DESIGN OF PID CONTROLLER WITH EMBEDDED CONDITIONAL INTEGRATOR (PID + iCON) FOR ACCURATE POSITIONING OF MACHINE TOOLS

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ABSTRACT *In general, a positioning system is looking for high accuracy and adaptive characteristics. The aim of this article is to evaluate the tracking performance of the PID controller with an embedded conditional integrator (iCON) module for positioning system application with the presence of disturbance in the form of cutting forces. The tracking performance of a classical PID controller is compared with the PID + iCON controller. It is observed that the PID + iCON controller performs better than the PID controller. The result of the Root Mean Square Error achieved by PID is 0.0.028 mm at frequency, f = 0.3 Hz, while 0.001064 mm for PID + iCON. The concluding design of PID + iCON control could be applied for positioning as well as machining application. The usage of PID + iCON will increase the quality of the final output and productivity in manufacturing sectors by saving the machine process time.*

KEYWORDS: PID controller, conditional integrator, ball screw drive, tracking performance

1.0 INTRODUCTION

The design of a controller is required to control a specific system which in this project is a machine tool. A closed-loop control system is an ideal and perfect fit for machine tools. There are several control methods that have been introduced by researchers such as Sliding Mode Control (SMC) and H-Infinity control among others [1]. The design of the controller plays a significant role in order to achieve a high and better performance. The type of controller could be presented in a linear or nonlinear form depending on the condition of the machine tools that will be used. Both linear and nonlinear controller have their own benefits and constraints. To enhance the tracking performance in machine tools applications, an efficient and reliable compensation technique is demanded in a controller [1]. For this project, the PID controller was designed with the addition of a conditional integrator to increase the tracking performance of the machine tools. The function of the conditional integrator module is to reduce phase lag while maintaining the steady-state error at a minimum [2]. The benefits of a closed-loop control system are (i) Reducing the system's sensitivity to external disturbances. (ii) Involuntary adjusting the system's input to diminish errors. (iii) It contributes to a more reliable and repeatable performance.

XY table ball-screw drive system is a type of machine tool that is driven by AC servo drives. It has been commonly used in many applications because of its low cost [3]. Today, the requirement to use machine tools is huge in the industrial sector as more innovative and complex products are being manufactured along with the current technologies. Several control system algorithms have been introduced and implemented in order for the machine tools to obtain precise positioning. For instance, conventional PID controllers are widely used in many previous research, especially in the manufacturing industry [4]. Some of the researchers also mentioned that 90% of controllers were implemented based on PID controllers [5-7]. This is because PID has advantages due to its simple structure that can be understood easily and its physical meaning of the control actions are clear. In addition, the PID controller is also able to provide good closed-loop response characteristics [8-11]. However, the PID controller alone is insufficient. An additional module that is integrated with the PID controller is demanded to further complement the tracking performance. Owing to this reason, a PID controller that is embedded with a Conditional Integrator (iCON) module for performance tracking of machine tools is proposed and analyzed.

2.0 EXPERIMENTAL SETUP

In this section, the research setup of the project is XY table ball screw drive system manufactured by Googol Tech is shown in Figure 1 while the schematic diagram of the experimental setup is shown in Figure 2. The motor that drives the two axes is coupled with a ball screw drive mechanism with a bracket and a sliding rod mechanism to guide it.

