UNIVERSITI TEKNIKAL MALAYSIA MELAKA

SIMULATION DESIGN OF LEAD COMPENSATOR FOR TRACKING PERFORMANCE OF XY TABLE BALL SCREW DRIVE SYSTEM

TENGKU MUSTAQIM BIN TENGKU MUHAMMAD DAUD

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Faculty of Industrial & Manufacturing Technology & Engineering

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**A master project submitted
in partial fulfillment of the requirements for the degree of
Master of Industrial In Manufacturing Engineering**

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DECLARATION

I declare that this master project entitled "**Simulation Design Of Lead Compensator For Tracking Performance Of Xy Table Ball Screw Drive System**" is the result of my own research except as cited in the references. The master project has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Signature :..

Name : Tengku Mustaqim Bin Tengku Muhammad Daud

Date :...

APPROVAL

I hereby declare that I have read this master project and in my opinion this master project is sufficient in terms of scope and quality as a partial fulfillment of Master of Industrial in Manufacturing Engineering

Signature : ....

Supervisor Name : **PM IR. Dr. Lokman Bin Abdullah**

Date : ....

DEDICATION

To my beloved mother and father who doesn't want me to quit study. To my wife who always support me at all times and all my friend who always nag not to quit master study. To my supervisor that keeps supporting me through this project. Thank you all.

ABSTRACT

The accuracy and effectiveness of control systems, especially in ball screw drive mechanisms, are critical to the operation of Computer Numerical Control (CNC) equipment. In order to improve the tracking capabilities of the XY table ball screw drive system, this research looks at the design and implementation of a Lead Compensator. The study focusses on using simulation-based approaches to improve important performance indicators, such as Maximum Tracking Error (MTE) and Root Mean Square Error (RMSE). A thorough literature analysis emphasises the necessity for sophisticated control systems by highlighting the difficulties presented by mechanical variations, frictional forces, and cutting forces in CNC machines. To overcome these obstacles, the paper suggests designing and simulating a Lead Compensator with MATLAB tools and the Frequency Response Approach (FRA). The performance of the compensator is contrasted with that of conventional proportional (P) controllers. An XY table ball screw drive system, precision AC servo motors, and sophisticated signal processing methods are all used in the experimental setting. A verified mathematical model of the drive system is created using system identification techniques, and this model serves as the foundation for compensator design. With an MTE of 0.103 mm and RMSE of 0.06563 mm, simulations show that the Lead Compensator considerably lowers tracking errors, exceeding the P-controller's metrics of 0.38 mm and 0.2617 mm, respectively. According to this study, the Lead Compensator provides exceptional stability and precision, which makes it a useful tool for high-precision CNC machining applications. In addition to advancing motion control systems, the results set the stage for further research into the integration of intelligent and adaptive control techniques in production systems.

ABSTRAK

Ketepatan dan keberkesanan sistem kawalan, terutamanya dalam mekanisme pemacu skru bola, adalah kritikal untuk operasi peralatan Kawalan Berangka Berkomputer (CNC). Bagi meningkatkan keupayaan penjejakan sistem pemacu skru bola meja XY, kajian ini meneliti reka bentuk dan pelaksanaan Pengimbang Pendahulu (Lead Compensator). Kajian ini memberi tumpuan kepada pendekatan berasaskan simulasi untuk meningkatkan penunjuk prestasi penting, seperti Ralat Penjejakan Maksimum (MTE) dan Ralat Akar Min Kuasa Dua (RMSE). Analisis literatur yang mendalam menekankan keperluan untuk sistem kawalan yang canggih dengan mengetengahkan cabaran yang ditimbulkan oleh variasi mekanikal, daya geseran, dan daya pemotongan dalam mesin CNC. Untuk mengatasi halangan ini, kertas kerja ini mencadangkan reka bentuk dan simulasi Pengimbang Pendahulu menggunakan alat MATLAB dan Pendekatan Tindak Balas Frekuensi (FRA). Prestasi pengimbang ini dibandingkan dengan pengawal proporsional konvensional (P).
Dalam persekitaran eksperimen, sistem pemacu skru bola meja XY, motor servo AC berketepatan tinggi, dan kaedah pemprosesan isyarat canggih digunakan. Model matematik yang telah disahkan untuk sistem pemacu ini dibangunkan menggunakan teknik pengenalpastian sistem, yang menjadi asas bagi reka bentuk pengimbang. Simulasi menunjukkan bahawa Pengimbang Pendahulu secara signifikan mengurangkan ralat penjejakan dengan MTE sebanyak 0.103 mm dan RMSE sebanyak 0.06563 mm, mengatasi metrik pengawal P yang mencatatkan 0.38 mm dan 0.2617 mm, masing-masing. Menurut kajian ini, Pengimbang Pendahulu menyediakan kestabilan dan ketepatan yang luar biasa, menjadikannya alat yang berguna untuk aplikasi pemesinan CNC berketepatan tinggi. Selain memajukan sistem kawalan gerakan, hasil kajian ini juga membuka jalan bagi penyelidikan lebih lanjut mengenai integrasi teknik kawalan pintar dan adaptif dalam sistem pengeluaran.

