Analysis of Nonlinear PID Controller for Tracking Performance of Ball Screw Drive

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***Abstract*— In control system industry, it is crucial to have good tracking performance at higher speed. However, cutting force disturbances in machining affect the performance. Therefore, a good controller is important to compensate the disturbances. The focus area in this paper is to evaluate the tracking performance of Nonlinear PID (NPID) controllers based on two conditions. The first condition is based on a bounded nonlinear gain, $K(e)$ and secondly i,s based on constructing two parameters of integral controlled quantity, U_i and differential control efficient, K_d. The performance measures for this research are 10mm for every 0.4Hz and 0.7Hz of reference input to evaluate the tracking performance of the controllers. This research focuses on the comparison of two sets of the condition of NPID controllers for x-axis of ball screw drive. There are three analyses to classify the performances; maximum tracking error, root means square error (RMSE) and error reduction. The results show that NPID based on a bounded nonlinear gain $K(e)$ has better tracking performance than NPID based on U_i and K_d. NPID controller ($K(e)$ based) successfully reduced 33%-37% of error compared to NPID controller (U_i and K_d based). The designed controllers can have an adaptive algorithm to improve the adaptation of the controllers to the system as the recommended purposes.**

***Index Terms*— Ball Screw Drive; Cutting Speed; NPID Controller; Tracking Performance.**

I. INTRODUCTION

Milling is the most common material removal process and popular in the machining industry. Furthermore, milling machines are among the most versatile and useful machine tool in performing cutting operation [1].The process is done by machine tool that performs the cutting and shaping processes. Therefore, besides flexibility and low cost, machine tool thirst for its good tracking performance. However, there are several challenges in fulfilling the requirement. The challenges include cutting force disturbance. Cutting force exists during milling operations resulting in an external effect on the ball screw drive [2].

High demand on this factor requires the industry to execute a good controller. There are many schemes of Nonlinear PID (NPID) controllers that have been explored. Armstrong et al. (2001) prove that the designed NPID controller capable of improving accuracy and friction compensation. The stability of the designed controller is identified before being implemented. Fourteen years later, Sy. Salim et al. (2015) have introduced Enhanced NPID (ENPID) controller based on NPID where multi-rate NPID (MN-PID) and Self-regulation NPID (SN-PID) are designed. However, the controllers are focused on pneumatic system. Besides that, NPID controller also has been discussed by Dong and Pedrycz (2015) where the nonlinear gain is designed in a cascaded way.

As there are many scholars that have studied NPID controllers, this paper focussed to compare between NPID controller with respect to bounded nonlinear gain, $K(e)$ and NPID controller with respect integral controlled quantity, U_i and differential control efficient, K_d [6]. The controllers aim to compensate various cutting speeds of 1500rpm, 2500rpm and 3500rpm for ball screw drive.

II. EXPERIMENTAL SETUP

There are four elements involved in this research. The first component is a computer with installed MATLAB and ControlDesk software. This computer act as an interface for interaction between human and the drive. Secondly is a digital signal processing that acts as an input-output signal that to be sent to the amplifier. The amplifier helps to increase the signal power before transmitting the information to the drive. Lastly is the main subject where the ball screw drive is used to determine the tracking performance based on the designed controllers. Those components are related towards each other as presented in Figure 1.

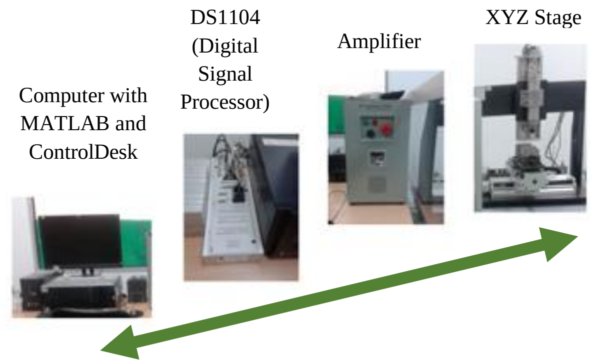


Figure 1: Experimental setup of ball screw drive

Before designing controllers, an identification process for the system is identified. The frequency response function in the system is estimated using H1 estimator for the overall modelling [7]. Eq. (1) shows the generated system identification.

$$G_m = \frac{78020}{s^2 + 163s + 193.3} \tag{1}$$

III. Controller Design

There are two controllers designed for this research namely NPID based on $K(e)$ and NPID based on U_i and, K_d. In order to design NPID controller, the very first step is to design PID controller. PID controller is a popular controller in the industry. The controller has three variables called Proportional (K_P), Integral (K_I) and Derivative (K_D). The transfer function of PID controller are shown in Eq. (2):

$$G_c(s) = K_p + \frac{K_i}{s} + K_d s \tag{2}$$

The controller is designed using SISOTOOL toolbox in MATLAB software. The toolbox helps to execute the best value for the variables based on several analyses. The first analyses are based on gain margin and phase margin. Figure 2 shows the open loop transfer function. The gain margin and the phase margin obtained are 9.94dB and 61.4deg respectively.

