UNIVERSITI TEKNIKAL MALAYSIA MELAKA

DESIGN OF PID AND NONLINEAR PID CONTROLLER FOR TRACKING PERFORMANCE OF XY TABLE BALL SCREW DRIVE SYSTEM

This report submitted in accordance with requirement of the Universiti Teknikal Malaysia Melaka (UTeM) for the Bachelor Degree of Manufacturing Engineering (Robotics and Automation) (Hons.)

by

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APPROVAL

This report is submitted to the Faculty of Manufacturing Engineering of UTeM as a partial fulfillment of the requirements for the degree of Bachelor of Manufacturing Engineering (Robotics & Automation) (Hons). The member of the supervisory is as follow:

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(DR. IR. LOKMAN BIN ABDULLAH)

ABSTRACT

This project report presents the work done on design of PID and Nonlinear PID (NPID) controller for XY table ball screw driven system in the CIM Laboratory, Faculty of Manufacturing Engineering, UTeM. High tracking accuracy, precision and robustness are three vital components demanded in controller design for machining processes in many manufacturing related activities. This recent requirements has led to a new and challenging era in the area of machining tools and control. The objective of this project is to design and validate a PID and NPID for tracking performance of the XY table ball screw driven system by Googoltech Inc and to validate the controller through simulation using MATLAB/Simulink software and experimental work using XY table ball screw driven system. This project proposes an approach to compensate multiple frequency components, named PID controller and NPID controller at the x-axis of the XY table ball screw driven system. The performance of the proposed controller was validated numerically and experimentally where actual machining process was performed on the test setup. The results indicated that the Nonlinear PID controller is able to compensate tracking errors better than PID controller. Results showed that the Nonlinear PID controller manages to have better performance in terms of maximum tracking error than PID controller. It is also 0.28% ($f = 0.3$ Hz) and 1.16% ($f = 0.5$ Hz) better performance in terms of Root Mean Square Error (RMSE) than PID controller. However, further studies and improvement are desired. The performance of the controller needs to be further enhanced so that it can adapt to different conditions of cutting force disturbance.

ABSTRAK

Laporan projek ini membentangkan kerja yang dilakukan ke atas sistem kawalan “PID” dan “Nonlinear PID (NPID)” terhadap ketepatan posisi sistem mesin XY di Makmal CIM, Fakulti Kejuruteraan Pembuatan, UTeM. Ketepatan, kepersisan dan keteguhan merupakan tiga komponen penting yang di perlukan dalam proses rekebentuk sistem kawalan bagi proses pemesinan dalam sektor pembuatan. Anjakan paradigma terhadap segala keperluan ini telah membuka dimensi baru dalam sektor pembuatan. Objektif laporan kajian ini adalah untuk mereka bentuk dan mengesahkan sistem kawalan “PID” dan “NPID” untuk ketepatan posisi sistem mesin XY didorong oleh sistem Googoltech Inc dan untuk mengesahkan pengawal melalui simulasi menggunakan perisian MATLAB /Simulink dan kerja uji kaji menggunakan mesin XY. Projek ini mencadangkan satu pendekatan untuk mengatasi frekuensi yang pelbagai, dipanggil sistem kawalan “PID” dan “NPID” di paksi x bagi mesin XY. Proses pemotongan sebenar dijalankan ke atas mesin XY bagi tujuan validasi. Berdasarkan keputusan yang dihasilkan, di dapati sistem kawalan ‘NPID” telah berjaya untuk mengatasi masalah pengesanan lebih baik daripada sistem kawalan“PID’. Hasil eksperimen menunjukkan bahawa sistem kawalan "NPID" berjaya membuahkan hasil yang lebih baik dari aspek kesilapan maksimum pengesanan daripada sistem kawalan PID. Ianya juga, 0.28% (f =0.3 Hz) dan 1.16% (f=0.5 Hz) lebih baik dalam aspek "Root Mean Square Error (RMSE) daipada sistem kawalan “PID”. Walaubagaimanapun, kajian lanjut dan pembaharuan terhadap kajian ini adalah diperlukan. Tujuan penambaikan ini dilakukan adalah untuk mempertingkatkan lagi kebolehan sistem kawalan tersebut agar ia mampu bertahan pada pelbagai keadaan daya pemotongan.

DEDICATION

To my beloved parents

Zulkifli bin Hussain and Suriani binti Mat Rashid.

