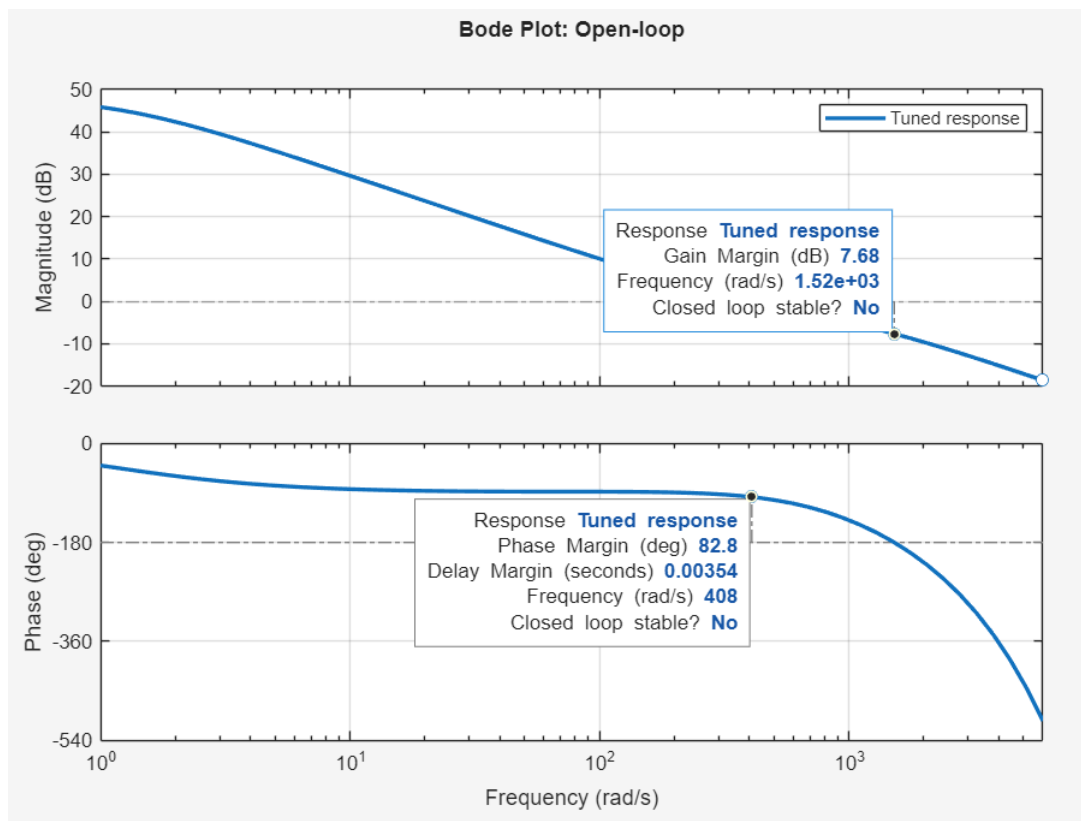


Figure 4.5: Bode diagram of the velocity open-loop transfer function

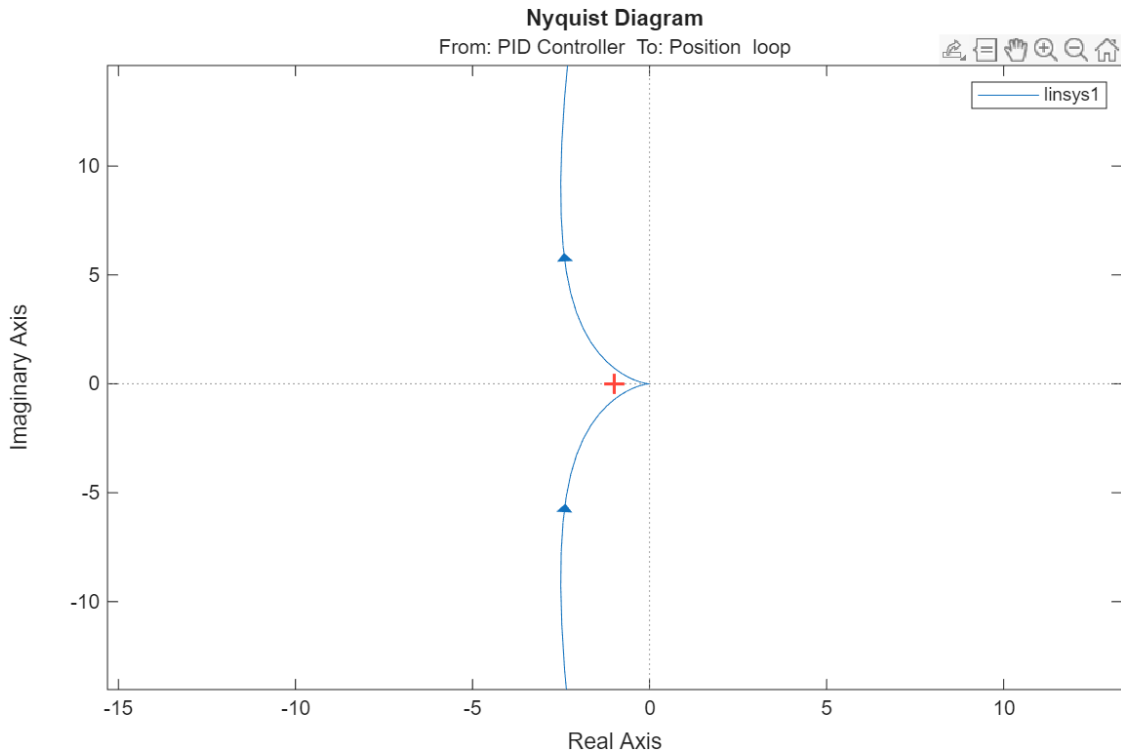


Figure 4.6: Nyquist plot of the velocity open-loop transfer function

The stability of the velocity loop was verified graphically by the Nyquist plot, which confirmed that the critical point $(-1,0)$ was not encircled.

4.3.2 Outer Position Loop (P) Design and Performance Optimization

With the inner velocity loop stabilized and fixed, the outer position loop is then tuned. This loop utilizes a simple Proportional (P) controller, $P(s)=K_v$, which provides stiffness against position tracking errors, $e_p(t)$.

