EVALUATION ON TRACKING PERFORMANCE OF NPID TRIPLE HYPERBOLIC AND NPID DOUBLE HYPERBOLIC CONTROLLER BASED ON FAST FOURIER TRANSFORM (FFT) FOR MACHINE TOOLS

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Article History: Received 9 January 2018; Revised 19 June 2018; Accepted 10 October 2018

ABSTRACT: Accuracy and precision are the area of interest in machine tools application. It is evaluated via the measurement of tracking performance of the controllers. This study presents a Fast Fourier Transform (FFT) technique that used to evaluate the tracking performance of two controllers, namely NPID Triple Hyperbolic controller and NPID Double Hyperbolic controller for XY Table Ball-screw driven system. The cutting force characteristics are observed by using a FFT technique. Peak amplitude of FFT error on harmonic frequency was observed as a cutting force occurrence on the control system. Two cutting force disturbances that are generated from spindle speed of 1500 rpm and 2500 rpm at frequency of 0.2 Hz of speed of motor were used as a configuration set up to compare the tracking performance between the two controllers. The average error reduction of FFT error at cutting force of 1500 rpm between NPID Double Hyperbolic and NPID Triple Hyperbolic was 25.12%. This average error reduction result showed that the NPID Double Hyperbolic controller produced better tracking performance compared to the other controller. For future work, it is recommended to explore the superiority features offered in artificial intelligence tool box for better judgment in tuning control parameters.

KEYWORDS: *Cutting Force Disturbance; Fast Fourier Transform (FFT) Error; Machine Tools; Nonlinear PID (NPID)*

1.0 INTRODUCTION

Accuracy and precision of positioning system are widely uttered by many researchers in the area of machine tools technology, especially in CNC machine [1-2]. There are quite a number of controllers were introduced by researchers in the area of machine tools technology especially for the purpose of improvement in tracking performance of machine tools. Recently, control system was designed by [3-4] in order to control the machine with the existence of different cutting force disturbances. Various controllers with an observer was designed by researcher [4-7] to name a few. PID in combination with disturbance force observer (DFO) produced better cutting force compensation based on Fast Fourier Transform (FFT) error technique compared to conventional PID, cascade P/PI and PID with inverse model based disturbance observer as recorded by [5]. In [8], an active magnetic bearing (AMB) technique, fuzzy logic algorithm and an adaptive self-tuning feedback loop were designed in order to adjust the spindle parameter and counterbalance the cutting force during milling process. On the other hand, friction compensation was also discussed by [9-10]. A PD controller and friction compensation were designed with a load estimator by [10] that produced a better positioning accuracy.

Pole-placement control was designed by [11] to attain good damping vibration with high bandwidth disturbance rejection of a ball-screw drive system. The control system was designed as a feedback loop. In addition, a feed-forward control was added to improve the command tracking. The result showed that the pole placement produced a superior disturbance rejection in the low frequency between 0 and 18 Hz compared to the P-PI controller. In [12], a feed-forward controller combining with PI controller was designed for novel XY piezo-actuated flexure-based mechanism positioning stage. The stability of the closed loop system was confirmed with Lyapunov function. This design produced a better tracking error compared to standalone feed-forward controller and open-loop controller. Moreover, a multilayer neural network was designed to compensate the geometrical error of the XY table machine as claimed by [13]. This network was designed in cascade form with PID controller.

Besides, a nonlinear controller was widely designed in order to improve a linear controller's effectiveness for a certain system. Three types of nonlinear function, namely sigmoidal, hyperbolic and piecewise-linear function were introduced by [14] in order to produce a zero steady-state error, low overshoot and rapid rise time. In [15], a nonlinear PID controller based on hyper-stability criteria was designed. In [16], the researcher proposed a nonlinear PD controller in order to obtain smaller settling time without increasing the proportional gain for servomechanism. A pair of sigmoid was used in this study. On the other hand, a modification of PID controller, in which a function was able to compress and expand the error signal was designed for electromechanical actuator system by [17]. The simulation and experimental result showed that the modification PID controller has a better transient response compared to PID controller. In [18], a new immune nonlinear PID controller was designed for material-level control of the heat milling system. A Popov plot was used to obtain a maximum allowable nonlinear gain. Rahmat et al. [19] presented a nonlinear PID controller for pneumatic application in order to obtain a robust performance with high weight of load. In [20], a nonlinear function was designed by using a Gaussian curve with an equation. The simulation result showed that the nonlinear PI controller produced a better performance compared to PI controller. Furthermore, [21] had introduced a controller named as NPID Triple Hyperbolic controller. The controller managed to provide good tracking performance. However, the disadvantages of NPID Triple Hyperbolic controller are it produces significant amount of noise. Owing to this reason, the author proposes new control strategy named as NPID Double Hyperbolic controller to address this issue.

