Faculty of Manufacturing Engineering

NPID DOUBLE HYPERBOLIC CONTROLLER FOR IMPROVING TRACKING PERFORMANCE OF XY TABLE BALLSCREW DRIVE SYSTEM

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DECLARATION

I declare that this thesis entitled "NPID Double Hyperbolic Controller for Improving Tracking Performance of XY Table Ballscrew Drive System" is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Signature	:	……………………………
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APPROVAL

I hereby declare that I have read this thesis and in my opinion this thesis is sufficient in terms of scope and quality for the award of Master of Science in Manufacturing Engineering.

Signature	:	………………………………
Supervisor Name	:	………………………………
Date	:	………………………………

DEDICATION

Alhamdulillah, all Praise and thank to Allah SWT the Almighty, the Most Gracious and the Most Merciful for giving me the Rahmah to fully complete my research

Especially for my beloved mum and dad, Saripah and Che Ku Junoh

Thank you for your never-ending prayer, impulse, and advice

May mum and dad are always in God's sight and may 'Allah' the Almighty bless both of you

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ABSTRACT

Higher tracking accuracy, robustness and disturbance rejection are the three most important elements that are highly demanded to be applied and achieved in the process of controller design in manufacturing process. In this new era where technology keeps rising, controller design for machine tools has caught the attention of most researchers nowadays. However, disturbances such as friction force and cutting force affect the tracking performance of the machine tool. Issues related to cutting force effect on machining have been studied extensively by previous researchers in which different controller techniques are designed to overcome this issue. The conventional controller such as a proportional-integral-derivative (PID) controller is proved to be inadequate in enhancing the tracking performance of the machine tool under the presence of cutting force. Consequently, PID structure is modified by cascading a nonlinear component and PID controller which is named as nonlinear proportional-integral-derivative (NPID) controller. However, an NPID controller also has limitation with respect to the range of stability of the nonlinear gain. Owing to this reason, NPID controller with more than one nonlinear components are proposed to address the issue. Thus, this thesis proposes an NPID Double Hyperbolic controller for improving the tracking performance of the machine tool application. First, the transfer function of the model is obtained via system identification approach which is known as black box approach. Then, the proposed controller is designed. It consists of two embedded hyperbolic nonlinear components known as the nonlinear proportional and the nonlinear integral which are located before the proportional and integral gains, respectively. This controller is validated via simulation and experimental works. The performance of this proposed controller is compared with the two conventional controllers; the PID and the NPID controllers to verify the effectiveness of the proposed controller. This thesis has successfully demonstrated that by adding additional nonlinear hyperbolic components, the tracking performance of a machine tool can increase significantly. The results showed that NPID Double Hyperbolic controller provide an improvement of 94.43% in terms of root mean square error (RMSE) performance and an enhancement of 62.59% in terms of fast fourier transform (FFT) error performance compared to the conventional NPID controller. However, further studies and improvement are needed to study the machine tool performance in view of the quadrant glitches existence produced by the friction force. In addition, further study is required on PID controller with three nonlinear components in order to produce better tracking machine tool performance.

