Faculty of Manufacturing Engineering

DESIGN OF CASCADE NP/PI CONTROLLER FOR CUTTING FORCE COMPENSATION OF BALL SCREW DRIVEN SYSTEM

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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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DECLARATION

I declare that this thesis entitled "Design of Cascade NP/PI Controller for Cutting Force Compensation of Ball Screw Driven 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	:	IR. DR. LOKMAN BIN ABDULLAH
Date	:	

DEDICATION

Thank you Allah for giving me strength to finish this research and thesis.

For my parents, Norriza Kasah and Anang Mohamad, who have been loved me since day one, who taught me trust in Allah, encouraging me to believe myself, very supportive and worked so hard for earning an honest living for me and brothers.

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ABSTRACT

This research explores control strategies for compensation on effect of cutting forces on accuracy of positioning table of a milling machine using a controller named cascade NP/PI. The control structure of cascade NP/PI controller was based on the conventional cascade P/PI controller with an add-on module of a nonlinear function. The system stability was guaranteed before the nonlinear parameters such as rate of variation of nonlinear gain (*KO*) and maximum value of error (e_{max}) were determined. Cutting forces exist during milling cutting process, exert additional force on the drive system of the positioning table that if left uncompensated would impact on the accuracy and precision of the system. Therefore, it is crucial that the negative effect of these cutting forces are damped so as to retain the positioning accuracy and precision of the drive system. Cutting forces contain harmonics frequencies depending on the spindle speed rotations. An efficient controller that is able to damp these harmonics content is then desired. In this research, another two controllers were designed, namely, PID controller and cascade P/PI controller to compared the results with the proposed cascade NP/PI controller. The controllers' performances were analysed numerically and validated experimentally on the *X*-axis of an XY ball screw driven positioning table using cutting forces measured at depth of cut of 0.2mm and 1mm and spindle speed rotations of 1500rpm, 2500rpm and 3500rpm. Analyses were performed on each of these controllers in terms of maximum tracking error, Root Mean Square (RMS) of tracking error and Fast Fourier Transform (FFT) of errors. Results of maximum tracking error showed that cascade NP/PI controller produced the lowest percentage error 0.25% compared to PID and cascade P/PI controller with 0.26% and 0.61% respectively whilst results on error reduction based on RMS of error showed that the proposed cascade NP/PI controller outperformed PID and cascade P/PI controller by as much as 62.1% and 6.3% respectively. Furthermore, spectrum analysis showed that cascade NP/PI controller has successfully compensated the negative effect of the cutting forces with the highest error reduction in term of damping of the peak frequencies by as much as 42.53% and 27.54% compared to PID and cascade P/PI controller respectively. As the research outcome, a review on precise positioning control strategy has been published in 2017. In 2018, the study on the nonlinear function implementing on PID and cascade P/PI controllers have been done and published in journal and book chapter.