In previous work, the usage of hyperbolic function for controller design is mainly in the area of hard disk drive system. In this paper, an improvement has been performed. To the best of author's knowledge, there is none of the researchers have utilized the hyperbolic function in the area of machine tools technology. The uniqueness of this new approach lies on the introduction of new control strategy named as NPID double hyperbolic. It consists of modification of hyperbolic function named as double hyperbolic function in which a reciprocal hyperbolic function is developed in order to design a nonlinear function for integral gain. The detail of this function was described from previous work by [21].

2.0 METHODOLOGY

2.1 Experiment Setup

The experimental setup consists of four main components comprises of personal computer, Digital and Analog converter (DAC/ADC) board, amplifier board and XY Table Ball-screw driven system. The personal computer is equipped with MATLAB/Simulink and dSPACE software in order to establish connection between computer and XY table. The digital signal from computer is converted to analog by using DAC/ADC board to the actuator, and vice versa. The amplifier is used to amplify an input signal by a factor of 10 to the actuator of the machine. In addition, an encoder with a resolution of 0.0005mm/pulse is attached on the servo motor of XY Table Ball-screw driven system. Meanwhile, encoder is utilized to measure the positioning of either x or y axis movement of the machine. The detail of experimental setup was discussed in previous work [21].

2.2 Cutting Force Analysis

The cutting force characteristics can be observed via Fast Fourier Transform (FFT) by obtaining the harmonics frequency [4]. In this study, two spindle speeds of cutting process of 1500 rpm and 2500 rpm are selected. The peak of amplitude of cutting force that is generated from those two spindle speeds are marked by a red dash circle as shown in Figure 1. The detail of peak of amplitude of cutting force can be seen in Table 1. It shows that maximum force of 0.1167 N is occurred at frequency of 52 Hz for the case of 1500 rpm and maximum force of 0.1301 N is occurred at frequency of 78 Hz for the case of 2500 rpm. The disturbances occurred at harmonic frequency were also discussed for other application as documented by [9-10].

These frequencies are used to discuss the capability of the controllers in controlling the system via the approach of cutting force disturbance rejection.

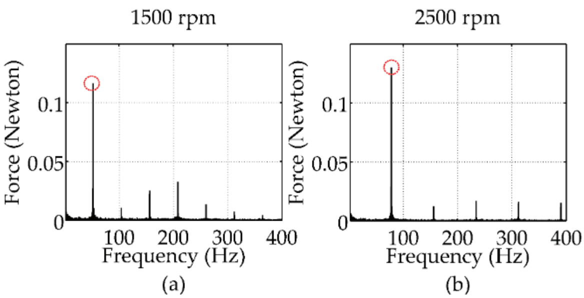

Figure 1: Cutting Force using Fast Fourier Transform (FFT) at (a) 1500 rpm and (b) 2500 rpm

Table 1: Peak of Force for Two Different Spindle Speeds

Cutting Force	1500 rpm	2500 rpm
Peak Frequency (Hz)	52	78
Highest Peak of Force, (Newton or N)	0.1167	0.1301

2.3 Controller Design

The very first step in designing a nonlinear controller is to obtain PID parameters. The design of PID and NPID Triple Hyperbolic controller are done and presented in previous work by [21]. In addition, NPID Double Hyperbolic controller is also designed in this study. Figure 2 illustrates the control scheme of NPID Double Hyperbolic controller. It consists of two nonlinear components that are added on the proportional and integral gains of the PID control structure.

