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Evaluation on Tracking Performance of PID, Gain Scheduling and Classical Cascade P/PI Controller on XY Table Ballscrew Drive System

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Abstract: Today, positioning systems in machine tools aim for high accuracy and robustness characteristics in order to accommodate against various disturbance forces. The objective of this paper is to evaluate the tracking performance of PID, Gain Scheduling and Cascade P/PI controller with the existence of disturbance forces in the form of cutting forces. Cutting force characteristics at different cutting parameters; such as spindle speed rotations is analysed using Fast Fourier Transform. The tracking performance of a classical cascade controller in presence of these cutting forces is compared to the PID controller and gain scheduling PID controller. Robustness of these controllers in compensating different cutting characteristics is compared based on reduction in the amplitudes of cutting force harmonics using Fast Fourier Transform. It is found that the cascade controller performs better than both PID controller and gain scheduling PID controller. The average percentage error reduction between cascade controller and Gain Scheduling controller is about 88% whereas the average percentage error reduction between cascade controller and Gain Scheduling controller is about 84% at spindle speed of 1000 rpm spindle speed rotation. The finalized design of cascade controller could be utilized further for machining application such as milling process. The implementation of cascade P/PI in machine tools applications will increase the quality of the end product and the productivity in industry by saving the machining time. It is suggested that the range of the spindle speed could be made wider to accommodate the needs for high speed machining.

Key words: Robust Control % Tracking Performance % Cutting Forces % Disturbance Compensation

INTRODUCTION

High tracking accuracy and precision are two vital components required in the manufacturing process. A good example of machining application is milling operation where a work piece is fed past a rotating cylindrical tool with multiple cutting edges. Both of these components are paramount important because it will lead to high-quality end product that will be delivered to customer. In an interrupted cutting operation, the teeth of a milling cutter enter and exit the work piece at each revolution. Therefore, it is highly critical that the tool material and the cutter geometry are chosen carefully to withstand the cycles of impact cutting forces and thermal shock that might result from these physical interactions [1]. These forces are natural consequences of the cutting process and could not be avoided. For performance purposes, the ability of the system to withstand these forces and its impact will determine the standard and quality of the end product to be manufactured.

Knowledge on characteristics of these cutting forces is essential in designing the appropriate technique for its compensation [2-5]. The cutting force characteristics are influenced by the cutting parameters such as feed rate,

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depth of cut and spindle speed. Variations in these cutting conditions will affect behaviour of the cutting forces in terms of its magnitudes and its harmonics content. Failure to realise this phenomenon could reduce the quality of the finished product as the cutting forces may cause vibration of the structure thus leading to a poor surface roughness measurement. Hence, an efficient and reliable compensation technique is desired in order to improve the tracking performance in machine tools applications. Previous researches on several compensation methods and approaches are discovered and have shown promising results; for example, Inverse Model Based Disturbance Observer [6], classical cascade controller [7] and Repetitive Controller [8,9] and based on the familiar PID control. Result based on PID controller [5] shows that the tracking error can be trim down until millimeter point only whereas results based on [8,9] show that the tracking error is reduced up to micron meter level via direct drive xy table. Furthermore, it is found that most of the research work were based on dedicated cutting forces and did not consider changing of the spindle speed. As a result, there is a need to conduct a research based on various spindle speed. In this research work, the controller designed is based on this needs in which the spindle speed is varied.

METHODS

Test Setup: Figure 1 shows the ball-screw driven XY milling table of an XYZ-Stage produced by Googol Tech. The XY milling table consists of two axes namely; x and y axes, driven by two Panasonic MSMD 022G1U A.C. servo motors respectively. Both axes are equipped with an incremental encoder for positioning measurement. The resolution of the encoder is 2500 pulse/rev with screw pitch of 5 mm and multiple frequencies of 4. In other words, the resolution of the encoder is 0.0005 mm/pulse. Two limit switches are located in the near end of both axes. The total mass of x-axis is 36.8 kg while the total mass of the y-axis is 23.4 kg. The XY milling table consists of two axes namely; x and y axes, driven by two Panasonic MSMD 022G1U A.C. servo motors respectively. Both axes are equipped with an incremental encoder for positioning measurement. The resolution of the encoder is 2500 pulse/ rev with screw pitch of 5 mm and multiple frequencies of 4. In other words, the resolution of the encoder is 0.0005 mm/pulse. Two limit switches are located in the near end of both axes. The total mass of x-axis is 36.8 kg while the total mass of the y-axis is 23.4 kg.

