DESIGN OF NONLINEAR PID WITH INTEGRATION OF TRACKING DIFFERENTIATOR (TD) MODULE FOR TRACKING PERFORMANCE OF MACHINE TOOLS

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

by

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APPROVAL

This report is submitted to the Faculty of Manufacturing Engineering of Universiti Teknikal Malaysia Melaka as a partial fulfilment 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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(IR. DR. LOKMAN BIN ABDULLAH)

ABSTRAK

Dalam industri pembuatan masa kini, permintaan untuk prestasi mesin alat yang lebih baik adalah tinggi untuk mengurangkan masa menunggu dan meningkatkan produktiviti. Semua peralatan mesin automatik disediakan dengan sistem kawalan mereka yang tersendiri. Terdapat tiga kriteria dalam reka bentuk sistem kawalan yang mempunyai permintaan dan penting iaitu ketepatan pengesanan yang tinggi, kepersisan pengesanan yang tinggi dan keteguhan. Tujuan projek penyelidikan ini adalah untuk mereka bentuk alat kawalan "Nonlinear PID (NPID)" dengan integrasi "tracking differentiator (TD)" dan tanpa "tracking differentiator". Kemudian, untuk membandingkan alat kawalan NPID dan NPID bersama TD dari segi prestasi pengesanan dan mengesahkan alat kawalan melalui simulasi dan eksperimen. Pengumpulan data untuk kedua-dua alat kawalan diperhati dan dianalisis dengan teliti. Projek penyelidikan ini mencadangkan satu pendekatan untuk mengimbangi pelbagai komponen frekuensi di paksi x mesin XY. Keputusan menunjukkan bahawa alat kawalan NPID mempunyai prestasi pengesanan yang lebih baik tanpa integrasi modul "tracking differentiator (TD)". Pengesanan kesilapan maksimum dicapai oleh NPID adalah 0.005881 mm pada frekuensi 0.5 Hz semasa simulasi, manakala 0.9044 mm untuk NPID bersama TD di bawah keadaan yang sama. dari segi "Root Mean Square Error (RMSE)", alat kawalan NPID juga mengatasi NPID bersama TD. Pada frekuensi 0.3 Hz, keputusan RMSE untuk NPID adalah 0.0029 mm berbanding 0.707 mm untuk NPID bersama TD. Bagi pengesahan eksperimen, alat kawalan NPID bersama TD tidak boleh dilakukan kerana mesin XY tidak bertindak balas. Prestasi alat kawalan perlu terus dibangunkan dan dipertingkatkan untuk ia menyesuaikan diri dan mengimbangi keadaan yang berbeza dalam mesin alat.

ABSTRACT

In current manufacturing industry, the demand for better machine tools performance is high in order to reduce lead time and increase productivity. All the automated machine tools are provided with their own control system. There are three criteria in controller design that are in demand and important which are high tracking accuracy, high tracking precision and robustness. The aim of this research project are to design nonlinear PID (NPID) controller with the integration of tracking differentiator (TD) and without tracking differentiator. Then, to compare NPID and NPID with TD controllers in terms of tracking performance and validate the controller through simulation and experimentally. Data collection for both controllers are observed and analysed thoroughly. This research project proposes an approach to compensate multiple frequency components at x-axis of the XY table. The results show that NPID controller has better tracking performance without the integration of tracking differentiator (TD) module. The maximum tracking error achieved by NPID is 0.005881 mm at frequency of 0.5 Hz during simulation, while 0.9044 mm for NPID with TD under the same condition. In terms of Root Mean Square Error (RMSE), NPID controller also outperformed NPID with TD controller. At frequency of 0.3 Hz, the result of RMSE for NPID is 0.0029 mm compared to 0.707 mm for NPID with TD. As for experimental validation, the NPID with TD controller could not be done as the XY table does not respond. The performance of the controller needs to be further exploited and enhanced for it to adapt and compensate to different conditions of machine tools.

