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EVALUATION AND COMPARISON OF THE TRACKING PERFORMANCE BETWEEN NPID ICOND CONTROLLER, NPID CONTROLLER, AND PID CONTROLLER

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Abstract

Precise positioning and tracking accuracy in machine tools applications are highly demanded in manufacturing sector. The cutting force disturbance is one of the factors that affect the tracking accuracy of the machine tools. The design and selection of the control mechanism for the tools and systems in the manufacturing industry are vital in reducing the disturbance occurrence. This paper presents the performance evaluation of a newly designed controller, namely, nonlinear proportional-integral-derivative controller with conditional integrator (NPID ICond), in terms of the root mean square error and maximum tracking error for an XYZ ball screw drive table. A few comparisons were made with the performance of the other two existing controllers, PID controller and NPID controller. The NPID ICond controller improved the tracking performance of the system by at least 3.172% and 4.139% in terms of RMSE and MTE, respectively. The conditional integrator in NPID ICond controller is proven useful in improving the tracking performance of machine tools application by acting as an anti-windup mechanism.

Keywords: Conditional integrator, Cutting force, Maximum tracking error, Nonlinear proportional-derivative-integral controller, Proportional-derivative-integral controller, Root mean square error.

1. Introduction

Machine tools play a vital role in the manufacturing industry. One of the machines widely used in the manufacturing industry is the computerized numerical control (CNC) machine, which is typically used in milling processes. An XYZ ball screw drive table is designed to emulate the milling process of the CNC machine and it is specifically used for research work. The XYZ ball screw drive table consists of three angular movements (X-, Y-, and Z-axes) to perform cutting action with a drilling mechanism. The positioning stage for each angle of the XYZ ball screw drive table is equipped with a rotary motor. The rotary motors are operated by a control scheme based on the input signal.

Various control schemes have been designed for the application of ball screw drive such as proportional-derivative-integral (PID) controller [1], sliding mode control [2], cascade controller [3], gain scheduling [4], continuous motion nominal characteristic trajectory following control (CM NCTF) [5] and fuzzy logic controller [6]. A controller can also combine with other controller or make some modification to form a new control algorithm depending on different types of needs. For example, a PID controller can form a Proportional-Integral-Derivative - Particle Swarm Optimization (PID-PSO) controller [7] when combines with Particle Swarm Optimization (PSO) while it can also form a Fractional Order Proportional-Integral-Derivative (FOPID) controller [8] by adding some parameters in the integral and derivative orders.

Another version of PID controller is a PID controller with conditional integrator. The integral output of the PID controller is based on certain conditions, which will be explained later in this paper. The conditional integrator is responsible for controlling the steady-state error present in the system. The system can be unstable due to the 90° phase lag at all frequencies and therefore, the conditional integrator functions to compensate this problem. The conditional integrator can reduce phase lag [9] while maintaining the steady-state error at a minimum and prevent integral windup [10, 11]. The usage of conditional integrator can tackle these issue since the desired integral value can be set initially when a threshold was triggered. The integral value in the conditions of the integrator was set at a value when the integration wind up can occur.

The previous researchers have implemented PID controller, NPID controller and other combination of controllers on XYZ ball screw drive table to reduce the cutting force which affects its tracking performance [12, 13]. However, based on reviews from the author, the usage of conditional integrator in the PID-based controller for cutting force reduction in machine tools application is still uncommon. Since the PID gains are not flexible to deal with the variation of error, there is a room of improvement for the controller. Hence, the purpose of this study is to evaluate the tracking performance of the newly proposed controller, the NPID controller with a conditional integrator (hereinafter NPID ICond). The controller is applied on the XYZ ball screw drive table for validation purpose.

The performance of the NPID ICond controller is then evaluated and compared with the performance of a PID controller and NPID controller in terms of the root mean square error (RMSE) and maximum tracking error (MTE). The cutting force is chosen as the disturbance force for the system. It is believed that the findings of this study will provide insight on the tracking performance of the three controllers on the XYZ ball screw drive table. The NPID ICond controller should outperform both benchmark controller to prove its ability in achieving better tracking performance in a machine tools application. The results of the comparison are presented in the result section.

2. Experimental setup

In this study, MATLAB and Simulink software, dSpace software and the XYZ ball screw drive table machine was used to evaluate the performance of the PID, NPID, and NPID ICond controllers. The machine performs a cutting process which can affect the overall performance of the system [14]. Figure 1 shows the experimental setup. The MATLAB and Simulink software were used to design the controllers while the dSpace software act as the data acquisition system for the control mechanism.