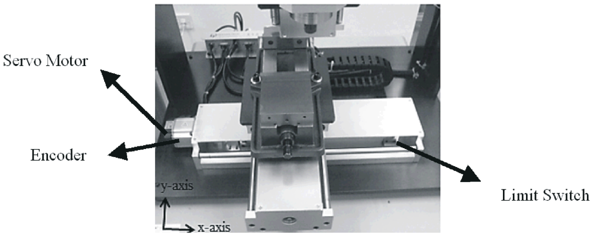

Fig. 1: Googoltech XY milling table ballscrew drive system

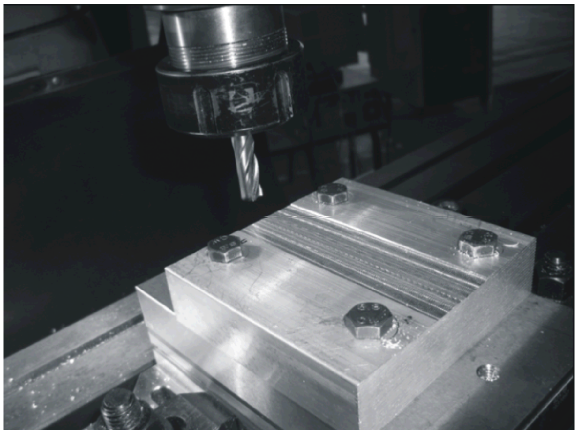

Fig. 2: Milling operation performed for the purpose of collection of cutting force data.

Figure 2 shows the milling process during the collection of disturbance cutting force data. The aluminium block is placed on top of the Kistler Dynamometer. The diameter of the milling cutter is 10mm. The depth of cut is 0.5mm with the feed rate of 502 mm/min.

