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Signature	: ....
Supervisor's Name	: Dr. Chong Shin Horng
Date	:

POSITIONING CONTROL OF A BALL SCREW MECHANISM USING DISTURBANCE OBSERVER

FOO JIA EN

A Report Submitted In Partial Fulfilment of Requirements for the Bachelor Degree of Electrical Engineering (Control, Instrumentation & Automation)

Faculty of Electrical Engineering

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

2015

I declare that this report entitle “Positioning Control of a Ball Screw Mechanism Using Disturbance Observer” is the result of my own research except as cited in the references. The report has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

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Name : Foo Jia En

Date :

To my beloved mother and father

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ABSTRACT

A ball screw mechanism is a mechanical actuator that is widely used in various high precision automated industries. Though it is highly efficient, the ball screw mechanism often exhibits non-linear behaviours due to various forms of external noises, frictions, unforeseen disturbances and parameters uncertainties. Such behaviours often cause instability, large steady-state error and poor transient performance in the mechanism. To overcome these problems, a Disturbance Observer with PD Controller (PDDO) is proposed. A PDDO is made up of nominal plant, low pass filter and a PD controller. Compare to classical controllers, the proposed controller has low sensitivity towards non-linearity of the mechanism. In this project, the plant model was modelled using non-linear least square method (NLLS). The nominal plant was designed based on the Ackermann's formula. The cutoff frequency was taken as half of the cut-off frequency of the plant model. The PD controller was constructed through manual tuning method. The performance of PDDO was examined experimentally in tracking motion with sinusoidal inputs of different frequencies and amplitudes. A manually tuned PID controller was designed in order to compare with the proposed controller. The robustness towards mass variation of the controllers were examined. Overall, the experimental result has proved that PDDO has demonstrated better tracking performance and higher adaptability to the change of input's amplitudes and frequencies. It was also found that PDDO is robust towards mass variation as compared to the PID controller.

ABSTRAK

Mekanisme skru bola merupakan sebuah penggerak mekanikal yang sering digunakan dalam industry automasi yang mementingkan ketepatan dalam pengukuran. Walaupun mekanisme ini mempunyai kecekapan yang tinggi, namun ciri-ciri tidak linear akibat gangguan luaran, geseran dan ketidaktepatan parameter dalam model mekanisme ini telah dilaporkan. Ciri-ciri ini dikatakan akan menyebabkan ketidakstabilan dan ralat yang besar dalam pergerakan mekanisme skru bola. Bagi mengatasi kekurangan mekanisme ini, sebuah pengawal pemerhati gangguan dengan pengawal PD(PDDO) telah dicadangkan. Berbanding dengan pengawal klasik, PDDO mempunyai sensitivti yang lebih rendah terhadap fenomena tidak linear yang berlaku dalam mekanisme ini. Pengawal pemerhati gangguan (DOB) mampu menganggar dan menolak perubahan dalam sistem, manakala pengawal PD mengawal pergerakan transien sistem ini. Dalam projek ini, PDDO telah menunjukkan prestasi pergerakan yang lebih mantap berbanding dengan pengawal PID. Dalam eksperimen penukaran beban, pengawal PDDO menunjukkan prestasi pergerakan yang lebih baik berbanding dengan pengawal PID.

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LIST OF SYMBOLS AND ABBREVIATIONS

CNC	Computer Numerical Control
DOB	Disturbance Observer
FR	Frequency Response
NCTF	Nominal characteristic Trajectory Following
NLLS	Non Linear Least Square
PDDO	Disturbance Observer with PD controller
PID	Proportional-Integral-Derivative Controller

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CHAPTER 1

INTRODUCTION

A ball screw mechanism is a mechanical actuator that translates rotary motion of the driver motor into linear displacement [1]. It is widely used in various automated industries such as aerospace industries, semiconductor industries and CNC machineries due to its high precision and efficiency [2]. Unlike lead screw, a ball screw contains ball bearing along the screw shaft and experiences less friction than a lead screw. However, it was discovered that the ball screw mechanism exhibits non-linear behaviours such as backlash, frictions, load variation and high frequency sensor noise [3], [4]. Based on [5], such behaviours are sometimes known as disturbances in the mechanism.

Figure 1.1: Difference between ball screw and lead screw [6]

To ensure the ball screw mechanism achieves high precision performance under these conditions, positioning control is vital and necessary to be applied in the mechanism. According to [7], positioning control can be performed by applying a controller and/or with the use of advance sensors. However, most industries opt for controller design as these sensors are relatively expensive. Among these industries, a conventional PID is still widely used due to its simplicity and ease of application. However, a PID controller has to be tuned frequently due to the non-linear characteristics in the mechanism. To overcome the limitation of classical PID controller, many advance controllers like H-infinity controllers (H-∞) [8-9], discrete time sliding mode controller [10], Fuzzy Logic Controller (FLC) [11], Fuzzy PID controller [12] were designed to achieve high performance and robustness.