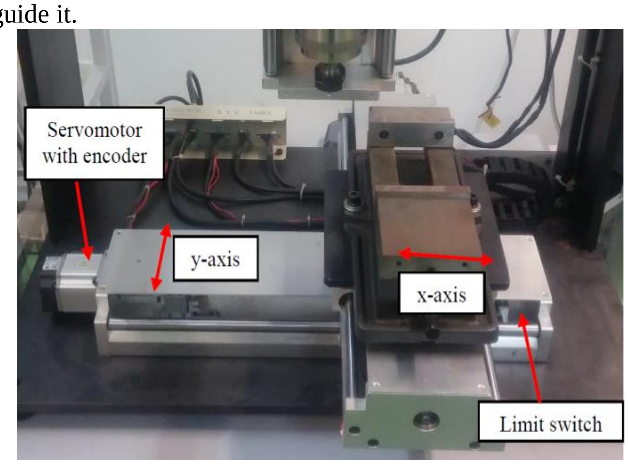

Figure 1: Plant for the research: XY Table ball-screw drive system

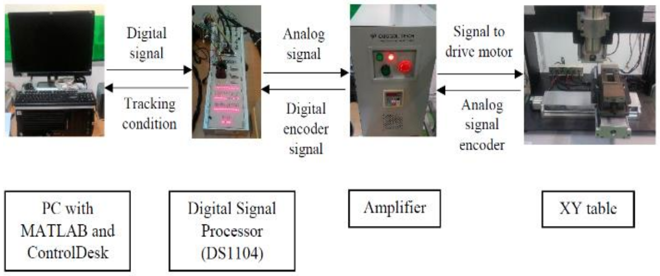

Figure 2: Schematic diagram of the experimental setup

Before designing controllers, an identification process for the system was identified to form a model transfer function. The frequency response function in the system is estimated using the H1 estimator for the overall modeling as one of the established techniques used by scholars [6,12]. The model transfer function, G_m is generated system identification approach as depicted in Equation 1.

$$G_m = \frac{78020}{s^2+163s+193.3} \quad (1)$$

3.0 CONTROLLER DESIGN

The classical PID control strategy offers a direct approach to the schematic design scheme. Unfortunately, the PID controller alone is inadequate to obtain a better tracking performance [2]. There are several design requirements that need to be considered when designing a controller. A controller is considered stable if the requirements enumerated below are fulfilled. The recommended design requirements [8] are (i) the Gain margin must be in the range between 4dB to 10dB (ii) the Phase margin must be in the range of 30 to 90 degrees (iii) the Sensitivity function must be less or equal to 6dB. (iv) Maximum peak complementary sensitivity must be less or equal to 2dB. The value of gain k_p, k_i, and k_d of the x-axis is shown in Table 1. The parameter value is determined based on design loop shaping as recommended by [8].

Table 1: Value of gain k_p, k_i, and k_d of the x-axis

Tuning value	k_p (V/mm)	k_i (V.s^{-1}/mm)	k_d (V.s/mm)
Gain value	1.305	0.006	4.143

3.1 PID with embedded Conditional Integrator (PID + iCON)

There are two controllers designed for this research namely; PID and PID with embedded conditional integrator (PID + iCON). Figure 3 shows the control scheme of PID + iCON. The function of the conditional integrator is to solve the regulation problem for a class of nonlinear systems that probably possess unstable zero dynamics. The detailed method of how to integrate the conditional integrator with the PID controller is shown in Figure 4.

