ROBUST MOTION CONTROLLER DESIGN FOR PRECISE TRACKING OF BALL SCREW DRIVEN POSITIONING SYSTEM

N.A. Anang[1], Z. Jamaludin[1], L. Abdullah[1], M. Maharof[1] and M.H. Nordin[2]

[1]Fakulti Kejuruteraan Pembuatan,
Universiti Teknikal Malaysia Melaka, Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia.

[2]London Southbank University, 103 Borough Road,
London SE1 00A, United Kingdom.

Corresponding Author's Email: [1]lokman@utem.edu.my

Article History: Received 14 January 2018; Revised 16 June 2018; Accepted 13 October 2018

ABSTRACT: This paper presents the design and analysis of cascade NP/PI position controller for machine tools application. The proposed control structure is an enhancement over the classical cascade P/PI position controller whereby a nonlinear function was designed and embedded onto cascade P/PI controller scheme to add element of robustness to the controller characteristics. The controller design consisted of three steps, namely; design of speed loop, design of position loop, and design of the nonlinear function. Both the speed loop and the position loop were designed based on loop shaping method in frequency domain using gain margin and phase margin as design considerations. The controller gains were confirmed based on results of stability. Three parameters identified for the nonlinear function were rate of variation of nonlinear gain (KO), maximum value of error, (e_{max}) and sampling frequency, (δ). The controller tracking performances were numerically analysed and validated on an XY feed table positioning system. Cascade NP/PI were found to produce superior tracking performance over cascade P/PI controller with improvement in tracking performance of 6.63% and 15.63% at reference tracking frequencies of 0.4Hz and 0.7Hz respectively.

KEYWORDS: *Cascade NP/PI; Cascade P/PI; Tracking Performance; Ball Screw Drive*

1.0 INTRODUCTION

In recent years, there have been marked increased in demands for high quality parts and product [1]. Besides demands for precision and accuracy of the finished parts and products, manufacturers are also challenged to be cost effective and efficient. This has led to overwhelming efforts by researchers in areas related to control strategy of machine tools, specifically in precision machining [2–5]. Precise machining is realized with excellent tracking performances of the machine tools drives system. Therefore, various control approaches have been proposed and implemented in literature to improve tracking performances of machine tools drives system [6-10]. These include conventional cascade P/PI, PID and gain scheduling controller [11-13]. A nonlinear function was embedded onto the position loop to improve robustness of the system resulting in improved control performance of up to 90% in term of reduction in the amplitudes of the cutting forces harmonics components using Fast Fourier Transform (FFT) of the position errors. Previously, the nonlinear function was mostly associated with conventional PID controller. In addition, the applications are mostly centred on robotics, pneumatic and hydraulic system, and in hard disk drive system [14-15]. To the best knowledge of the authors, study of the nonlinear function with cascade P/PI controller was still lacking. In this paper, a further enhancement of the classical cascade P/PI controller is proposed. The uniqueness of this new approach lies on the introduction of a new control strategy named cascade NP/PI. It consists of a nonlinear function integrated with the proportional gain controller of the cascade position loop.

This paper is organized as follows: section two introduces the research methodology, section three details the design steps for the synthesis of the proposed controller, section four then presented the results obtained followed by discussion and finally, section five concludes the research findings.

2.0 METHODOLOGY

2.1 Experimental Setup

This section outlines the experimental setup where numerical analysis and validations were performed. The system consists of four main components, namely; (i) a computer with MATLAB/Simulink and ControlDesk control monitoring user interface software, (ii) a dSPACE DS1104 digital signal processing (DSP) board, (iii) a servo amplifier and (iv) an XY milling machine positioning table from Googol Technology. The DSP board works as Input-Output (I/O) interface and a DAC converter for communication between the computer and the servo amplifier while it functions as a ADC unit for communication between the positioning table and the servo amplifier. Position data that was collected from each encoder of the drive system was sent back to the computer for monitoring and further control actions. Figure 1 shows schematics diagram of the test setup.