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LIST OF ABBREVIATIONS, SYMBOLS AND NOMENCLATURE

CCC	-	Cross-Coupling Controller
CNC	-	Control Numerical Computer
ENPID	-	Enhanced Nonlinear PID
FLC	-	Fuzzy Logic Control
FRF	-	Frequency Response Function
I/O	-	Input/Output
LTI	-	Linear Time Invariant
MMI	-	Man-Machine Interphase
MRR	-	Material Removal Rate
NPID	-	Nonlinear PID
PID	-	Proportional, Integral and Derivative
RMSE	-	Root Mean Square Error
SISO	-	Single Input Single Output
SMC	-	Sliding Mode Controller
Fc	-	Cutting Force
Ft	-	Thrust Force
Fs	-	Cutting Speed
N	-	Normal Direction
R	-	Resultant Force

CHAPTER 1
INTRODUCTION

This chapter presents a brief introduction about the project. Firstly is the background of the project entitle Design of PID and Nonlinear PID Controller for Tracking Performance of XY Table Ball Screw Drive System. Then, the detail of the problem statement of the project and followed by the objectives of the project. Based on the problem statement and the objectives of the project, the scope of this project is identified. Finally the organization of the project is elaborated in Section 1.5.

1.1 Background

XY table ball screw drive system is a basic structure of CNC machine. In machine tools environment, the area of interest of CNC machine is to obtain high accuracy, precise positioning and robustness of a system. In order to obtain high accuracy and precise positioning of machine tools, it is important to consider the presence of disturbance forces in the system. The disturbance forces will negatively limit the performance of the controlled system. The disturbance forces are friction force and cutting force.

Cutting force disturbance exist in nature during milling process. It is not possible to avoid the cutting force disturbance as it is automatically generate from the interaction between the cutting tool and the work piece. The cutting force characteristics are influenced by the cutting parameters such as depth of cut, spindle speed, and feed rate. Variations in these cutting conditions will affect behaviour of the cutting forces in terms of its magnitudes and its harmonics content. Failure to realize this phenomenon could reduce the quality of the finished product as the cutting forces may cause vibration of the structure thus leading to a poor surface finish. Hence, an efficient and reliable compensation technique is desired in order to improve the tracking performance in machine tools applications (Abdullah et al., 2013)

Previously, PID controller has been designed to compensate the cutting force disturbance. However, the conventional PID position controller shows its limitation especially at varying cutting force disturbance (Zhao et al., 2009). In this project, PID controller and nonlinear PID (NPID) controller is designed to obtain tracking performance in XY table ball screw drive system. However, in this research project the disturbance is not consider because we focusing on the performance of the tracking error with different frequencies.

1.2 Problem Statement

XY table ball-screw driven system is a mechanism that is actuated by AC servo drives. It has been widely used in many applications due to its low cost (Tao et al., 2006). Nowadays, machine tools industries are looking for high accuracy and precise positioning and to obtain better surface finish product. There are various types of controller that can be used to obtain these criteria. However to design a good controller for the machine tools, the understanding about the control system is needed.

According to (Rao, 2006), there are three requirement of the control systems analysis and design. First is to produce a good transient response. Second is to minimize the steady-state error. Last but not least is to achieve the stability. The main problem of this research is to design a controller that have a good stability with the lowest error.

1.3 Objective

The objectives of this project are:

i. To design PID and Nonlinear PID controller for improvement in tracking performance of the XY table ball screw drive system.

ii. To validate the controller through simulation using MATLAB/Simulink software and experimental work using XY table ball screw drive system.

1.4 Scope of Project

The scopes of this project are:

i. Analysis of the performance of the XY table ball screw drive system is using PID and nonlinear PID controller.
ii. The axis used in this research is focused on the *x*-axis of the XY table ball screw drive system. This is due to the transfer function that been used is just for *x*-axis.
iii. In order to obtain tracking performance of XY table ball screw drive system, the input signal used must be sinusoidal or sine input.
iv. The frequencies used in this research are 0.3 Hz and 0.5 Hz. This is because of the machine limitation.

1.5 Organization of the Report

The report is organized as follows:

i. Chapter 2 consists of literature review on mechanical drive system in machine tools, disturbance forces in drive system and a controller design of tracking performance of machine tools.

ii. Chapter 3 describes the methodology of this research work. In general, it includes the overall flowchart on how the research is carried out. In addition, it discusses about experimental setup and system identification and system modelling of the system and finally it touches Gantt chart during this final year project.

iii. Chapter 4 elaborates and discusses on design and analysis of the controller. Basically, it involves the procedural steps on how to design the selected control techniques. This chapter also discussed on general structure and configuration of the controller. Next, the result and discussion on the numerical and experimental results of each design controller in term of maximum tracking error and root mean square error (RMSE). The discussion also focusses on performance measures analysis of the controllers.

iv. Chapter 5 concludes the findings and the main results obtained.

