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ORIGINAL PAPER

Comparison Between Three Tuning Methods of PID Control for High Precision Positioning Stage

R. Sen[1], C. Pati[2], S. Dutta[2] and R. Sen[2]*

[1]Electrical and Computer Engineering Department, University of Texas, Austin, USA

[2]Precision Engineering and Metrology Group, CSIR-Central Mechanical Engineering Research Institute, Durgapur, India

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Abstract: Advances in micro and nano metrology are inevitable to satisfy the need to maintain product quality of miniaturized components by the utilization of well controlled positioning stage. Proportional, integral and derivative (PID) control has been proved to have most robust and simpler performance. However, tuning of the key parameters of a PID controller is most inevitable to build a robust controller to accomplish high precision positioning performance. Therefore, many tuning methods are proposed for PID controllers. In this work, three tuning methods, namely, Ziegler–Nichols step response method, Chien–Hrones–Reswick method and Cohen–Coon method are compared for PID control of a single axis of a XY stage of a 3D surface profiler. Positional errors are also measured using a miniature plane mirror interferometer. Cohen–Coon method is found to be the best technique to minimize the controller error.

Keywords: PID control; Tuning; Controller error; Positional error; Miniature interferometer

1. Introduction

Precision of multi-axis machine has long been one of the principal concerns in modern machine tool technology. With the increasing demand for miniaturization, high precision positioning of translational stage of machine tool is inevitable. Positional errors of translational stages in micro-coordinate measuring machines, atomic force microscope, scanning tunnelling microscope and other high precision metrological equipments are the main obstacle towards the path for reaching nano-scale accuracy [1–3]. Therefore, many works related to compensation of positioning error of translational stages of high precision machine tools has been performed over the years [4, 5]. Error compensation through different position control methods are highly reliable regarding this purpose [6, 7]. Direct drive design using linear motors is widely used in high precision positioning system in translational stage. Therefore, the positioning performance is primarily dependent on the control performance of linear motor. Thus, high precision control of linear motors has got a prime importance for accurate tracking performance. PID controller is widely used in the industry due to their simple structure and widely acceptable performance in industrial process [8]. However, for getting high precision performance using PID controller is dependent on three co-efficient, namely, proportional gain, integral gain and derivative gain. Tuning of these parameters are essential to accomplish high precision performance of PID controller. Over the years, different types of tuning methods, which are application specific, have been used [9–12]. In this work, three tuning methods, namely, Ziegler–Nichols step response method [13], Chien–Hrones–Reswick method [14] and Cohen–Coon method [15] are compared to tune the key parameters of a PID controller used to position a high precision single-axis system incorporated with a universal length measuring machine. Ziegler–Nichols tuning method is one of the oldest and most used methods of PID tuning. Paulusova et al. [16] discussed about PID controller in a electrical function model and found that Cohen–Coon method gives a better settling time and maximum overshoot than Ziegler–Nichols method. Vainshav et al. [17] compared some PID tuning methods for a second order spring mass system with monotonic step response and showed that Ziegler–Nichols exhibited a large maximum overshoot and settling time than Chien–Hrones–Reswick method, which was not acceptable. Shahrokhi et al. [18] compared various

*Corresponding author, E-mail: rsen@cmeri.res.in

tuning methods for various order single input and single output systems and suggested that traditional Ziegler–Nichols method could be used for most of them. Chien–Hrones–Reswick method is a good tuning method for higher order systems, however the exact process model is require which is less possible in real time operation [19]. Ziegler–Nichols have shorter settling time and for a system with varying lag, Chien–Hrones–Reswick gives best performance. However, in all the above mentioned works, three tuning methods, namely, Ziegler–Nichols, Chien–Hrones–Reswick, Cohen–Coon have not been compared or studied for a practical high precision metrological system.

Thus, in this work, these three tuning methods have been studied and compared for a typical PID controller utilized for a high precision metrological system. Presentation of a typical PID controller model and various sub- parts in this model has been described in Sect. 2. Demonstration of three tuning methods to achieve high precision, experimental results and conclusions are presented in this paper in subsequent sections.

2. Generalized model of PID controller and its tuning methods

PID controller, as shown in Fig. 1, is the most used feedback controller to estimate and minimize the error between a the process output and a desired input by involving three mathematical operations, namely, proportional (P), derivative (D) and integral (I) operations.