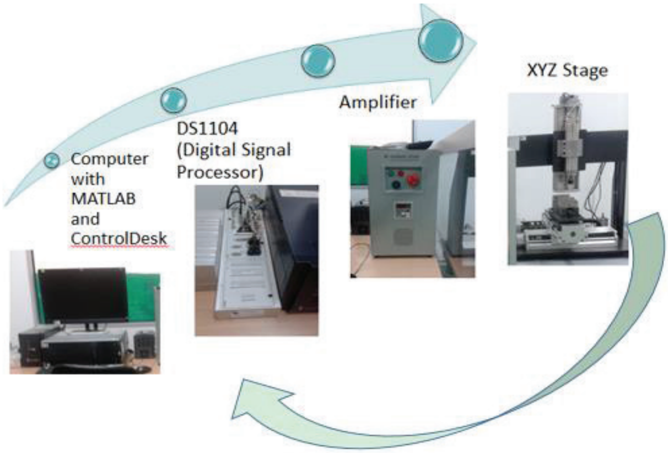


Figure 1: Experimental setup for this research

2.2 System Identification

System identification is the first step in any controller design process. It describes the system dynamics behavior. An accurate system model is necessary for effective controller design. A frequency response function (FRF) of the system was first generated using an H_1 estimator [15] based on measured input voltage to the drive system, $u(t)$ and the output encoder position of the positioning table, $y(t)$. A second order system transfer function, $G_m(s)$ with time delay of 0.0012 seconds was mapped onto the FRF data using Frequency Domain System Identification (Fdident) toolbox in Matlab. The identified transfer function is shown in Equation (1):

$$G_m(s) = \frac{Y(s)}{U(s)} = \frac{78020}{s^2 + 163s + 193.3} e^{-0.0012s} \tag{1}$$

3.0 CONTROLLER DESIGN

Next, a cascade P/PI and a cascade NP/PI position controller were designed based on measured FRF of the system which represents the actual dynamic behavior of the system. First, a cascade P/PI controller was designed. The controller consists of a PI-based speed loop and a P-based position controller loop. Figure 2 shows schematic diagram of the cascade P/PI controller. The next section elaborates on design of cascade PI speed loop.

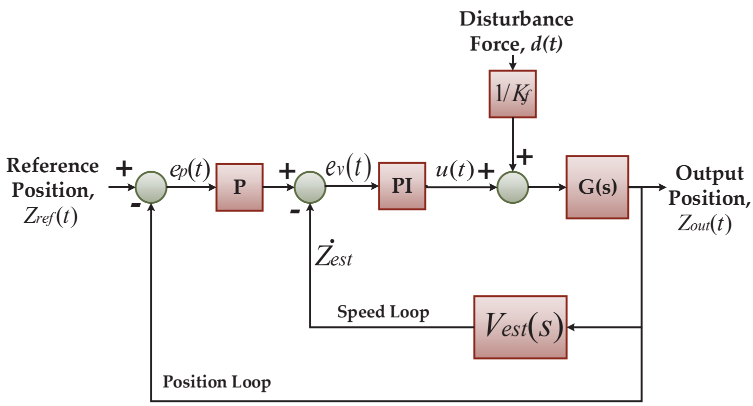


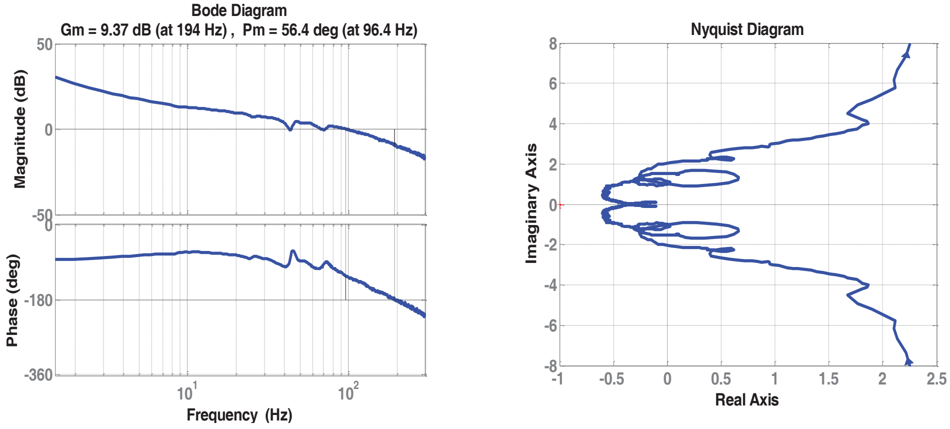
Figure 2: Schematic diagram of a cascade P/PI controller