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In the Name of Allah, the Most Gracious, the Most Merciful. First and foremost, I would like to convey my deepest gratitude to my respected supervisor, Prof Madya Ir. Dr Lokman bin Abdullah his priceless and non-stop efforts in assisting me whenever I find even the slightest difficulties in completing my research. It is a great honour and pleasure to be able to work with him, a person of great control system background, experience and ideas. Your kind advice, time and attention towards realizing this works are greatly appreciated. I would like to extend my gratitude to UTeM and FTKIP, UTeM and to all academic and supporting staffs for assisting me in terms of facility and moral support.

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y	-	output of the validation data
$\bar{y}$	-	test system output
$\widehat{y}$	-	mean of the output of the validation data
U(t)	-	control effort
Kp	-	proportional gain
α	-	Alpha
	-	
	-	

CHAPTER 1

INTRODUCTION

1.1 Background

In practically every area of life, control systems are involved and play a significant role. Numerous control system applications in a variety of domains, from home to business, have ingrained themselves into society. Because clients always anticipate accuracy and precision, control systems play a crucial role in the use of machine tools in industries like computer numerical control (CNC) milling centres. The mechanical structure of the machine tools, the mass of the workpiece, and disturbance forces like cutting and friction forces are some of the numerous variables influencing the accuracy and precision of the machine tool drive system (Zamberi Jamaludin, 2008) .

The demand for high precision in CNC machining has grown substantially, driven by advancements in industrial sectors such as aerospace, automotive, and electronics. These industries require components with tight tolerances and complex geometries, making high accuracy CNC machines indispensable (Zheng Xu, Jianliang Xu, Xihui Chen, 2023; Jinwei Fan, H. Tao, Peitong Wang, 2020). These machines are pivotal in achieving the required precision for complex parts, further evidenced by continuous improvements in machine tool speed and precision capabilities to meet increasing demands.

The CNC machining process involves translating computer-aided designs into commands that control the movement of the machine, allowing for precise cuts and detailed component shaping. Enhancements in CNC technologies, such as the use of multi-body systems and error compensation methods, have been developed to increase the accuracy of machine tools (Ye. Aksonov, V. Kombarov, O. Fojtů, V. Sorokin, Ye. Kryzhyvets, 2019). Innovations in speed-error representation and machining accuracy reliability are further contributions to the field, making CNC machines more precise and reliable over time (Toshiaki Otsuki, H. Sasahara)

Ball screw drive systems are a crucial component of CNC machines, responsible for converting rotational motion into linear motion. This linear motion is used to move the machine table or column, allowing for precise positioning and movement of the material being machined. The use of ball screws in CNC machines offers several advantages, including high precision, high efficiency, and low maintenance requirements. By referring Figure 1, Ball screw drive systems consist of several key components, including the ball screw, ball nut, drive motor, support bearings, guideway or slide, table, and encoder sensors. The ball screw and ball nut are the primary components that convert rotational motion into linear motion. The ball screw is a type of screw with a helical groove that contains ball bearings. These ball bearings are contained within the ball nut, which is attached to the table or column of the CNC machine. When the ball screw is rotated by the drive motor, the ball bearings within the ball nut roll along the helical groove, causing the table or column to move in a linear motion.