The open-loop transfer function, $P_{ol}(s)$, incorporates the dynamics of the closed inner loop:

$$P_{ol}(s) = \frac{P(s) \times V_{cl}(s)}{s}$$

The proportional gain, K_v , was adjusted iteratively based on ensuring robust stability margins for $P_{ol}(s)$ and optimizing the overall closed-loop transient performance. The optimized P-gain for the outer position loop was applied:

$$K_v=408.065215497263$$

Table 4.3: Gain margin and phase margin of the position open loop

Gain margin	Phase margin
6.41 dB (at 1300 rad/s)	66.1 (at 340 rad/s)

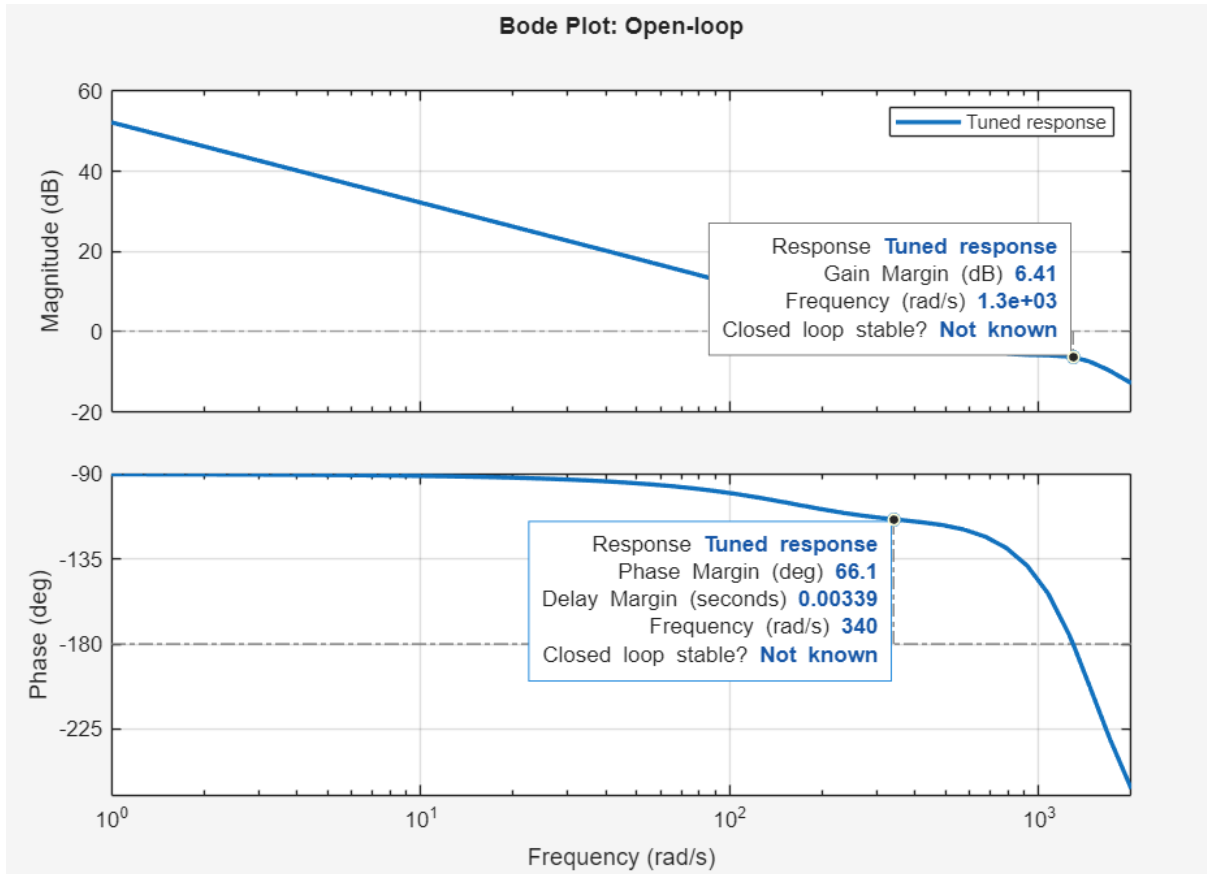


Figure 4.7: Bode diagram of the velocity position-loop transfer function

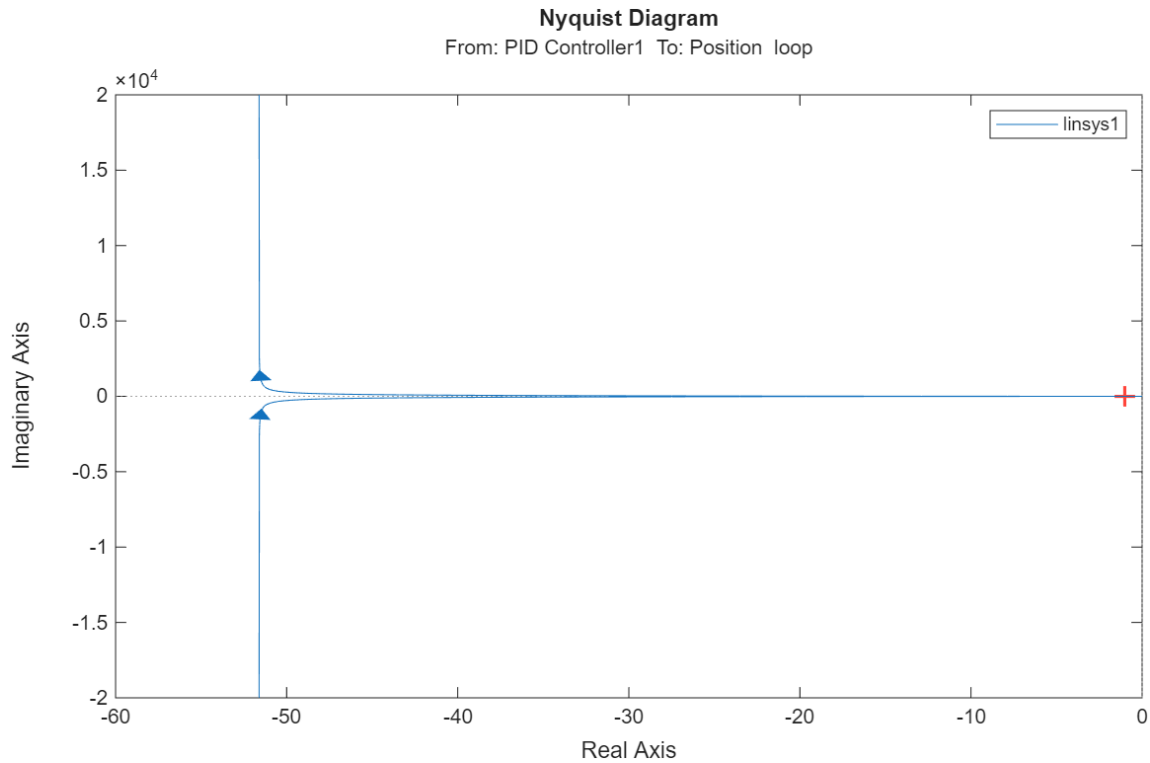


Figure 4.8: Nyquist diagram of the velocity position-loop transfer function

The stability of the velocity loop was verified graphically by the Nyquist plot, which confirmed that the critical point $(-1,0)$ was not encircled.

4.3.3 Principle of Cascade Control

The theoretical efficacy of the cascade structure hinges on the strict separation of bandwidths. A fundamental requirement in cascade control system design is that the inner loop must operate at a faster dynamic response than the outer loop. This ensures that the inner loop effectively stabilizes and regulates its controlled variable before the outer loop imposes additional control actions. In practical terms, this hierarchy is validated by examining the gain crossover frequencies of the inner (velocity) and outer (position) loops. For the system under study, the measured values are as follows:

Table 4.4: Measured Gain Crossover Frequencies for Velocity and Position Loops

Loop	Metric	Value(rad/s)	Equivalent (Hz)
Velocity (Inner)	$\omega_{gc,v}$	408 rad/s	64.9 Hz
Position (Outer)	$\omega_{gc,p}$	340 rad/s	54.1 Hz

4.4.1 Motivation for Feedforward Compensation

While the cascade P/PI controller provides robust feedback-based disturbance rejection, its performance is inherently limited by loop bandwidth and stability margins. Disturbances that enter directly before the plant are particularly difficult to suppress quickly using feedback alone. To address this, a feedforward compensation path was introduced. The purpose of the feedforward path is to process a measured disturbance signal and inject an opposing control action directly at the plant input, thereby attenuating the effect of the disturbance before it propagates through the plant dynamics.

4.4.2 Disturbance Characterization

The disturbance signal was recorded from the cutting process and analyzed in the frequency domain using the Fast Fourier Transform (FFT). The spectrum revealed a dominant narrowband component centered at 26 Hz. This frequency component was identified as the principal contributor to the oscillatory disturbance observed in the plant output. Since the disturbance is strongly concentrated at a single frequency, a notch filter is an appropriate choice for shaping the feedforward path.

4.4.3 Notch Filter Design in Continuous Time

A standard second-order notch filter can be expressed as:

$$H(s) = \frac{s^2 + \omega_n^2}{s^2 + \omega_n^2 + \frac{\omega_n}{Q}s}$$