A PID controller is described by a transfer function, $G(s)$ as stated in Eq. (1) [20].

$$\begin{aligned} G(s) &= P + I + D = K_{\mathrm{P}} + \frac{K_I}{s} + K_{\mathrm{D}}.s \\ &= K_{\mathrm{P}}(1 + \frac{1}{T_{\mathrm{I}}.s} + T_{\mathrm{D}}.s) \end{aligned} \tag{1}$$

where K_{P} is proportional gain co-efficient, K_{I} $(=\frac{K_{\mathrm{P}}}{T_{\mathrm{I}}})$ is integral gain co-efficient and $K_{\mathrm{D}}(= K_{\mathrm{P}}.T_{\mathrm{D}})$is derivative gain co-efficient. T_{I} and T_{D} are integral and derivative action times, respectively. Such a controller is tuned by adjusting these parameters. It requires some effort to tune these three parameters in order to obtain best control performance.

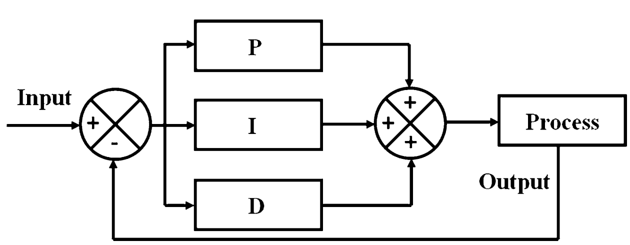

Fig. 1 Flow chart of a generalized PID controller

Proportional control depends on the difference between system's output and system's input (i.e. error). System response becomes faster with a larger value of proportional gain. However, a high value of proportional gain creates instability in a system. Integral gain co-efficient, $\boldsymbol{K}_{\mathrm{I}}$ is dependent on the magnitude of error and the duration time of the error ($\boldsymbol{T}_{\mathrm{I}}$). Integral controller sums up errors and explains how long and how far the measured process variable has been from the set point over time. Derivative controller is proportional to the rate of change of the process variable. If the process variable increases rapidly derivative controller causes the output to be decrease. If the derivative time is increased, control system will react more strongly to change in the error. It also speeds up the overall control system response.

Performance of a PID controller is dependent on the value of three parameters, K_P, K_I and K_D. Thus, there is a requirement to tune these three parameters based on the specific application. There has been significant research on the tuning techniques of a PID controller as discussed in Sect. 1. In this paper, three tuning methods, namely, Ziegler–Nichols, Chien–Hrones–Reswick method and Cohen–Coon method are compared for tuning of a specific PID controller used in ultra-precision machine tool. These tuning methods are described as follows [20].

2.1. Ziegler–Nichols Step Response Method

Ziegler and Nichols proposed a tuning method for PID controller which is mostly used in industries. This is manual mode process based on an open loop step response of a system. It is proposed for a first order plus dead time plant model as expressed in Eq. 2 [20],

$$G(s) = \frac{k}{1 + sT}e^{-sL} \tag{2}$$

where L is the delay time; T is the time constant and k stands for static gain of the controller. If the output of the step response measured through an experiment then the parameters k, L, T (or, a where $a = kL/T$) can be extracted from the plotted graph shown in Fig. 2.

The values of K_{P}, T_{I} and T_{D} are $1.2/a$, 2 $L$and $L/2$, respectively.

2.2. Chien–Hrones–Reswick Method

Chien, Hrones, and Reswick (CHR) method was derived from the original Ziegler–Nichols Open Loop method. It gives quickest response without overshoot and also with 20 % overshoot. This method has the ability for tuning the set point and disturbance. To tune the controller according to the CHR method, the parameters L and T are to be determined. The controller parameter values for Chien–Hrones–Reswick method are given in Table 1.