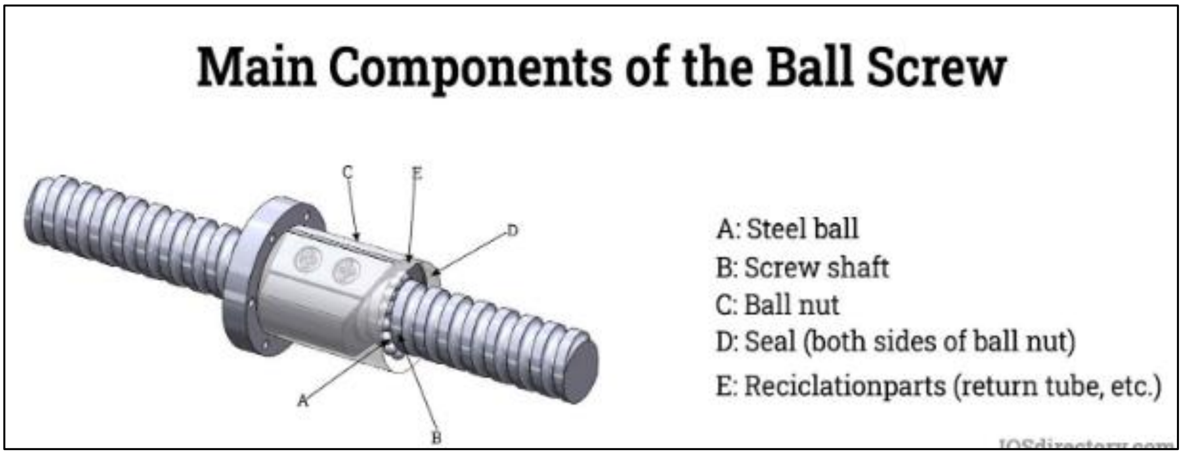

Figure 1.1: Structure of ball screw feed system

In recent years, there has been a growing interest in the use of smart systems and machine learning to monitor the condition of machine tool feed drives, including ball screw drive systems. This is an area of research that has the potential to significantly improve the performance and reliability of CNC machines. For example, a study published in the Journal of Manufacturing Science and Engineering in 2021 used finite element methods to model the complexities of ball screw drives and analyzed the effects of excitation amplitude and design parameters on the axial vibration of the feed system (Chang Liu, Chang Liu)

In summary, ball screw drive systems are a crucial component of CNC machines, responsible for converting rotational motion into linear motion. The use of ball screws in CNC machines offers several advantages, including high precision, high efficiency, and low maintenance requirements. The control and regulation of ball screw drive systems are achieved through the use of closed-loop servo mechanisms and mathematical models, ensuring smooth and precise movement. Ball screw drive systems have numerous applications in various industries, and recent research in the area of smart systems and machine learning has the potential to significantly improve the performance and reliability of these systems in the future.

1.2 Problem Statement

The precision of CNC (Computer Numerical Control) machines is highly influenced by various disturbance forces that impact their mechanical structures. These forces include mechanical stresses, mass variances, frictional forces, and cutting forces, each contributing differently to the challenges of maintaining machining accuracy.

1.2.1 Mechanical Structures and Mass Variances:

Mechanical structures of CNC machines can be affected by the integrity and alignment of their components. Discrepancies in component weights (mass variances) can lead to imbalances that affect machine stability and precision. Studies such as those by Guzeev, Deryabin, and Ardashev (2023) explore how changes in the direction of feed motion and the increase in the active length of the main cutting edge due to contour turning influence cutting forces and subsequently.

1.2.2 Frictional Forces:

Frictional forces, especially within spindle bearings and along guide rails, significantly impact the smooth operation of CNC machines. Miao et al. (2021) have addressed how the characteristics of spindle systems, including time-varying stiffness and radial clearance of bearings, affect the dynamic behavior of CNC milling machines. Their findings highlight the complex relationship between bearing characteristics and machine vibrations (Miao, Li, Wang, Xu, & Zhang, 2021).

1.2.3 Cutting Forces:

Cutting forces are among the most critical factors affecting CNC machine operations. Altintas, Yang, and Kilic (2019) discuss how cutting force disturbances can lead to contour errors in multi-axis CNC machine tools. They propose a strategy for virtually predicting and constraining these errors to enhance machining accuracy (Altintas, Yang, & Kilic, 2019).

1.2.4 Role of Controllers in Managing Disturbances:

The role of controllers in managing these disturbances is pivotal. Controllers in CNC machines are tasked with compensating for the dynamics and inaccuracies introduced by these forces. For example, Yamato and Kakinuma (2020) have highlighted the use of a disturbance observer with dynamic compensation to enhance cutting force estimation accuracy. This demonstrates how advanced control strategies can mitigate the adverse effects of dynamic forces and improve the precision of machining processes (Yamato & Kakinuma, 2020).

