Design and Implementation of Cascade NP/PI Controller for Feed Table Ball Screw Driven Milling Machine

Nur Amira Anang, Lokman Abdullah, Zamberi Jamaludin, Madihah Maharof and Tsung Heng Chiew

Abstract This paper presents improvements on conventional cascade P/PI position control structure with implementation of nonlinear function onto the existing control structure resulting in cascade NP/PI controller. The controller design process involved three main steps, namely; (i) design of PI controller for the speed loop, (ii) design of P controller for the position loop, and (iii) design of the nonlinear function. The speed and position controllers were designed based on gain margin and phase margin considerations. There were three main elements involved in the design of the nonlinear function, namely; rate of variation of nonlinear gain (KO), maximum value of error, (e_{max}) and sampling frequency, (δ). Results obtained from implementation on the *x*-axis of a milling machine feed table shows that the proposed cascade NP/PI controller generated an improvement of 1.3% in tracking performance in term of RMS error values compared to the classical cascade P/PI controller.

Keywords Cascade NP/PI · Cascade P/PI · Tracking performance
Ball screw driven system

1 Introduction

The developments in control system technologies have resulted in stark increment in areas related to process efficiency, cost effectiveness [1] and energy saving [2]. Over the last decades, overwhelming efforts have been made by researchers in the field of machine tools control strategy, especially in precision machining [3–5]. Precise machining is characterized by astute tracking performance of the machine tools drive system. Therefore, tremendous research have been done to improve tracking performances of various control systems [6–8]. Examples of control

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M. H. A. Hassan (ed.), *Intelligent Manufacturing & Mechatronics*,
Lecture Notes in Mechanical Engineering,
https://doi.org/10.1007/978-981-10-8788-2_8

strategies that are based on classical P + I+D controllers are PID itself, cascade P/PI and nonlinear PID (NPID) controllers [9–11]. Recently, Rafan [12] has published an improvement for the conventional cascade P/PI controller utilizing two friction compensation techniques; namely, Generalized Maxwell Slip (GMS) and Sigmoid like Curve function (SLCF). This has proven that cascade P/PI controller is capable to be implemented for friction compensation and cutting force compensation; two elements that often affect tracking performance in machine tools. A further enhancement is desired especially for the purpose of improving the controller robustness and ability to address non-linear issues during application. The addition of nonlinear function within the structure of a linear controller has been proposed and developed in literature. However, most of these approaches are performed in combination with PID controller. The collaboration between nonlinear function and classical cascade P/PI needs further investigation and analysis. This paper presents design analyses and experimental results relating to the implementation of combined nonlinear function and cascade P/PI controller; where the nonlinear function was embedded at the position loop of the control structure.

2 Methodology

2.1 Experimental Setup

The experimental setup consisted of four important components; such as, (i) a computer, (ii) a Digital Signal Processing (DSP) board, (iii) an amplifier, and (iv) a ball screw driven XY milling machine feed table. The computer was installed with MATLAB and dSPACE software for interaction with the DSP board. DS1104 board was interfaced with the servo amplifier connected to the XY ball screw system. Figure 1 shows the experimental setup applied for this research.

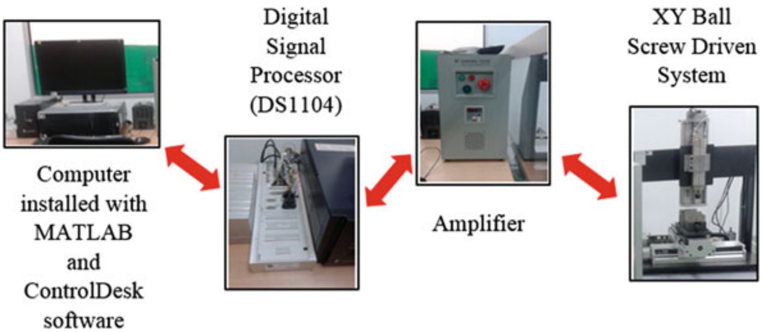

Fig. 1 Experimental setup

2.2 System Identification

System identification is initial and important step in any controller design process. This process helps to identify the dynamic behaviour of the electro-mechanical system using single-input single-output (SISO) model in frequency domain. The dynamics characteristics of the system were captured based on the measured and synthesized Frequency Response Function (FRF).