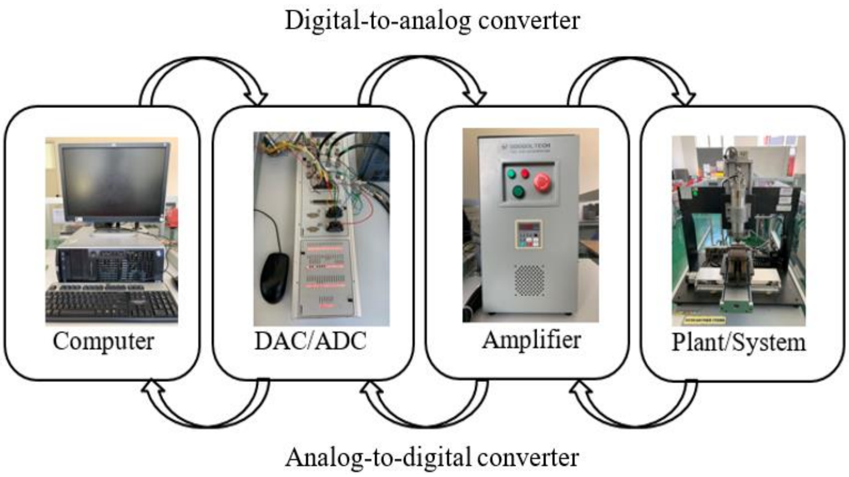


Fig. 1. Experimental setup.

The XYZ ball screw drive table machine replicates the CNC milling machine according to ISO 230- 4:1996(E). The machine consists of several parts as shown in Fig. 2. The movement of the table was through a ball screw mechanism which used MSMD022G1U AC servo motor to actuate a rotating motion. The servo motor was equipped to the tables on all three axes.

The size of the ball screw lead is 1.25 mm/rev. The X- axis, which is the slider that was placed horizontally is the one used as the investigated layer and can be regarded as the actual plant in the control system in this paper. The position of the X- axis will be the measuring point of the tracking error that caused by the cutting process. The range of movement for the table on the X- axis is limited to 175 mm.

The X- axis of the XYZ table is positioned horizontally at the bottom part of the machine. The X- axis table can hold up to 16 kg of mass that includes the vertical Y- axis table above it. The position of the table is calculated by an incremental encoder of 0.5 μm/pulse before providing feedback to the system. The sampling frequency of the controller was set at 1 kHz.

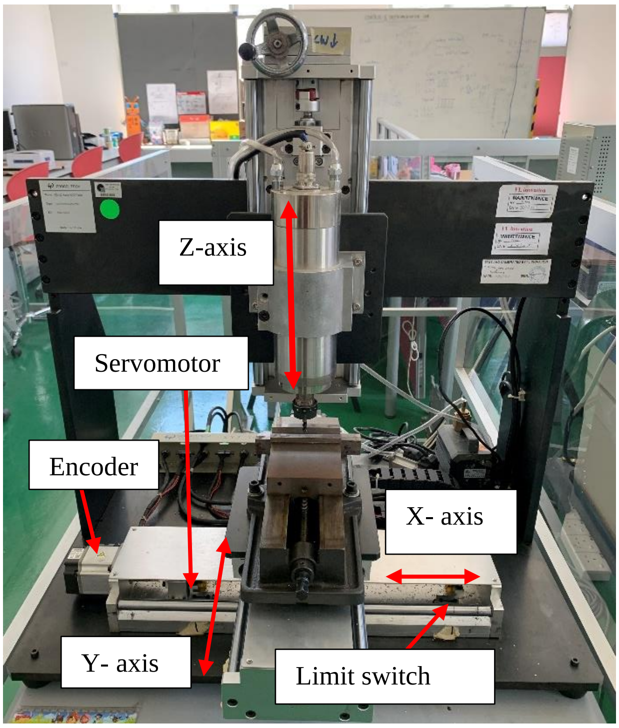


Fig. 2. XYZ ball screw drive table.