3.1 Design of PI Controller Speed Loop

A Proportional (P) plus Integral (I) controller was designed for the speed loop. The controller parameters, k_p and k_i were tune based on gain margin and phase margin considerations of the open loop transfer function [16]. The gain margin and the phase margin considered were between 4dB - 10dB and 30°- 70° respectively. These values were selected to ensure good stability margin and improved system transient response performance [17]. Equation (2) states the open loop transfer functions shown in Figure 2.

$$V_{openloop}(s) = \frac{Z_{est}(s)}{E_v(s)} = PI \times G(s) \times V_{est}(s) \tag{2}$$

Figure 3 shows the open loop bode diagram of the speed loop for K_p and K_i values of 0.006607 and 0.12075 respectively. The gain margin and the phase margin obtained were 9.31dB and 56.4° respectively. A compromise was made between stability margin and transient response performance. The system stability was confirmed by the Nyquist plot since the point (-1,0) was not encircled.



(a) (b)

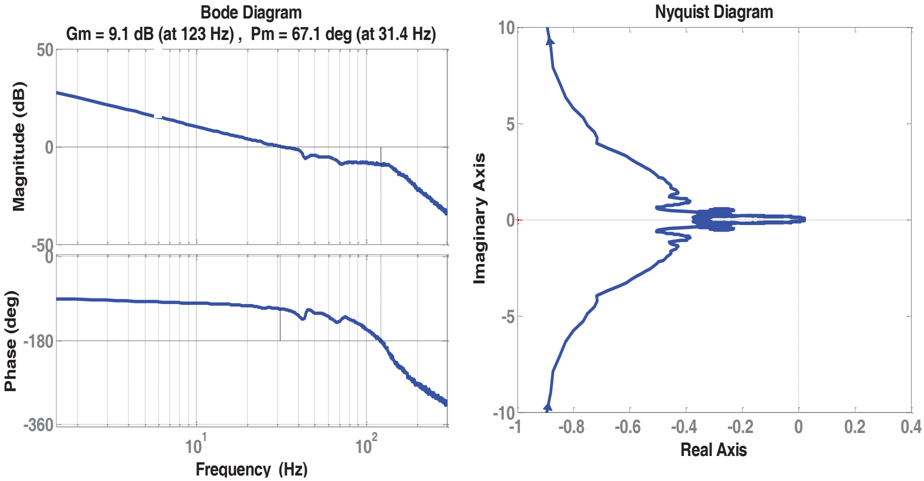
Figure 3: Bode diagrams (a) Open loop transfer function and (b) Nyquist plot

3.2 Design of Position Loop Controller

Next, the position control loop consisting of a proportional gain, k_v was designed over the speed controller loop. Similar control design strategies previously applied for the speed loop were repeated resulting in a k_v value of $225s^{-1}$. The open loop transfer function based on the schematics diagram shown in Figure 2 is shown in Equation (3):

$$P_{openloop}(s) = \frac{Z(s)}{E_p(s)} = \frac{P \times PI \times G(s)}{1 + PI \times G(s) \times V_{est}(s)} \tag{3}$$

Figure 4 shows the Bode diagram of the open loop transfer function, and Nyquist stability plot of the position loop. A gain margin and phase margin values of 9.1dB and 67.1° were observed. The Nyquist plot confirmed the system stability.



(a) (b)

Figure 4: Bode diagrams (a) Open loop transfer function and (b) Nyquist plot

3.3 Design of Nonlinear Function

This section describes design of the nonlinear function that is embedded on the control structure of the cascade P/PI controller. The nonlinear function N receives the position error signal and becomes an input to the P controller of the position loop. Figure 7 shows the control structure of cascade NP/PI controller. The nonlinear function consists of the rate of variation of the nonlinear gain (KO), maximum value of error (e_{max}) and sampling frequency (δ). Table 1 lists the tuned parameters of the nonlinear function.