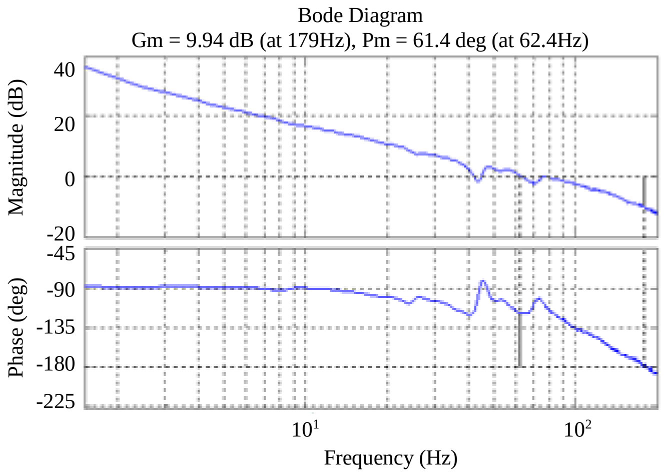


Figure 2: Gain Margin and Phase Margin

Besides that, the system stability is showed by the Nyquist plot in Figure 3. The system stability is confirmed since the plot not encircled at point (-1,0). The system speed of response also identified by the bandwidth of the position loop. Furthermore, the maximum peak of sensitivity is examined for a good transient response when the maximum peak sensitivity is not exceeding 6dB [8]. Figure 4 and Figure 5 show the bandwidth of 44.4Hz and maximum peak sensitivity of 5.12dB respectively.

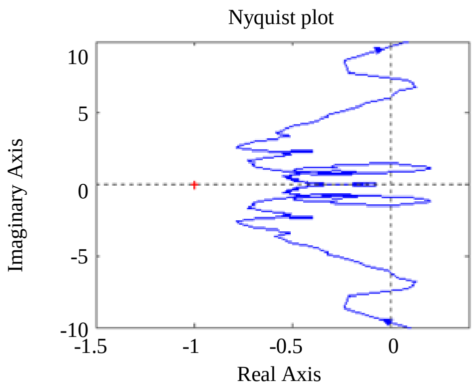


Figure 3: Nyquist plot for Stability

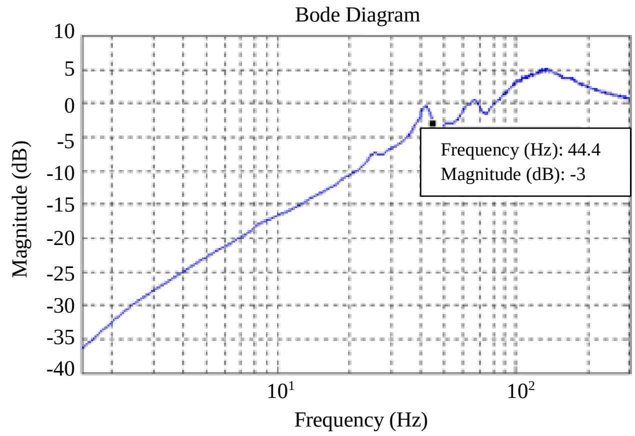


Figure 4: Bandwidth of the System

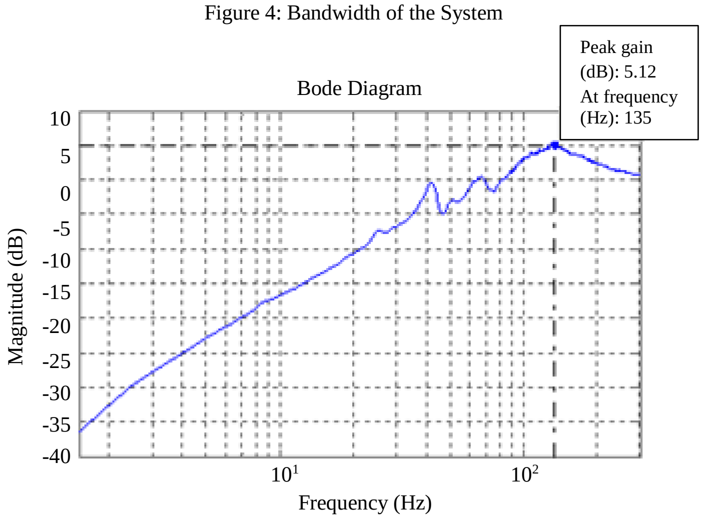


Figure 5: Maximum Peak Sensitivity

The last analysis of PID controller design is the maximum peak complimentary sensitivity. Figure 6 below shows the peak sensitivity is 0.931dB which is not exceeding 2dB and thus shows a good transient response.