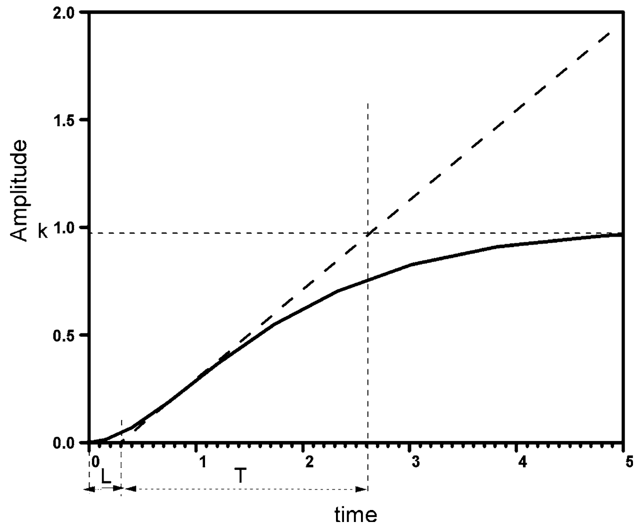

Fig. 2 Step response plot

Table 1 Controller parameters for Chien–Hrones–Reswick method

Controller type	With 0 % overshoot			With 20 % overshoot		
	K_P	T_I	T_D	K_P	T_I	T_D
PID	$\frac{0.6}{a}$	T	$0.5L$	$\frac{0.95}{a}$	$1.4T$	$0.47L$

2.3. Cohen–Coon Method

Cohen–Coon (CC) tuning technique of PID controller is an extension to the Ziegler–Nichols method. ZN method shows a slow steady-state response. However, CC method of tuning can overcome this limitation. It uses PID parameters obtained from open loop transfer function experiment. It gives better result than Ziegler–Nichols process if there is a large process delay relative to the open loop time constant. The systems response is modeled to a step change using the Cohen–Coon method. The system response is not only affected by the dynamics of main process but also by the dynamics of measuring sensor and finite control element. From this response, three parameters: K, τ, and t are found where K is the output steady state divided by the input step change, τ is the effective time constant of the first order response, and t is the dead time. The controller parameters for Cohen–Coon method is given in Table 2.

3. Experimental details

In this work, the positional error of X-axis of a XY stage connected with Talysurf CCI Lite 3D surface profiler (Made Taylor Hobson) has been measured using a double

Table 2 Controller parameters for Cohen–Coon method

Controller	K_P	T_I	T_D
PID	$\frac{01.35}{a}\left(1+\frac{0.18\tau}{1-\tau}\right)$	$\frac{2.5-2\tau}{1-0.39\tau}$	$\frac{0.0.37-0.37\tau}{1-0.81\tau}L$

beam plane mirror interferometer. The double beam plane mirror miniature interferometer is made of SIOS GmbH. The specifications of this interferometer are given in Table 3.

Both positional and angular information can be captured using this interferometer. Also the size of the interferometer is small which leads to maneuver the measurement for precision machine tools. The working principle of this interferometer is explained in [21]. However, the angular error has not been corrected using PID controller in this work. Since it can be seen from [21] that the variation of step size affecting the measurement accuracy of precision translational stage, the step sizes are varied for different ranges of measurement in this work. The stepsizes are taken as 0.001, 0.01, 0.1 and 5 mm for the range of 0–0.01, 0.01–0.1, 0.1–1 and 1–51 mm, respectively. The overall experimental set up for position measurement is shown in Fig. 3. The feedback control using PID controller is

Table 3 Specifications of double beam plane mirror miniature interferometer

Double beam plane mirror miniature interferometer (Made by SIOS GmbH)	
Measurement range (linear)	2 m
Linear resolution	0.1 nm
Measurement range (angular)	±2 arcmin
Angular resolution	0.002 arcsec
Interferometer software	INFAS
Dimension of the interferometer box	33 mm × 139 mm × 94 mm
Beam separation	12.7 mm
Flatness of the plane mirror	0.15 µm