Where,

$$\omega_n = 2\pi f_n$$

is the notch frequency in radians per second, $f_n = 26$ Hz, and Q is the quality factor. A value of $Q \approx 30$ was selected to ensure that the notch is narrow and does not excessively affect neighboring frequencies. Substituting the design parameters yields:

$$H(s) = \frac{(s^2 + (2\pi \times 26)^2)}{s^2 + \frac{2\pi \times 26}{30}s + (2\pi \times 26)^2}$$

This transfer function attenuates the 26 Hz component of the disturbance while leaving most of the spectrum unaffected.

4.4.4 Discrete-Time Implementation

The system operates at a sampling frequency of 1000 Hz, corresponding to a sampling period of:

$$T_s = \frac{1}{1000} = 0.001$$

To implement the notch filter in discrete time, the bilinear transform (Tustin approximation) was applied, defined by:

$$\frac{2}{T_s} \times \frac{1 + z^{-1}}{1 - z^{-1}}$$

Applying this substitution to the continuous transfer function $H(s)$ results in a rational discrete transfer function of the form:

$$H(z) = \frac{b_0 + b_1 z^{-1} + b_2 z^{-2}}{1 + a_1 z^{-1} + a_2 z^{-2}}$$

The coefficients (b_i , a_i) were computed numerically and then implemented directly in Simulink using the Discrete transfer function block.

4.4.5 Feedforward Path Integration

The complete feedforward compensation path consists of three elements:

- i. **Scaling Gain:** The measured disturbance is first multiplied by a static gain of 30. This value was chosen to match the relative magnitude between the disturbance input and the plant sensitivity.
- ii. **Notch Filter:** The scaled disturbance passes through the discrete-time notch filter $H(z)$, attenuating the 26 Hz component.
- iii. **Summation with Negative Sign:** The filter output is inverted and summed with the existing plant input. The plant input equation is therefore:

$$u_{\text{plant}}[k] = u_{PID}[k] + d[k] - 30 \times H(z) \times d[k]$$

Here, $u_{PID}[k]$ is the cascade controller output, and $d[k]$ is the disturbance.

4.4.6 Benefits

This configuration ensures that the disturbance component at 26 Hz is strongly suppressed before reaching the plant. The cascade feedback loops then focus on compensating for residual broadband disturbances and modeling uncertainties. As a result, the combined cascade plus feedforward controller achieves improved disturbance rejection, reduced steady-state error, and enhanced closed-loop performance without compromising stability margins.

CHAPTER 5

RESULT & DISCUSSION

5.1 Analysis of the Study

To contextualize the following evaluations, it is vital to compare all control strategies. Each controller PID, Cascade P/PID, PID plus Feedforward, and Cascade P/PID plus Feedforward were implemented in MATLAB/Simulink and set under similar simulation conditions. The system's performance under the same reference trajectories and cutting-force disturbance profile was assessed uniformly on Maximum Tracking Error (MTE) and Root Mean Square Error (RMSE), which helped us to quantify tracking fidelity and disturbance rejection. Below is a detailed analysis of how each controller performs compared to these performance measures.

