DESIGN OF A PID CONTROLLER EMBEDDED WITH TAGUCHI METHOD FOR PRECISE POSITIONING OF AN XY TABLE BALL SCREW DRIVE SYSTEM

L. Abdullah[1], K.N. Kamaludin[1], A.M.M.A. Mohamad[1], Z. Jamaludin[1] and M.H. Nordin[2]

[1]Faculty of Manufacturing Engineering, Universiti Teknikal Malaysia Melaka, Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia.

[2]School of Engineering, Computing and Mathematics, University of Plymouth, Drake Circus, PL4 8AA, United Kingdom.

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

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ABSTRACT: There are huge demands on producing high accuracy precision products, with a controller that is able to compensate the existence of disturbance forces, which consists of mechanical structures, mass variances, frictional forces, and cutting forces. The objective of this study is to further optimize PID controller to overcome the disturbance forces. Optimization method employed is the Taguchi method, for the purpose of tuning the proportional gain (K_P), integral gain (K_I) and derivative gain (K_D) of the proposed controller. The controller is then performed experimentally on a real plant, consisting of an XY table ball screw drive system. The tracking performance of the controller is evaluated based on the maximum tracking error. The effectiveness of the proposed controller is determined by comparing the performance to the tuning method of the classical Ziegler-Nichols approach. The contribution of the study is the adaptation of Taguchi method with PID controller during tuning of the parameter. It shows a significant result, where minimum of 52 % improvement is observed over the classical Ziegler-Nichols tuned PID controller.

KEYWORDS: *PID Controller; Taguchi Method; Ziegler-Nichols Method; XY Table; Tracking Performance*

1.0 INTRODUCTION

In manufacturing industries, high accuracy and precision are the two most crucial criteria in producing geometric products to meet customer demand. Machining accuracy for a regular shape can be easily satisfied, but for a complex shaped products, for example an automotive parts, are still difficult to achieve the ultimate desired precision [1]. In a study on controller design conducted by [2-3] on electrochemical machining (ECM) and machine tools, accuracy problem is inevitable during the machining processes. Therefore, the accuracy and precision of any manufacturing process is a very important criteria, and are always in need for a better solution which is consistent with the findings of Niranjan et al. [4].

On the other hand, the reason on why PID controller is preferred is due to its simplicity, where 90 % of industrial based controllers implement PID controller [4-5]. Many researchers used this controller because of its advantages in terms of the ability to provide a good close-loop response [6-7] has a simple structure that can be easily understood [4], and has a good adjustability of the parameters to any specific plant or system [5]. However, the drawback is the difficulty to match suitable combinations of PID gains. Owing to this factor, research in this area is always demanded especially improvement by the means of optimized control parameter.

Moreover, optimization technique called the Taguchi method is employed to tune the PID controller. Taguchi method was established to improve the quality of products in machining processes [6]. This method is also known as one of the most effective tool for solving an optimization problems in various application [8-10]. There are many advantages in using this method that is, efficiency, cost effectiveness, robustness, and the ability to interpret the data. In Taguchi method, a special set of arrays called orthogonal arrays (OA) is used when conducting the data collection and data analysis [10]. By implementing OA, researchers are able to drastically minimized the number of required experiments whilst maintaining the accuracy of the analytical data [11].

It is widely known that various modified PID controller have been explored and reported by previous scholars. However, to the best of author's knowledge, the approach of mixing a Taguchi Method as a tool for optimization method combined with PID controller in the application of machine tools is still limited and infrequent. Therefore, the aim of this work is to analyse the effectiveness of the proposed approach in which it is implemented at XY Table ball screw drive system for the purpose of validation of the result. For this purpose, the comparison results between the proposed controller (PID plus Taguchi) with the basic PID controller that is tuned through Ziegler-Nichols method were also obtained and reported in this paper.

The description of the system identification or known as the transfer function will be the main focus in Section 2. Section 3 elaborates on how the controller is designed and developed, followed by results and discussion in Section 4. Finally, in Section 5, the conclusion and suggestion of future work is enlightened.

2.0 SYSTEM IDENTIFICATION

In the control system methodology, system identification is the first step in the design of a controller. System identification is one of the methods in the system modelling to obtain the mathematical equation of the actual plant, which is then known as a transfer function. Ljung et al. [12] noted that system identification is a process of understanding and developing the dynamic behavior of the machine or plant. The system identification has been carried out by studies presented by [13]. As a result, the transfer function is generated as

$$\frac{72230}{s^2 + 153s + 106.4} \quad (1)$$

3.0 CONTROLLER DESIGN

Figure 1 shows the basic control scheme of PID controller that is applied as the basic structure for the proposed controller.