3. Cutting Force Identification

The performance of the PID, NPID, and NPID ICond controllers for the XYZ ball screw drive table can be affected by the presence of disturbance forces. One of the disturbance forces present is the cutting force. The cutting force can be defined as in Eq. (1).

$$F_c = \frac{P_C}{v} \tag{1}$$

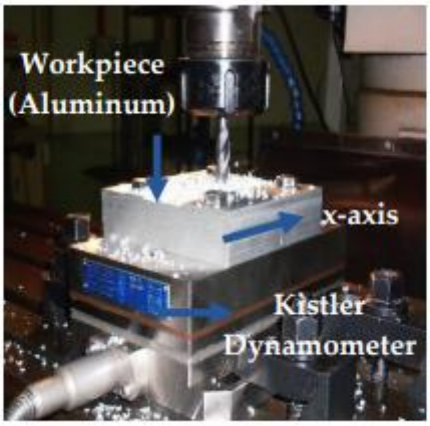
In this study, the cutting force data were obtained from [15] since the experimental setup was the same for both studies. The cutting force measurements were made using Kistler dynamometer, where the cutting tool was operating at a spindle speed of 1500 rpm.

Figure 3(a) shows the process of measuring the cutting force while Fig. 3(b) shows the measured cutting force data. The cutting force data were fed into the system to emulate the presence of disturbance force.

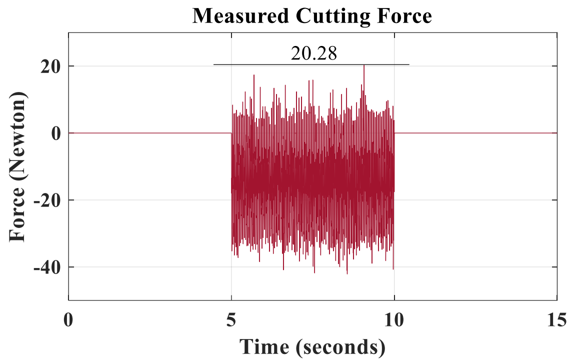
4. Controller Design

4.1. PID controller

The PID controller was designed as the first benchmark controller. As the name implies, the PID controller comprises proportional, integral, and derivative gains. The value of the PID gains can determine the stability of the system. A high value of proportional gain can make the response time shorter but can also resulted in an unstable system [16]. The integral gain responsible for controlling the steady-state error [17] and the derivative gain provides stability to the system. Figure 4 shows the structure of the PID controller.



(a)



(b)

Fig. 3. (a) Process of measuring the cutting force.
(b) Measured cutting force data.

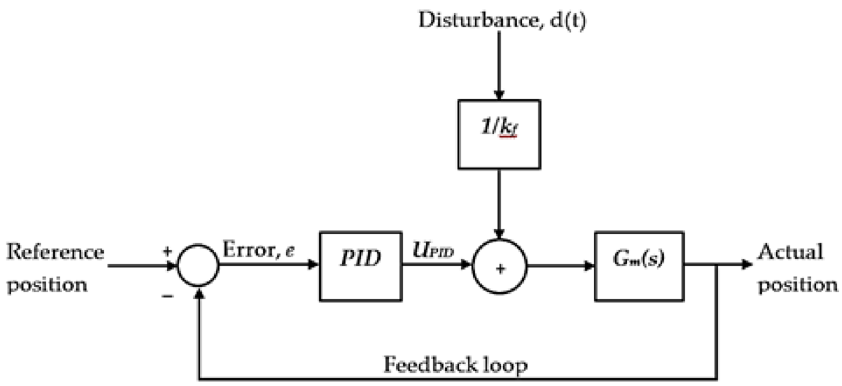


Fig. 4. Structure of the system with PID controller.

The initial values of the proportional, integral, and derivative gains were tuned using a heuristic method and the tracking error graph was observed. The value of the maximum tracking error, number of oscillations and peak value at initial condition were recorded in a table. The gain that produced the least maximum tracking error, the least number of oscillation as well as the least peak value at initial condition will be selected as the best gain to be used in the PID controller.

The proportional, integral, and derivative gains obtained were K_P = 1.8, K_I = 0.0012, and K_D = 0.0018, respectively.

The stability of the PID controller was tested based on the gain margin and phase margin for an open-loop system of the controller. The open-loop test was done through MATLAB coding using the Eq. (2). The gain margin and phase margin obtained was recorded as 8.45 dB ((at 176 Hz) and 52.3º (at 89.9Hz) respectively.

$$L = (G_{PID}(s)) \times (G_m(s)) \quad (2)$$

4.2. NPID controller

The second benchmark controller used for comparison is the NPID controller. The controller was designed as an extension of the PID controller to counteract the nonlinearities in a machine tool system. Figure 5 shows the structure of the NPID controller.