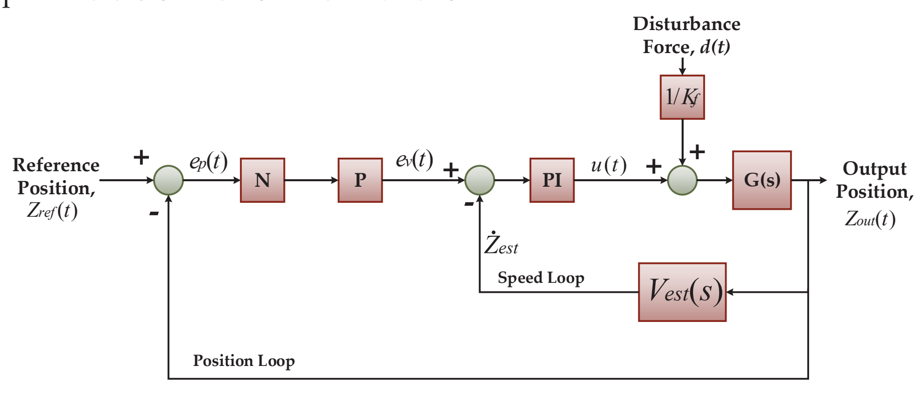


Figure 7: Schematic diagram of cascade *NP/PI*

Table 1: Tuned parameters of nonlinear function for cascade *NP/PI*

$K(e_{max})$	KO_1	Ke_1	KO_2	Ke_2	e_{max}	δ
3.8139	3.5	2.9642	4.0	3.7622	0.5mm	0.0005

The nonlinear function parameters are shown in Equations (4)-(7):

$$KO = \begin{cases} 3.5 & \text{if } |e| \le e_{max} \\ 4.0 & \text{else } |e| < e_{max} \end{cases} \tag{4}$$

Nonlinear gain such as

$$K_e = \frac{\exp(KO \times e) + \exp(-KO \times e)}{2} \tag{5}$$

Switching function, sigmoid expressed as

$$(e) = \frac{e}{|e| + \delta} \tag{6}$$

Maximum nonlinear gain such as

$$K(e_{max}) = -\frac{1}{R_e + [G(jw)] + w \times I_m [G(jw)]} \tag{7}$$

Parameters KO and e_{max} were first identified using the Popov stability plot that analysed stability of the nonlinear function. Figure 8 shows that the plot crosses the real axis at (-0.2622, *j*0). Then, parameter $K(e_{max})$ was calculated based on equation (9) resulting in a value of 3.8139. Next, parameters KO and e_{max} were identified based on value of $K(e_{max})$ which lies between $0 \le KO \le 3.8139$. Variations in KO affected the values of Ke and e as shown in Figure 9.