DEDICATION

To my beloved parents

Raja Izam bin Raja Amran and Raja Mahfuzha binti Raja Tahir

To my siblings

Raja Izhar Azuan bin Raja Izam, Raja Azfazilla binti Raja Izam,

and Raja Izdwan Shah bin Raja Izam

To all my friends, lecturers and supervisor

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LIST OF ABBREVIATIONS

BSD	-	Ball Screw Drive system
CNC	-	Computer Numerical Control
DDL	-	Direct Drive Linear drive system
DFT	-	Discrete Fourier Transform
DSP	-	Digital Signal Processing
EA	-	Evolutionary Algorithm
EN-PID	-	Enhanced Proportional-Integral-Derivative
FRF	-	Frequency Response Function
I/O	-	Input / Output
LTD	-	Linear Tracking Differentiator
LTI	-	Linear Time Invariant
MMI	-	Man-machine Interface
NCasFF	-	Nonlinear Cascade FeedForward
NPID	-	Non-linear Proportional-Integral-Derivative
NTD	-	Non-linear Tracking Differentiator
PID	-	Proportional-Integral-Derivative
PI	-	Proportional-Integral
P/PI	-	Proportional / Proportional-Integrator
RMSE	-	Root Mean Square Error
RPD	-	Rack and Pinion Drive system
SISO	-	Single Input Single Output
TD	-	Tracking Differentiator

LIST OF SYMBOLS

δ - Filtering factor
$d(t)$ - Disturbance
$e(t)$ - System error
$e_p(t)$ - Position tracking error
G_m - Transfer Function of Reference Model
k_d - Derivative gain
k_i - Integral gain
k_p - Proportional gain
K_e - Nonlinear gain
KO - Rate of variation for nonlinear gain
R - Velocity factor
T_d - Time delay
T_r - Rise time
T_s - Settling time
μ - Coefficient of friction
π - Pi
$u(t)$ - System input
Z_{ref} - Reference position
Z - Output position

CHAPTER 1

INTRODUCTION

In this chapter, an introduction of control system and its categories including the background are discussed. Next, the problem statement which leads to the idea of this project is discussed. The objectives, scope of project and report structure are also discussed in this chapter.

1.1 Background

In current manufacturing industry, the demand for better machine tools performance is high in order to reduce lead time and increase productivity. All the automated machine tools are provided with their own control system. A control system is a device or combination of devices that manages the overall system behaviour of the machine. This is done by giving commands directly or indirectly using machine languages. There are two types of control system which are open-loop and closed-loop control system. Every machines in the manufacturing industry are using closed-loop or known as feedback type of control system. This is because the closed-loop control system is more accurate due to feedback response and correction made by the controller. Thus, a controller must be developed in order to control the actual output to achieve the desired output. A basic example of system controller is PID controller.

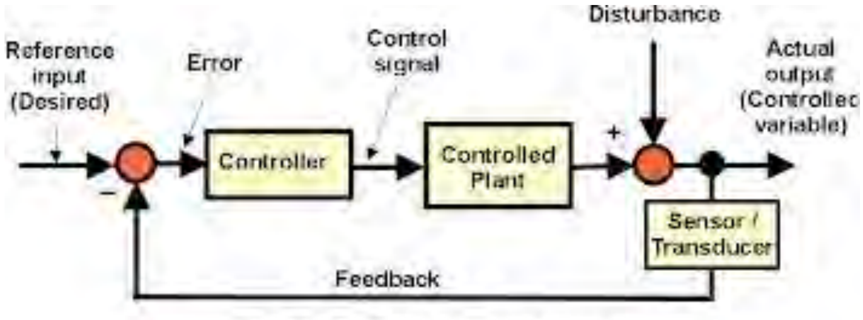

Fig.15: Feedback control system

Figure 1.1: Basic closed-loop control system (Belwal, 2015)

Closed-loop control system have many advantages compared to open-loop control system. Some advantages of closed-loop control system:

i. Decreases system's sensitivity to external disturbances.
ii. Automatically adjusting the systems input to reduce errors.
iii. Improves stability of a system.
iv. Manipulate the systems sensitivity.
v. Increase robustness of system against external disturbances.
vi. Makes the performance more reliable and repeatable.