ABSTRAK

Ketepatan, keteguhan dan penyingkiran gangguan yang tinggi adalah antara tiga elemen yang amat penting dalam proses rekabentuk sistem kawalan dalam sektor pembuatan. Proses rekabentuk sistem kawalan bagi memastikan peningkatan prestasi sesebuah alat mesin adalah suatu era yang baru di mana ramai penyelidik mula mengkaji dan merekabentuk pelbagai jenis sistem kawalan. Walau bagaimanapun, gangguan pada alat mesin seperti daya geseran dan daya pemotongan memberi kesan kepada prestasi proses pemesinan. Isu berkaitan daya pemotongan ketika proses pemesinan telah dikaji dengan lebih meluas di mana pelbagai jenis sistem kawalan telah diperkenalkan oleh ahli penyelidik sebelum ini. Sistem kawalan konvensional seperti "proportional-integral-derivative (PID)" sahaja tidak mencukupi bagi meningkatkan prestasi ketepatan proses pemesinan ketika kehadiran daya pemotongan berlaku. Akibatnya, rekabentuk sistem kawalan "PID" yang terhad telah ditambah baik dengan menjalankan proses ubah suai rekabentuk di mana satu penambahan sesuatu komponen dalam reka bentuk sistem kawalan "PID" yang dinamakan sebagai sistem kawalan "nonlinear proportional-integral-derivative (NPID)". Walau bagaimanapun, sistem kawalan "NPID" juga mempunyai kepelbagaian nilai kestabilan yang terhad. Oleh kerana itu, sistem kawalan "NPID" mesti direkabentuk dengan lebih komponen tidak linear. Dalam tesis ini, satu rekabentuk sistem kawalan "NPID Double Hyperbolic" diperkenalkan bertujuan untuk menambahbaik prestasi ketepatan sesuatu alat mesin. Pertama, satu model matematik yang dinamakan rangkap pindah dihasilkan melalui proses pengenalan sistem yang dikenali sebagai "black box". Kemudian, cadangan sistem kawalan ini terdiri daripada dua fungsi "hyperbolic" tidak linear yang dinamakan sebagai fungsi tidak linear "P" dan fungsi tidak linear "I". Hasil prestasi "NPID Double Hyperbolic" ini kemudian dibandingkan dengan sistem kawalan konvensional "PID" dan "NPID" bagi mengesahkan keberkesanan cadangan sistem kawalan ini. Tesis ini juga telah menunjukkan dua fungsi "hyperbolic" tidak linear berpotensi dalam meningkatan prestasi ketepatan ketika proses pemesinan. Hasil eksperimen menunjukkan bahawa sistem kawalan "NPID Double Hyperbolic" telah berjaya membuahkan hasil yang lebih baik sebanyak 94.43% dari aspek "Root mean square error (RMSE)" dan 62.59% dari aspek "Fast Fourier Transform (FFT) error" berbanding sistem kawalan konvensional "NPID". Walau bagaimanapun, kajian lanjut dan penambahbaikan adalah diperlukan. Tujuan kajian lanjut adalah bagi memastikan prestasi proses pemesinan dapat ditingkatkan lagi. Prestasi proses pemesinan ini dapat ditingkatkan dengan menghasilkan satu model geseran dalam cadangan sistem kawalan bagi mengurangkan daya geseran dan dalam masa yang sama meningkatkan lagi ketepatan proses pemesinan. Sebagai tambahan, sistem kawalan "PID" dengan tiga fungsi tidak linear perlu dikaji dengan lebih teliti pada masa akan datang bagi meningkatkan lagi prestasi proses pemesinan.

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LIST OF SYMBOLS

N	-	Rotational spindle speed of cutter
v	-	Cutting speed or feed rate
π	-	Pi
d	-	Diameter of the cutter
f	-	Feed per tooth
n	-	Number of teeth on the cutter
V	-	Voltage
mm	-	Millimetre
$Z(s)$	-	Position of the XY Table Ball-screw Drive System
$R(s)$	-	Input voltage
e^{-sT}	-	Transfer function of time delay
G_m	-	Transfer function of system model
N_P	-	Nonlinear proportional gain
N_I	-	Nonlinear integral gain
K_P	-	Proportional gain
K_I	-	Integral gain
K_D	-	Derivative gain
$S(j\omega)$	-	Sensitivity
L	-	Open loop of the control system
$e(t)$	-	Tracking error
f, g	-	Parameter of N_P

m, q, r	-	Parameter of N_I
e_{maxP}	-	Maximum allowable tracking error for proportional
e_{maxI}	-	Maximum allowable tracking error for integral
L_I	-	Open loop for integral
L_{maxP}	-	Maximum allowable proportional gain
L_{maxI}	-	Maximum allowable integral gain
L_P	-	Open loop for proportional
P_{best}	-	Personal best
G_{best}	-	Global best
t	-	Time
f	-	Frequency
$U_{double} = U_{NPID\_Double\_Hyperbolic}$	-	Control signal of NPID Double Hyperbolic controller