ABSTRAK

Kajian ini meneroka strategi kendalian untuk pengurangan daya pemotongan terhadap ketepatan kedudukan meja bagi mesin pengisaran menggunakan pengawal yang diberi nama pengawal lata NP/PI. Struktur kawalan pengawal lata NP/PI adalah berdasarkan pengawal konvensional lata P/PI dengan fungsi tidak linear sebagai modul tambahan. Kestabilan sistem telah dijamin terlebih dahulu sebelum parameter tidak linear seperti kadar variasi nilai tak linear (KO) dan nilai ralat maksimum (e_{max}) telah ditentukan. Daya pemotongan wujud semasa proses pemotongan, menghasilkan daya tambahan pada sistem pemacu meja kedudukan yang jika dibiarkan tidak dikurangkan akan memberi kesan kepada kejituan dan ketepatan sistem. Oleh itu, adalah penting supaya kesan negatif dari daya pemotongan ini diatasi untuk mengekalkan kejituan kedudukan dan ketepatan sistem pemacu. Daya memotong mengandungi frekuensi harmonik bergantung kepada putaran kelajuan pengumpar. Pengawal yang cekap yang dapat menampung kandungan harmonik adalah diingini. Dalam kajian ini dua lagi pengawal telah direka iaitu pengawal PID dan pengawal lata P/PI untuk dibandingkan dengan pengawal lata NP/PI yang dicadangkan. Prestasi pengawal dianalisa secara numerik dan disahkan secara uji kaji pada paksi X yang didorong oleh bola skru meja kedudukan XY menggunakan daya pemotong yang diukur pada kedalaman pemotongan 0.2mm dan 1mm dan putaran kelajuan pengumpar 1500rpm, 2500rpm dan 3500rpm. Analisis dilakukan pada setiap pengawal dari segi ralat trajektori maksimum, ralat trajektori 'Root Mean Square' (RMS) dan magnitud ralat trajektori 'Fast-Fourier-Transform' (FFT). Keputusan ralat trajektori maksimum menunjukkan pengawal lata NP/PI menghasilkan ralat peratusan terendah 0.25% berbanding PID dan pengawal lata P/PI dengan 0.26% dan 0.61% masing-masing manakala keputusan pengurangan ralat berdasarkan ralat trajektori RMS menunjukkan bahawa pengawal yang dicadangkan pengawal lata NP/PI mengatasi PID dan pengawal lata P/PI masing-masing sebanyak 62.1% dan 6.3%. Tambahan pula, analisis spektrum menunjukkan bahawa pengawal lata NP / PI telah berjaya mengurangkan kesan negatif daya pemotongan dengan pengurangan kesilapan yang paling tinggi dalam tempoh redaman frekuensi puncak sebanyak 42.53% dan 27.54% berbanding dengan PID dan pengawal lata P/PI masing-masing. Sebagai hasil penyelidikan, kajian semula mengenai strategi kawalan kedudukan tepat telah diterbitkan pada 2017. Pada tahun 2018, kajian mengenai fungsi tidak linear yang telah dilaksanakan pada pengawal PID dan pengawal lata P/PI telah dilakukan dan diterbitkan dalam jurnal dan bab buku.

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a	–	Ferraris relative acceleration signal
d	–	Disturbance force
$\hat{d}$	–	Estimated disturbance force
δ	–	Sampling frequency
D	–	Diameter of the cutter
$e_p(t)$	–	Position tracking error
$e_v(t)$	–	Velocity tracking error
e_{max}	–	Maximum value of error
f	–	Feed per tooth
F	–	Friction force
F_c	–	Cutting force
F_t	–	Thrust force
G	–	System
G_p	–	Position controller
G_{pi}	–	Velocity controller
k_f	–	Motor force constant
K_p	–	Proportional controller
K_i	–	Integral controller
K_d	–	Derivative controller
KO	–	Rate of variation of nonlinear gain
m	–	Order of numerator
M	–	Mass of the motor/system
n	–	Order of denominator (n > m)
n_t	–	Teeth number of the cutter
N	–	Rotational speed of the cutter

N_f	–	Normal force
q_i, s	–	Filter numerator coefficients
Q	–	Low pass filter
R	–	Resultant force
u	–	Voltage to the drive amplifier
u_p	–	Position control signal
u_{pi}	–	Velocity control signal
v	–	Linear speed of the work piece or feed rate
vel	–	Velocity
V	–	Cutting speed
V_{est}	–	Estimated velocity
Z	–	Output position
$\dot{Z}est$	–	Estimate position
Z_{ref}	–	Reference position
Z_{act}	–	Actual position
ω_c	–	Cut-off frequency
$\ddot{x}$	–	Absolute acceleration
π	–	Pi

LIST OF ABBREVIATIONS

ADRTC	–	Adaptive disturbance rejection tracking controller
AGE	–	Approximation grid evaluation
CL	–	Closed loop transfer function
CNC	–	Computer numerical control
DoE	–	Design of experiment
DRTC	–	Disturbance rejection tracking controller
DSP	–	Digital signal processing
EDM	–	Electrical discharge machining
FFT	–	Fast fourier transform
FNPID	–	Feedforward NPID
FPID	–	Fuzzy PID
FRF	–	Frequency response function
GA	–	Genetic algorithm
IMBDO	–	Inverse model based disturbance observer
I/O	–	Input output
IoT	–	Internet of things
JITL	–	Just in time learning
LTI	–	Linear time invariant
MMI	–	Man machine interface
NPID	–	Nonlinear PID
OL	–	Open loop transfer function
PD	–	Proportional-derivative
PID	–	Proportional-Integral-Derivative
PI	–	Proportional-integral
PLC	–	Programmable logic controller

RMS	–	Root mean square
SISO	–	Single input single output
TGPID	–	Taguchi-grey-PID