Table 5.1: Results Comparison

Tracking Performance	PID [mm]	PID plus Feedforward [mm]	Cascade P/PID [mm]	Cascade P/PID plus Feedforward [mm]
MTE	0.00985	0.00980	0.00405	0.00400
RMSE	0.00302	0.00295	0.00135	0.00129
FFT	0.00066	0.00058	0.00044	0.00027

5.1.1 Comparative Analysis of Maximum Tracking Error (MTE)

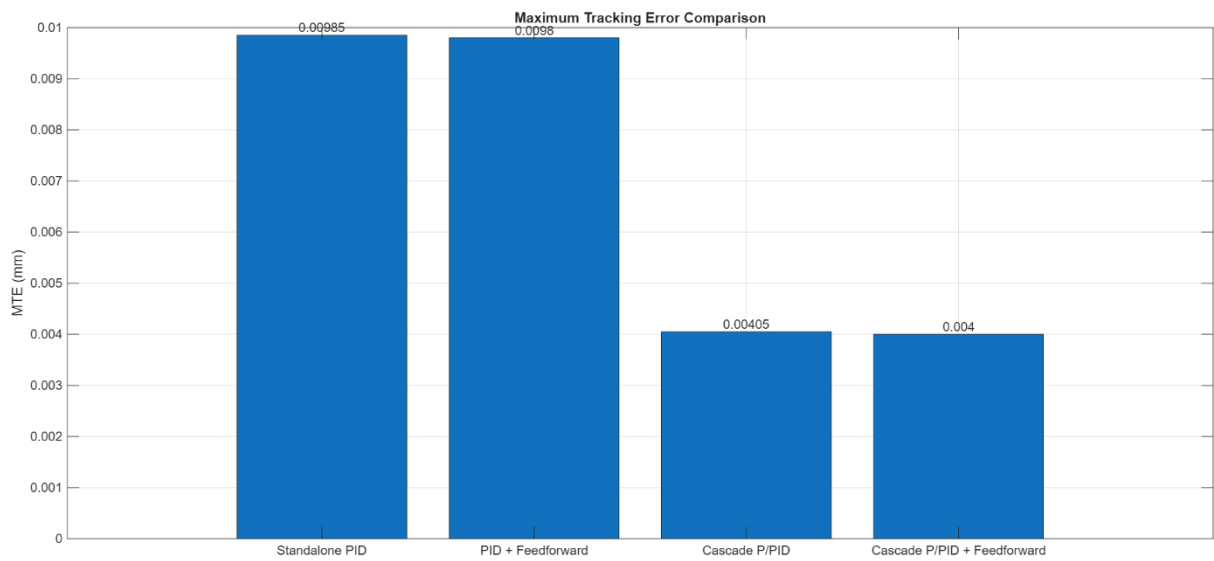


Figure 5.1: MTE Comparison among Controllers

The Maximum Tracking Error (MTE) values illustrate the system’s ability to withstand the largest instantaneous deviations caused by high acceleration demands or peak disturbances. The Standalone PID controller exhibited the highest MTE of 0.00985 mm, highlighting the inherent limitations of a single-loop system in a high-inertia environment. Owing to its purely reactive nature, the PID struggled during transient states, leading to significant lag and overshoot when subjected to abrupt dynamic loads. Introducing Feedforward compensation into the PID architecture marginally reduced the MTE to 0.00980 mm, corresponding to a 0.51% improvement.

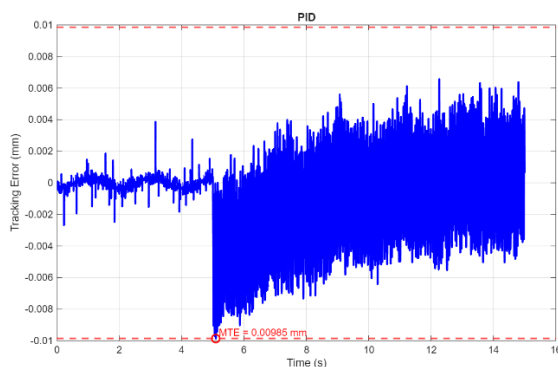


Figure 5.2: MTE for PID

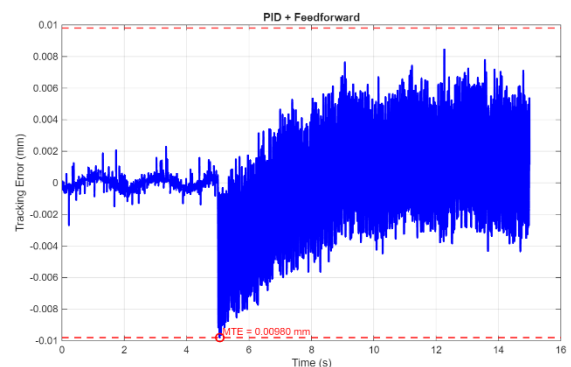


Figure 5.3: MTE for PID plus Feedforward

By contrast, the Cascade P/PID controller substantially lowered the MTE to 0.00405 mm, representing a 58.8% reduction compared to the Standalone PID. This outcome underscores the structural advantage of the cascade design, where the faster inner velocity loop effectively mitigates sudden inertial and load-based disturbances that dominate peak error behavior. Adding Feedforward to the Cascade structure produced some additional benefit, with the MTE reduced further to 0.00400 mm (a 1.23% improvement over the Cascade baseline). This finding reinforces that, for peak error suppression, the cascade's hierarchical loop design is the dominant contributor, while Feedforward plays only a secondary role.