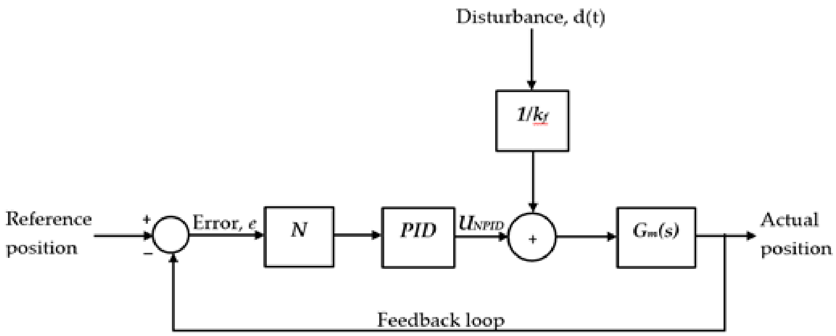


Fig. 5. Structure of the system with NPID controller.

The proportional, derivative, and integral gains of the NPID controller were the same as those used for the PID controller. The nonlinear parameters (such as k_o and e_{max}) were determined from the Popov plot. The method used by Chiew et al. [18] was used in this study to determine the maximum allowable nonlinear gain. The nonlinear gain will modify the initial values of the proportional, integral, and derivative gains based on the tracking error.

4.3. NPID ICond controller

The NPID ICond controller is the newly proposed controller in this study. Figure 6 shows the structure of the NPID ICond controller. The structure of the NPID ICond controller is essentially the same as that for the NPID controller with the exception that an integral part of the controller is constructed based on Eq. (3).

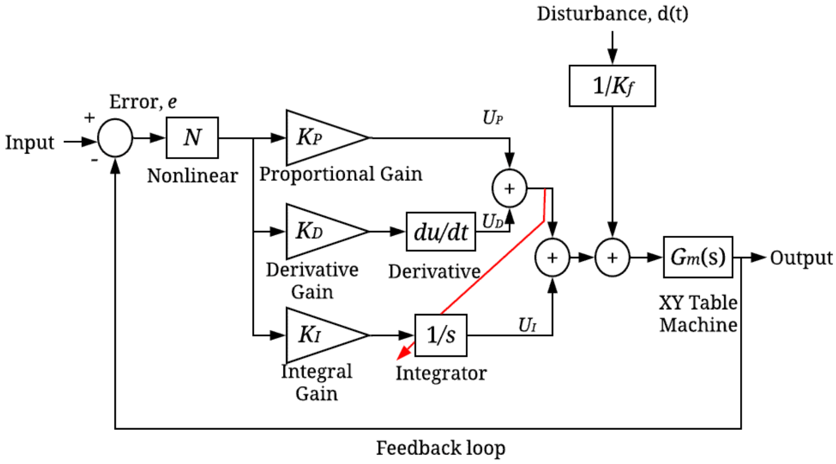


Fig. 6. Structure of the system with NPID ICond controller.

The controller is an extension from the PID controller and NPID controller. The same initial proportional, integral, and derivative gains as well as the same initial nonlinear function parameters used for the NPID controller were used for the NPID ICond controller.

The integral part of the NPID controller is basically modified to become a conditional integrator. The conditions for the conditional integrator are given by Eq. (3):

$$\Delta u_i = \begin{cases} 0, \begin{pmatrix} |u_p + u_i + u_d| > u_s \\ \text{and} \\ e.u_i \geq 0 \end{pmatrix} \\ e, \ \text{otherwise} \end{cases} \tag{3}$$

where u_p is the proportional signal, u_i is the integral signal, and u_d is the derivative signal. Here, the value of u_s, is the maximum desired value of the PID signal, which is set at 0.06 and Δu_i is the variation of integral signal value while e is the error. The integral signal value, Δu_i will automatically set to zero when two conditions are met in which the absolute sum of proportional, integral and derivative signals exceeds the value of u_s and product of error with integral signal is equal or greater than zero. Otherwise, the error will be use as the integral signal, meaning that no integral gain is use for the controller. This rule was implemented by Maslan et al. [19] and Heng et al. [20] as a solution to the anti-windup.