Unlike these advance and complicated controllers, a disturbance observer (DOB) appears to be simpler and easier to use. A DOB does not compensate the system directly [13]. Instead, DOB estimates the disturbances arise from frictions, vibrations and/or parameters variations that occurs in a plant and feeds the error negatively back to perform compensation. Such compensation is usually done with controllers like H-infinity [14] and conventional PD or PID [5,13].

This project aims at designing a DOB with the use of PD controller for the ball screw mechanism. The DOB rejects the disturbances while the PD controller compensates the system so that it achieves desired positioning and tracking performance. The controller performance will be validated and the robustness of the controller will be examined with change of load mass.

1.1 Project Motivation

Precision performance in ball screw mechanism has always been the major consideration in industries. Different controllers were designed and built to improve the transient responses of the system. However, it is observed that under normal conditions, the transfer function model of the mechanism is difficult to be built accurately due to surrounding disturbances, as well as the uncertainty of parameters of the model itself. Taking conventional PID as an example, it demonstrates instability when the mechanism experiences sudden disturbances and parameter variations. To avoid these issues, a disturbance observer is proposed to minimize the effect of such disturbances and unforeseen changes of parameters.

1.2 Problem Statement

Conventional PID is widely used in different industries to improve transient performance of ball screw mechanism due to its ease of use and implementation. However, it is noticed that this controller has low adaptability to parameters variation and has to be tuned frequently to maintain its optimum performance. This procedure is troublesome and not effective as the transfer function has to be determined again whenever there's a change in the parameters involved. Due to the limitation of PID, many advance controllers such as the H_∞ controller and NCTF were designed. These controllers had proven their robustness under parameters uncertainties, mostly due to disturbances and load change. Though these controllers are robust, it is observed that these controllers require one to have a high level of relevant understanding before designing it. Compare to these controllers, a DOB is simpler and does not require an exact model of the plant. It rejects sudden disturbances while adapting itself to variation of parameters in the model. As DOB only performs disturbance rejection, thus an external PD controller is proposed to improve the positioning performance of the ball screw mechanism.

1.3 Objectives

The main objectives of this project are:

i. To construct a second order mathematical model of the ball screw mechanism;
ii. To propose a Disturbance Observer with PD controller (PDDO) for the ball screw mechanism;
iii. To validate the positioning performance and robustness against mass variation of the PDDO in tracking motion in comparison to PID controller;

1.4 Scope of Work

In order to complete this project, the limitations are presented as follow:

i. The maximum working range of the ball screw mechanism is set as 160mm;
ii. The range of input voltage used in the experiments is 0 to ±10V;
iii. The resolution of the linear encoder is given as 0.5µm/pulse;

1.5 Report Outline

This report presents the positioning control of a ball screw mechanism using disturbance observer. Chapter 2 summarizes the background of different controllers applied on ball screw mechanism. PDDO is discussed in details on its structure together with the different applications applied. Chapter 3 begins with demonstration of the steps to model the ball screw mechanism and follow by the design procedures of PDDO and PID controller. Steps for performance and robustness evaluation for the controllers are presented as well. The results from conducted experiments are presented in Chapter 4 with the analysis and discussions. Lastly, this project is concluded in Chapter 5 and recommendations are given for future works and improvement. This report is ended with the reference list and the appendices of the related works.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

In most automated industries, precise positioning control is no longer an unfamiliar term. According to A. Kato and K. Ohnishi, positioning control is one of the examples of basic components in motion control technology [15]. This technology aims at ensuring the controlled target achieves desired positioning performance despite occurrence of unwanted noise signals, disturbances or force deviations [16]. Based on a F. Yakub and R. Akmeliawati, positioning control can be further classified into two subcategories: point-to-point positioning control (PTP) and continuous path tracking control [17]. S. Chong and K. Sato stated that controllers of simple structures, rapid response and non significant overshoot are highly demanded in any of the automated industries and high-end mechanisms [18]. C. Tsui added that such controllers should also exhibit low sensitivity, i.e. robustness towards model parameters uncertainties and sudden disturbances[19].