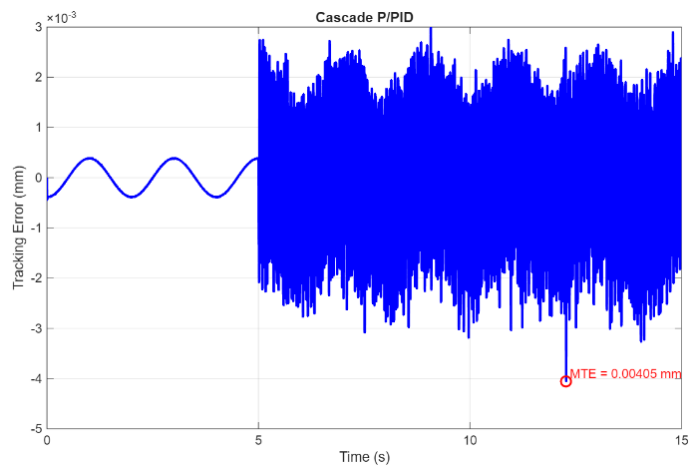


Figure 5.4: MTE for Cascade P/PID

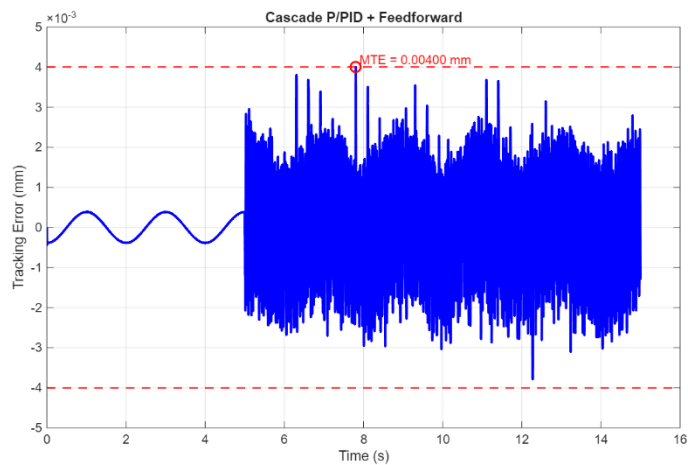


Figure 5.5: Cascade P/PID plus Feedforward

5.1.2 Comparative Analysis of Root Mean Square Error (RMSE)

The Root Mean Square Error (RMSE) offers a more comprehensive measure of tracking fidelity, as it captures how consistently the controller maintains accuracy against the quasi-periodic cutting force disturbance over the entire simulation. The Standalone PID controller recorded an RMSE of 0.00302 mm, showing that the single-loop structure struggles to provide steady accuracy when faced with continuous load fluctuations from the cutting force. Adding Feedforward (PID plus FF) slightly reduced the error to 0.00295 mm, a 2.32% improvement. While the effect is modest, this result indicates that Feedforward can anticipate a portion of the disturbance. However, its influence is limited because the PID loop itself lacks sufficient bandwidth to fully handle periodic high-frequency inputs. A much more significant improvement came from the Cascade architecture, which reduced the RMSE to 0.00135 mm; a 55.30% reduction compared to the PID baseline. This demonstrates the clear advantage of the inner velocity loop, which actively regulates motor dynamics and better suppresses the oscillatory forces introduced by the cutting process.

The Cascade plus Feedforward configuration delivered the best performance overall, achieving the lowest RMSE of 0.00129 mm. This corresponds to a 57.28% improvement compared to the baseline PID system and a 4.44% reduction relative to the Cascade alone as shown in Table 5.2 below. Notably, the Feedforward term is more effective when combined with the robust Cascade structure than when added to the PID. This highlights a principle of control synergy: the high-bandwidth cascade feedback loop efficiently handles unmodeled disturbances and low-frequency effects, while the Feedforward term precisely targets the predictable harmonic components of the cutting force. Together, they minimize both random and repetitive errors, resulting in the most consistent and reliable tracking accuracy.

Table 5.2: RMSE Comparison among Controllers

Controllers	RMSE [mm]	Percentage Improvement over Baseline PID (RMSE)
Standalone PID	0.00985	Baseline
PID plus Feedforward	0.00980	2.32%
Cascade P/PID	0.00405	55.30%
Cascade P/PID plus Feedforward	0.00400	57.28%

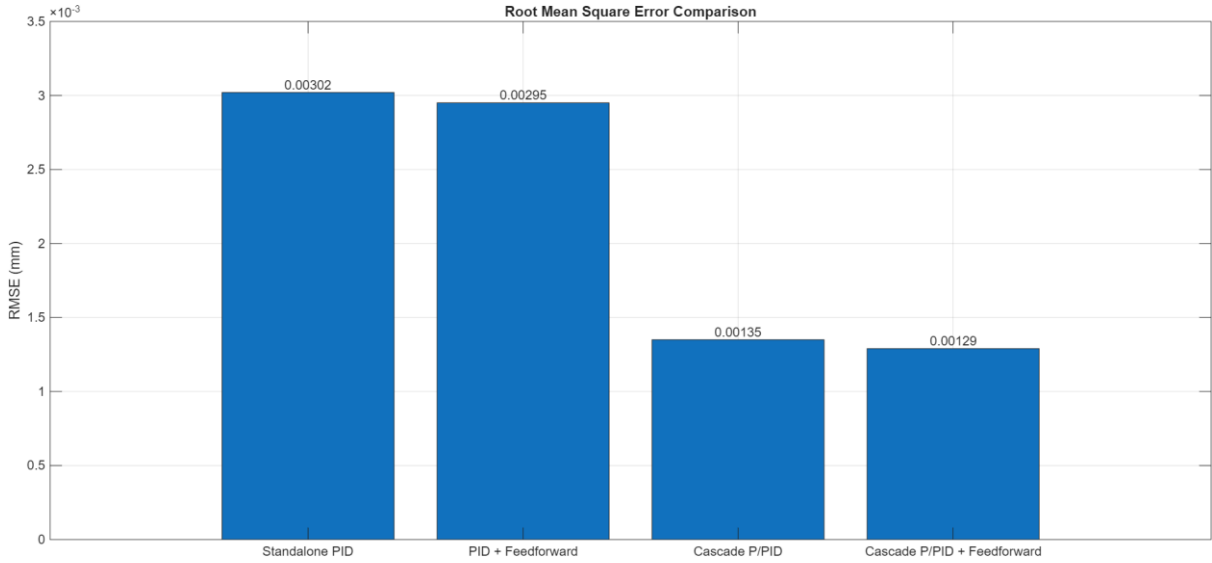


Figure 5.6: RMSE Comparison among Controllers

5.1.3 Frequency Domain Error Analysis via Fast Fourier Transform (FFT)

While time-domain metrics like RMSE and MTE provide an overall idea of tracking performance, they do not show which frequencies contribute most to the error. Since the cutting force in our system is periodic, the Fast Fourier Transform (FFT) is used to identify specific disturbance frequencies in the tracking error that the controllers fail to reject.

