

Faculty of Manufacturing Engineering

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

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

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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 here	by o	declare	that 1	have r	ead	this t	thesis ar	nd i	n my	opinic	on this t	hesis	is	sufficien	t in
terms	of	scope	and	quality	for	the	award	of	Maste	er of	Scienc	e in	Ma	anufactui	ring
Engine	eeri	ng.													

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.

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LIST OF SYMBOLS

Control:

r(t) -	Reference	input	signal
$I \cup \iota$, -	IXCICI CIICC	mput	Signa

Output signal y(t)

u(t)Control input

Error e(t)

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

Open loop transfer function L

S Sensitivity function

TClose loop transfer function

Gain crossover frequency w_c

Bandwidth from sensitivity function W_B

Bandwidth from close loop transfer function W_{BT}

f(e)Scaled error

 T_d Time delay

 k_f Motor constant

MMass

k(*e*) Nonlinear gain

Rate of variation of nonlinear gain k_o

Range of variation of error e_{max}

Friction:

 \mathbf{Z}

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

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

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LIST OF PUBLICATIONS

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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.

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