The FRF plot was generated based on measured input voltage to the drive system, $u(t)$ and the output positions, $z(t)$ of the ball screw table [13]. The FRF was then estimated using H1 estimator [14]. The system was modelled using Matlab toolbox 'fdident' yielding a second order model with time delay [15]:

$$G_m = \frac{Z(s)}{U(s)} = \frac{78020}{s^2 + 163s + 193.3} e^{-s0.0012} \tag{1}$$

3 Controller Design

3.1 Design of PI Controller (Speed Loop)

The first step in designing the controller was to design the speed PI controller. As shown in Fig. 2, the PI controller was represented in terms of controller parameters k_p and k_i. The controller was designed in frequency domain based on gain margin and phase margin consideration. This method was used to maintain the stability margin and improved the system transient response [16]. As a rule of thumb, the gain margin and the phase margin are advised to be within the range of 4–10 dB and 30° to 70° respectively. Equation (2) shows the speed open loop transfer function that generated 9.37 dB and 56.4° of gain margin and phase margin. The tuned parameters of k_p and k_i were 0.006607 and 0.12075 respectively.

$$V_{openloop}(s) = \frac{\dot{Z}_{est}(s)}{E_v(s)} = PI \cdot G(s) \cdot V_{est}(s) \tag{2}$$

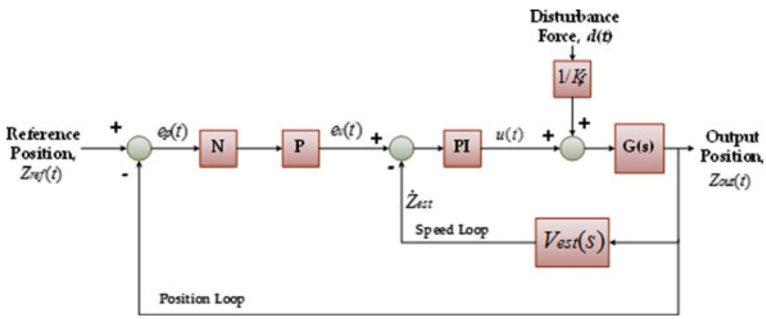

Fig. 2 Schematic diagram of cascade P/PI

3.2 Design of P Controller (Position Loop)

The position loop consisted of a proportional gain, k_v. The controller was designed over the speed controller loop whereby the gain margin and the phase margin obtained for k_v equals 225 s^{-1}were 9.1 dB and 67.1° respectively. The position open loop transfer function is represented in Eq. (3).

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

3.3 Design of Nonlinear Function

This section discusses design of the nonlinear function that is embedded on the position loop of the cascade P/PI controller. The design process involved tuning of three control parameters, namely; sampling frequency (δ) which is set at 0.0005, maximum value of error (e_{max}) of 0.5 and rate of variation of the nonlinear gain (KO). The values of KO1 and KO2 were set at 3.5 and 4.0 respectively. The related equations of the nonlinear function parameters are shown below:

$$KO = \begin{cases} 3.5 & if\ |e| \leq e_{\max} \\ 4.0 & else\ |e| < e_{\max} \end{cases} \quad (4)$$

$$\text{Nonlinear gain, } K_e = \frac{\exp(KO \times e) + \exp(-KO \times e)}{2} \quad (5)$$

$$\text{Switching function, sigmoid } (e) = \frac{e}{|e| + \delta} \quad (6)$$

$$\text{Maximum Nonlinear Gain, } K(e_{\max}) = -\frac{1}{R_e + [G(jw)] + w^* I_m[G(jw)]} \quad (7)$$