CHAPTER 2

LITERATURE REVIEW

This chapter provide the information that relevant to the project. The introduction of the project is elaborated in section 2.1. In section 2.2, the state of the art on motion control in machine tools is elaborate in details. It covers the mechanical drive system and disturbance force in drive system in section 2.2.1 and section 2.2.2 respectively. Finally in section 2.3, a controller design approach is elaborated in great detail. It consist of section 2.3.1 controller design, section 2.3.2 a controller design based on PID and section 2.3.3 a controller design base on NPID. Last but not least is a summary of the literature review in section 2.4.

2.1 Introduction

In machine tools environment, the demand of CNC machine is high accuracy, precision and robustness attributes (Moriwaki, 2008). Besides, a low cost and great control system towards various disturbance force also an advantage to control engineer if they able to fulfil these need. According to Moriwaki (2008), in order to increase flexibility in the design of machine tool controllers, the open controller architecture is also an important issue. In order to obtain high accuracy, precise positioning and robustness in machine tools, presence of disturbance force must be considered. This is because these disturbance forces will affect the tracking performance of machine tools. In general, with the intention of improving tracking performance of the XY table, this research is concentrate on compensating cutting force disturbance.

2.2 State of the Art on Motion Control in Machine Tool

Nowadays, mechanical drive system move toward new technology in order to meet the demand for precision positioning and high speed of the system. This technology gives more challenging task to the control society in order to compensating disturbance force and achieving better tracking performance. This section is a discussion on the change in the mechanical drive system and a literature review on the disturbance force and a controller design approach in order to obtain tracking performance of the machine tools.

2.2.1 Mechanical Drive System

Mechanical drives system technology has seen a change from rack and pinion drive system to a more sophisticated linear direct drive and piezoelectric drive system. The changes of direct drive systems over conservative electromechanical drive systems have provided the industry with high tracking performance and speed. In addition it will eliminate the conservative electromechanical drive system as discussed in the following paragraph. There are four types of mechanical drive systems in machine tools namely;

i. Rack and pinion drives system.
ii. Linear direct drive system
iii. Ball screw drive system
iv. Piezoelectric drive system.

Rack and pinion drive system is a first mechanical drive system that consists of a pair of gears which are a circular gear known as pinion and a linear gear recognize as rack. As illustrates in Figure 2.1, it show that rack and pinion drive system change rotational motion to a linear motion. According to (Altintas et al., 2011) the rack and pinion drives are suitable for long travel distances machine tools. This is because the rack and pinion drive system with low revolution in power transfer produced high torque. The rack and pinion drive system is possible to be improvised in term of performance by designing it with clearance freedom and high torsional stiffness (Altintas et al., 2011).

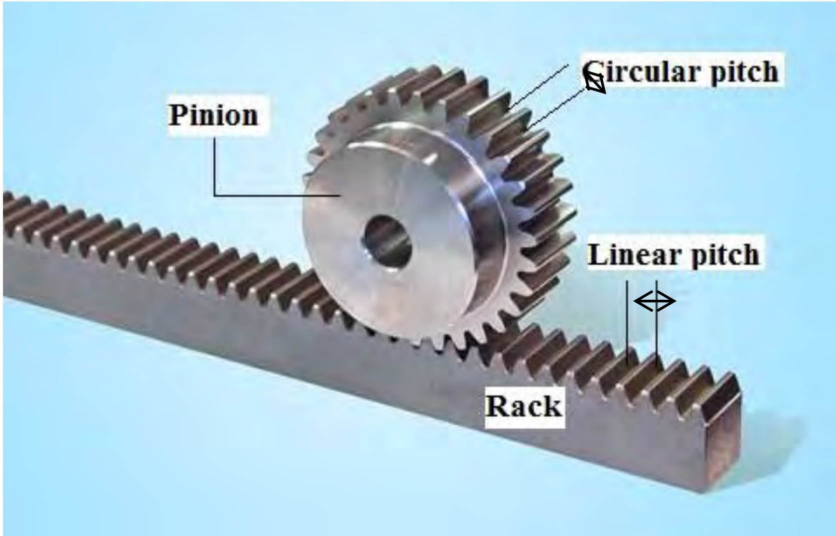

Figure 2.1: Rack and pinion drive system

Secondly is the direct drive linear motors drive system. Direct drive linear motors drive system started to capture attention within the machine tools society. Linear motor stages are directly driven axes with linear motors, which are designed as a plug and play solution. Standardized cable chains and customized cable guides are possible as an option. They are complete axes with distance measurement system, linear guide way, limit switch and optionally covers as protection against ambient influences (Anonymous, n.d.). Besides, an arresting brake also can be added as an option. Due to the direct drive, the linear stages are backlash-free, very dynamic, low maintenance and can be equipped with several blocks.