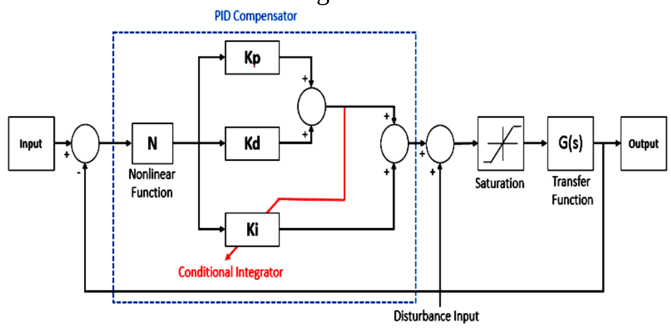

Figure 3: Control scheme of PID + iCON controller

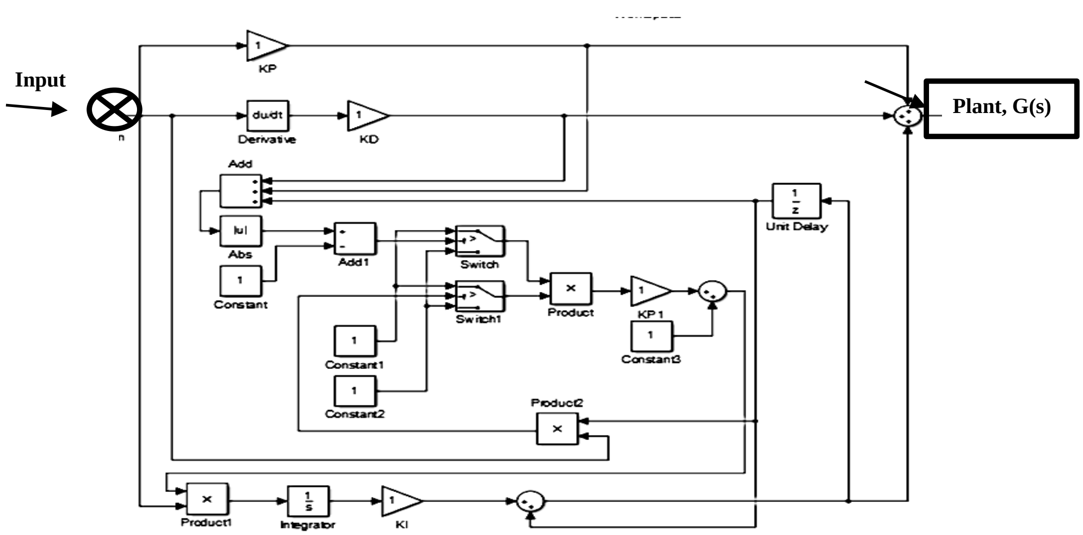

Figure 4: Method on how to integrate PID with conditional integrator

In order to design NPID embedded with I-Con, the conditional integrator output will be multiplied by the main input itself. The type of signal is being used is sine waveform. Then, the output from the integrator will be added together with the proportional and the derivative gain before disturbance is added.

4.0 RESULT AND DISCUSSION

The displayed result of maximum tracking error as shown in Figures 5 and 6 for this research is with respect to these two types of controller:

i) PID controller

ii) PID with embedded conditional integrator (PID + iCON) controller

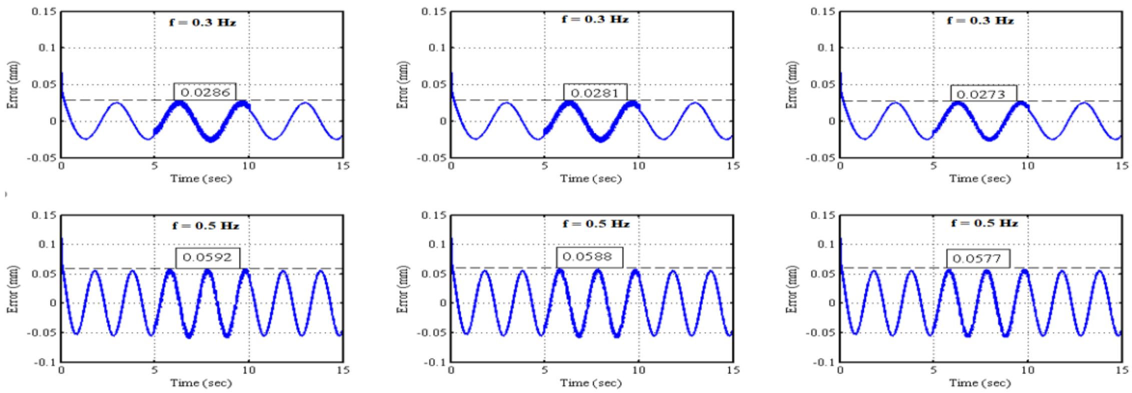

Figure 5: Result of maximum tracking error of PID Controller at *f* = 0.3 Hz and *f* = 0.5 Hz