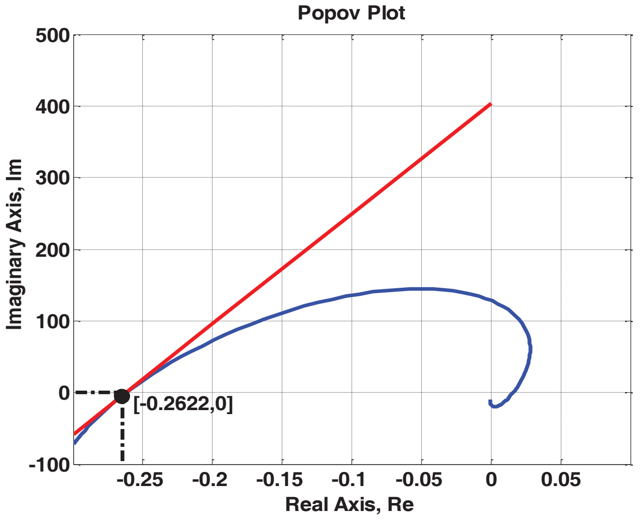


Figure 8: Popov plot for stability

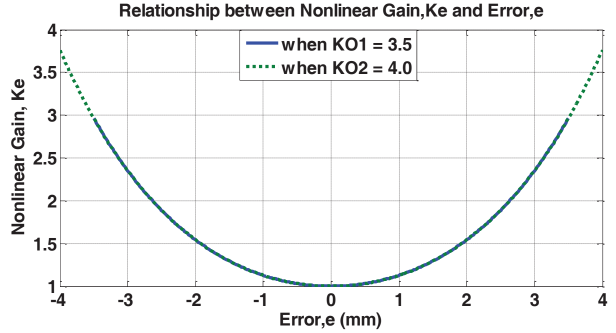


Figure 9: Relationship of nonlinear gain and error

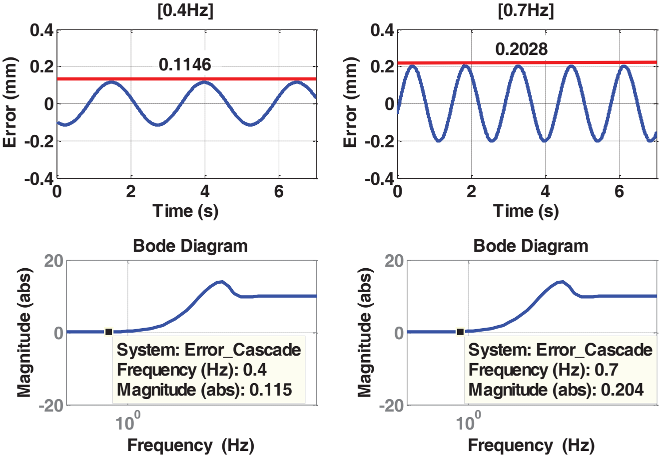
4.0 RESULT AND DISCUSSION

This paper presents a design of cascade NP/PI controller; a controller than is an enhancement over the classical cascade P/PI controller often applied for position control in machine tools. The tracking performances of cascade NP/PI was compared to cascade P/PI controller to analyse its advantages. Position errors of cascade P/PI and cascade NP/PI were analysed based on the control structures shown in Figure 2 and Figure 7. The respective position error transfer functions were stated in Equation (8) and Equation (9):

$$E_{p\_pi} = \frac{1+PI\times G\times V_{est}}{1+PI\times G\times V_{est}+P\times PI\times G} Z_{ref}(s) - \frac{\frac{G}{K_f}}{1+PI\times G\times V_{est}+P\times PI\times G} D(s) \quad (8)$$

$$E_{np\_pi} = \frac{1+PI\times G\times V_{est}}{1+PI\times G\times V_{est}+N\times P\times PI\times G} Z_{ref}(s) - \frac{\frac{G}{K_f}}{1+PI\times G\times V_{est}+N\times P\times PI\times G} D(s) \quad (9)$$

For numerical analysis and validations of both controllers' tracking performance, the control systems were subjected to sinusoidal input reference signal of amplitude 10mm and frequencies of 0.4Hz and 0.7Hz. For controller design validation, the numerical results were compared to the theoretical position errors values obtained based on Equations 11 and 12. Figure 10 shows numerical results of tracking errors for cascade P/PI controller at 0.4Hz and 0.7Hz excitations frequencies respectively. At 0.4Hz, the maximum tracking error recorded was 0.115mm compared to theoretical value of 0.115mm while at 0.7Hz, the maximum tracking error was 0.203mm compared to theoretical value of 0.204mm. The results showed an almost exact agreement between theoretical and numerical values of the tracking errors thus validating the controller design.



(a) (b)

Figure 10: Numerical validation of cascade P/PI controller (a) 0.4Hz and (b) 0.7Hz

In case of cascade NP/PI controller, the nonlinear gain, Ke was calculated based on the difference of the tuned parameters of nonlinear function of Ke_1 and Ke_2 that were 3.762 and 2.964 respectively. Figure 11 shows the numerical results of tracking errors for cascade NP/PI controller excited at 0.4 Hz and 0.7Hz respectively for Ke value equals 0.8. At 0.4 Hz excitation frequency, the maximum tracking error recorded was 0.107mm compared to theoretical value of 0.093mm. On the other hand, at 0.7Hz, the maximum tracking error obtained was 0.171mm compared to theoretical value of 0.164mm.