5.1.4 Spectral Analysis and Identification of Disturbance Harmonics

From the FFT analysis, it was confirmed that the main source of error in all controllers was a strong harmonic at 26 Hz, which corresponds to the tooth-pass frequency at the 1500 RPM cutting condition. The size of the FFT peak at this frequency shows how much of the periodic error remains in the system.

Table 5.3: FFT Comparison among Controllers

Controller	FFT Peak Amplitude	% Reduction vs PID
Standalone PID	0.000658	Baseline
PID plus Feedforward	0.000581	11.7%
Cascade P/PID	0.000443	32.7%
Cascade P/PID plus Feedforward	0.000269	59.1%

- The Standalone PID controller had the highest FFT peak amplitude of 0.000658, meaning it was least effective at rejecting the 26 Hz disturbance.

- When Feedforward was added to the PID controller, the peak dropped to 0.000581, an 11.7% reduction. This shows that Feedforward helps by anticipating part of the periodic disturbance, though the effect is modest

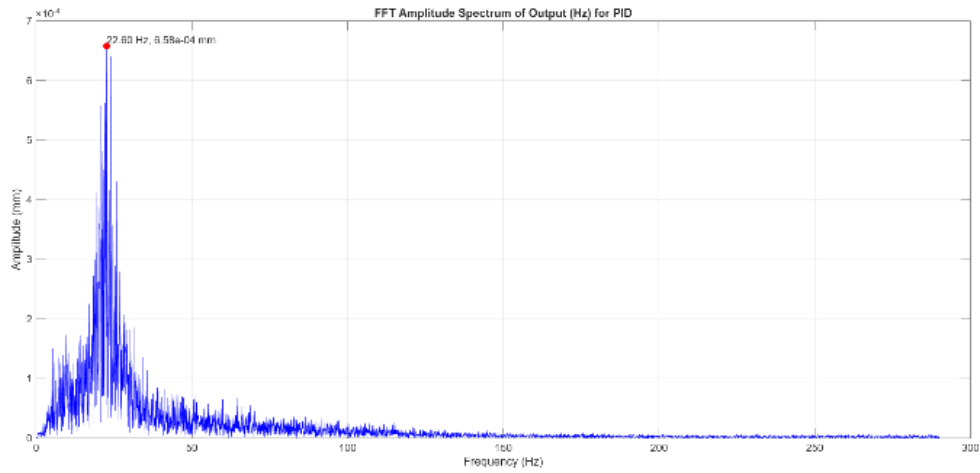


Figure 5.7: FFT of PID Standalone

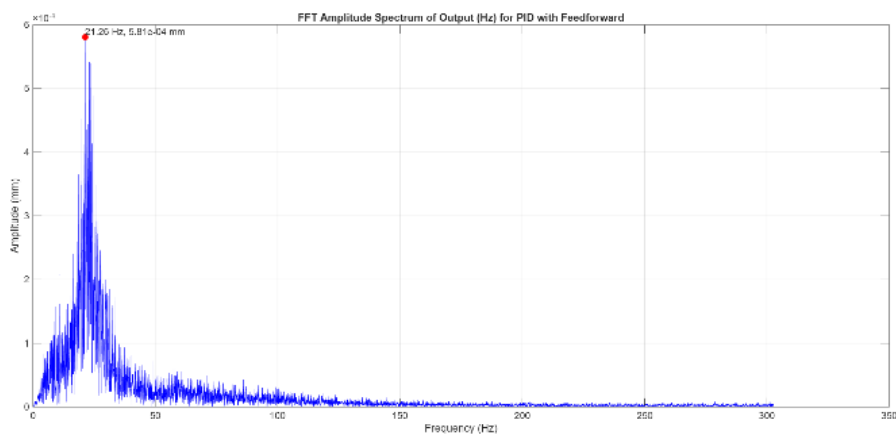


Figure 5.8: FFT of PID plus Feedforward

- The Cascade P/PID controller reduced the 26 Hz peak to 0.000443, demonstrating the inner velocity loop's ability to better reject periodic disturbances even without Feedforward.

- Adding Feedforward to the Cascade controller further reduced the peak to 0.000269, a 39.3% reduction compared to Cascade alone. This shows the strong effect of the Feedforward path in cancelling the targeted harmonic.

