"I hereby declare that I have read through this report entitle "*Positioning Control of XY Table*" and found that it has comply the partial fulfillment for awarding the degree of Bachelor of Electrical Engineering (Control, Instrumentation and Automation)"

Signature : ....

Supervisor name : Dr. Chong Shin Horng

Date : 16/6/2014

POSITIONING CONTROL OF XY TABLE

ONG YEE TENG

A report submitted in partial fulfillment of the requirements for the degree of Bachelor in Electrical Engineering (Control, Instrumentations and Instrumentations)

Faculty of Electrical Engineering

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

2014

I declare that this report entitle "*Positioning Control of XY Table*" is the result of my own research except as cited in 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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Date : 16/6/2014

ACKNOWLEDGEMENT

It would not have been possible to complete this final year project without the help and support of the kind people around me. Above all, I would like to thank my parents for their personal support and great patience at all times. My course mates have given me their unequivocal support throughout the whole production of this report too.

This thesis would not have been possible without the support and patience of my supervisor, Dr. Chong Shin Horng. I am very grateful to fellow seniors for providing valuable information and guidelines on how to write the report. It was particularly kind of them to allow me to refer to their previous research materials.

I would like to acknowledge the financial, academic and technical support of the Universiti Teknikal Malaysia Melaka and its staff. The library facilities and computer facilities of the University have been indispensable.

I would like to thank fellow lecturers who had taught me before. There are really too many lecturers whom I owe deep gratitude towards. The effort made in promoting a stimulating and welcoming academic and social environment will stand as an example to those that succeed them. For any errors or inadequacies that may remain in this work, of course, the responsibility is entirely my own.

ABSTRACT

In this project, the design of a two-degree-of-freedom (2-DOF) PID controller for an AC Servo Ball Screw Driven XY table is considered. XY table is commonly used in CNC machines and other industries which emphasizes motion control especially point-to-point (PTP) and tracking positioning control. XY table has the advantage of being low cost and high availability. Many types of controllers had been designed for positioning control of XY table. The most common type of controller is 1-DOF conventional type PID controller. This controller has satisfactory performance and simple structure. However, in most cases, 1-DOF PID controller can only achieve either good set-point response or good disturbance response. Thus, 2-DOF PID controller which is easy to design yet can achieve both good set-point response and good disturbance response is introduced. A 2-DOF PID controller is designed in this project for accurate tracking purpose. The effectiveness of 2-DOF PID controller is validated at the end of project too. 2-DOF PID controller is controller that has two tuning elements, which means more tuning parameters. The 2-DOF PID controller is designed using two-steps-tuning-method. Disturbance response are optimized by tuning parameters of $K_P, T_i, and\, T_D$ using Ziegler-Nichols 2nd method, followed by optimization of set-point response by tuning of 2-DOF parameters, α and β. Tracking control performance of 2-DOF PID controller is evaluated by comparing with PI and 1-DOF PID controller. The effectiveness of 2-DOF PID controller in tracking control is validated by examining sinusoidal inputs of different frequency and amplitude in experiments. Maximum absolute error, sum of absolute error, and mean square error are analyzed for all tracking performance of compensated system. Result shows that tracking error compensation (set-point response) of 1-DOF PID controller is better than 2-DOF PID controller. However, this is due to tuning of α and β parameters in simulation in this project. α and β values should be tuned experimentally. Disturbance response of 1-DOF PID and 2-DOF PID are almost similar due to same $K_P, T_i, and\, T_D$ values are used in both controllers.