As for result, understanding and mitigating the impact of disturbance forces in CNC machines is crucial for enhancing their performance and accuracy. The development and integration of sophisticated control systems play an essential role in managing these disturbances, ensuring the precision and efficiency of CNC machining.

1.3 Research Objective

The objectives of this research are presented as follows.

(a) To design LEAD compensator that will provide good tracking performance of the XY Table Ballscrew Drive system.

(b) To analyze the tracking performance of the designed compensator in term of maximum tracking error (MTE) and root mean square error (RMSE).

1.4 Research scope and limitation

1.4.1 Scope:

The scopes of the research are as follows:

i. The analysis was focused only on the unit operated by the XY Table ball screw.

ii. It is conducted in simulation designed.

iii. Frequency uses are 0.2HZ and 0.4HZ, with an amplitude of 15 mm.

iv. The performance of controllers is compared based on the tracking performance which is tracking error (MTE) and root mean square error (RMSE)

v. Only X direction will be used in XYZ ball screw drive table

1.4.2 Limitations:

(i) **Model Accuracy**: The accuracy of the simulation results depends on the precision of the system model. Simplifications or assumptions in modeling may affect the outcomes.

(ii) **Environmental Factors**: The study does not account for all possible environmental factors (e.g., temperature variations, external vibrations) that may impact the real-world performance of the CNC machine.

(iii) **Hardware Constraints**: The research focuses on simulation; thus, real-world hardware limitations and nonlinearities are not fully addressed.

(iv) **Scope of Application**: The designed compensator is specific to the XY table ball screw drive system and may require adjustments for different configurations or types of CNC machines.

(v) **Validation**: While simulation provides valuable insights, experimental validation is necessary to confirm the practical effectiveness of the compensator, which is beyond the scope of this study.

1.5 Significance of study

(i) Enhanced Precision and Accuracy: By improving the tracking performance of the XY table ball screw drive system, the study contributes to achieving higher precision and accuracy in CNC machining processes.

(ii) Operational Efficiency: Improved control performance can lead to faster machining times and reduced errors, enhancing the overall operational efficiency of CNC machines.

(iii) Cost Reduction: Enhanced performance reduces the need for frequent maintenance and part replacements, leading to cost savings.

(iv) Innovation in Control Design: The study provides insights into the design and implementation of lead compensators, potentially benefiting other applications requiring precise motion control.

(v) Foundation for Future Research: This research lays the groundwork for future studies on advanced control strategies and their practical implementation in CNC and other automated systems.

1.6 Research Outline

The scope of this research are as follows:

Chapter 2 provide a review of the statement describes a project focused on enhancing the performance of a Proportional (P) controller by integrating a LEAD compensator. Further, it's also has an overview of LEAD compensators and their integration into control systems. This chapter also cover an analysis of Auto-tuned methods and their applications in industrial.

Chapter 3 will discuss the methodology, covering description of the P controller and the role of the LEAD compensator. Research paper will detailed methodology for implementing the Auto-tuned method. This chapter also will covering setup of the simulation environment representing an XY table ball screw drive system in a CNC machine.

Chapter 4 discuss the detail of the purpose improvement controller by integrating a LEAD compensator in XY table ball screw system. A step-by-step for implementing the Auto-tuned method and setup of the simulation environment representing an XY table ball screw drive system in a CNC machine.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

The 4th Industrial Revolution (Industry 4.0) concentrates on smart manufacturing by implementing IOT, big data, machine learning, and deep learning. In CNC machine, it is necessary to improve the performance of the embedded motion controller. Currently, industrial production is employing sugar, paper, and textile mills containing a discontinued automation level in some cases. Than that of the CNC machines, it is necessary for the control system to automatically carry out positioning and speed control tasks of adjustable period-5 or period-10 in the command signal given by the user to the speed and positioning of the ball screw drive in a CNC machine. Due to its greater precision in distinguishing the slow speed movement of the ball screw drive from that of fast speed and because it can seamlessly extend the p-period Posicast Control to better adapt this control to sub-period tracking tasks, some researcher proposed a Block Extended Posicast Controller based on a lead compensator with Poisson poles, to automatically execute the sub-period speed control tasks of adjustable period-2 or period-4 at the phase-plane trajectory of the ball screw drive in CNC machine with good trajectory tracking regulation and response time performance.