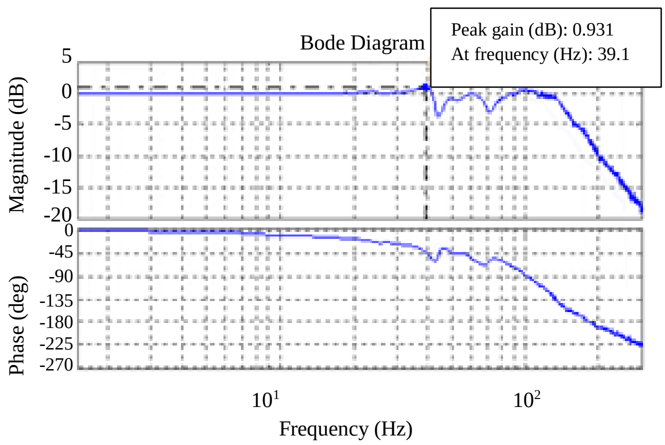


Figure 6: Maximum Peak Complimentary Sensitivity

Therefore, the values for K_P, K_I and K_D are 0.8998, 0.0006077 and 0.005155 respectively.

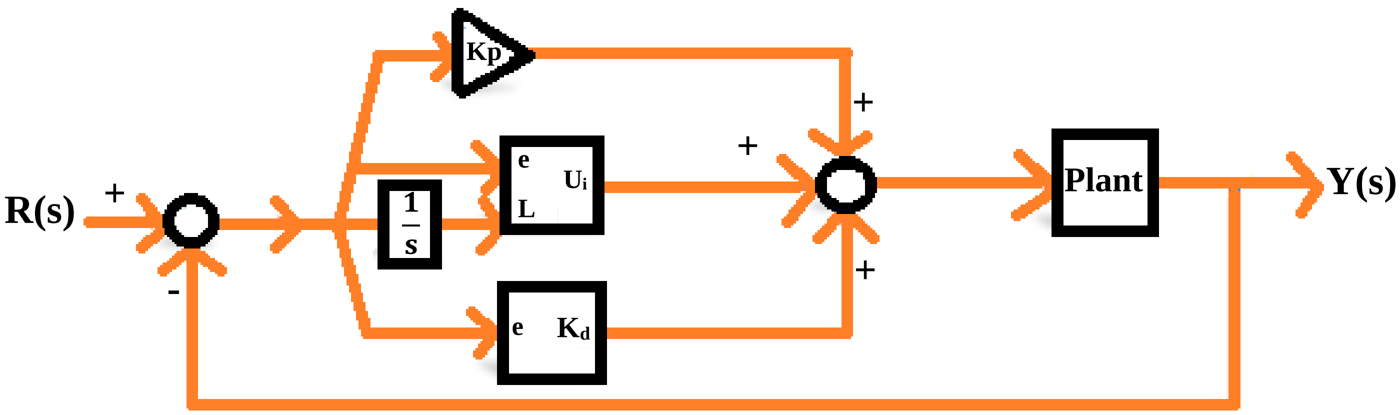


Figure 7: Design of NPID based on U_i and K_d

Figure 7 shows the design of a NPID controller that is focused on determining two parameters of integral controlled quantity, U_i and differential control efficient, K_d. The purpose of this modification is to improve the tracking performance of the system. A function *T[E(k)]* is designed to fulfilled two conditions. The conditions are to weaken the integral control when *E(k)* increases and to strengthen the integral control when *E(k)* decreases. While for K_D function, the formulation is shown as in Eq. (3).

$$K_D(k) = c.E(k) + d \tag{3}$$

where the *c* and *d* are set constants, and the values are determined based on the suitability of the system. Meanwhile, the second controller is NPID controller based on *K(e)*. After that, the nonlinear function is designed. After the maximum peak sensitivity is observed, the Popov plot is analysed for its stability as shown in Figure 8.