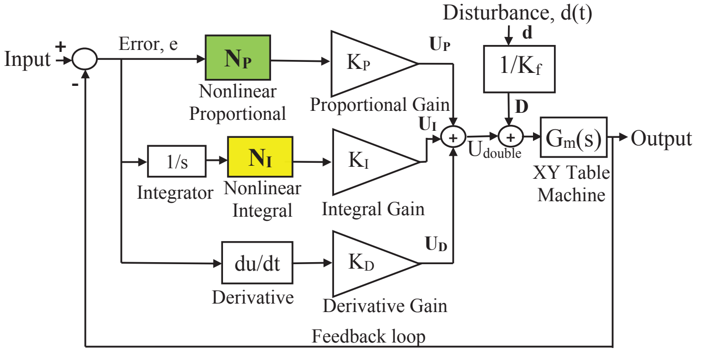

Figure 2: Nonlinear PID (NPID) Double Hyperbolic control scheme

The nonlinear functions and control signal of this controller are expressed in the following equations:

$$N_P = 1 + f * (1 - \operatorname{sech}(g * e_P)) \tag{1}$$

$$N_I = \frac{1}{p + (q * (1 - \operatorname{sech}(r * e_I)))} \tag{2}$$

$$U_{double} = K_P\,(N_P.e\,(t)) + K_I \left(N_I \int_0^t e\,(t) \right) dt + K_D \frac{d}{dt} e\,(t) \tag{3}$$

where K_P, K_I and K_d are proportional, integral and derivative gain that are injected into the system respectively. e(t), e_P and e_I are the position error, error in nonlinear proportional gain, and error in nonlinear integral gain, respectively that are generated from the system. f, g, p, q, and r are parameters in nonlinear gains.

3.0 RESULTS AND DISCUSSION

3.1 FFT Error at Fundamental Peak Frequency

The Fast Fourier Transform (FFT) error at fundamental peak frequency is conducted to observe the effectiveness of the control design when a cutting force disturbance is injected on the system. Thus, the smallest fundamental peak of FFT error with no big amplification after fundamental peak frequency indicates that the control design produces a better performance. For this reason, the performances of the two controllers, namely NPID Triple Hyperbolic and NPID Double Hyperbolic controller are compared in this study. The FFT is utilized to convert the data in time domain structure into the data in frequency domain structure [22].

Furthermore, a frequency of 0.2 Hz (for speed of rotation of motor) is used in addition to two different cutting forces, 1500 rpm and 2500 rpm as the configuration of the system. For the case of 1500 rpm, the FFT error at peak frequency of NPID Triple Hyperbolic and NPID Double Hyperbolic are 1.2993 mm and 1.0302 mm respectivelyas shown in Figure 4. These errors are obtained at fundamental peak frequency of 52 Hz. The result indicates that the NPID Double Hyperbolic controller has the best performance compared to the other controllers.

On the other hand, for the case of 2500 rpm, the FFT error at peak frequency of NPID Triple Hyperbolic and NPID Double Hyperbolic are 0.8270 mm and 0.4954 mm respectively as shown in Figure 5. These errors are obtained at fundamental peak frequency of 78 Hz. For this case, the result indicated that NPID Double Hyperbolic controller produced a better performance with smallest peak of tracking error compared to the other controller. NPID Triple Hyperbolic controller produced slight higher peak of tracking error. This controller also produced an amplification after frequency of 52 Hz and 78 Hz that shown in blue dash circle as shown in Figure 3 and Figure 4 respectively. This phenomenon is called waterbed effect, which had discussed by previous researcher [4]. It refers to a situation in which suppression in errors at some frequencies lead to expansion of errors in some other frequencies. It is like sitting on a waterbed, pushing it down at one point which reduces the water level locally but resulted in an increased level at some other locations on the bed - naturally occurred and a trade-off in system performance.

The detail of highest peak of error based on FFT technique for two controllers is tabulated in Table 2.