ABSTRAK

Dalam projek ini, pengawal PID dengan dua darjah kebebasan telah direka untuk mesin jadual XY yang didorong oleh mekanisme skru bola. Jadual XY biasanya digunakan dalam mesin CNC dan industri lain yang menekankan kawalan gerakan terutamanya dari *point-to-point (PTP)* and *tracking*. Jadual XY mempunyai kelebihannya kerana berkos rendah dansenang didapati dalam pasaran. Pelbagai jenis pengawal telah direka untuk mengawal kedudukan dan gerakan mesin jadual XY. Jenis yang paling biasa digunakan ialah jenis konvensional pengawal PID dengan satu darjah kebebasan. Pengawal ini mempunyai prestasi yang memuaskan dan struktur yang mudah . Walau bagaimanapun , dalam kebanyakan kes , jenis konvensional pengawal PID hanya boleh mencapai sama ada kawalan gerakan terhadap arahan yang tepat atau kawalan gerakan terhadap gangguan yang tepat . Oleh itu, pengawal PID dengan dua darjah kebebasan yang senang direka dan boleh mencapai prestasi baik bagi kedua-dua kes telah diperkenalkan. Pengawal PID ini direka dalam projek ini untuk tujuan *tracking control* sahaja. Keberkesanan pengawal PID dengan dua darjah kebebasan telah disahkan pada akhir projek. pengawal PID dengan dua darjah kebebasan mempunyai dua pemampas, iaitu lebih banyak parameter dalam pengawal untuk menambahbaikan prestasi pengawal tersebut.. Pengawal PID dengan dua darjah kebebasan direka dengan menggunakan dua langkah. Pertama, kawalan gerakan terhadap gangguan dioptimumkan oleh parameter $K_P, T_i, dan\ T_D$ dengan menggunakan kaedah dua *Ziegler- Nichols*. Seterusnya, proses mengoptimumkan kawalan gerakan terhadap arahan dijalankan dengan penalaan dua parameter, α dan β. Prestasi kawalan pengawal PID dengan dua darjah kebebasan dinilai dengan membandingkannya dengan PI dan pengawal PID dengan satu darjah kebebasan. Keberkesanan pengawal dalam *tracking* disahkan dengan memberi input bentuk sinus dengan frekuensi dan amplitude yang berbeza dalam eksperimen. Ralat maksimum mutlak, jumlah ralat mutlak, dan min kuasa dua ralat dianalisis. Analisis menunjukkan bahawa jenis konvensional pengawal PID dengan satu darjah kebebasan mempunyai kawalan gerakan terhadap arahan yang lebih tepat,

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CHAPTER 1

INTRODUCTION

1.1. Project Background

XY table is used widely in many industries due to cheap cost, large stroke, availability and generality. Each axis of the XY table is linked to an AC Servo motor through a ball screw mechanism. This mechanism acts like a torsional spring. XY table is widely used in industries such as general machinery, pharmaceutical, manufacturing, semiconductor, material handling, and automation. In addition, XY table is also used in scientific research such as precision position control equipment research & development, and sometimes used in educational experiments.

XY tables are most often mounted horizontally and mostly used in applications such as water jet cutting, milling, and table sawing. XY tables may also be used in microelectronics assembly, laser machining and factory automation but depending on the specifications. XY table consists of two degree of freedom (2-DOF) motion. Each positioning axis consists of a one degree of freedom linear guide-way, a servo motor, a ball screw mechanism, and an encoder. XY table is realized by stacking two one-DOF axes together. Variation of XY table includes the ways and the drive mechanism. Drive mechanism determines the smoothness and speed while the ways determine the load capacity, straight-line accuracy, and stiffness. XY table is normally related to factors such as accuracy, repeatability, resolution, type of motor used, and encoder. Figure 1.1 shows the XY table manufactured by GoogolTech that is used in this project.

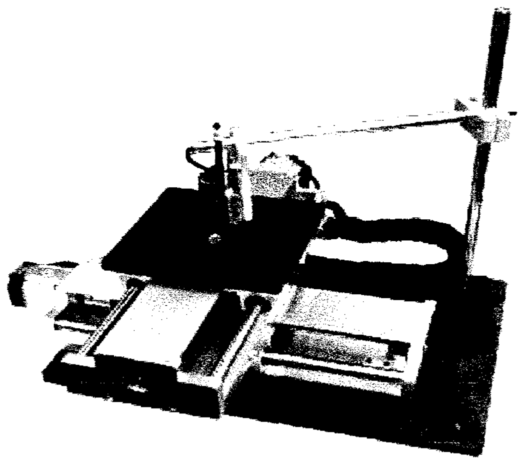

Figure 1.1: GXY series XY table used in this project

Positioning control is major issue in various industrial applications such as CNC (Computerized Numerical Control) machines or robots, electronic manufacturing equipment or robots especially semiconductor manufacturing. There are two fundamental types in positioning control of XY table. They are point-to-point (PTP) positioning which involves one position point to another point either in linear or angular position. The other is CP (Continuous-Path) positioning which is the control of movement for moving along a prescribed position trajectory or in other word, tracking control [2].

