UNIVERSITI TEKNIKAL MALAYSIA MELAKA

Faculty of Manufacturing Engineering

N-PID CONTROLLER WITH FEEDFORWARD OF GENERALIZED MAXWELL-SLIP AND STATIC FRICTION MODEL FOR FRICTION COMPENSATION IN MACHINE TOOLS

Chiew Tsung Heng

Master of Science in Manufacturing Engineering

2014

N-PID CONTROLLER WITH FEEDFORWARD OF GENERALIZED MAXWELL-SLIP AND STATIC FRICTION MODEL FOR FRICTION COMPENSATION IN MACHINE TOOLS

CHIEW TSUNG HENG

A thesis submitted
in fulfillment of the requirements for the degree of Master of Science in Manufacturing Engineering

Faculty of Manufacturing Engineering

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

2014

DECLARATION

I declare that this thesis entitled "N-PID Controller with Feedforward of Generalized Maxwell-Slip and Static Friction Model for Friction Compensation in Machine Tools" 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	:	....
Name	:	CHIEW TSUNG HENG
Date	:	....

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	:	....
Name	:	DR. ZAMBERI JAMALUDIN
Date	:	....

DEDICATION

For my beloved father and mother

Their loving and unconditional support throughout my life

To my brothers,

Without whose love and assistance this may not be completed

And also for those I love very much.

ABSTRACT

Increasing demand for accuracy and precision in machine tools application has placed greater pressure on researchers and machine developers for better products performance. Several factors that have been identified in literature that could affect machine performance are the active presence of disturbance forces such as cutting forces and friction forces. This research focuses only on the effect of friction forces as disturbance in a positioning system. “Spikes” on milled surface are normally observed in computer numerical control machine based on recent research and analysis. These “spikes” are known as quadrant glitches and is mainly due to the friction forces, which is an undesirable and nonlinear phenomenon that cannot be avoided during positioning process. The main objective of this research is the compensation of these friction forces to improve tracking performance of system by utilizing two different approaches, namely; non-model based method and friction model-based feedforward method. Two controllers, namely, proportional-integral-derivative (PID) controller and nonlinear PID (N-PID) controller, were designed, implemented and validated as non-model based technique to compensate friction forces on a XYZ-Stage, which is a fundamental block of a milling machine. In friction model-based method, two friction models, namely; static friction model and Generalized Maxwell-slip (GMS) model, were identified, modeled and applied as friction model-based feedforward. The system frequency response function was identified using a data acquisition unit, dSPACE 1104 with MATLAB software and H1 estimator, a nonlinear least square frequency domain identification method. Parameters for static friction and GMS model were identified using heuristic method and virgin curve respectively. PID and N-PID controllers were designed based on traditional loop shaping frequency domain approach and Popov stability criterion respectively. Numerical simulation and experimental validation for non-model based method showed that N-PID controller provided 25.0% improved performance in terms of quadrant glitches magnitude reduction than the PID controller. This is due to its automatic gain adjustment based on the chosen nonlinear function. For friction model-based feedforward method, the static friction model produced 95.9% reduction in tracking errors using PID controller and 95.8% reduction using the N-PID controller. For GMS friction model feedforward, the quadrant glitches magnitude was reduced by 33.3% using PID controller and 30.0% while using the N-PID controller. Finally, a combined feedforward of static and GMS friction models with the N-PID controller has resulted in the best performance that was a 96.5% reduction in tracking errors, and a 50.0% reduction in quadrant glitches magnitude. It is concluded that this combined approach would benefits to machine tools manufacturers and users as it improves the tracking performance as well as precision especially during circular motion and low tracking velocity.