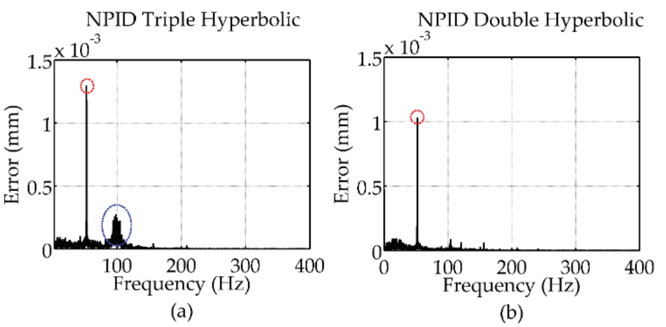

Figure 3: Peak Frequency at 1500 rpm: (a) Triple Hyperbolic and (b) Double Hyperbolic

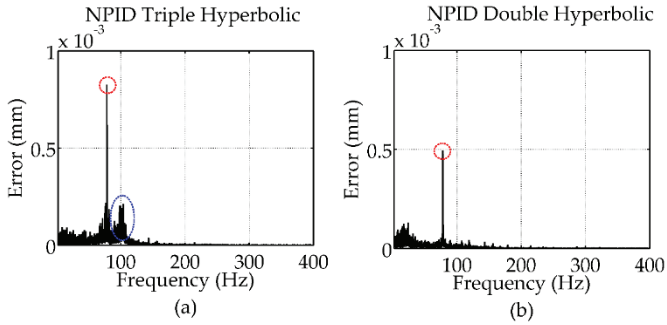

Figure 4: Peak Frequency at 2500 rpm: (a) Triple Hyperbolic and (b) Double Hyperbolic

Table 2: Peak of Tracking Error for Two Controllers

Cutting Force		1500 rpm	2500 rpm
Peak Frequency (Hz)		52	78
Highest Peak of Error (mm)	NPID Triple	1.2993	0.8270
	NPID Double	1.0302	0.4954

3.2 FFT Error at Harmonic Frequencies

From different point of view, the FFT error not only can be evaluated at fundamental peak frequency (as discussed in Section 3.1) but also at multiple harmonic frequencies. It is important to evaluate the position tracking performance of the system. In this study, the selected harmonic frequencies are from 2 Hz until 10 Hz. The chosen frequencies are selected based on limitation of the bandwidth of the system. The results obtained are with respect to the existence of cutting force disturbance that is injected onto the system. For the case of 1500 rpm, the result shows that the average error reduction between NPID Double Hyperbolic and NPID Triple Hyperbolic has an average error reduction of 25.12% as tabulated in Table 3 and shown in Figure 5.

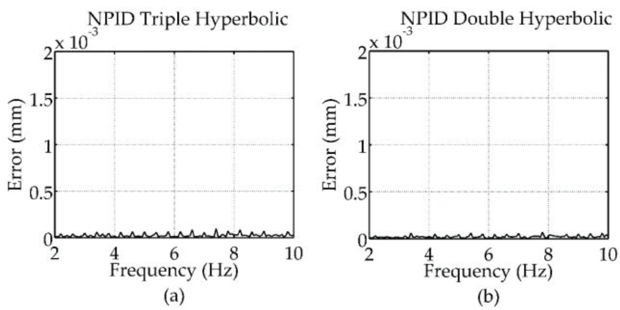

Figure 5: Fast Fourier Transform (FFT) Tracking Error at 1500 rpm: (a) Triple Hyperbolic and (b) Double Hyperbolic

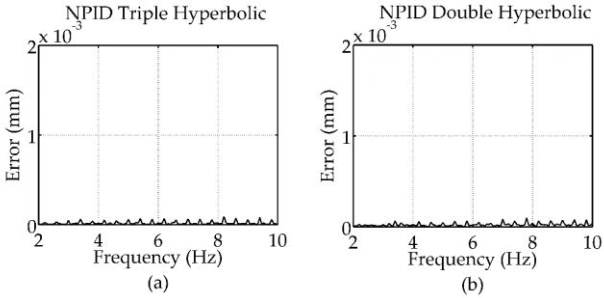

Figure 6: Fast Fourier Transform (FFT) Tracking Error at 2500 rpm: (a) Triple Hyperbolic and (b) Double Hyperbolic

In Figure 6, the tracking performances of the NPID Triple Hyperbolic and NPID Double Hyperbolic controller are shown when 2500 rpm spindle speed is injected on the system. The NPID Double Hyperbolic has a negative value of average of error reduction compared to NPID Triple Hyperbolic controller. The detail results of positioning error based on harmonic frequencies of FFT error for 1500 rpm and 2500 rpm spindle speed are shown in Table 3 and Table 4, respectively.