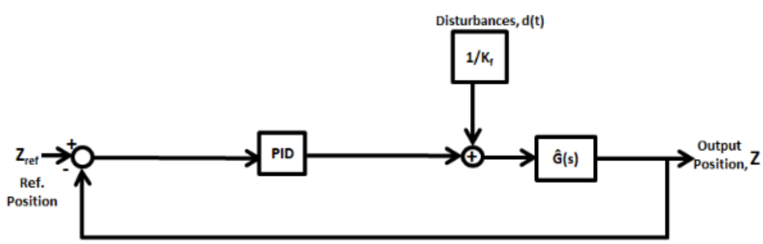

Figure 1: Control scheme of a PID controller

Two tuning methods, which Ziegler-Nichols and Taguchi were utilized for the tuning the PID parameters. Three levels of the cutting forces were applied at 1500 rpm, 2500 rpm and 3500 rpm. The selected frequencies were 0.2 Hz and 0.4 Hz. PID control parameter were tuned using both the Ziegler-Nichols and Taguchi method in order to obtain the gain values of each parameter. This Ziegler-Nichols method was used as baseline because of its proven functionality and the ability to provide the best parameters compared to the other classical tuning method [3], proposed embedded Taguchi method will be compared with the Ziegler-Nichols to show the effectiveness of the proposed approach. The known stability test was then conducted to validate the stability of the parameters from them method. This is an important step before testing the controller in the real plant. For the stability test, the recommended range was between 4 dB until 10 dB for the gain margin and 30° to 90° for the phase margin. This statement was consistent with the study by Heng [14].

3.1 Ziegler-Nichols Method

Figure 2 shows the stability test results through Ziegler-Nichols method for the gain and phase margin. Figure 2 also shows the results are 8.29 dB and 54.4° for the gain and phase margin, respectively. According to the basic rule mentioned earlier, the values are within the recommended stability range, therefore the gain values could be applied for the experimental analysis. Meanwhile, the PID parameters of this study are shown in Table 1.

Table 1: Parameters of the PID controller tuned by Ziegler-Nichols method

Parameter	Gain Value
K_P	1.120
K_I	0.006
K_D	0.007

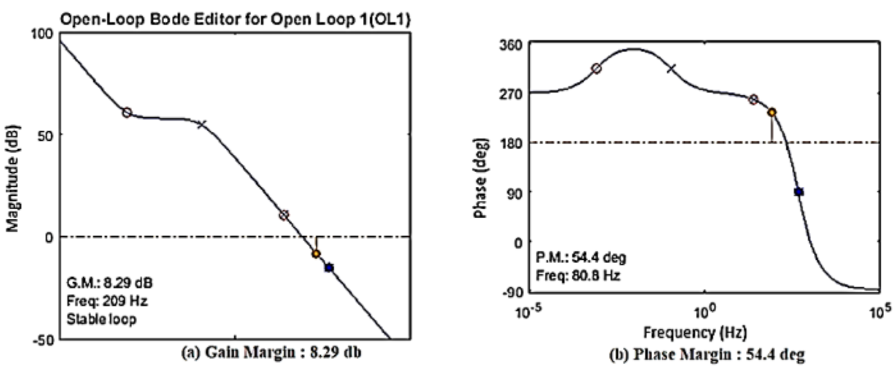

Figure 2: Results of the stability test for PID tuned through Ziegler-Nichols as shown in [15]

3.2 Taguchi Method

In order to use the Taguchi method, the set of PID parameters that needs to be determined are given in two sets. These two sets are then used to develop the Orthogonal Array (OA). The two sets of PID gain values will then be used as minimum and maximum values for the controller. The stability test needs to be determined for both sets of PID parameter. For the minimum value of PID stability test, the value of the gain margin obtained at 5.37 dB while the phase margin at 35.6° as the results shown in Figure 3.