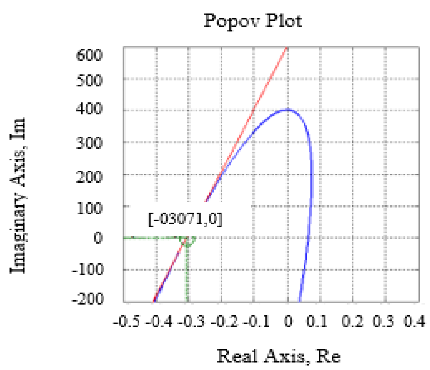


Figure 8: Popov Plot

From the figure, it is observed that the crossing point occurred at (-0.3071, j0). Eq. (4) shows the point is then used to calculate the K_{emax}.

$$K_{e\max} = \frac{1}{\left|G_{openloop}\, jw\right|} \tag{4}$$

Therefore, the K_{emax} is 3.2563. Next, the *KO* and *emax* is tuned in order to calculate K_e as shown in Eq. (5).
With that, Eq. (6) is the rule in order to determine the K_e is K_e must be less or same as the K_{emax}. After several attempts, the chosen *KO* and *emax* is 6 and 0.3 respectively which resulting in the K_e is 3.1075. The structure of this controller is shown in Figure 9:

$$0 \le K_e \le K_{e\max} \tag{6}$$

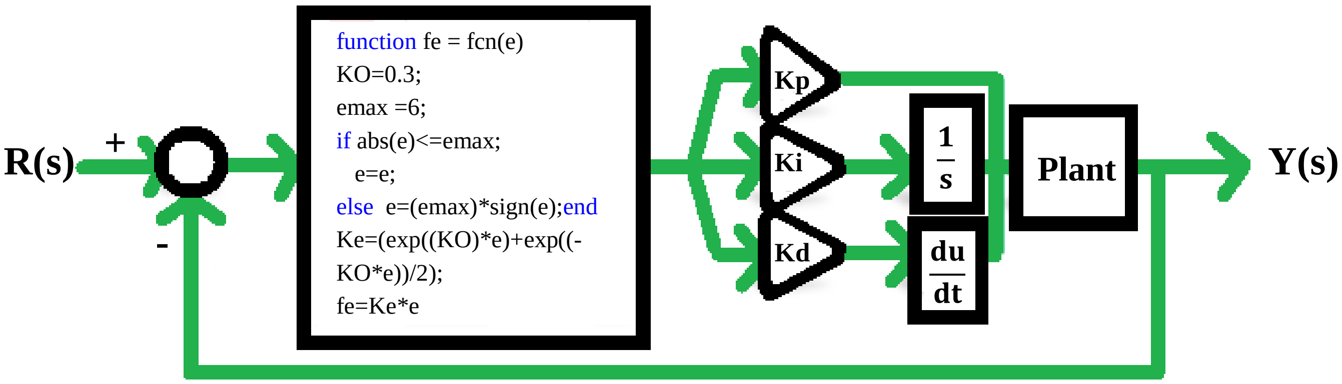


Figure 9: Design of NPID based on K(e)

IV. RESULTS AND DISCUSSION

A. Maximum Tracking Error

The maximum tracking error for this research is based on two types of nonlinear PID controller that are K_e based and U_i and K_d based. Table 1 and Table 2 show the maximum tracking error based on reference input of 10mm for every 0.4Hz and 0.7Hz respectively. From the result, spindle speed at 2500rpm generates the highest maximum tracking error for both input frequency when NPID (U_i and K_d) controller is injected with disturbances. Meanwhile, NPID controller (K_e based) does not produced the same results as NPID (U_i and K_d) controller where the maximum tracking error shows a decrement as the speeds increases. As there are no specific trends on cutting force, the results depict that every controller has their own mechanism in compensating the cutting force. Furthermore, the result at 0.7Hz produces higher tracking error compare to 0.4Hz.