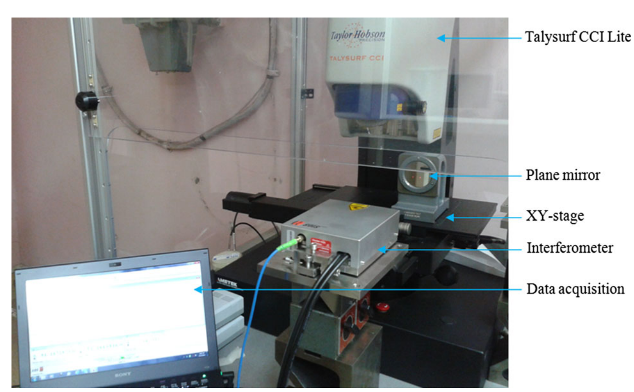

Fig. 3 Experimental set up

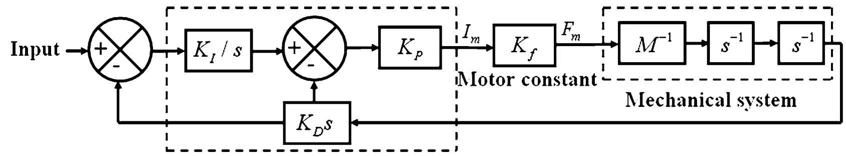

Fig. 4 Control model

performed in MATLAB® (version 7.8.0.347 R2009a) environment.

In the methodology of this work, a control model has been developed by considering a PID controller, an effect of drive motor (considering drive motor constant K_f) and an effect of mechanical system as shown in Fig. 4.

According to this control model, the thrust force (F_m) produced from the motor is proportional to the drive current (I_m) as stated in Eq. (3).

$$F_m = K_f I_m \tag{3}$$

The relationship between the system dynamics of the mechanical system with thrust force can be stated in Eq. (4).

$$F_m = M\ddot{x} \tag{4}$$

where x is the displacement and M is the mass of the mechanical system. In this work, mass of the measuring head travelling over the platform is considered and it is around 6 kg. The motor constant, K_f is 6.8 N/amp. Therefore, the overall transfer function ($G(s)$) considering the mechanical system and feed-drive is 6.8/6 s^2.

4. Results and discussion

In this research, control parameters, K_P, K_I and K_D for the PID control model has been determined using three tuning techniques viz. Ziegler–Nichols step response (ZN), Chien–Hrones–Reswick (CHR) method and Cohen–Coon (CC) method. The obtained parameters are given in Table 4.

Maximum overshoot values found to be 21.11, 17.51 and 12.87 % for ZN, CHR and CC methods, respectively. Therefore, CC technique is found to be better in terms of overshoot in this control model. The controller error obtained for various step size and range (stated in Sect. 3) are plotted against the set point (i.e. position) and the plots are shown in Fig. 5a–d. Positional errors have been measured using miniature interferometer without employing the PID controller and these errors are also plotted against set point as depicted in Fig. 5e–h.

It can be depicted from Fig. 5 that the errors obtained with the PID controller are much less than the measured positional error. It can also be observed from Fig. 5a–d that the controller errors obtained by using the Cohen–Coon control tuning technique are much less than that of ZN and CHR methods for each step size and each range. It happens due to the ability for coping up the dynamic disturbance of Cohen–Coon tuning method, whereas, ZN and CHR methods are not performing better in the presence of dynamic disturbance. However, the CHR and ZN methods for correcting controller errors are showing almost similar performance but the CHR method is doing well marginally than ZN. It can also be seen from Fig. 5 that the trend of controller errors are increasing for every range whereas the positional errors are showing random trends in ranges of 0–0.01, 0.01–0.1 and 0.1–1 mm. However, the positional error trend is found to be linear in the range of 1 to 51 mm (Fig. 5h). This may happen due to the improper alignment of measuring device and motion path which cannot be detected in theoretical control errors.

Table 4 Obtained values of control parameters

Tuning process	K_P	K_I	K_D
ZN	3.0099	2.7787	0.8151
CHR	3.6118	2.6588	0.9780
CC	8.7099	7.4070	1.6226

5. Conclusions

In this work, a PID control model of a single axis movement of a XY stage has been developed. Three tuning techniques, namely, Ziegler–Nichols step response, Chien–Hrones–Reswick tuning and Cohen–Coon tuning methods are employed with respect to the developed control model to find optimum control parameters. Also a performance comparison of these three tuning techniques has been done based on the obtained controller errors offline. Cohen–Coon tuning technique is found to be the best control tuning technique among them due to its ability to cop up the dynamic disturbance. Here positional errors have also been measured using a miniature plane mirror interferometer and it is found that the errors are much higher without employing a control model. Therefore, it can be concluded that the developed PID control model (with Cohen–Coon tuning) can be utilized for enhancing the performance of this precision positioning stage. The uncertainty comparison of these three tuning method for real time performance will be sought for the future scope of this work.