ABSTRAK

Peningkatan permintaan terhadap ketepatan dan kepersisan dalam aplikasi perkakasan mesin sering membebankan para penyelidik dan pengeluar mesin untuk mendapatkan prestasi produk yang lebih baik. Antara faktor-faktor yang dikenalpastikan dapat mempengaruhi prestasi mesin dalam hasil-hasil kajian lepas ialah kewujudan daya-daya gangguan seperti daya pemotongan dan daya geseran. Penyelidikan ini hanya fokus terhadap kesan-kesan daya geseran sebagai gangguan dalam sistem keposisian. Berdasarkan kajian and analisa baru-baru ini,"spikes" atas permukaan kisaran hasil mesin kawalan berangka computer biasanya dapat diperhatikan. "Spikes" ini adalah dikenali sebagai "glic" sukuan dan diakibatkan oleh suatu situasi yang tidak sekata, tidak diinginkan dan tidak dapat dielakkan ketika proses keposisian, iaitu daya geseran. Objektif utama penyelidikan ini ialah pengurangan daya geseran ini untuk meningkatkan prestasi sistem melalui penggunaan dua pendekatan yang berbeza, iaitu kaedah bukan berasaskan model dan kaedah suap depan model geseran. Dua jenis pengawal, iaitu pengawal "proportional-integral-derivative" (PID) dan pengawal PID tidak linear (N-PID) direka, dilaksanakan dan disahkan sebagai teknik bukan berasaskan model untuk mengimbangi daya geseran di XYZ-Stage yang merupakan blok asas mesin pengisaran. Dua jenis model geseran, iaitu model geseran statik dan model "Generalized Maxwell-slip" (GMS) telah dikenalpastikan, dimodelkan dan digunakan sebagai teknik model geseran suap depan. Fungsi respon frekuensi sistem dikenalpastikan dengan menggunakan unit perolehan data, iaitu dSPACE 1104 bersama MATLAB dan anggaran H1, iaitu teknik "nonlinear least square frequency domain". Parameter-parameter model geseran statik dan model GMS telah dikenalpastikan menggunakan kaedah heuristik manakala parameter-parameter model GMS dikenalpastikan melalui "virgin curve". Pengawal PID telah direka berdasarkan "loop shaping" dalam domain frekuensi manakala pengawal N-PID telah direka berdassarkan kriteria kestabilan Popov. Simulasi dan pengesahan eksperimen menunjukkan bahawa kawalan N-PID memberi 25.0% prestasi yang lebih baik dari segi pengurangan sukuan glic kerana pelarasan gandaan secara automatik berdasarkan fungsi tidak linear yang terpilih. Untuk teknik suap depan model geseran pula, model geseran statik telah mengurangkan 95.9% ralat apabila menggunakan pengawal PID dan 95.8% ketika menggunakan pengawal N-PID. Dalam kes suap depan model GMS, sukuan "glic" dikurangkan sebanyak 33.3% dengnan menggunakan pengawal PID manakala 30.0% ketika menggunakan pengawal N-PID. Akhirnya, suap depan kombinasi kedua-dua model geseran bersama pengawal N-PID menghasilkan prestasi yang terbaik iaitu pengurangan ralat sebanyak 96.5% dan pengurangan sukuan "glic" sebanyak 50.0%. Kesimpulannya, kaedah kombinasi antara pengawal N-PID dan suap depan model-model geseran akan membawa faedah-faedah kepada para pembuat and pengguna perkakasan mesin kerana kemampuannya dalam meningkantkan prestasi dan kepersisan ketika pergerakan dalam bentuk bulatan dan halaju yang rendah.

ACKNOWLEDGEMENT

I would like to give thanks to my family for supporting me all the time without knowing the meaning of tiredness. Thank you for the warm care that provided by them in every moment of my life.

Thank you to my supervisor, Dr. Zamberi Jamaludin and my co-supervisor Dr. Ahmad Yusairi Bani Hashim for teaching and guiding me throughout the research. Special thanks to Dr. Zamberi Jamaludin, who is spending his precious time for giving me ideas in report writing and providing golden opinions throughout the research.

I also would like to give a big thank you to Ir. Lokman Abdullah and Miss Nur Aidawati Rafan who willing to spend their precious times in sharing knowledge of system identification and controller design with me. Thank you for the related journals and information as this research cannot be succeeded without the kindly help from Ir. Lokman Abdullah and Miss Nur Aidawati Rafan.

Thank you to Mr. Jaafar who sharing his knowledge on equipment with me and providing various suggestions for the experiment.

Last but not least, a special thanks to my friends, Mr. Jailani Jamaludin and Mr. Tang Teng Fong that sharing information of the research with me. Thank you for the supporting throughout the project.