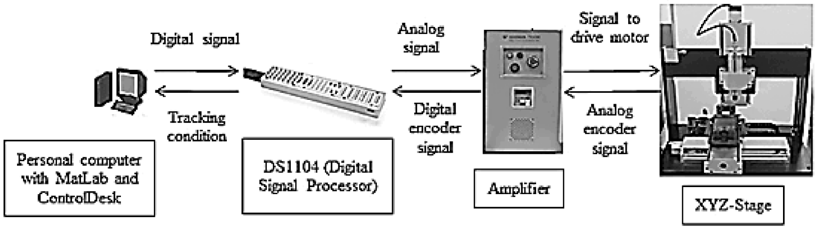

Fig. 3: Schematic diagram of the overall system

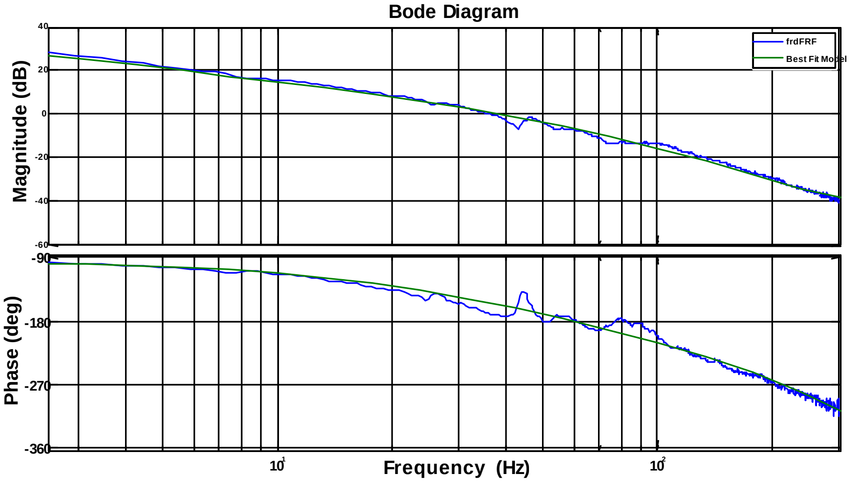

Fig. 4: FRF measurement and estimated model

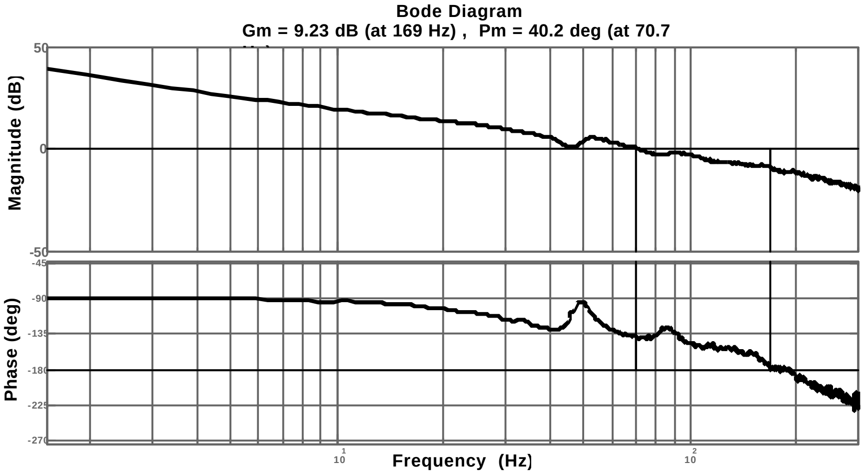

Fig. 5: Bode Diagram of open loop system with PID control

Figure 3 shows a schematic diagram of the overall system. The XY milling table is linked to a servo amplifier which is then connected to a DS1104 DSP board. A personal computer, equipped with ControlDesk and MATLAB software is linked to the DSP board to apply control design and data collection.

System Identification of XY Milling Table: By using the experimental setup in Figure 3, the system identifications are conducted on both x-axis and y-axis of the XY milling table. The system dynamic is described as single-input-single-output (SISO) model. Band-limited white noise signal is used to excite the system in order to measure the frequency response function (FRF) of the system. The sampling frequency is 2000 Hz and the duration of measurement is 5 minutes. A Hanning window is used to reduce leakage on measurement [10] and the number of samples per window is 4096. The H1 estimator is applied in estimating the FRF of the system. The input voltage, V in unit volt, *U* from excitation signals and output encoder measurement, *Y* in unit mm are recorded. Figure 4 shows the Bode diagram of the measured FRF and the model transfer function of the system for the x-axis. The parametric model is fitted using nonlinear least square frequency domain identification method [11,12] through the frequency domain identification toolbox in MATLAB.

The second order transfer function is in continuous domain, S with time delay of 0.0013 seconds in which Y is the output and U is the input signal. The model is as follows:

$$\frac{Y(s)}{U(s)} = \frac{69380}{s^2 + 144.8s + 166.3} \tag{1}$$

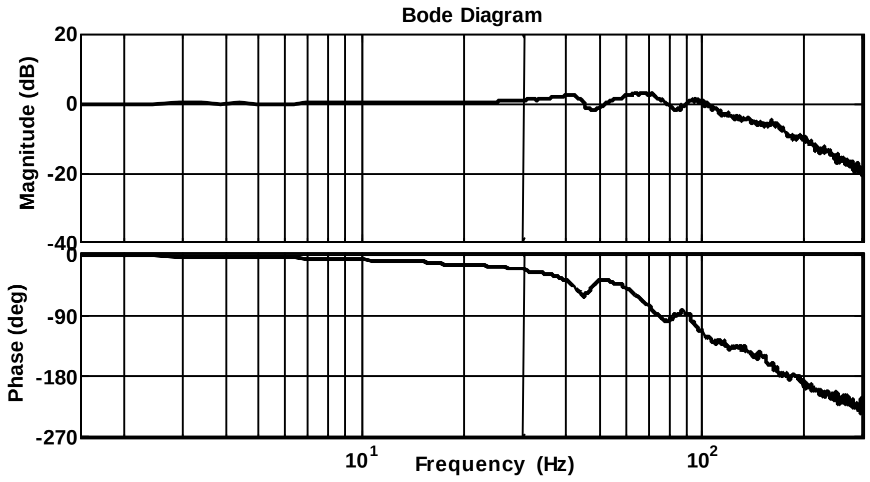

Fig. 6: Bode diagram of close loop system with PID control

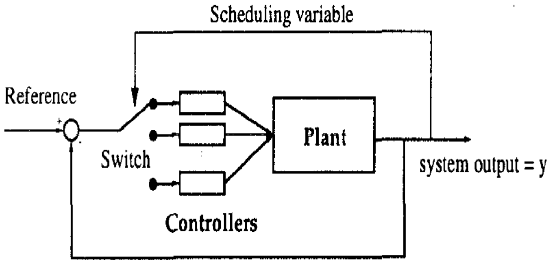

Fig. 7: General structure of a gain scheduling controller

Design of Controller 1 (PID Controller): Three different controllers are designed and their performance against cutting force acting as disturbance input signal are analysed. Analyses are performed using the plant transfer function (1). A Proportional Integral Derivative (PID) controller is a generic controller widely used in industrial control systems. The PID control equation involves three separate parameters, Proportional, Integral and Derivative terms.