In all industries which focus on point-to-point positioning system, fast response, robust and no/low overshoot is the main consideration for controller design [2]. However, the nonlinearities and uncertainties phenomena of the plant have been a major problem in point-to-point positioning system. Main nonlinearities in XY table are existence of friction and saturation of actuator and/or power amplifier. These nonlinearity causes steady-state error and slow transient response for the positioning output. Besides, they can also affect the stability of plant [1]. Nonlinear phenomena affect the positioning precision and tracking accuracy.

One of the controllers that is introduced for position control is two-degree-of-freedom (2-DOF) PID controller. 2DOF PID controller is an improved version of conventional PID. Although it still carries the advantage of simple controller structure, it has better compensation performance in terms of set-point response and disturbance response. [1]

1.2. Problem statement

Positioning control of XY table is commonly applied in industries such as Printed Circuit Board, fixed length cutting, bending machine control and other related industries.

The most common controller, PID controller has simple design procedure but only a satisfactory positioning performance. This refers to the conventional one-degree-of-freedom PID. In conventional PID controller, there is only one-degree-of-freedom for the controller tuning. When controller parameters are tuned to have good set-point response, the disturbance response becomes poor. On the other hand, when tuning of parameters give good disturbance response, the controller cannot compensate to follow set-point perfectly. Apart from that, when applied in industrial plants that have nonlinearities and uncertainties, tuning of PID controller parameters become very difficult.

Two-Degree-Of-Freedom (2-DOF) PID has been introduced to allow better performance despite simple controller structure. By having more than one tuning element, 2-DOF PID enables good set-point response and disturbance response to be achieved simultaneously. A 2-DOF PID has its advantage of being simple and can be integrated with many other types of compensation techniques such as fuzzy, auto-tuning, or neural network. Thus, it has high flexibility to be applied in industries. In this project, a 2-DOF PID controller is designed to improve the tracking performance of XY table.

1.3. Objectives

The objectives of this project are:-

1. To design a two-degree-of-freedom PID controller for positioning control of a XY table system
2. To validate the effectiveness of two-degree-of-freedom PID controller in tracking and positioning control of XY table

1.4. Scope

1. To obtain dynamic modelling of XY table (one-axis performance) in frequency domain
2. Experimental setup for design of two-degree-of-freedom PID controller:

   Plant Specification for XY table (GXY2020VP4)

   - 2D AC Servo Ball Screw Driven XY table
   - Effective Distance route: X = 175mm, Y = 175mm
   - Incremental encoder (Resolution: 2000 pulse/rev = 1 pulse/mm)
3. Design of two-degree-of-freedom PID controller for one-axis performance of XY table
4. Performance evaluation
   - Tracking positioning performance (Evaluation of maximum absolute tracking error, sum of absolute tracking error, and mean square error)
     - Test with sinusoidal input of different frequencies & amplitudes

CHAPTER 2

LITERATURE REVIEW

2.1. Type of controllers being proposed

Ideally, precise positioning and accurate tracking can be done using linear control techniques such as PID controllers. However, in reality, the existence of nonlinearities and uncertainties has a significant effect on the positioning control [10-13].

Many controllers have been proposed for the positioning control of XY table. Most of the controllers designed has the need to compensate the friction of the plant in order to achieve high precision positioning. In most industrial applications, PID controllers are the most common controller for positioning control. This is due to their simple design and satisfactory performance. However, PID does not compensate the friction that exists in the system.