5. Results and Discussion

Error analysis was performed for the PID, NPID, and NPID ICond controllers. The control system of the machine was designed as in Figs. 4, 5, and 6 by using Simulink software based on the controller used. The designed system was linked to the real plant with the aid of dSPACE software in a computer together with the DAC/ADC converter and the amplifier, with the flow of the processes were shown in Fig. 1. The input signal and input frequency of the XYZ ball screw drive table were 15 mm and 0.2 Hz, respectively. The disturbance force (i.e., cutting force) was fed into the control scheme for the three controllers. In the Simulink software, the incremental encoder is used to measure the actual output from the plant in millimetre, mm before the data was transferred by the DS1104 DAQ board (in the dSPACE software) back to the computer. The position of the encoder together with the unit converter are shown in the control system in Figs .4, 5, and 6. The process of converting the digital data from the computer and the analog data from the actual plant was carried out by the DAC/ADC converter.

The performance of the controllers was evaluated based on the root mean square error (RMSE) and maximum tracking error (MTE), the same method used as Heng et al. [20] and Abdullah et al.[4], respectively. The results for both methods are shown in Figs. 7 and 8 respectively. The RMSE accounts for the overall tracking error for each controller while the MTE focuses on the peak of tracking error produced by the system. The values of the RMSE and MTE for the three controllers considered in this study are summarized in Table 1.

Based on the results, the conditional integrator of the NPID ICond controller improves the RMSE and MTE by 3.172% and 4.139%, respectively. The RMSE values of the NPID ICond controller reduce by 3.243% and 3.172% with respect to those for the PID controller and NPID controller, respectively. Meanwhile, the MTE values of the NPID ICond controller reduce by 5.834% and 4.139% with respect to those for the PID controller and NPID controller, respectively.

Table 1. RMSE and MTE values for the PID, NPID, and NPID ICond controllers.

Controller	RMSE (mm)	MTE (mm)
PID	0.05458	0.1697
NPID	0.05454	0.1667
NPID ICond	0.05281	0.1598

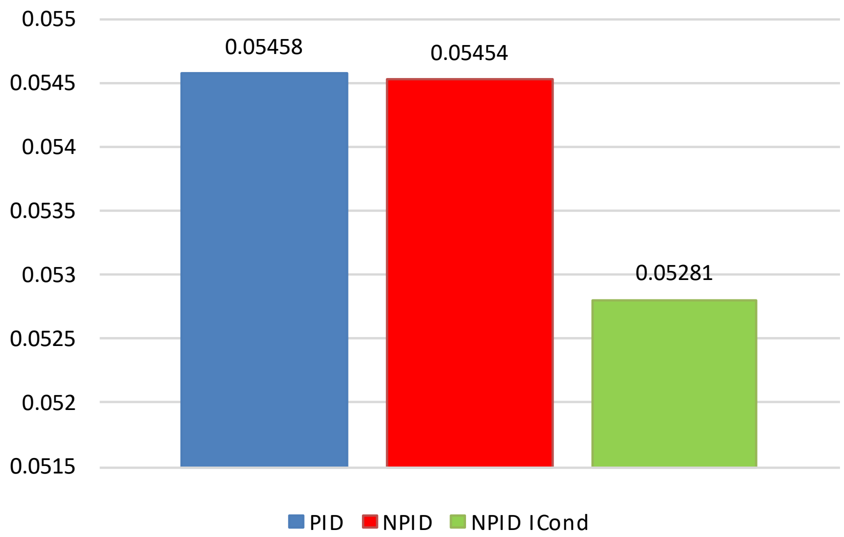
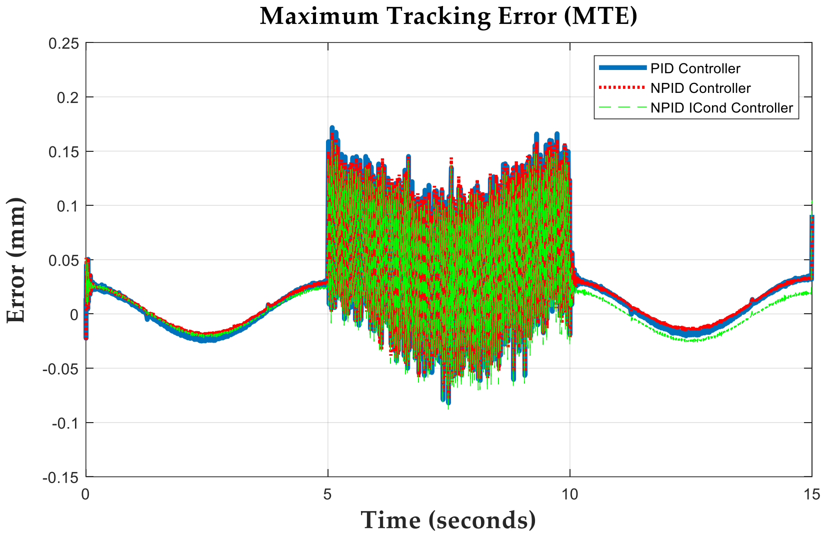
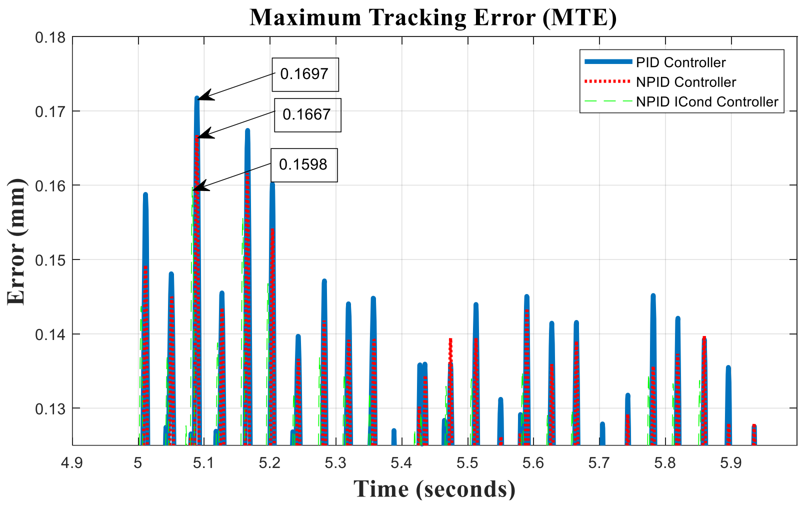