$$G_{PID}(s) = k_p + \frac{k_i}{s} + k_d s \qquad (2)$$

The controller parameters, k_p, k_i and k_d are designed based on the phase margin and gain margin requirements of the open loop system. Figure 5 and 6 show the open loop and closed loop transfer function of the system with PID control. The gain margin of the open loop system is recorded at 9.23 dB while the phase margin is 40.2 degree. The result obtained authenticate with the rule of thumb design requirement of gain margin to be within the range of 3 to 10 dB and phase margin of 40 to 60 degree. Nyquist plot of the open loop transfer function verify the stability of the system, that is, the point [-1,0] is not encircled.

Table 1: Parameters of the look-up table

Spindle Speed (rpm)	K_p	K_i	K_d
1000	1.3250	0.0004525	0.0067970
2000	1.2651	0.0005998	0.0057835
3000	1.2398	0.0006343	0.0057798

The PID transfer function is therefore,

$$G_{pid} = \frac{0.006805s^2 + 1.32s + 0.0008248}{s} \qquad (3)$$

Design of Controller 2 (Gain Scheduling PID Controller): Gain scheduling control belongs to the nonlinear group of controllers. A gain scheduling controller based on PID control is designed. Figure 7 shows a general structure of a gain scheduling controller [13]. Table 1 lists the parameters of the look-up table.

The Gain Scheduling transfer function for each respective spindle speed are as follows,

$$G_{PID\_1000rpm} = \frac{0.006797s^2 + 1.325s + 0.0004525}{s} \qquad (4)$$

$$G_{PID\_2000rpm} = \frac{0.005783s^2 + 1.265s + 0.0005998}{s} \qquad (5)$$

$$G_{PID\_3000rpm} = \frac{0.00578s^2 + 1.24s + 0.0006343}{s} \qquad (6)$$

Design of Controller 3 (Cascade P/PI Controller): Cascade P/PI controller belongs to the classical group of controller and this control structure is widely applied in most machine control algorithm. The cascade P/PI control consists of a PI controlled inner velocity loop with a P controller in the outer position loop. Figure 8 shows the basic structure of a cascade P/PI controller.