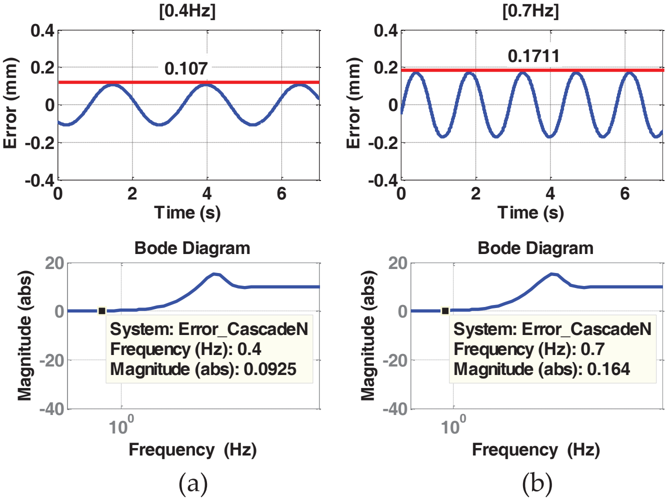


Figure 11: Numerical validation of cascade NP/PI controller (a) 0.4Hz and (b) 0.7Hz

The close agreement between numerical and theoretical results of the tracking errors validates the design and analysis of cascade NP/PI controller. In comparison to tracking performance of cascade P/PI, the results obtained showed the tracking superiority of cascade NP/PI controller. The nonlinear function N applied on the P position controller has enhanced the tracking performance of cascade P/PI controller. The nonlinear function has successfully varied the proportional gain of the position loop controller according to changing magnitudes of the tracking errors; that is larger gain was applied at higher tracking error magnitude and likewise. Bode diagrams of both controllers were used to compare the theoretical results (based on equation) with numerical (by simulation) analysis.

Table 2 shows comparison in maximum tracking errors between both controllers where the improvements of tracking errors observed were 6.63% and 15.63% for 0.4Hz and 0.7Hz respectively.

Table 2: Comparisons between cascade P/PI and cascade NP/PI controllers

Frequency (Hz)	0.4		0.7	
Type of Errors / Type of Controllers	Maximum Tracking Error	Theoretical Error	Maximum Tracking Error	Theoretical Error
Cascade P/PI	0.1146	0.1150	0.2028	0.2040
Cascade NP/PI	0.1070	0.0925	0.1711	0.1640

5.0 CONCLUSION

This paper presents design and validation of cascade NP/PI that is an enhanced version of cascade P/PI controller. Cascade NP/PI is an extension of the classical cascade P/PI controller; a controller that is widely applied in machine tools. Both controllers were designed, numerically analysed and validated using an XY milling positioning table as the system setup. The controller's parameters were tuned based on open loop characteristics such as gain margin, phase margin and Nyquist criterion. The nonlinear function consisted of components such as KO, e_{max} and δ. Both KO and e_{max} were tuned based on Popov stability plot that identified the range of nonlinear gain to be less than 3.8139. The tracking errors of both controllers were compared using sinusoidal input signal of amplitude 10mm and frequencies of 0.4Hz and 0.7 Hz. Both controllers were successfully validated as results of numerical tracking errors closely matched the theoretical results. Cascade NP/PI produced superior tracking performance over cascade P/PI controller with improvement in tracking performance of 6.63% and 15.63% for tracking frequencies of 0.4Hz and 0.7Hz respectively.

ACKNOWLEDGEMENT

The authors would like to acknowledge the financial support by Universiti Teknikal Malaysia Melaka (UTeM) under the scholarship of 'Skim Zamalah UTeM' and PJP grant with reference number PJP/2018/FKP(7C)/S01588 and FRGS grant with reference number FRGS/1/2016/TK03/FKP-AMC/F00320.

REFERENCES

[1] T. Moriwaki, "Multi-functional machine tool", *CIRP Annals - Manufacturing Technology*, vol. 57, no. 2, pp. 736–749, 2008.

[2] I. Nuella, C. Cheng and M.S. Chiu, "Adaptive PID Controller Design for Nonlinear Systems", *Industrial & Engineering Chemical Research*, vol. 48, no. 10, pp. 4877–4883, 2009.