2.2 Previous Works on Positioning Control of a Ball Screw Mechanism

Ball screw mechanisms are used in different applications such as CNC machineries, airplane wing flap release mechanism and automobile power steering that seek for high precision, stiffness and efficiency. However, past studies indicated that ball screw mechanisms exhibit nonlinear behaviour in micro movement [20]. Chen, Jang and Lin also pointed out that such microdynamic behaviours are caused by hysteresis, Stribeck effect and the preload of the ball bearings in the mechanism [21]. In another similar research, Dong and Tang added that a ball screw mechanism has varying natural frequencies along its screw shaft [22]. Due to these phenomena, many works were performed to identify the model of a ball screw mechanism while considering the macrodynamics and microdynamics of the system.

In [22], Dong and Tang proposed a hybrid modeling that characterize the axial, torsional and flexural vibration dynamics of the ball screw mechanism. In this model, the screw shaft characters, including the Young's modulus and Poisson's Modulus are considered. It was concluded that this hybrid model is capable of demonstrating the structure dynamics accurately. In another similar research, Liu, Zhao and Zhang introduced a hybrid modeling that presents the high frequency behaviours of the ball screw mechanism [23]. The screw shaft dynamics is demonstrated in longitudinal and torsional dimension. In this work, the authors only consider a low order model with two inertias: one from motor while another is from the table.

From these researches, it can be seen that it is relatively complicated to model a ball screw mechanism while considering all the microdynamic parameters. Besides that, G. J. Maeda and K. Sato also pointed out that it is relatively difficult to model the microdynamic model as these parameters change over time and position [24]. In order to ease the procedure, it is common to lump the parameters in the system. This approach is also known as macrodynamic modelling. In [4], Sepasi, Nagamune and Sassani lumped the equivalent inertia and damping coefficient of a ball screw mechanism as a second order model. The same approach was adopted by another research as shown in [25]. For this method, Lin and Chen explained that since the ball screw frictional torque dominates the system, thus the model can be reduced where the parameters are lumped together [11]. Though this method proves to be easier, a controller is highly necessary to adapt to the possible mismatch or parameter variations in the macrodynamic model.

Over the years, classical PID controller is widely applied due to its practical and simple applications. A PID controller includes three terms: Proportional, Integral and Derivative [26]. Based on [18], a PID controller is an effective and reliable controller provided that it is properly tuned. However, this controller meets its limitation should higher precision performance and system robustness are demanded. To improve this controller, different advance controllers were designed based on the characteristics of classical PID. In [27], Chen had demonstrated the ability of PID with Fuzzy Logic Controller in achieving high speed response with high precision positioning despite varying frictions in linear DC motors. In this thesis, Chen had designed a two stage controller that included a Hybrid Reduced Rule Fuzzy PID controller (PIDFLC) and a relay-tuned PID controller. Based on his observations, a PID controller has limited positioning performance due to the parameters uncertainties in the DC motor model whereas a PIDFLC is capable in achieving the desired performance under similar condition. In a similar research, T. Ting designed a Fuzzy PID controller to perform positioning control on a ball screw mechanism [12]. Unlike PID controller that requires frequent tuning, this paper concluded that a Fuzzy PID works with different input. A Fuzzy PID has a larger stability range while possesses a higher adaptability towards parameters variations. However, T. Ting also pointed out that a Fuzzy PID controller has a slower response time compared to conventional PID.

In year 2004, a H_∞ framework was designed to achieve robust, fast and precise positioning control of a ball screw system [8]. In this research, two vibrations mode were considered: the low stiffness between motor and table, as well as the oscillatory disturbance force of load to table. A 2 DOF feed-forward compensator was designed using coprime factorization approach to improve the transient response of ball screw mechanism. On the other hand, H_∞ framework was designed by selecting the appropriate weighting function to achieve robustness over servo bandwidth expansion as suggested in [28]. This research had proven that H_∞ framework is capable of achieving system robust stability over different vibration modes and increased response speed towards expansion of servo bandwidth. In [9], a H_∞ controller was proposed to compensate friction and improve the reference tracking performance. The loop shaping approach used in the research was originally proposed by D. Mcfarlane and K. Glover to achieve system robustness while improving performance and stability [29]. In [9], a suitable dynamic frequency shaping function was selected based on the frequency region where frictions occur. Differ from [28], this research improves controlled performance by multiplying the specified weight function to front and rear of the open loop transfer function.

In recent years, positioning control with NCTF controller is proposed on different applications including one mass rotary system [7], vibration control in two mass rotary system [30] and ball screw mechanisms [17,31]. According to A. Sabanovic and K. Ohnishi, it was pointed out that an exact mathematical model of the plant can never be modeled since uncertainties of model parameters may present due to noise and surrounding disturbances [32]. With this issue taken into consideration, the NCTF controller was designed such that the exact parameters are not necessary in the process [17]. In [31], NCT controller was proposed to preserve the robustness of a ball screw mechanism despite variation of mass. Another similar research demonstrated in [33] proved that a continuous-motion NCTF (CM NCTF) is capable of reducing vibration in the ball screw mechanism and improves motion accuracy.