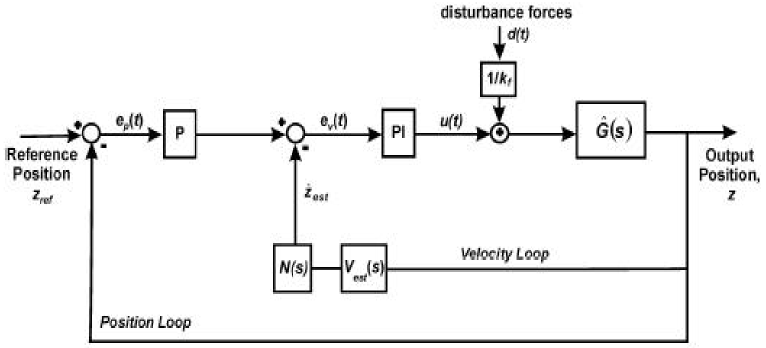

Fig. 8: Basic structure of a cascade P/PI controller

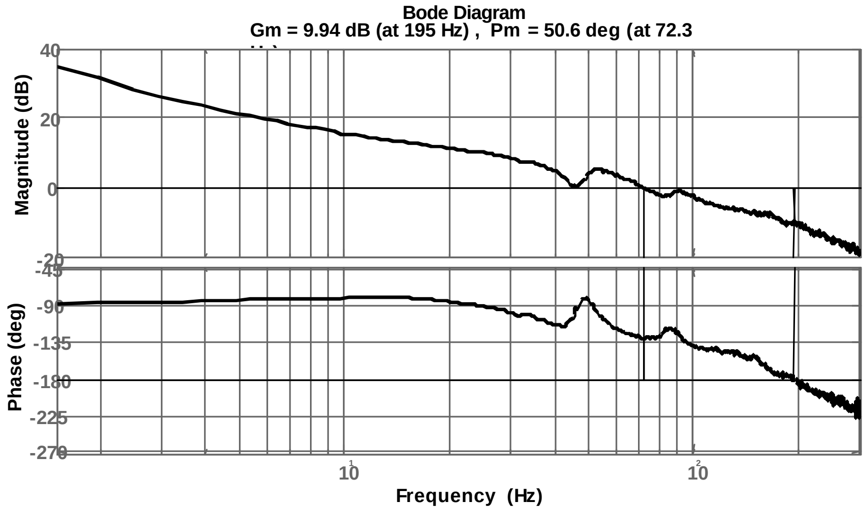

Fig. 9: Bode plot of speed open loop transfer function using Cascade P/PI

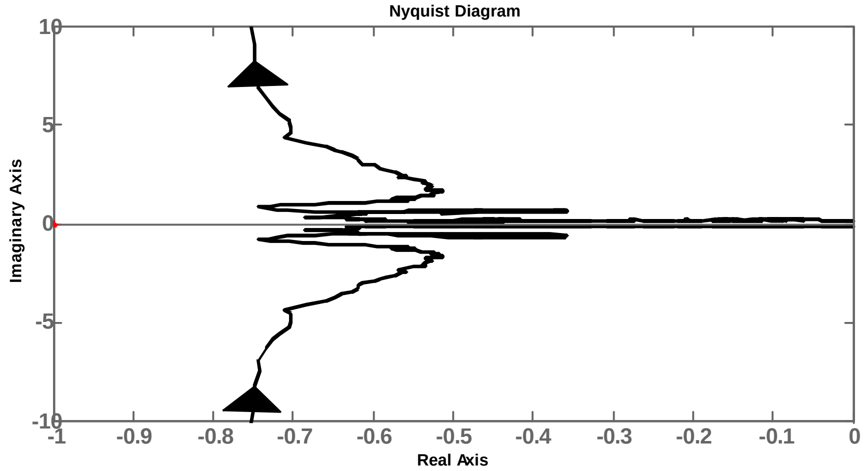

Fig. 10: Nyquist plot of open loop position transfer function using Cascade P/PI

The velocity PI controller is first designed before the P position controller. Figure 9 and 10 show the Bode open loop transfer function of the speed loop and the Nyquist plot of the position open loop respectively. Figure 11 shows the Bode diagram of the position loop sensitivity transfer function that indicates a system bandwidth of about 41.2 Hz. To conclude, Table 2 illustrates the finalized values of K_p, K_i and K_v for the controlled system.

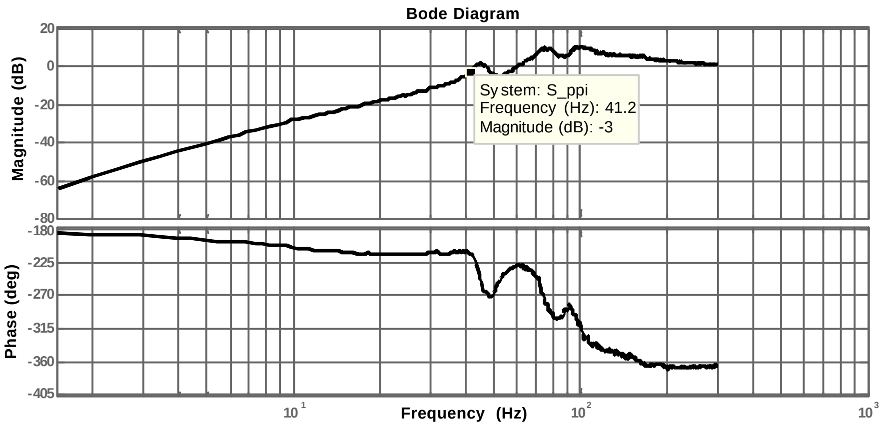

Fig. 11: Bode plot of position sensitivity transfer function using Cascade P/PI

Table 2: List of the control parameters of the cascade P/PI controller

Parameters	Values
K_p (velocity loop)	0.0326 [volts.s]
K_i (velocity loop)	0.0015 [volts.??2]
K_v (position loop)	282sG^1
Force-voltage converter	1/1623.49 N/V