TABLE OF CONTENT

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

Control:

$r(t)$	-	Reference input signal
$y(t)$	-	Output signal
$u(t)$	-	Control input
$e(t)$	-	Error
$G(s)$	-	System
$G_m (s)$	-	System model transfer function
$G_m'(s)$	-	System model with friction term
$d(t)$	-	Disturbances
$n(t)$	-	Noises
$G_c (s)$	-	Controller
L	-	Open loop transfer function
S	-	Sensitivity function
T	-	Close loop transfer function
w_c	-	Gain crossover frequency
w_B	-	Bandwidth from sensitivity function
w_{BT}	-	Bandwidth from close loop transfer function
$f(e)$	-	Scaled error
T_d	-	Time delay
k_f	-	Motor constant
M	-	Mass
$k(e)$	-	Nonlinear gain
k_o	-	Rate of variation of nonlinear gain
e_{max}	-	Range of variation of error

Friction:

F_n	-	Compressive force
F_t	-	Tangential force
k_t	-	Tangential stiffness
k_n	-	Normal stiffness
F_f	-	Total friction force
F_s	-	Static friction force
F_c	-	Coulomb friction force
σ	-	Viscous friction force
δ	-	Stribeck shape factor
v	-	Velocity
V_s	-	Stribeck velocity
δ_d	-	Determinant of shape of hysteresis
σ_o	-	Asperity stiffness
σ_1	-	Micro-viscous friction coefficient
σ_2	-	Viscous friction coefficient
z	-	Average deflection of asperities
$s(v)$	-	Stribeck curve
i	-	Elementary
k_i	-	Elementary stiffness
W_i	-	Maximum elementary Coulomb force
F_i	-	Friction output
z_i	-	Elementary displacement
C	-	Constant for rate of friction force followed Stribeck effect in sliding
α_i	-	Elementary normalized friction force
α	-	Mean ratio of characteristic length between inactivity and activity
w	-	Randomly chosen wavelength
z	-	Randomly chosen height

LIST OF ABBREVIATION

AC	-	Alternating current
CNC	-	Computer numerical control
D	-	Derivative
DSP	-	Digital signal processor
FRF	-	Frequency response function
GMS	-	Generalized Maxwell-slip
I	-	Integral
I/O	-	Input/output
NCTF	-	Nominal characteristic trajectory following
N-PID	-	Nonlinear proportional-integral-derivative
P	-	Proportional
PD	-	Proportional-derivative
PID	-	Proportional-integral-derivative
S-GMS	-	Smoothed Generalized Maxwell-slip
SISO	-	Single input single output
SMC	-	Sliding mode control
XGMS	-	Extended Generalized Maxwell-slip

LIST OF APPENDICES

LIST OF PUBLICATIONS

Conferences:

Chiew, T. H., Jamaludin, Z., Bani Hashim, A. Y., Rafan, N. A., Abdullah, L., and Mat Ali, M., 2012. System and Friction Identification of XY Milling Table using dSPACE Digital Signal Processor Board. In: Bani Hashim, A. Y., *International Conference on Design and Concurrent Engineering 2012 (iDECON 2012)*, Melaka, 15 – 16 October 2012, UTeM Publication.

Rafan, N. A., Jamaludin, Z., Abdullah, L., Chiew, T. H., and Mat Ali, M., 2012a. Review on Friction Compensation Approach for Machine Tools Application. In: Bani Hashim, A. Y., *International Conference on Design and Concurrent Engineering 2012 (iDECON 2012)*, Melaka, 15 – 16 October 2012, UTeM Publication.

Journals:

Chiew, T. H., Jamaludin, Z., Bani Hashim, A. Y., Rafan, N. A., and Abdullah, L., 2013. Identification of Friction Models for Precise Positioning System in Machine Tools. *Procedia Engineering*, 53, pp. 569 – 578.

Abdullah, L., Jamaludin, Z., Chiew, T. H., Rafan, N. A., and Syed Mohamed, M. S., 2012. System Identification of XY Table Ballscrew Drive using Parametric and Non Parametric Freqeuncy Domain Estimation via Deterministic Approach. *Procedia Engineering*, 41, pp. 567 – 574.

Abdullah, L., Jamaludin, Z., Chiew, T. H., Rafan, N. A., and Yuhazri, M. Y., 2012. Extensive Tracking Performance Analysis of Classical Feedback Control for XY Stage Ballscrew System. *Applied Mechanics and Materials*, 229 – 231, pp. 750 – 755.

Rafan, N. A., Jamaludin, Z., Tjahjowidodo, T., Chey, L. S., and Chiew, T. H., 2012. Theoretical Analysis of Friction Compensation using Sliding Mode Control. *Applied Mechanics and Materials*, 229 – 231, pp. 2385 – 2388.