Fig. 7. RMSE values for the PID, NPID, and NPID ICond controllers.



(a)



(b)

Fig. 8. (a) Variation of the MTE with respect to time for the PID, NPID, and NPID ICond controllers. (b) The position of the maximum tracking error for the PID, NPID, and NPID ICond controllers.

It is evident from Table 1 that the NPID ICond controller has the lowest RMSE and MTE values among all of the controllers assessed in this study. This indicates that the conditional integrator of the NPID ICond controller boosts the control performance such that the controller outperforms the PID and NPID controllers. The integral windup that occurs in a control system often reduces the system efficiency and the addition of the conditional integrator compensates this problem by reducing the excess error while maintaining a low steady-state error. This statement is in line with the research done in [19]. The conditional integrator is proven to be a robust addition to the NPID controller.

6. Conclusion

Based on the results, it is concluded that the newly proposed NPID ICond controller has the lowest RMSE and MTE for the XYZ ball screw drive table. The NPID ICond controller has the best tracking performance compared with the PID and NPID controllers. The addition of a conditional integrator in the NPID controller maintains a low steady-state error and prevents integral spike, which will reduce the efficiency of the XYZ ball screw drive table. Future works can be carried out to explore other control schemes by adapting the NPID ICond controller to further enhance the system tracking performance and hence, achieve precise positioning.

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Nomenclatures

$d(t)$	Disturbance, which varies with time t
e	Error, mm
e_{max}	Maximum error, mm
F_C	Cutting force, kN
$G_{PID}(s)$	Transfer function of PID controller
$G_m(s)$	Transfer function of plant
k_o	Nonlinear gain
K_f	Cutting force converter coefficient
K_D	Derivative gain
K_I	Integral gain
K_P	Proportional gain
L	Open loop transfer function
P_C	Cutting power, W
u_d	Derivative signal
u_i	Integral signal
u_p	Proportional signal
U_{NPID}	NPID controller signal
U_{PID}	PID controller signal
v	Cutting speed, m/min

Abbreviations

MTE	Maximum tracking error, mm
NPID	Nonlinear proportional-integral-derivative
NPID ICond	Nonlinear proportional-integral-derivative with conditional integrator
PID	Proportional-integral-derivative
RMSE	Root mean square error, mm

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