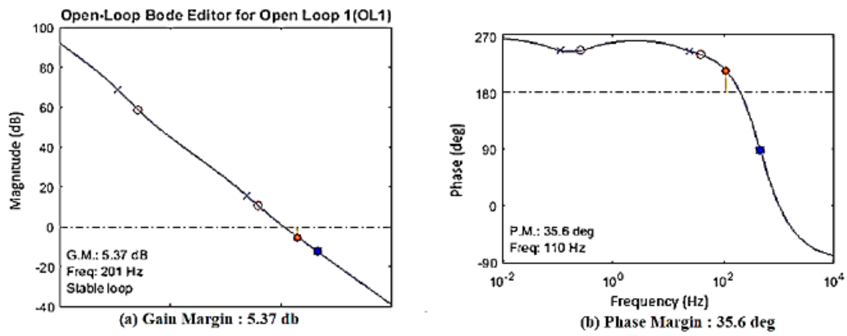

Figure 3: Stability test for minimum value of PID tuned by Taguchi method [15]

These values are within the recommended stability range. Next, the stability test for maximum value of PID gain parameter are portrays in Figure 4. Based on Figure 4, it is observed that the controller is predicted to perform well in the experimental analysis due to the fact that the gain margin and phase margin are obeying the suggested region which is 5.97 dB and 33.1°, respectively. Using these two ranges of PID controller parameter, the range of gain values is determined, as tabulated in Table 2. Level 2 parameters (which is third row in Table 2) are obtained by calculating the midrange between level 1 and level 3 of the gain values using a simple interpolation.

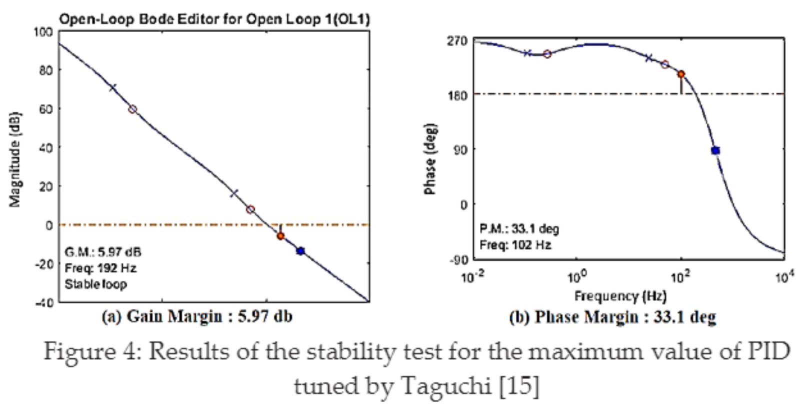

Figure 4: Results of the stability test for the maximum value of PID tuned by Taguchi [15]

Table 2: Range of gain values for the Taguchi method

Level	K_P	K_I	K_D
Level 1	2.238	3.655	0.0093
Level 2	2.413	4.025	0.0088
Level 3	2.587	4.395	0.0082

By using Table 2, an Orthogonal Array (OA) of Taguchi method can be developed and the structure of the OA are shown in Table 3. As presented in Table 3, indicators A, B and C represent the number of factors that is considered in the experiment. In this case, it can be represented as the value of the gain parameters such as K_P, K_I and K_D. The values inside the table represent the number of levels that is used. Therefore, from the structure of the OA, the value of gains shown in Table 2, were arranged accordingly to the OA in Table 3. The results of the arrangements of the gain parameters are presented in Table 4.

Table 3: Orthogonal array (OA) L_9 with indicators A, B and C

Trials	A	B	C
1	1	1	1
2	1	2	2
3	1	3	3
4	2	1	2
5	2	2	3
6	2	3	1
7	3	1	3
8	3	2	1
9	3	3	2

Table 4: Orthogonal array (OA) L_9 with the gain parameters

Trials	K_P	K_I	K_D
1	2.238	3.655	0.0093
2	2.238	4.025	0.0088
3	2.238	4.395	0.0082
4	2.413	3.655	0.0088
5	2.413	4.025	0.0082
6	2.413	4.395	0.0093
7	2.587	3.655	0.0082
8	2.587	4.025	0.0093
9	2.587	4.395	0.0088

4.0 RESULTS AND DISCUSSION

Maximum tracking errors are obtained from both simulation and experimental work. Maximum tracking error is the highest error produced by the system throughout the experiment. During the simulation and experimental work, the time used for the data collection period is 15 s. As mentioned in the previous sections, the cutting force is injected to the controller as a disturbance. The purpose of this process is to predict the performance of the PID controller during real application. The following result shows the data analysis of maximum tracking error for both, PID-Ziegler-Nichols and PID-Taguchi. These results agreed with the findings from other studies such as [3, 8-9, 17], in which the integration of an additional module like Taguchi into the normal classical PID controller will definitely increase the capability of the controller especially the robustness.