[3] F.J. Villegas, R.L. Hecker, M.E. Peña, D.A. Vicente and G.M. Flores, "Modeling of a linear motor feed drive including pre-rolling friction and aperiodic cogging and ripple", *International Journal of Advanced Manufacturing Technology*, vol. 73, no. 1–4, pp. 267–277, 2014.

[4] P. Strakos and T. Karasek, "Adaptive model predictive control as a prospect for control of machine tools with significant flexibility," in International Conference on Numerical Analysis and Applied Mathematics, Rhodes, Greece, 2015, pp. 830001 - 830006.

[5] M.H. Abu Bakar, M.A. Md. Ali and R.I. Raja Abdullah, "Machining model of TI-6AL-4V titanium alloy using FEM analysis", *Journal of Advanced Manufacturing Technology*, vol. 6, no. 2, pp. 1-9, 2012.

[6] C. Singh, "Genetic algorithms based PID controller design", *International Journal of Enginering Development and Research*, vol. 3, no. 3, pp. 2–5, 2015.

[7] D.A. Vicente, R.L. Hecker, F.J. Villegas and G.M. Flores, "Modeling and vibration mode analysis of a ball screw drive", *International Journal of Advanced Manufacturing Technology*, vol. 58, no. 1–4, pp. 257–265, 2012.

[8] S.N.S. Salim, Z.H. Ismail, M.F. Rahmat, A.A.M. Faudzi, N.H. Sunar and S.I. Samsudin "Tracking performance and disturbance rejection of pneumatic actuator system," in 9th Asian Control Conference, Istanbul, 2013. doi: 10.1109/ASCC.2013.6606083.

[9] Y. Altintas, A. Verl, C. Brecher, L. Uriarte and G. Pritschow, "Machine tool feed drives", *CIRP Annals - Manufacturing Technology*, vol. 60, no. 2, pp. 779–796, 2011.

[10] K. H. Ang, G. Chong and Y. Li, "PID control system analysis, design, and technology", *IEEE Transactions on Control Systems Technology*, vol. 13, no. 4, pp. 559–576, 2005.

[11] J. P. Segovia, D. Sbarbaro, and E. Ceballos, "An Adaptive Pattern based Nonlinear PID Controller," *ISA Transactions*, vol. 43, no. 2, pp. 271–281, 2004.

[12] C. Singh, "Genetic Algorithms Based PID controller Design," *International Journal of Engineering Development and Research*, vol. 3, no. 3, pp. 2–5, 2015.

[13] Z. Retas, L. Abdullah, S. N. S. Salim, Z. Jamaludin and N. A. Anang, "Tracking error compensation of XY table ball screw driven system using cascade fuzzy P+PI," *International Review of Automatic Control*, vol. 9, no. 5, pp. 324–329, 2016.

[14] B. Armstrong, D. Neevel and T. Kusik, "New results in NPID control: Tracking, integral control, friction compensation and experimental results", *IEEE Transactions on Control Systems Technology*, vol. 9, no. 2, pp. 399–406, 2001.

[15] S.N.S. Salim, A.C. Amran, A.A.M. Faudzi, Z.H. Ismail, M.F. Rahmat, N.H. Sunar and S.A. Shamsudin "A study on tracking performance of the pneumatic system with enhanced NPID controller," in 10th Asian Control Conference, Sabah, 2015. doi: 10.1109/ASCC.2015.7244442.

[16] R. Pintelon and J. Schoukens, *System Identification: A Frequency Domain Approach*, *Second Edition*. New Jersey: John Wiley & Sons, Inc., 2012.

[17] Z. Jamaludin, "*Disturbance Compensation for Machine Tools with Linear Motor Drives*," Ph.D. dissertation, Department of Werktuigkunde, Katholieke Universiteit Leuven, Belgium, 2008.

[18] L. Abdullah, "*A new control strategy for cutting force disturbance compensation for XY table ball screw driven system*," Ph.D. dissertation, Universiti Teknikal Malaysia Melaka, Durian Tunggal, Melaka, 2014.