Basically, controller is needed for controlling a specific system which in this project is a machine tools. As the advantages of a closed-loop control system shown above, it is perfect fit machine tools. But, different machine tools will have different design of the control system. The design of the controller is playing an important role in order to achieve high performance. The type of controller could be linear or nonlinear depends on the condition of the machine tools will be working on. Both linear and nonlinear controller have their own pros and cons. For this project, a nonlinear controller will be designed with the addition of tracking differentiator to identify whether it can increase the tracking performance of the machine tools or will it be the other way around.

1.2 Problem Statement

XY table ball-screw driven system is a type of machine tools that is actuated by AC servo drives. It has been widely used in many applications due to its low cost (Tao *et al*., 2006). These days, the usage of machine tools are in demand in the industrial sector as more innovative and complex products are being manufactured vary to the current technologies. As companies are fighting for the title “Best Manufacturer” and making more profits and less loss, their machine tools must robust and able to produce the products that meet the customer’s requirements and fast (accurate and high precision). Therefore, the control system of the machine tools is important in determining the performance of the machine tools. Several control system algorithm have been proposed and implemented in order for the machine tools to achieve “zero error” but it is impossible to achieve it. Thus, they are aiming to implement the best control system algorithm to the machine tools to reduce the error as possible and makes the system stable and run smoothly. This is important because in the manufacturing world, every second counts. In this case, a nonlinear PID (NPID) with integration of tracking differentiator (TD) module for tracking performance of machine tools will be simulated and analysed to see whether it is stable and suitable enough to be implemented to the industrial sector.

1.3 Objectives

The objectives of this project are:

i. To design nonlinear PID (NPID) controller with the integration of tracking differentiator (TD) and without tracking differentiator.
ii. To compare the tracking performance of NPID controller with tracking differentiator and without tracking differentiator.
iii. To validate the designed controller through simulation and experimental work.

1.4 Scope of Project

The scope of this project are:

i. The software used is MATLAB/Simulink version R2009b.
ii. The plant used is Googol Tech XY table ball screw drive system.
iii. Only X-axis is considered.
iv. The frequency for the simulation and experiment is limited to 0.3 Hz and 0.5 Hz only.

1.5 Report Structure

This report focuses on designing a nonlinear PID with integration of tracking differentiator (TD) module for tracking performance of machine tools. This report is divided into 5 major chapters which are introduction, literature review, methodology, result and discussions, and conclusion and recommendation. Chapter 1 discusses about the background of the project, problem statement, objectives, scope of project and the report structure.

Chapter 2 discusses about the literature review which includes the introduction, and other studies that relates to this project which are mechanical drive system, Proportional, Integral, Derivative (PID), Nonlinear Proportional, Integral, Derivative (NPID), Tracking Differentiator (TD), gap analysis and summary.

Chapter 3 discusses about the methodology used to fulfil the objectives and the scope of project. In this chapter, experimental setup, software requirement, system identification, flowchart which illustrates the project progress from the beginning through the end of the project and summary will be discussed.

Chapter 4 focuses on the discussion of all the data collected, response of the machine tools system analysis. Results obtained from the simulations and experimental work on NPID with TD module for tracking performance of machine tools were discussed thoroughly regarding the results and summary are also being discussed in this chapter.

Chapter 5 discusses about the conclusion of the overall project based on the findings of the research and experimental works that had been done. Recommendation for future work is also discussed in this chapter.