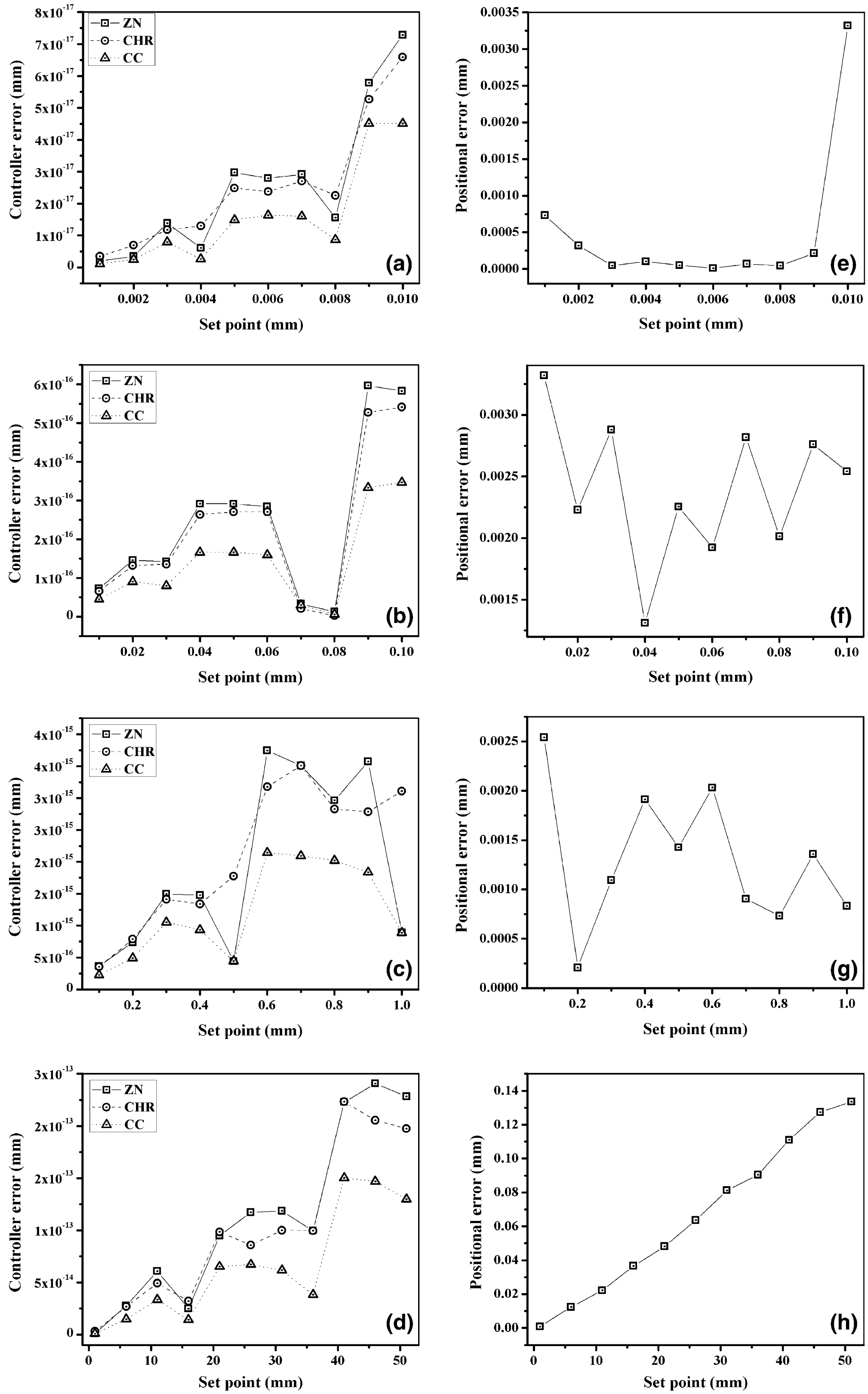

Fig. 5 Plots of controller error versus set point for stepsize of **a** 0.001 mm, **b** 0.01 mm, **c** 0.1 mm and **d** 5 mm and plots of positional error versus set point for stepsize of **e** 0.001 mm, **f** 0.01 mm, **g** 0.1 mm and **h** 5 mm

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