LIST OF ABBREVIATIONS

ABS	-	Anti-lock brake system
AFC	-	Adaptive feed-forward cancellation
CCC	-	Cross-coupling controller
CNC	-	Computer numerical control
DAC/ADC	-	Digital and Analog converter
DADSC	-	Disturbance adaptive discrete-time sliding model controller
DFO	-	Disturbance force observer
DOB	-	Disturbance observer
DSP	-	Digital signal processor
DZC	-	Dead zone compensator
EN-PI	-	Enhanced nonlinear proportional-integral
FDIDENT	-	Frequency domain identification
FFT	-	Fast Fourier Transform
FRF	-	Frequency response function
FSMC	-	Fuzzy sliding mode control
GMS	-	Generalized Maxwell-slip
HDD	-	Hard disk drive
IAE	-	Integral absolute error
IMBDO	-	Inverse model based disturbance observer
ITAE	-	Integral time absolute error
LS	-	Loop shaping

MBDA	-	Model-based disturbance attenuator
MN-PID	-	Multi-rate nonlinear PID
MPC	-	Model predictive control
MRC	-	Model reference control
NCasFF	-	Nonlinear cascade feed-forward
NPD	-	Nonlinear proportional-derivative
NPID	-	Nonlinear proportional-integral-derivative
P/PI	-	Proportional/proportional-integral
P	-	Proportional
PD	-	Proportional-derivative
PDC-NPD	-	Position domain NPD controller
PDC-PD	-	Position domain PD controller
PI	-	Proportional-integral
PID	-	Proportional-integral-derivative
PPC	-	Pole-placement controller
PSO	-	Particle swarm optimization
QFT	-	Quantitative feedback theory
RLS	-	Recursive least squares
RMSE	-	Root mean square error
SISO	-	Single input single output
SLD	-	Stability lobe diagram
SMC	-	Sliding mode control
SN-PID	-	Self-regulation nonlinear proportional-integral-derivative
TDC-NPD	-	Time domain NPD controller
TDC-PD	-	Time domain PD controller
TLBO	-	Teaching learning based optimization
TSMC	-	Traditional sliding mode control

ZPETC	-	Zero phase error tracking controller

LIST OF APPENDICES

LIST OF PUBLICATIONS

Journals (Scopus)

1. Abdullah, L., Junoh, S.C.K., Salim, S.N.S., Jamaludin, Z., Chiew, T.H., Anang, N.A. and Retas, Z., 2018. Evaluation on Tracking Performance of NPID Triple Hyperbolic and NPID Double Hyperbolic Controller Based on Fast Fourier Transform (FFT) for Machine Tools. *Journal of Advanced Manufacturing Technology*.
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2. Junoh, S.C.K., Ooi, S.H., Abdullah, L., Salim, S.N.S., Anang, N.A., Chiew, T.H. and Retas, Z., 2017. Tracking Performance of Nonlinear Proportional-Integral-Derivative for XY Table Ballscrew Drive System. In *Proceedings of Innovative Research and Industrial Dialogue 2016*, 1, pp.91-92.

CHAPTER 1

INTRODUCTION

1.1 Background

Machine tool is a machine for shaping material parts into a product with desired shapes by performing a cutting process. One example of a machine tool is the milling machine in which this machine provides a rotating tool that is located at the Z-axis machine and provides X-axis and Y-axis movement tables in order to perform various milling operations. In general, the milling machine is able to perform a continuous path system (Kalpakjian and Schmid, 2006) which is included in some milling operations such as pocket milling, profile milling, surface contouring, slotting, and others. The milling machine is also usually related to the precision mechanical system in the manufacturing industry.

Due to the superiority of the milling machine, various shapes of products or known as the work-piece can be produced by the industrial companies (Kalpakjian and Schmid, 2001). The milling machine operates by rotating the cutting tool to cut the unwanted part of the work-piece which is located on the milling machine table. However, the cutting process produces cutting force disturbance which is contributing to the poor performance of the machine tool and affecting the quality of the product surface (Abdullah et al., 2013a). Ogun and Jackson (2017) claimed that the performance of the XY table was recently still being investigated in order to produce a good surface quality of a product.

Other than the cutting force disturbance, the friction force also affects the performance of the machine tools. According to previous researchers (Chen et al., 2004,