CHAPTER 2

LITERATURE REVIEW

This chapter provides the past research on the motion control in machine tools, tracking performance of machine tools which are PID, Nonlinear PID (NPID), and Tracking Differentiator (TD). This section is divided into subsection in which section 2.2 discusses about state of the art on motion control in machine tools. Section 2.2.1 discusses about the mechanical drive system and section 2.2.2 is about disturbance in drive system. Tracking performance of machine tools is discussed in section 2.3. Section 2.3.1 discusses about the basic structure of PID controller, section 2.3.2 discusses about nonlinear PID, and section 2.3.3 discusses about the component that will be combined with nonlinear PID which is tracking differentiator (TD). Tracking differentiator is divided into two sections which are 2.3.3.1 for linear tracking differentiator and 2.3.3.2 for nonlinear tracking differentiator. Section 2.4 discusses about the gap analysis. Last but not least is the summary of the whole literature review.

2.1 Introduction

Nowadays in manufacturing industry, companies are searching for high accuracy and robustness for their machine tools. The machine tools performance must be in best condition at all time. The characteristic is important in order to accommodate against various disturbances. There are several controllers that can be used to obtain better tracking performance of machine tools. Tracking performance of a machine tools can be increased significantly by adding dedicated compensation elements to simple and widely used cascade P/PI position controller. A nonlinear PID controller is simply better than proportional gain,

k_p, integral gain, k_i, differential gain, k_d as it changes with error control. It is because nonlinear PID controller has advantages of rapidity, high precision and without overshoot, it can achieve good control effect (Zhang and Hu, 2012).

2.2 State of the Art of Motion Control in Machine Tools

Nowadays in the developing world of technologies, the mechanical drive system for machine tools also affected by the changes in technology. These technologies are implemented in the mechanical drive system in order to fulfil the demand for precision positioning and high speed of the system in the industry. The progression of the changes in mechanical drive system towards the latest technology has created a new challenge task to the control community with respect to compensate the disturbances in order to achieve better tracking performance (Jamaludin, 2008). Generally, this section will provide the chronological changes of the mechanical drive system and literature review on the disturbances in the drive system of the machine tools and controller design approach in order to achieve better tracking performance of the machine tools.

2.2.1 Mechanical Drive System

There are four types of mechanical drive system that is used in machine tools. The types are:

i. Rack and pinion drive system (RPD).
ii. Direct drive linear drive system (DDL).
iii. Ball screw drive system (BSD).
iv. Piezoelectric drive system.

Rack and pinion drive system (RPD) is used to translate rotation motion into a linear motion. The gear of the pinion usually attached to a motor that makes it moves rotationally while the gear of the rack is in linear that will moves side-to-side when the teeth of the pinion meshed with the teeth of the rack. It is a simple mechanism where a pair of gears come together to steer a vehicle by circular and linear motion (Hagerty, n.d.). The primary building block of a linear axis drive is usually a rack and pinion system. It has virtually unlimited maximum length of travel and constant dynamic characteristics along the travel. These features makes the rack and pinion drive system recommended for feed drive systems with long travel distances (Ehrmann *et al*., 2016). According to Altintas *et al*. (2011), because of the low revolution in power transfer by the rack and pinion drive system, it produces high torque. Improvisation of the system is possible in terms of performance by designing it with clearance freedom and high torsional stiffness (Altintas *et al*., 2011).

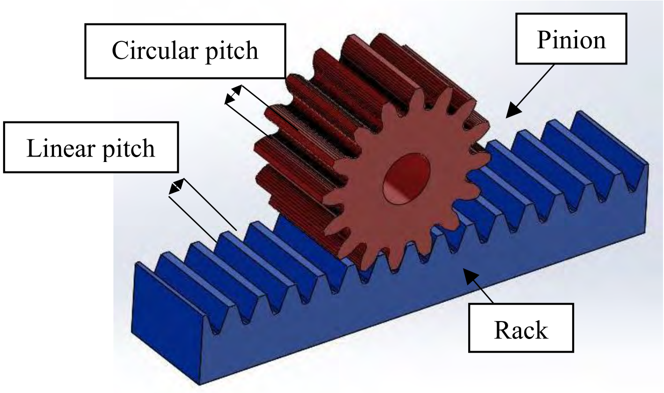

Figure 2.1: Rack and pinion drive system (Dreyfusduke, 2015)