RESULTS AND DISCUSSION

The measured cutting forces are inserted prior to the system (as illustrated in Figure 8) as disturbance cutting forces. The tracking performance of the PID, gain scheduling controller and the cascade P/PI controller are analysed and compared based on their robustness against different cutting conditions. Analyses on magnitudes of the harmonic components of the error signal and analyses on maximum position tracking errors are performed in order to quantify the compensation performance of these controllers against external cutting forces. Table 3 compares the harmonic amplitudes of the position error signal recorded between PID, Gain Scheduling and Cascade P/PI controllers at varying spindle speed rotations. As anticipated, the cascade P/PI controller produces improved performance compared to the classical PID and Gain Scheduling controller. The results appeared to concur as cascade controller has higher system bandwidth compared to the PID and Gain Scheduling controller.

Harmonic Components of Tracking Errors: Figures 12-14 show the spectrum analyses of the position errors obtained using PID, Gain Scheduling and Cascade P/PI at 1000 rpm spindle speed rotation. The detailed results of the spectrum analyses of the position errors for each respective controller for the case of 2000 and 3000 rpm spindle rotation are tabulated in Table 3. Results show an improved performance using cascade P/PI compared to both PID and Gain Scheduling controllers. The amplitude tracking error drops from 1.4050 µm at 2.0 Hz of PID controller to 0.7865 µm of Gain Scheduling controller. This result demonstrates an improvement of about 44 percent. A smaller improvement from 0.7670-0.7294 µm is recorded at the 4th harmonic frequency. However, due to its conservative design, the performance of the gain scheduling control drops beyond its bandwidth at 40.2 Hz. This performance indicates the limitation of the existing control design. Results show that cascade P/PI controller is able to compensate and reduce tracking error components generated from the cutting forces. Its performance is only limited by the control bandwidth. The cascade P/PI controller still maintains good performance even at a high harmonics frequencies region.

Corresponding Trend of Tracking Errors Between Controllers: Figure 15 shows the trend of tracking errors between PID, Gain Scheduling and Cascade P/PI controller at 1000 rpm spindle speed rotation. It shows that the tracking error using Gain scheduling controller is better than PID controller at lower frequency until 6.3 Hz. On the other hand, the trend shows PID controller performs better than Gain Scheduling controller at higher frequency above 6.3 Hz. On top of that, the result shows the superiority of Cascade P/PI in which the tracking error is very much lower than both PID and Gain Scheduling PID. In addition, the performance of the Cascade P/PI controller is better than both PID and Gain Scheduling PID for both lower and higher frequency range. The reason why cascade P/PI is better than both of the controllers is because the controller caters both the velocity and the position of the system whereas the other controllers are just controlling the position of the system.

Table 3: FFT Analyses on harmonic components of the position errors

Spindle speed [rpm]	Harmonic Frequencies [Hz]	Amplitude of Tracking Error [µm]			Error Reduction [%]		
		PID	Gain Scheduling	Cascade P/PI	Gain Scheduling with PID	Cascade P/PI with PID	Cascade P/PI with Gain Scheduling
1000	2.0	1.4050	0.7865	0.03495	44.02	97.51	95.56
	3.5	1.0250	0.4205	0.13260	58.98	87.06	68.47
	5.0	0.7650	0.4922	0.08883	35.66	88.39	81.95
	6.3	0.7670	0.7294	0.09024	4.90	88.23	87.62
	7.7	0.5239	0.9500	0.10050	-81.33	80.82	89.42
2000	2.0	0.9456	0.9665	0.04617	-2.21	95.12	95.22
	3.5	0.8731	0.6292	0.05869	27.93	93.28	90.67
	5.0	0.7412	0.4342	0.07327	41.42	90.11	83.12
	6.3	1.1800	0.1100	0.05534	90.67	95.31	49.69
	7.7	1.3270	0.1148	0.05068	91.34	96.18	55.85
3000	2.0	0.7870	1.3620	0.07913	-73.06	89.95	94.19
	3.5	0.7276	0.5917	0.07545	18.67	89.63	87.25
	5.0	0.4130	0.4964	0.16180	-20.19	60.82	67.41
	6.3	0.2539	0.3663	0.19010	-44.27	25.12	48.10
	7.7	0.2854	0.1744	0.28960	38.89	-1.47	-66.05