Kempf, C.J. and Kobayashi, S. proposed the disturbance observer and feedforward controllers [3], Park, M.H. and Wong, C.Y. proposed the time optimal controller [4] while Fujimoto, Y., and Kawamura, A. proposed a sliding mode controllers [5]. All three types of controllers mentioned can give precise positioning performance and are robust to parameter variations that are caused by plant uncertainties. Nevertheless, these controllers require complicated modelling that involves parameter identification process. To design these controllers, one has to have deep knowledge in control theory. This is impractical in industrial applications which most of the operators has less or no knowledge in control theory.

T. Iwasaki, Sato T., Morita A. and Marayuma H. had proposed an auto-tuning controller [7]. Auto-tuning controller can be used by industrial operator since it does not

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CHAPTER 2

LITERATURE REVIEW

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T. Iwasaki, Sato T., Morita A. and Marayuma H. had proposed an auto-tuning controller [7]. Auto-tuning controller can be used by industrial operator since it does not require deep control knowledge. However, the control process required a long and time-consuming process. It is very complicated and thus not suitable for real applications that emphasizes efficiency.

There are also other advanced controllers such as fuzzy logic controllers [8] and neural network controllers [9]. These intelligent controllers do not require exact modelling and parameter identification processes. Nonetheless, they still involve in certain level of complexity. For instance, in fuzzy logic controllers, adjustable elements such as selection of membership functions and fuzzy rules can sometimes be confusing for operators. In neural controllers, the operator has to select the number of inputs and outputs needed, and also the type of neural controller structure. Overall, these intelligent controllers do not gain the advantage over other controllers on simplicity.

Y. X. Su, B. Y. Duan and Y. F. Zhang had developed an auto-disturbance rejection controller [28]. They used a nonlinear tracking differentiator, an extended state observer, and a nonlinear proportional derivative controller. The aim is to achieve high performance for robust motion control. However, this controller that they proposed cannot make sure that the system is stable. For most of the back propagation neural network controller designed, the dynamic parameters of the plant have to be identified. This process is normally complicated and long.

For other friction compensation method, Z. Jamaluddin, H. Brussel and J. Swevers had tried to use friction-model- based feed-forward and inverse-model-based disturbance observer [20]. This controller is used to reduce the radial tracking error and quadrant glitches of linear-drive XY table. With this kind of compensation, the bandwidth of frequency increases. As system bandwidth increases, the tracking control performance become better. However, robustness to variations of parameters and uncertainties such as saturation were not considered in the design.

Eun-Chan Park, Hyuk Lim, and Chong-Ho Choi had proposed on precise positioning control of XY table at velocity reversal [19]. They investigated on friction, torsional displacement, and backlash. They used the presliding and sliding friction characteristics for the compensation of friction. By investigating the transition time from presliding to sliding, they succeeded in deriving that transition time is inversely proportional to the square-root of the acceleration at zero velocity. The relationship can be shown in the proposed friction model. Without accurate measurement, the transition time can be estimated. In the experiment, it is proved that this method works for a wide range of dynamics (acceleration). This compensation of friction at velocity reversal had proved its effectiveness in the experimental results. However, it still requires development of a friction model.

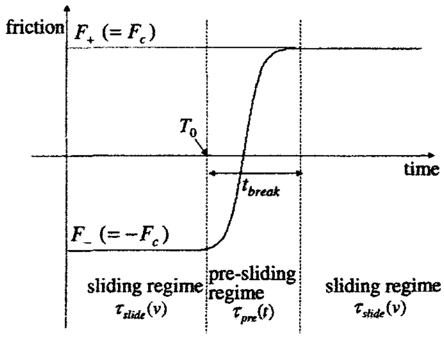

Figure 2.1: Proposed friction model at velocity reversal [19]

A discrete sliding mode controller with robust perfect tracking control had been proposed by Jian Wang, Hendrik Van Brussel, and Jan Swevers [6]. A feedforward tracking controller combined with a sliding mode controller has been designed. Using state-space canonical form, the closed-loop transfer function obtained is independent from the plant model. As with sliding mode controllers, the closed-loop plant characteristic is independent of the dynamics such as friction when on switching line, the controller designed is robust. However, in this design, the model uncertainties of the plant or other disturbances may have cause problems to reach quasi-sliding mode.