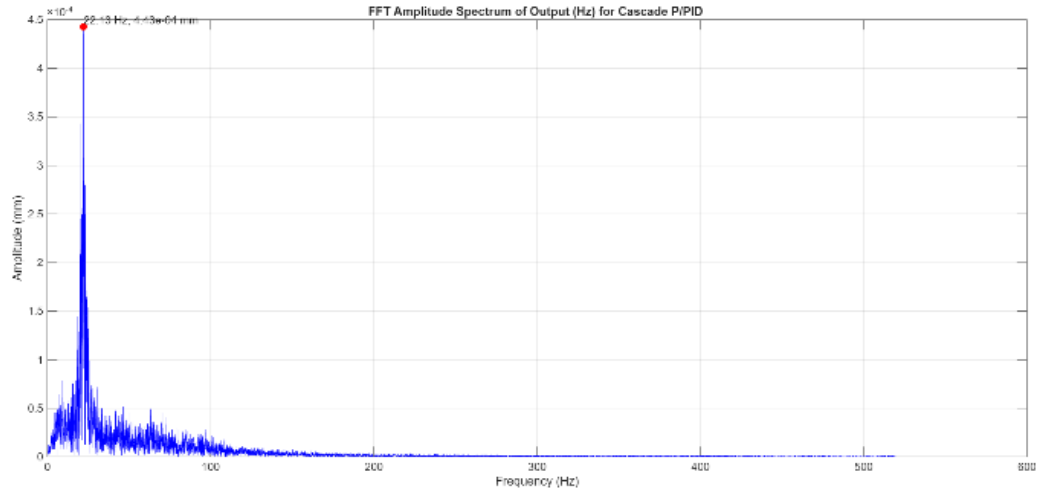


Figure 5.9: FFT of Cascade P/PID

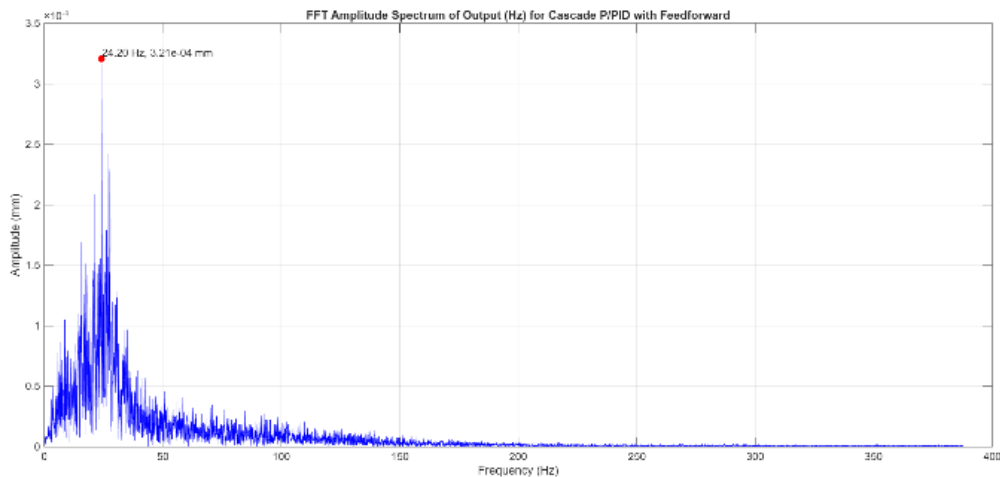


Figure 5.10: FFT of Cascade P/PID plus Feedforward

5.2 Application in Mechanical Engineering Practice

The control strategies developed in this work, PID, PID plus Feedforward, Cascade P/PID, Cascade P/PID plus Feedforward, have direct relevance to modern mechanical engineering practice. Precision motion control is a cornerstone of systems such as CNC machining, automated manufacturing, and robotics, where reliability, accuracy, and repeatability are essential. These strategies are equally important in precision instrumentation and robotics, where sub-millimeter accuracy and repeatability are critical. Cascaded loops make it easier

to control different dynamic ranges effectively, while feedforward compensation can counteract predictable disturbances like inertia or friction. Together, these approaches enhance stability, reduce oscillations, and help extend machine lifespan by minimizing wear and unexpected downtime.

In CNC machine tools, well-tuned PID controllers, often arranged in cascaded position and velocity loops, help cutting tools follow their programmed paths with minimal deviation. This ensures high precision, reduces material waste, and maintains consistent product quality. In automated production lines, systems such as conveyors, robotic arms, and gantry mechanisms rely on similar control strategies to maintain speed, synchronize movements, and handle changing loads smoothly. Adding cascaded loops and feedforward elements further improves performance, allowing faster responses, less overshoot, and smoother motion, which in turn increases overall throughput.

In practical terms, applying these control strategies translates into higher productivity, thanks to faster settling times and shorter cycles; improved reliability through reduced vibrations and mechanical stress, and better accuracy by precisely rejecting disturbances. Overall, they play a key role in integrating advanced control systems into a wide range of mechanical engineering applications, from machining centers to high-end robotic systems.

5.3 Relation to Environmental Benefits

Improved control strategies contribute to sustainable manufacturing practices in several ways:

- i. **Energy Efficiency:** As hinted in section 5.1.1, controllers that operate more smoothly and predictably, like the Cascade plus Feedforward, reduce the energy wasted on excessive corrective actions and braking. This leads to lower overall energy consumption per manufactured part.
- ii. **Reduction of Material Waste:** In machining, a part that is scrapped due to a dimensional error represents a waste of raw material and all the energy embedded in it. By significantly improving tracking accuracy and reducing errors, the proposed controller minimizes scrap rates, directly conserving resources.
- iii. **Extended Machine Lifespan:** By reducing mechanical vibrations and thermal cycling, the control system decreases the rate of component degradation. This

extends the service life of capital equipment, reducing the environmental impact associated with manufacturing replacement parts and disposing of old machinery.

5.4 Financial and Time Management Analysis

The implementation of the advanced control strategies can be justified through a cost–benefit analysis that considers both the investment required and the financial/time-related returns.

5.4.1 Implementation Costs

The primary cost is the Non-Recurring Engineering (NRE) time for the expertise required in:

- System identification.
- Advanced controller design (cascade and feedforward).
- Tuning and validation in an environment like MATLAB/Simulink.

Hardware costs are minimal or negligible. The feedforward path and cascade structure can be implemented within most existing industrial controllers (e.g., PLCs or motion controllers), provided there is sufficient computational capacity. Thus, implementation mainly leverages standard PID blocks already available in control platforms.

5.4.2 Financial Benefits and Return on Investment (ROI)

- i. **Increased Throughput:** By improving tracking accuracy and reducing settling time, machines can operate at higher feed rates without sacrificing quality. This leads to more parts produced per unit time, directly improving productivity.
- ii. **Reduced Scrap and Material Costs:** The improved precision and disturbance rejection capabilities lower the scrap rate. Fewer defective parts translate into reduced material losses, directly improving profit margins.
- iii. **Lower Maintenance Costs:** Smoother operation with fewer oscillations reduces mechanical stress, extending the lifespan of motors, gears, and bearings. Predictive control and reduced wear decrease maintenance frequency, lowering annual service costs and minimizing unplanned downtime.

- iv. **Energy Efficiency:** By minimizing overshoot and unnecessary motion, the optimized control structure reduces energy consumption per part produced, further reducing operational costs.
- v. **Labor Efficiency:** With greater reliability and less need for manual intervention, operators spend less time monitoring and retuning systems. This enables a reduction in supervision requirements and frees skilled personnel for higher-value tasks.