Table 3: Harmonic frequencies at 1500 rpm for two controllers

Harmonic Frequencies (Hz)	Spindle Speed (1500 rpm)		
	Amplitude of Tracking Error (μm)		Error Reduction (%)
	NPID Triple	NPID Double	NPID Double versus NPID Triple
2.2	0.0417	0.0307	26.38
3.4	0.0617	0.0608	1.46
4.2	0.0608	0.0486	20.07
4.6	0.0667	0.0354	46.93
5.0	0.0636	0.0453	28.77
5.8	0.0665	0.0517	22.26
6.2	0.0676	0.0474	29.88
6.6	0.0867	0.0472	45.56
7.8	0.0716	0.071	0.84
9.0	0.0719	0.051	29.07
Average of Error Reduction (%)			25.12

Table 4: Harmonic frequencies at 2500 rpm for two controllers

Harmonic Frequencies (Hz)	Spindle Speed (2500 rpm)		
	Amplitude Tracking Error (μm)		Error Reduction (%)
	NPID Triple	NPID Double	NPID Double versus NPID Triple
2.2	0.0261	0.0263	-0.77
3.4	0.0639	0.0649	-1.56
4.2	0.0525	0.0583	-11.05
4.6	0.0454	0.0500	-10.13
5.0	0.0604	0.0458	24.17
5.8	0.0612	0.0665	-8.66
6.2	0.0699	0.0497	28.90
6.6	0.0536	0.0375	30.04
7.8	0.0562	0.0959	-70.64
9.0	0.0580	0.07425	-28.02
Average of Error Reduction (%)			-4.77

4.0 CONCLUSION

In conclusion, NPID Double Hyperbolic controller produces better performance as a whole compared to NPID Triple hyperbolic in which it manages to obtain smaller tracking error on fundamental peak frequency as well as harmonic frequencies of Fast Fourier Transform (FFT) error for the case of spindle speed of 1500 rpm with an average error reduction of 25.12%. For the case of spindle speed of 2500 rpm, although the result of average error reduction of NPID Double Hyperbolic is slightly higher compared to NPID Triple Hyperbolic, there is no big amplification of noise when a cutting force is injected on the system when dealing with NPID Double Hyperbolic compared to NPID Triple Hyperbolic controller. For future works, it is recommended to explore for a more robust controller in order to accommodate with different types of disturbances.

ACKNOWLEDGMENTS

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

REFERENCES

[1] T. Yamazaki, "Development of A Hybrid Multi-tasking Machine Tool: Integration of Additive Manufacturing Technology with CNC Machining," in 18th CIRP Conference on Electro Physical and Chemical Machining, Ito International Research Center Conference, The University of Tokyo, Japan, 2016, pp. 81–86.

[2] C. C. Hong, C.-L. Chang, and C.-Y. Lin, "Static Structural Analysis of Great Five-Axis Turning–Milling Complex CNC Machine", *Engineering Science and Technology*, an *International Journal*, vol. 19, no. 4, pp. 1971–1984, 2016.

[3] Z. Sang and X. Xu, "The Framework of a Cloud-Based CNC System," in 50th CIRP Conference on Manufacturing Systems, Taichung City HallTaichung, Taiwan, 2017, pp. 82–88.

[4] Z. Jamaludin, J. Jamaludin, T. H. Chiew, L. Abdullah, N. A. Rafan, and M. Maharof, "Sustainable Cutting Process for Milling Operation using Disturbance Observer," in 13th Global Conference on Sustainable Manufacturing, Binh Du'o'ng New City, Vietnam, 2016, pp. 486–491.

[5] A. E. Cetin, M. Arif Adli, D. E. Barkana, and H. Kucuk, "Adaptive On-Line Parameter Identification of a Steer-by-Wire System", *Mechatronics*, vol. 22, no. 2, pp. 152–166, 2012.

[6] C. Kharrat, E. Colinet, and A. Besancon-Voda, "A robust control method for electrostatic microbeam dynamic shaping with capacitive detection," in 17th World Congress, International Federation of Automatic Control, Seoul, South Korea, 2008, pp. 568-573.