Lately there has been a robust adaptive network controller developed for XY table. This proposed controller is implemented in a DSP-based motion board. The stability and the convergence of the system are proved using Lyapunov theory [21]. Despite the uncertainties and disturbances, this controller confirm that convergence and stability of plant. The positioning performance of the motor for tracking is good. The neural network developed is two-layer feed-forward neural network. It has the disadvantage of being highly nonlinear in parameter [21]. This neural network is used to approximate the nonlinear factors of the AC servo motor. Although this designed controller is robust, the process is quite complex to be applied practically.

Although PID controller does not necessarily bring perfect compensation to the industrial plant, it still remains as the most common compensation technique used in industries to date. This is due to its simple structure and intuitively comprehensible tuning techniques when it comes to practical applications.

2.1. Problem of one-degree-of-freedom Conventional PID controller

Since introduction of PID controller in 1911 by Elmer Sperry, PID controller has been the most commonly used controller in industries [12]. Its main advantages are simple structure and design procedures. A conventional PID controller has three terms which are consists of proportional, derivative, and integral. The control signal of controller output is by the following algorithm:

$$u(t) = K_P e(t) + K_i \int_0^t e(\tau)d\tau + K_d \frac{d}{dt} e(t) \quad (2.1)$$

where K_p : Proportional gain

K_i : Integral gain

K_d : Derivative gain

e : error

t : time

τ : variable of integration

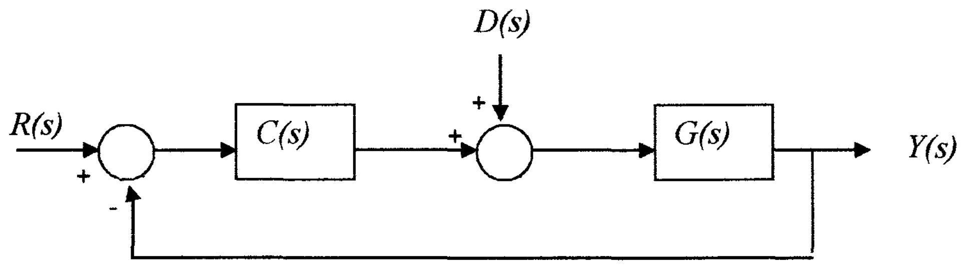

Figure 2.2: Conventional PID control system

Considering Figure 2.2, it is found that this structure has one-degree-of-freedom structure. The degree-of-freedom of a control system refers to how many of the closed-loop transfer functions are independent. The closed-loop transfer function of Figure 2.2 is derived as the following:

$$Gyr1(s) = \frac{C(s)G(s)}{1+C(s)G(s)} \tag{2.2}$$

$$Gyd1(s) = \frac{G(s)}{1+C(s)G(s)} \tag{2.3}$$

Combining these two equations, it is found that:

$$Gyr(s) = \frac{G(s)-Gyd(s)}{G(s)} \tag{2.4}$$

Since *Gyr1(s)* and *Gyd2(s)* are dependent on each other, this control system has only one tunable element, that is *C(s)*. They cannot be tuned independently. In this kind of system, when the tuning of controller parameters get optimal set-point response, the disturbance response is often poor, and vice-versa [10].

This tuning of controller parameters has simple theories but in real life, there are many limitations of PID control especially in nonlinear systems. Aside from nonlinearities, noises at high frequency usually causes problem with the derivative gain in PID. K_d will amplify these noises thus causes large amount of changes in output. In such cases, it is preferable to insert a low-pass filter to eliminate the noises [15].

Also, when there is actuator saturation, a phenomenon called integral windup might happen in PID control. This happens when error, *e(t)* is integrated by K_i and hence accumulate. The saturation cannot be released even when error, $e(t) = 0$. This will lead to large oscillation at the output which is undesirable. The overshoot for a large-amplitude step input can be very high and persistent. At most of the time, the wind-up can be many times longer than the overshoot as compared to the overshoot during linear operation mode. Normally, an anti-windup mechanism is used to cope with this situation [15].