Table 1
Maximum Tracking Error for 0.4Hz

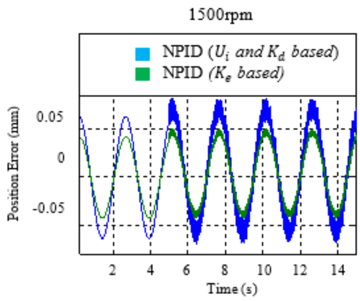
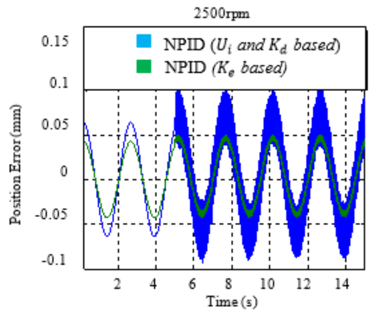
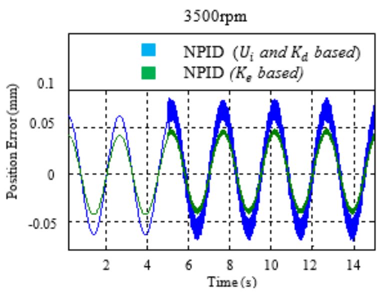
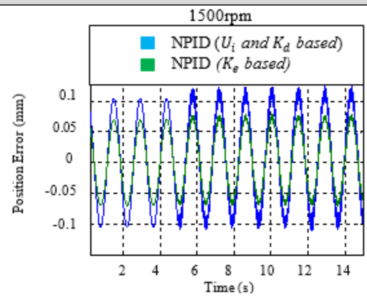
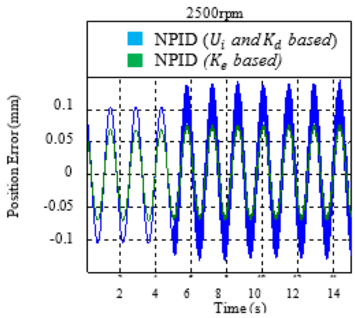
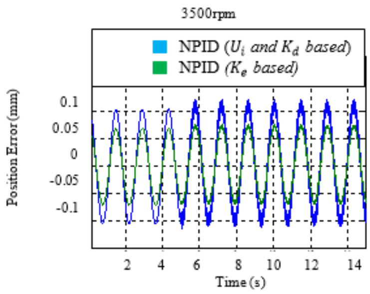
0.4Hz	Maximum Tracking Error (mm)
	0.0831 0.0503
	0.1044 0.0495
	0.0831 0.0490

Table 2
Maximum Tracking Error for 0.7Hz

0.7Hz	Maximum Tracking Error (mm)
	0.1255 0.0777
	0.1444 0.0771
	0.1237 0.0762

The maximum tracking error occurs during 2500rpm for NPID (U_i and K_d) because higher friction causes nonlinearities at 2500rpm and the result is due to high amplitude component at the speed [9]. However, NPID controller (K_e based) shows a decrement as the speeds increases as the controller has compensated the disturbances according to the increment of the speeds. To add, 0.7Hz shows higher tracking error compared when 0.4Hz as the frequency is inversely proportional to the time taken to complete an oscillation. Thus, the outcome is due to the processing time factor. Hence, the controller has more time to response at a lower frequency.

B. Root Mean Square Error

The second analysis is the root mean square error. Eq. 7 shows the coding for this analysis.

$$RMSE=sqrt\ (mean(Error\_NPID(:,2).^\wedge 2)) \qquad (7)$$

Table 3 shows the RMSE at 0.4Hz. The results show that the highest spindle speed resulted in the lowest RMSE. However, there is no specific pattern of RMSE as the spindle speed increases. The error also shows that higher frequency produces higher root mean square error due to volume and processing time factor. This can be shown as tabulated in Table 4 where the results increases compared to the results in Table 3 where 0.4Hz was implemented. Furthermore, NPID (U_i and K_d based) controller shows an increment from 1500rpm to 2500rpm and decreasing towards 3500rpm. This shows that speed of 2500rpm generates higher error compared to 1500 rpm and 2500 rpm due to nonlinearities during machining as mentioned in maximum tracking error analysis.

Table 3
Root Mean Square Error for 0.4Hz

Spindle Speed (rpm)		1500	2500	3500
Controllers	NPID (K_e based)	0.0305	0.0304	0.0304
	NPID (U_i and K_d based)	0.0461	0.0488	0.0460
Error Reduction (%)		33.8	37.7	33.9

Table 4
Root Mean Square Error for 0.7Hz

Spindle Speed (rpm)		1500	2500	3500
Controllers	NPID (K_e based)	0.0495	0.0495	0.0495
	NPID (U_i and K_d based)	0.0746	0.0763	0.0746
Error Reduction (%)		33.6	33.6	33.6

V. Conclusion

In short, NPID controller (U_i and K_d based) shows highest maximum tracking error and RMSE at 2500rpm. This is because spindle speed at 2500rpm generates the highest nonlinearity. In contrast, NPID controller (K_e based) shows a decrement of maximum tracking error and RMSE as the spindle speeds increases. To conclude, NPID controller (K_e based) shows better tracking performance compared to NPID controller (U_i and K_d based). The statement is strongly acceptable as the controller shows lower error in terms of maximum tracking and root mean square error regardless any amplitude at 0.4Hz and 0.7Hz frequency compared to NPID (U_i and K_d based) controller. With that, there are second conclusions are made. Firstly, the higher the spindle speed, the lower the error. Moreover, higher frequency shows higher error.

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