4.1 PID-Ziegler Nichols Tuned Controller

The results of the maximum tracking error are depicted in Table 5. From the maximum tracking error obtained in Table 5, it is observed that the percentage error is applied to define the accuracy of the controller. Percentage error is obtained using equation as formulated in [16]. It is also observed that the tracking error at lower frequency (0.2 Hz) is better than at higher frequency (0.4 Hz) due to the controller is more capable to function at lower speed as compared to higher speed [16].

Table 5: Maximum tracking error for PID-Ziegler Nichols controller

Spindle Speed (RPM)	Maximum Tracking Error (mm)		Percentage Error (%)	
	0.2 Hz	0.4 Hz	0.2 Hz	0.4 Hz
1500	0.04850	0.08198	0.3233	0.5465
2500	0.04842	0.08126	0.3228	0.5417
3500	0.04727	0.08002	0.3151	0.5335

4.2 PID-Taguchi Tuned Controller

A few extensions are required for the Taguchi tuned method. Based on the gain values in the OA as in Table 4, the maximum tracking errors are recorded and tabulated in Table 6. This analysis known as experiment performance required the smallest Signal-to-Noise Ratio (SN Ratio). The SN ratio requirements differed for every study. Dewantoro [17] explained the requirement for the study is to obtain the smallest mean and standard deviation of final offset value, which results in the best performance of the system. Then, followed by calculating the largest difference of the SN ratio in the same group of data and the largest difference contains the most effect and also the required SN Ratio. The following equations are used to calculate the SN.

Table 6: Maximum tracking error for PID-Taguchi controller

Trials	0.2 Hz			0.4 Hz		
	1500 RPM	2500 RPM	3500 RPM	1500 RPM	2500 RPM	3500 RPM
1	0.0161	0.0161	0.0155	0.0341	0.0339	0.0335
2	0.0153	0.0153	0.0147	0.0341	0.0331	0.0325
3	0.0146	0.0147	0.0147	0.0318	0.0320	0.0317
4	0.0158	0.0159	0.0154	0.0328	0.0330	0.0323
5	0.0151	0.0153	0.0147	0.0317	0.0316	0.0310
6	0.0141	0.0142	0.0136	0.0190	0.0304	0.0304
7	0.0156	0.0159	0.0153	0.0315	0.0317	0.0309
8	0.0146	0.0147	0.0142	0.0303	0.0303	0.0302
9	0.0139	0.0141	0.0136	0.0293	0.0294	0.0290

$$SN = -10\log(MSD) \tag{2}$$

$$MSD = \frac{1}{n}\sum_{i=1}^{n} y_i^2 \tag{3}$$

where MSD is mean square derivative, y_i equals to performance index (maximum tracking error) and n is a number of the measurements. The result of the SN ratios is presented in Table 7.

Table 7: The SN ratios of the maximum tracking error

Trials	0.2 Hz			0.4 Hz		
	1500 RPM	2500 RPM	3500 RPM	1500 RPM	2500 RPM	3500 RPM
1	35.87	29.36	35.86	29.40	36.21	29.50
2	36.33	29.69	36.30	29.60	36.66	29.76
3	36.72	29.97	36.68	29.90	37.05	29.97
4	36.00	29.70	35.95	29.64	36.26	29.82
5	36.41	29.99	36.32	30.02	36.65	30.17
6	37.02	30.37	36.98	30.33	37.33	30.34
7	36.14	30.05	35.96	29.97	36.31	30.20
8	36.72	30.38	36.64	30.38	36.95	30.40
9	37.11	30.66	36.99	30.62	37.33	30.75

The main effect analysis is calculated for each criterion. Since the numbers of disturbances are tested at three levels of RPM, at two different frequencies, the total number of main effect analysis produced are six sets of data. The results of main effect analysis are recorded in Table 8 until Table 13.

By referring to Table 8 until Table 10, the determination of the parameters that has the significant effect on the controller is then performed. From the observed data, it is found that at 0.2 Hz, the most important parameter is integral gain, K_i (Rank 1) followed by proportional gain, K_p (Rank 2) and derivative gain, K_d (Rank 3). The rank is judged based on the highest value of SN number (Difference, Δ = Max *SN* – Min *SN*).