In general, direct drive system comprises of lamination stacks, coils and magnets while the type of motor associated with the direct drive is the special class of synchronous brushless servo motor as shown in Figure 2.2. The key attribute of a direct drive system is the mechanism that transform the electrical energy to linear mechanical movement as a result of the electromagnetic interaction between a coil assembly which is the fundamental part and the permanent magnet assemble (secondary part).

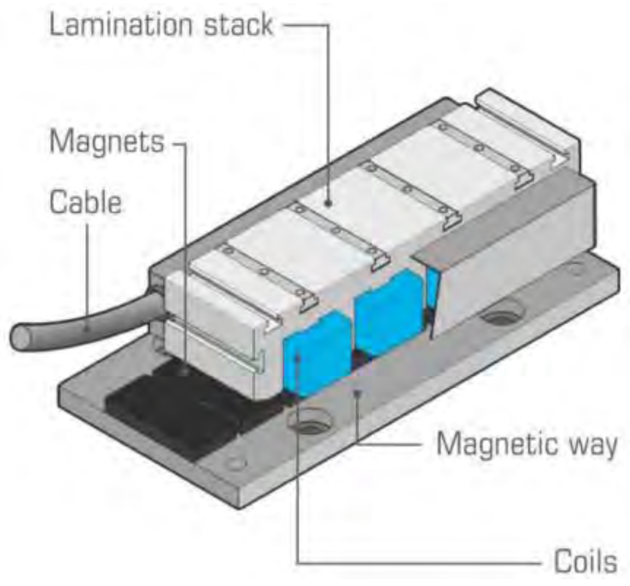

Figure 2.2: Structure of iron-core linear drive system

Direct drive system has no physical transmission between motor and load (Chiew,2013). These conditions as a result lead to eliminating the negative effect of friction and backlash that are naturally exist in the transmission mechanism in ball screw drive system. Hence, better tracking performance is now possible to be achieved in the absence of the transmission errors. There are some disadvantages in linear direct drive system. First, due to the absence of transmission mechanism, load variations, external disturbances and cogging forces will greatly affect the tracking performance of the system. Thus, it makes the design of controller becomes more overwhelming job. Secondly, direct drive is more expensive than ball screw drive. Pritschow (1998) claims that for same level of power values, the size of ball screw drive is smaller than the total size of linear drive. There are a lot of criteria for the direct drive linear to be a good drive system. There are:

i. Drive is free of friction and wear
ii. Several blocks per axis
iii. Can be combined with other linear stage
iv. Smooth running
v. Long operating life and reliability
vi. High moving speed

Figure 2.3: Direct linear drive system

The third drive system is ball screw drive system. Ball screw drive system is more efficiency and because of that it has widely used in manufacturing industrial all over the world because of the efficiency factor that is offered by the ball screw drive system. Ball screws also known as ball bearing screws or recirculating ball screws consist of a nut integrated with balls and a screw spindle and the balls' return mechanism, return caps or return tubes. Ball screws are the most common type of drive system that used in precision machines and industrial machinery. The primary function of a ball screw is to transform rotary motion to linear motion or torque to thrust, and vice versa, with the features of reversibility, high accuracy and efficiency. Ball screw drive system consists of a nut with recirculating balls, and a lead screw supported by bearings at two ends as shown in Figure 2.4.

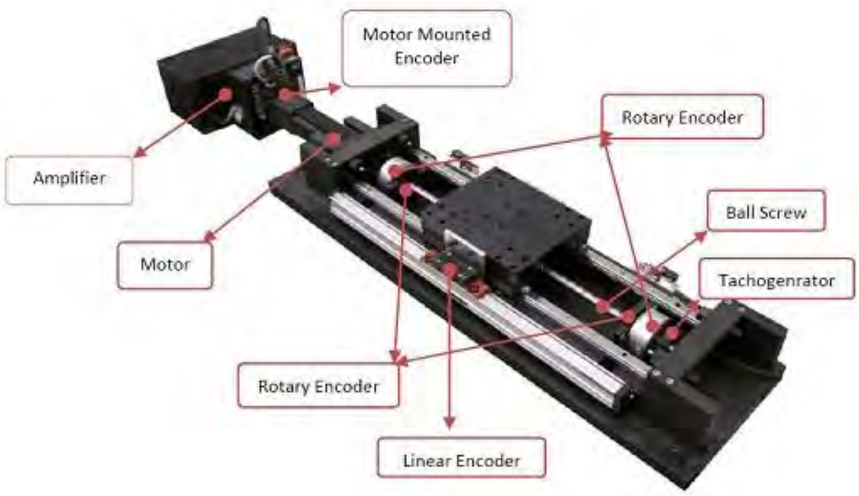

Figure 2.4: Ball screw drive system