4 Result and Discussion

For validation purposes and controller performances analyses, the designed controller was subjected to a sinusoidal input reference signal of amplitude 10 mm at 0.7 Hz. Figure 3 shows results of tracking errors for cascade P/PI controller and cascade NP/PI controller. The maximum tracking errors recorded by cascade P/PI and cascade NP/PI controller were 0.0652 mm and 0.0681 mm respectively. Cascade NP/PI controller shows greater maximum tracking error compared to cascade P/PI controller; suggesting a negative influence of the nonlinear function on the

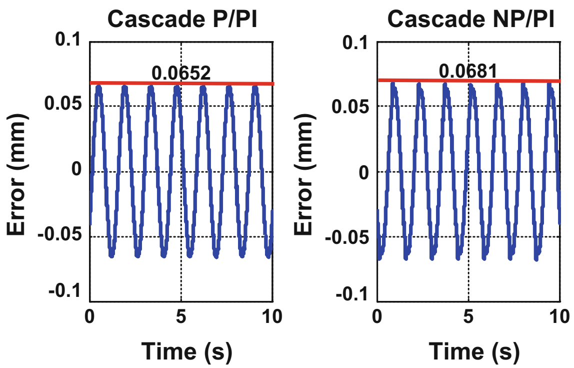

Fig. 3 Tracking errors for cascade P/PI and cascade NP/PI controllers

controller performance. A closer analysis on the tracking errors of cascade NP/PI as shown in Fig. 4 reveals the existence of spikes at near maximum position, commonly associated with the presence of nonlinear friction at near zero velocity. This phenomenon then led to significant positioning error [17]. The magnitude of the spike was identified at 0.01 mm. Therefore, in-fact, the real maximum tracking error for the proposed cascade NP/PI controller was 0.0581 mm instead of 0.0681 mm.

A root mean square of the errors (RMS) produced a more balance conclusion regarding the controller tracking performance when compared to maximum tracking errors measurement. Here, the proposed cascade NP/PI produced an RMS errors value of 0.0453 mm compared to conventional cascade P/PI controller that produced an RMS error value of 0.0459 mm. The error reduction between the two controllers was 1.31%. Therefore, the experimental results have showed that the nonlinear function embedded on the position controller of cascade P/PI has managed to improve the tracking performance of the control system.

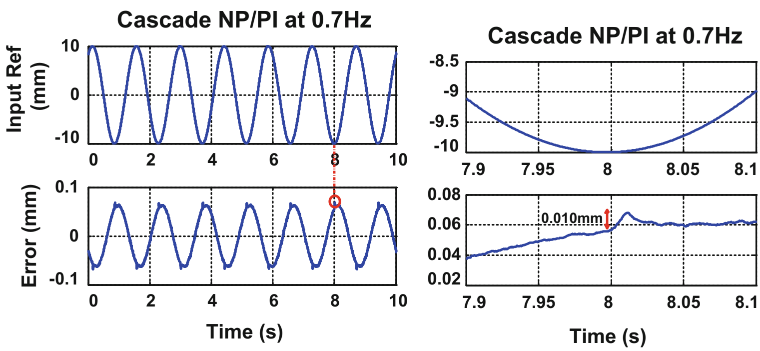

Fig. 4 Formation of significant spike

5 Conclusion

The paper presents design and validation of proposed cascade NP/PI controller for the x-axis of a XY table ball screw driven system. The controllers' parameters were tuned and designed in frequency domain based on open loop characteristics such as gain margin and phase margin. Meanwhile, the nonlinear function was designed based on three components that are KO, e_{max} and δ. The tracking performances for both controllers were compared based on sinusoidal input reference signal of amplitude 10 mm at 0.7 Hz. Based on maximum tracking error, cascade P/PI controller has lower error compared to proposed cascade NP/PI controller that is 0.0652 mm and 0.0681 mm respectively. This is because the proposed controller was affected by friction produced during maximum position. However, the proposed cascade NP/PI controller produced an RMS error value that is 1.31% lower compared to the cascade P/PI controller. This proved that the nonlinear function of cascade NP/PI controller managed to produce an improvement in overall tracking performance of the control system.

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

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