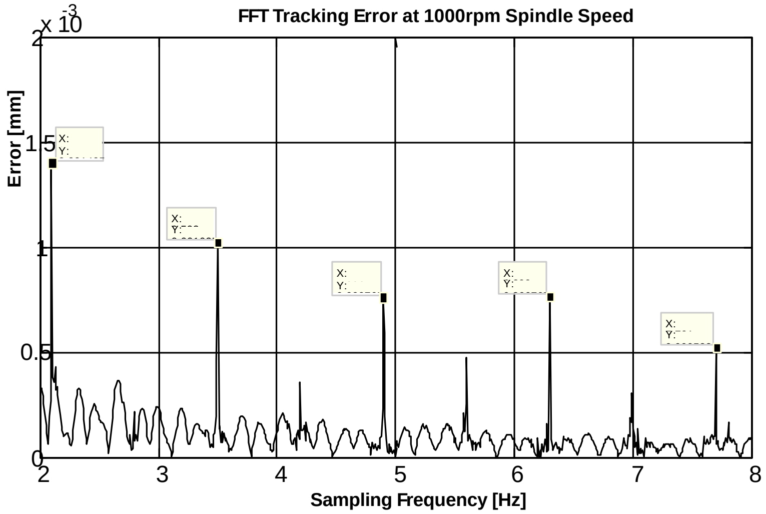

Fig. 12: Spectrum analysis of position error via PID controller

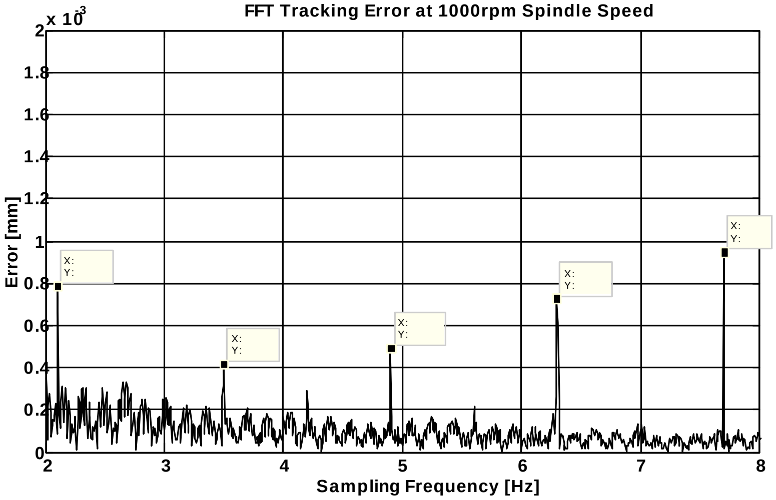

Fig. 13: Spectrum analysis of position error via gain scheduling controller

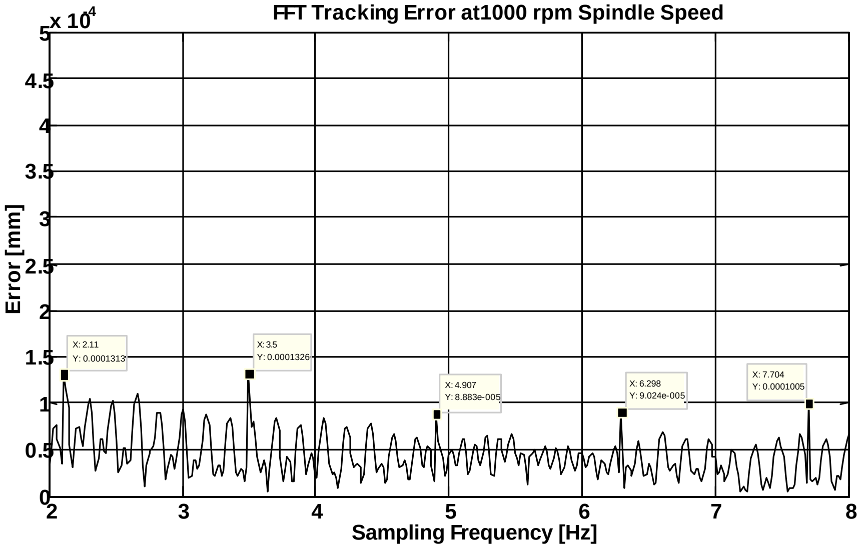

Fig. 14: Spectrum analysis of position error via cascade P/PI controller

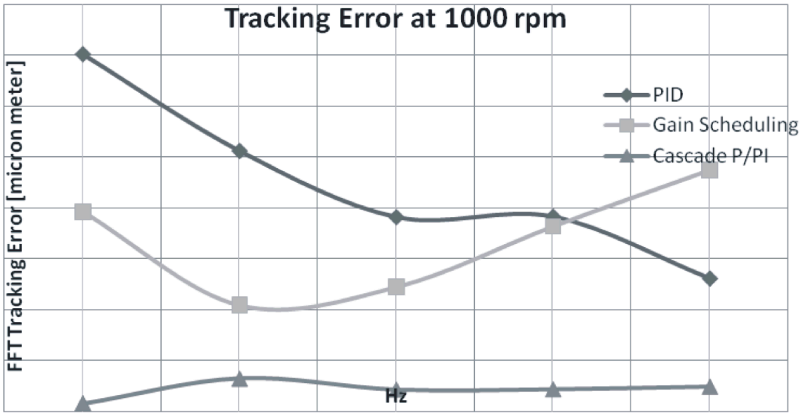

Fig. 15: Trend of FFT tracking error between PID, Gain Scheduling and Cascade P/PI

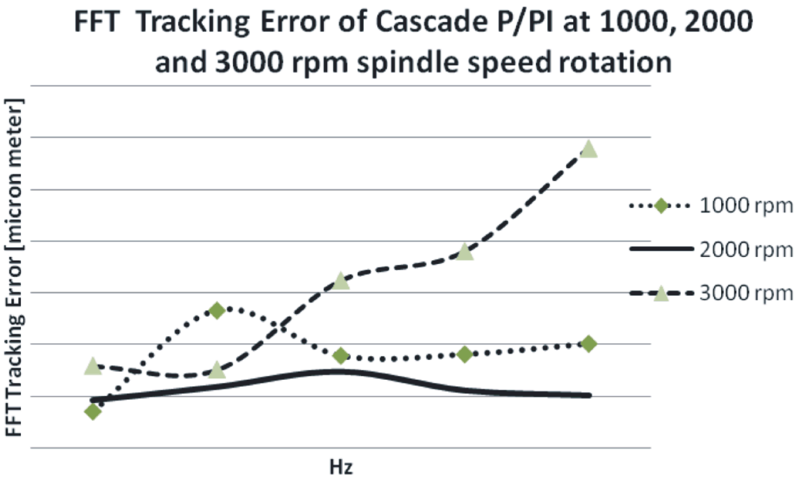

Fig. 16: Trend of FFT tracking error of Cascade P/PI at 1000, 2000 and 3000 rpm

Corresponding Trend of Tracking Errors at Different Spindle Speed: Figure 16 shows the trend of tracking errors of Cascade P/PI controller at 1000, 2000 and 3000 rpm spindle speed rotation. The reason why the tracking errors at multiple spindle speed rotation was tabulated for Cascade P/PI only is simply because the performance of Cascade controller is better than the other controllers. Furthermore, the purpose of constructing Figure 16 is to recommend the best cutting condition in order to obtain the best result from the cascade controller in term of the lowest tracking error achieved. The result portrays that in order to acquire the best result; it is recommended to perform the machining operation at 2000 rpm spindle speed rotation since the lowest tracking errors occurred at this point of cutting condition. In addition, it is observed that the cascade P/PI is no longer frequency independent at 3000 rpm spindle speed rotation. This is due to the fluctuating pattern of cutting force characteristics that occurred naturally.

CONCLUSION

It can be concluded that Cascade P/PI controller performs better than both PID and Gain Scheduling controller. The maximum tracking errors of Cascade P/PI is approximately about 0.3 micron meter, while for the case of PID and Gain Scheduling controllers, the maximum tracking errors are 1.405 and 1.3620 micron meter respectively. Analyses on the harmonics content of the position tracking errors have shown the supremacy of cascade P/PI controller. The benefits of the implementation of cascade P/PI in machine tools applications are obvious in which it will increase the quality of the end product and the productivity in industry by saving the machining time. It is suggested that the range of the spindle speed could be made wider to accommodate the needs for high speed machining.

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