[7] V. I. Utkin, H.-C. Chang, and A. Keyhani, "Sliding mode control for automobile air conditioner," in 15th World Congress of the International Federation of Automatic Control, Barcelona, Spain, 2002, pp. 421-425.

[8] N. C. Tsai, L. W. Shih, and R. M. Lee, "Counterbalance of cutting force for advanced milling operations", *Mechanical Systems and Signal Processing*, vol. 24, no. 4, pp. 1191–1208, 2010.

[9] W. Chen, K. Kong, and M. Tomizuka, "Dual-stage adaptive friction compensation for precise load side position tracking of indirect drive mechanisms", *IEEE Transactions on Control Systems Technology*, vol. 23, no. 1, pp. 164–175, 2015.

[10] W. Lee, C. Y. Lee, Y. H. Jeong, and B. K. Min, "Friction compensation controller for load varying machine tool feed drive", *International Journal of Machine Tools and Manufacture*, vol. 96, no. 1, pp. 47–54, 2015.

[11] D. J. Gordon and K. Erkorkmaz, "Accurate control of ball screw drives using pole-placement vibration damping and a novel trajectory prefilter", *Precision Engineering*, vol. 37, no. 2, pp. 308–322, 2013.

[12] C. J. Lin and P. T. Lin, "Particle swarm optimization based feedforward controller for a XY PZT positioning stage", *Mechatronics*, vol. 22, no. 5, pp. 614–628, 2012.

[13] K. K. Tan, S. N. Huang, and T. H. Lee, "Geometrical error compensation and control of an XY table using neural networks", *Control Engineering Practice*, vol. 14, no. 1, pp. 59–69, 2006.

[14] H. Seraji, "A New Class of Nonlinear PID Controllers for Robotic Applications", *Journal of Robotic Systems*, vol. 15, no. 3, pp. 161–181, 1998.

[15] A. Maddi, A. Guessoum, and D. Berkani, "Design of nonlinear PID controllers based on hyper-stability criteria," in 15th International Conference on Sciences and Techniques of Automatic Control and Computer Engineering, Hammamet, Tunisia, 2014, pp. 736–741.

[16] R. Garrido and A. Soria, "Control of a servomechanism using non-linear damping", *Journal of Systems and Control Engineering*, vol. 219, no. 4, pp. 295–299, 2005.

[17] M. R. Ristanovic, D. V Lazic, and I. Indin, "Nonlinear PID controller modification of the electromechanical actuator system for aerofin control with a PWM controlled DC motor", *Automatic Control and Robotics*, vol. 7, no. 1, pp. 131-139, 2008.

[18] J. Q. Liu and W. Wang, "Nonlinear immune PID controller and its application to the heat milling system's material-level control," in International Conference on Manufacturing Science and Technology, Singapore, 2012, pp. 743–749.

[19] M. F. Rahmat, S. N. S. Salim, N. H. Sunar, A. A. M. Faudzi, Z. Hilmi, and I. K. Huda "Identification and non-linear control strategy for industrial pneumatic actuator", *International Journal of Physical Sciences*, vol. 7, no. 17, pp. 2565–2579, 2012.

[20] L. Agnoletti, S. Kaster, and S. Augusto, "Applying a nonlinear PID in a single- phase PLL control," in IEEE International Conference on Power Electronics, Drives and Energy Systems, PEDES 2012, Bengaluru, Karnataka, India, 2012, pp. 3–6.

[21] S. C. K. Junoh, S. N. S. Salim, L. Abdullah, N. A. Anang, T. H. Chiew, and Z. Retas, "Nonlinear PID triple hyperbolic controller design for XY table ball-screw *drive* system", *International Journal of Mechanical and Mechatronics Engineering*, vol. 17, no. 3, pp. 1-10, 2017.

[22] L. Abdullah, Z. Jamaludin, T. H. Chiew, and N. A. Rafan, "Systematic method for cutting forces characterization for XY milling table ballscrew drive system", *International Journal of Mechanical and Mechatronics Engineering*, vol. 12, no. 6, pp. 28-33, 2012.