The second drive system is Direct Drive Linear drive system (DDL). The best explanation for direct drive linear drive system is there is no physical transmission between the motor and load (Chiew, 2013). It is a brushless servomotor and the needs of mechanical transmission elements such as timing belts, leadscrews, and rack and pinion were eliminated by the direct coupling of the payload to the motor's moving part. Generally, direct drive linear drive system consists of lamination stacks, coils and magnets while the type of motor associates with the direct drive is the special class of synchronous brushless servomotor as shown in figure 2.2 and 2.3 (Anonymous, 2011). The technology used in the direct drive linear is intrinsic to a linear motor based system that makes it efficient and effective gearless assembly. There are two parts of the direct drive linear which are the coil assembly (primary part) and permanent magnet assembly (secondary part). Both parts are interacted through electromagnetic and the electrical energy is converted into linear mechanical energy with a high level of efficiency. This makes the drive system a better choice for precision. The positioning error will reduce to small value when a motor uses gears, chains or belts. Otherwise the more there are, the greater the errors (Barett, 2014). The design of the linear motor is specified to produce high force at low speeds or even when not in any kind of motion (static). The size is not based on power but purely on force what makes it different from the traditional drives.

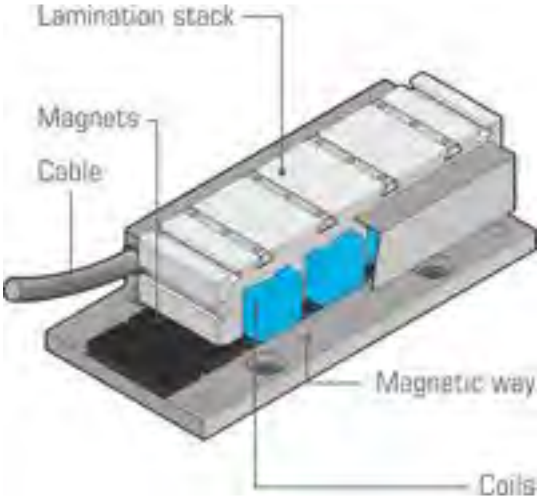

Figure 2.2: Iron-core linear drive system (Anonymous, 2011)

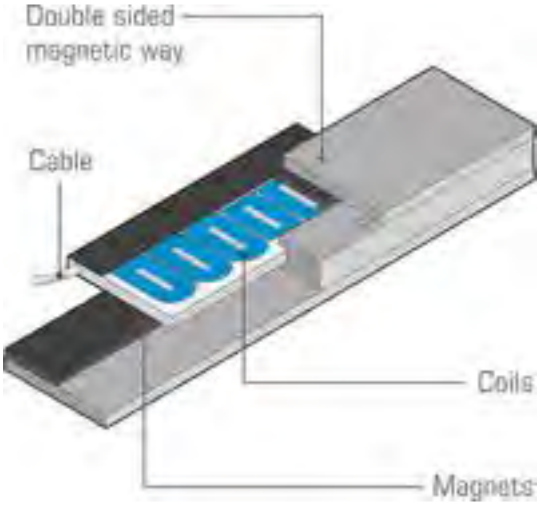

Figure 2.3: Ironless linear drive system (Anonymous, 2011)

The third drive system is the ball screw drive system (BSD). The mechanism is the same as rack and pinion which converts the rotary motion into linear motion. But ball screw drive system can revert the process by converting linear motion into rotary motion. The linear motion can be provided by the drive system in a high speed machine tools and the accuracy of positioning and achievable closed loop bandwidth is usually limited by the structural vibration modes of the mechanical components (Frey, 2011). Generally, ball screw drive system consists of a ball screw and a ball nut packaged as an assembly with recirculating ball bearings.