5.4.3 Time Management and Workflow Efficiency

- i. **Systematic Development Path:** The staged approach; starting with a single PID, extending to cascade, and finally integrating feedforward, proved efficient. This incremental method built an understanding of system dynamics while minimizing design risks.
- ii. **Frequency-Domain Tools:** The use of Bode plots, Nyquist diagrams, and loop-shaping techniques provided a structured, model-based path to controller design. This reduced reliance on empirical trial-and-error tuning, saving time during development.
- iii. **Virtual Prototyping:** MATLAB/Simulink enabled rapid prototyping and simulation of controllers under realistic disturbance scenarios. This virtual testing environment saved significant setup time and resources compared to repeated physical testing, while ensuring confidence before hardware implementation.

CHAPTER 6

CONCLUSION

6.1 Conclusion

This thesis set out to evaluate and enhance the tracking performance of a ball-screw-driven XY milling table under the influence of dynamic cutting forces. The primary objective was to investigate the efficacy of integrating Feedforward control with conventional feedback controllers to improve precision and disturbance rejection. Four distinct control architectures were designed, simulated, and rigorously compared: a standalone PID controller, a PID controller with Feedforward (PID plus FF), a Cascade P/PID controller, and a Cascade P/PID controller augmented with Feedforward (Cascade plus FF). The system was modeled using a second-order transfer function with a time delay, identified through frequency response methods. Simulations in MATLAB/Simulink were conducted under a realistic cutting force disturbance profile measured at 1500 RPM spindle speed. The performance was quantified using key metrics: Maximum Tracking Error (MTE), Root Mean Square Error (RMSE), and a frequency-domain analysis via Fast Fourier Transform (FFT).

The results conclusively demonstrate a clear hierarchy in controller performance. The standalone PID controller, while functional, exhibited significant limitations in suppressing the periodic disturbance, resulting in the highest MTE and RMSE. The addition of a model-based Feedforward path to the PID controller provided a marginal improvement, primarily by anticipating part of the predictable disturbance. A substantial performance leap was achieved with the Cascade P/PID controller, which reduced the MTE and RMSE by over 55% compared to the baseline PID. This underscores the fundamental advantage of the cascade structure, where the high-bandwidth inner velocity loop actively rejects disturbances before they significantly affect the outer position loop.

The most effective control strategy was the Cascade P/PID plus Feedforward controller. It achieved the lowest error metrics across the board, reducing the RMSE by 57.3% compared to the standalone PID and by 4.4% compared to the Cascade alone. Crucially, the FFT analysis revealed that this configuration was exceptionally effective at attenuating the dominant 26 Hz disturbance harmonic, achieving a 59.1% reduction in its amplitude. This

synergy demonstrates that Feedforward compensation is most potent when paired with a robust, high-performance feedback structure like the cascade controller, allowing it to precisely cancel known disturbances while the feedback handles uncertainties and unmodeled dynamics.

6.2 Contributions of the Study

The key contributions of this thesis are as follows:

- i. **Comparison of Control Strategies:** This work sets up a fair comparison between four widely used industrial control methods for a precision positioning system. All strategies were tested under the same disturbance conditions and evaluated using the same performance measures, so the results can be directly compared.
- ii. **Cascade plus Feedforward Validation:** The results show that combining cascade feedback with feedforward gives better overall performance. The study explains how each part plays its role; feedback improves stability and robustness, while feedforward helps predict and cancel out disturbances.
- iii. **Practical Design Approach:** A step-by-step design process is presented, mainly in the frequency domain, for tuning both the cascade P/PID loops and the discrete-time feedforward notch filter. This makes it easier for others to repeat or adapt the method in practice.
- iv. **Use of Virtual Prototyping:** MATLAB/Simulink was used throughout as a virtual test platform for controller design and validation. This shows how simulation can reduce the time, effort, and cost needed before moving to real hardware.

6.3 Limitations of the Study

While this study provides valuable insights, it is subject to certain limitations

- i. **Simulation-Based Validation:** The findings are based entirely on simulation models. Although the model was derived from system identification, it may not capture all the non-linear complexities of a physical system, such as non-linear friction, backlash, or thermal effects.
- ii. **Single Disturbance Profile:** The controllers were evaluated against a single, fixed cutting force profile at 1500 RPM. Performance under a wider range of operating

conditions, such as varying spindle speeds (2500 RPM, 3500 RPM) and different material cuts, remains to be fully investigated.

- iii. **Idealized Feedforward Model:** The Feedforward controller was designed based on a perfectly known disturbance frequency. In a real-world setting, time-varying disturbances and model inaccuracies could degrade its performance.

6.4 Recommendations for Future Work

The following directions are proposed for future work

- i. **Experimental Validation:** The immediate next step is to implement and validate these control strategies on a physical XY milling table setup to confirm the simulation results and refine the models with real-world data.
- ii. **Extended Operating Conditions:** Future simulations and experiments should include a broader spectrum of disturbance profiles, including different spindle speeds (2500 RPM, 3500 RPM) and more complex, multi-frequency cutting forces.
- iii. **Investigation of Advanced Controllers:** Exploring more sophisticated control techniques is a natural progression. Future work could investigate:
 - **Adaptive Control:** To automatically adjust controller parameters as system dynamics or disturbance characteristics change.
 - **Robust Control (e.g., H-infinity, Sliding Mode Control):** To explicitly handle model uncertainties and unmodeled dynamics.
 - **Iterative Learning Control (ILC):** For applications involving repetitive machining paths, ILC could learn and cancel repeating errors over successive cycles.
- iv. **Multi-Axis Coordination:** Since this work only studied the X-axis, extending the control design to both X and Y axes will be important. This would include handling cross-coupling between axes and evaluating performance in contouring operations such as circular interpolation.
- v. **Real-Time Implementation Analysis:** Another important step is testing the computational requirements of the Cascade plus Feedforward approach on standard industrial platforms (e.g., PLCs or PACs) to check feasibility for real-time machining

applications.

- vi. **Machine Learning and Vision-Based Enhancement:** Looking ahead, machine learning could be applied to improve performance further. For example, neural networks or reinforcement learning could adaptively tune controllers in real time.

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