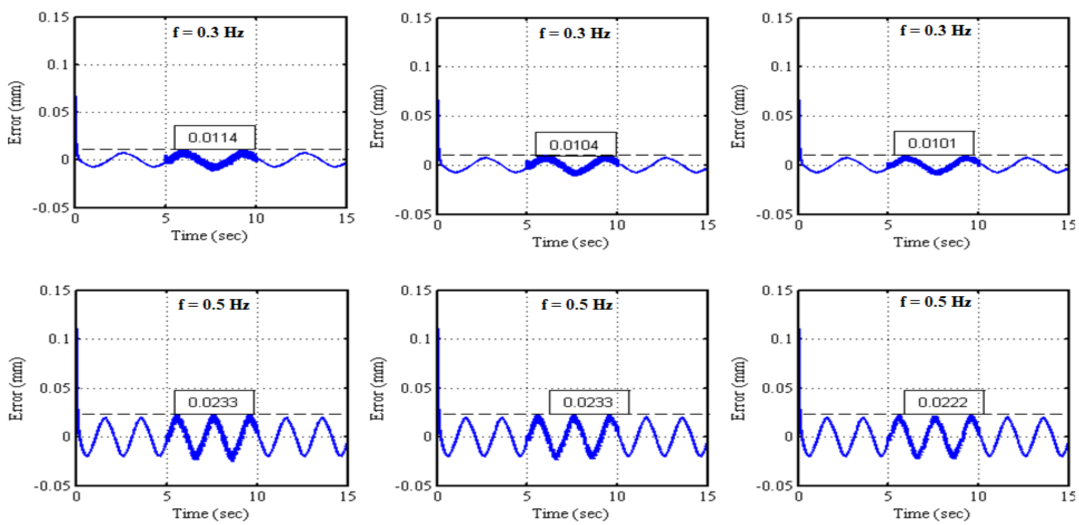

Figure 6: Result of maximum tracking error of PID + iCON Controller at *f* = 0.3 Hz and *f* = 0.5 Hz

Table 2: Maximum tracking error of PID Controller

Maximum Tracking Error (mm)		
Spindle Speed (rpm)	**Frequency (Hz)**	
	0.3	0.5
1500	0.0286	0.0592
2500	0.0281	0.0588
3500	0.0273	0.0577

Table 3: Maximum tracking error of PID + iCON controller

Maximum Tracking Error (mm)		
Spindle Speed (rpm)	**Frequency (Hz)**	
	0.3	0.5
1500	0.0114	0.0233
2500	0.0104	0.0233
3500	0.0101	0.0222

Table 4: Comparison of RMS Error between PID and PID +iCON controller

Frequency (Hz)	Root Mean Square Error (mm)	
	PID Controller	**PID embedded with iCON**
0.3	0.02800	0.01064
0.5	0.05857	0.02293

while Tables 2, 3, and 4 tabulated the numerical value of the maximum tracking error and root mean square error (RMSE) for the case of both PID and PID + iCON at frequencies 0.3 Hz and 0.5 Hz respectively. Based on the result, it is observed that the result of the maximum tracking error of PID + iCON outweighs the basic PID controller in each and every case of different spindle speeds. For instance, at a spindle speed of 1500 rpm (f = 0.3 Hz), the maximum tracking error of PID is 0.0286 mm while 0.0114 mm for PID + iCON controller. It shows the superiority of conditional integrators in reducing error. The reasoning behind the result is due to the fact that the conditional integrator managed to prevent integration wind-up towards the system [7]. In addition, in the literature, Heng [10] claimed that the conditional integrator has the capability for disturbance rejection by the concept of reducing the chattering in the system. Finally, the result also shows a higher tracking error when 0.5 Hz is implemented compared to when 0.3 Hz is applied. As the frequency is inversely proportional to the time taken to complete an oscillation, it is concluded that the outcome is due to the processing time factor [9]. This is because the controller has more time to respond at a lower frequency. Higher frequency also shows higher pitch compared to lower frequency

5.0 CONCLUSION

This research project investigated the design of PID embedded with iCON controller for XY table and it is compared to a normal PID controller. The two controllers were compared based on their tracking performance in machine tools. In order to enhance the performance of the system in the frequency domain, there are several requirements need to be fulfilled according to guidelines advised by the control system theory. The gain value of the PID controller must be designed first as the parameters k_p, k_i and k_d must be tuned and fulfill the design requirements. The design requirements that need to be fulfilled are gain margin and phase margin requirement, bandwidth, maximum peak sensitivity and complimentary sensitivity and stability requirement. Based on the results obtained, these design requirements were successfully achieved. It can be concluded that the PID + iCON controller performs better than the PID controller. The maximum tracking error of PID + iCON was 0.0114 mm for the case of frequency, f = 0.3 Hz among others, while for the case of PID controller, the maximum tracking error was 0.0286 mm.

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