Table 8: Main effect analysis 1500 rpm at 0.2 Hz

Gain level		Parameters		
		K_p	K_i	K_d
Level	Level 1	36.3093	36.0074	36.5363
	Level 2	36.4784	36.4875	36.483
	Level 3	36.6589	36.9517	36.4275
Difference		0.3496	0.9443	0.1087
Rank		2	1	3

Table 9: Main effect analysis 2500 rpm at 0.2 Hz

Gain level		Parameters		
		K_p	K_i	K_d
Level	Level 1	36.2804	35.9250	36.4947
	Level 2	36.4155	36.4200	36.4139
	Level 3	36.5313	36.8824	36.3187
Difference		0.2509	0.9574	0.1760
Rank		2	1	3

Table 10: Main effect analysis 3500 rpm at 0.2 Hz

Gain level		Parameters		
		K_p	K_i	K_d
Level	Level 1	36.6408	36.2591	36.8312
	Level 2	36.7479	36.7558	36.7499
	Level 3	36.8632	37.2370	36.6708
Difference		0.2224	0.9780	0.1604
Rank		2	1	3

The obtained optimum gain value is at Level 3 for K_p and K_d while Level 1 for K_i. Thus, the optimum values for PID controller are 2.587, 4.395 and 0.0093 for K_p, K_i and K_d.

Meanwhile at 0.4 Hz, the most significant parameter is the proportional gain, K_p followed by integral gain, K_i and derivative gain, K_d. The same analysis process is conducted at 0.2 Hz frequency in which the optimum gain value for PID controller is similar at the tracking frequency of 0.2 Hz. The optimum gain values for K_p, K_i and K_d are 2.587, 4.395 and 0.0093.

Table 11: Main effect analysis for 1500 rpm at 0.4 Hz

Gain level		Parameters		
		K_p	K_i	K_d
Level	Level 1	29.6685	29.7021	30.0372
	Level 2	30.0216	30.0183	30.0152
	Level 3	30.3623	30.3320	29.9999
Difference		0.6938	0.6298	0.0373
Rank		1	2	3

Table 12: Main effect analysis for 2500 rpm at 0.4 Hz

Gain level		Parameters		
		K_p	K_i	K_d
Level	Level 1	29.6365	29.6733	30.0372
	Level 2	29.9980	30.0001	29.9559
	Level 3	30.3238	30.2849	29.9653
Difference		0.6873	0.6116	0.0814
Rank		1	2	3

Table 13: Main effect analysis for 3500 rpm at 0.4 Hz

Gain level		Parameters		
		K_p	K_i	K_d
Level	Level 1	29.7440	29.8395	30.1156
	Level 2	30.1094	30.1108	30.1063
	Level 3	30.4499	30.3530	30.0814
Difference		0.7059	0.5135	0.0343
Rank		1	2	3

4.3 Validation between PID-Taguchi and PID-Ziegler Methods

Once the optimum sets of gain value for the PID controller were obtained, the validation process was conducted to determine the error produced by the optimum sets. The simulation and experimental is repeated to determine maximum tracking error. The comparison result of the maximum tracking errors between the PID-Taguchi and PID-Ziegler methods is shown in Table 14.

Table 14: Maximum tracking error for PID-Taguchi controller

Spindle Speed (RPM)	Maximum Tracking Error (mm)				Error Reduction (%)	
	PID-Ziegler		PID-Taguchi		PID-Taguchi with PID-Ziegler	
	0.2 Hz	0.4 Hz	0.2 Hz	0.4 Hz	0.2 Hz	0.4 Hz
1500	0.04850	0.08198	0.01649	0.03720	66.00	54.62
2500	0.04842	0.08126	0.01523	0.03601	68.55	55.69
3500	0.04727	0.08002	0.01623	0.03781	65.67	52.75

Table 14 shows the PID-Taguchi method outweigh the classical Ziegler-Nichols method at 0.2 Hz and 0.4 Hz. These results are in line with the studies by [6] in which it reflected the superiority of PID-

Taguchi method in providing more optimum value for the PID parameter. There are at least 52 % of the error reduction between these methods. Moreover, Table 14 summarizes that the additional module (Taguchi method) has successfully applied for reducing the tracking error and also, giving the detailed and systematic manner in optimizing the values for the PID controller. The statement is consistent with the studies by [17].

5.0 CONCLUSION

This study emphasized the effectiveness of the proposed approach which is the integration of Taguchi technique with PID controller for precise positioning of a machine tool. Implementation of Taguchi method had increased the controller's performance by lowering the error, from 0.3 % of percentage error to 0.1 % for 0.2 Hz and from 0.5 % to 0.2 % at tracking frequency 0.4 Hz. The result showed in Table 14 from the error reduction analysis in each category, the percentage improvements are in positive values indicating that the performance has clearly improved. The proposed Taguchi method tuned-PID controller is able to perform better than the classical Ziegler-Nichols method-PID controller in optimizing the gain parameters. The precise positioning of the machine tools could be improved in the future by modifying the optimization technique in various ways.

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