In [34], C. Lu and M.-C. Shih proposed fuzzy sliding mode control method to perform positioning control in the ball screw mechanism driven by pneumatic servomotor. Initially researched by Mamdani and his colleagues [35], this paper uses triangular membership function and Mamdani rules to perform fuzzyfication and fuzzy reasoning. From the experimental results, [34] proved the robustness of the controller when non-linear compressed air is supplied into the ball screw mechanism.

Another common controller used to perform positioning control is the disturbance observer (DOB). DOB was first proposed by K.Ohnishi in 1983 to perform torque-speed regulation in DC motor [36]. In later years, DOB was widely applied in different mechanisms such as magnetic hard drive servo system and ball screw mechanism [13], [37]. A DOB is capable of estimating the disturbance torque due to non-linear characteristics and subsequently rejects such disturbances and compensates model uncertainties [38]. In another research, DOB was designed to control vibrations occurred in the plant [5]. Since a DOB only works on disturbance rejections, thus it is necessary to include an external controller to perform positioning control [13]. In [13], a DOB was proposed to compensate a ball screw servo system with the aid of a PD controller. This research has also pointed out that a PID controller could not be used with the observer as it produces large overshoot and major oscillations. This statement was supported by P. I. Ro *et.al.* stating that a PID exhibits severe transient oscillations that may lead to positioning error [39]. Taking step and sinusoidal disturbance into consideration, PDDO showed robustness though parameter variations and non-linear frictions existed in the ball screw mechanism [13]. In another research, P. I. Ro *et.al.* proposed a PDDO controller for sub micrometer positioning control [39]. From this research, it was found that a PDDO produces consistent and desired positioning and tracking response despite existence of non-linear frictions.

From the controllers mentioned earlier, a PDDO is proposed to perform positioning control on a ball screw mechanism. Compared to H_∞, the PDDO controller has a much simpler design procedure [40]. It also has a less complex structure compare to Fuzzy PID controller [17]. A DOB has the ability to estimate disturbances and rejects them from the system as well as compensate parameters uncertainties due to nonlinear behaviour [5,38]. In [38], it is also stated that a DOB is capable of shaping the plant to behave as the nominal plant model at low frequencies.

2.3 Disturbance Observer with PD Controller (PDDO)

The PDDO is made up of three important elements: a nominal plant, $P_n(s)$, low pass filter, Q(s), and a PD controller, C(s). The general structure of a PDDO is presented in Figure 2.1 while the symbols are presented in Table 2.1.

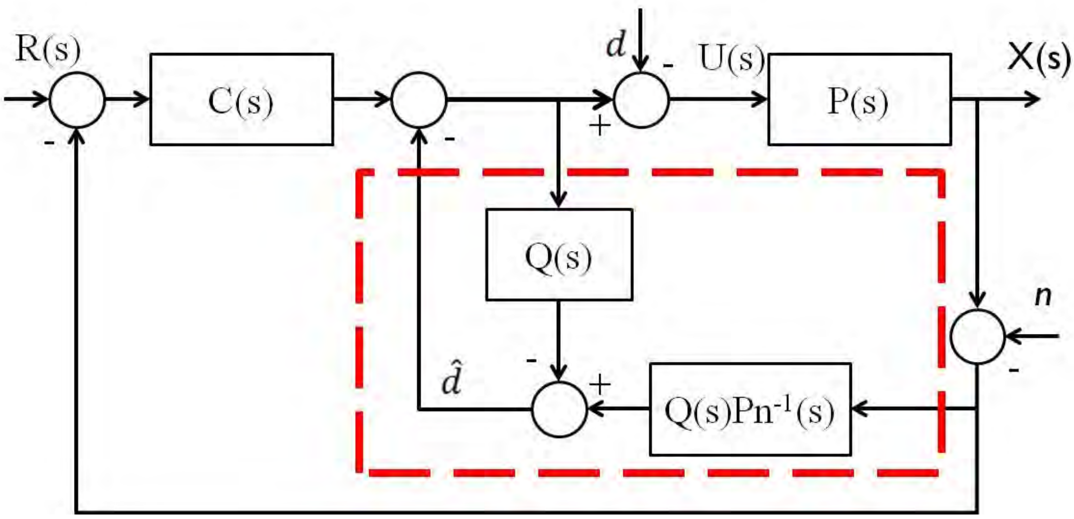

Figure 2.1: General Structure of PDDO [3]