UNIVERSITI TEKNIKAL MALAYSIA MELAKA

Faculty of Manufacturing Engineering

A NEW CONTROL STRATEGY FOR CUTTING FORCE DISTURBANCE COMPENSATION FOR XY TABLE BALL SCREW DRIVEN SYSTEM

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A thesis submitted
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DECLARATION

I declare that this thesis entitle "A New Control Strategy for Cutting Force Disturbance Compensation for *XY* Table 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 Doctor of Philosophy in Manufacturing Engineering.

Signature	:	....
Name	:	ASSOC. PROF. DR. ZAMBERI JAMALUDIN
Date	:	....

DEDIKASI

Ya Allah, hanya dengan keizinan-Mu kajian ini dapat disempurnakan.

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ABSTRACT

High tracking accuracy, precision and robustness are three vital components demanded in controller design for machining processes in many manufacturing related activities. This recent requirements or paradigm shift has led to a new and challenging era in the area of machining tools and control. However, the presence of disturbances during machining processes in the form of friction forces and cutting forces have greatly reduced positioning and tracking accuracy of the system. The objective of this thesis is to propose, design, develop and validate a new control strategy to further compensate effects of cutting forces on the positioning accuracy of a XY table ball screw driven system by Googoltech Inc. Issues pertaining to cutting force effects on machining process have been explored comprehensively in the past where various techniques and thoughts were introduced and validated. Conventional linear feedback control approach such as PI, PID or cascade control alone are inadequate to totally compensate the cutting force disturbance. This is due to the absence of adaptive element in the control scheme. Adaptive element is essential to solve the issue of nonlinearity of cutting force disturbance. This thesis proposes a new approach to compensate multiple frequency components of cutting forces, named Nonlinear Cascade Feedforward (NCasFF) controller. This new approach combined and embedded a modified nonlinear function, an inverse plant model feedforward and a speed feedforward onto the Cascade P/PI controller that serves as the primary position controller to further reduced the tracking error. The performance of the proposed controller was validated numerically and experimentally where actual machining process was performed on the test setup. The results indicated that the Nonlinear Cascade Feedforward (NCasFF) controller is able to compensate tracking errors introduced by the cutting forces. This thesis has successfully demonstrated that the tracking performance of a machine tool was increased significantly by the addition of dedicated compensation elements that supplement the classical Cascade P/PI position controller. Results showed that the newly proposed NCasFF control strategy manage to provide 33.80 % improved performance in terms of Root Mean Square Error (RMSE) reduction than Cascade P/PI controller and 16.03 % better performance in terms of Fast Fourier Transform (FFT) error than Cascade P/PI controller. Finally, in terms of surface roughness, R_a value, NCasFF controller provide 20 % improved performance than Cascade P/PI controller. However, further studies and improvement are desired. The performance of the controller needs to be further enhanced so that it can adapt to different conditions of cutting force disturbance. The improvement includes addition of adaptive elements to the controller to compensate changing cutting force characteristics and variable disturbance friction force resulting from different cutting conditions. For example, changes in tools diameter, tracking speed and depth of cut.

ABSTRAK

Ketepatan, kepersisan dan keteguhan merupakan tiga komponen penting yang di perlukan dalam proses rekebentuk sistem kawalan bagi proses pemesinan dalam sektor pembuatan. Anjakan paradigma terhadap segala keperluan ini telah membuka dimensi baru dalam sektor pembuatan. Namun, gangguan proses pemesinan seperti daya geseran dan daya pemotongan boleh menyebabkan berlakunya banyak ketidaktepatan pada posisi dan kebolehan mesin untuk bergerak mengikut trajektori yang di tetapkan. Objektif tesis ini adalah untuk mencadang, merekabentuk, membangunkan dan membuat validasi terhadap sistem kawalan yang akan direkabentuk bagi membolehkan ia mengatasi gangguan daya pemotongan terhadap ketepatan posisi sistem mesin XY. Isu-isu berkaitan kesan daya pemotongan terhadap proses pemesinan telah di kaji secara menyeluruh di mana pelbagai kaedah telah pun di perkenalkan. Sistem kawalan konvensional seperti "PI","PID" dan "Cascade" sahaja sebagai sistem kawalan tunggal adalah tidak mencukupi untuk mengatasi kesan negatif gangguan daya pemotongan secara holistik. Ini adalah di sebabkan oleh ketiadaan elemen "adaptive" pada struktur sistem kawalan tersebut. Elemen "adaptive" ini adalah amat diperlukan bagi mengatasi masalah gangguan dan ketidaktentuan pada daya pemotongan. Dalam tesis ini, pendekatan baru yang digunakan untuk mengatasi gangguan daya pemotongan pelbagai dipanggil sistem kawalan Nonlinear Cascade Feedforward (NCasFF). Sistem kawalan yang baru direkabentuk ini adalah hasil gabungan fungsi tidak linear yang telah diubahsuai yang digabungkan bersama sistem kawalan "Cascade P/PI" yang bertindak sebagai sistem kawalan utama. Di samping itu, modul "inverse plant model feedforward" dan modul "speed feedforward" juga digabungkan bersama "Cascade P/PI" bagi membantu mengurangkan lagi masalah kesilapan trajektori oleh sistem. Proses pemotongan sebenar dijalankan ke atas mesin XY bagi tujuan validasi. Berdasarkan keputusan yang dihasilkan, di dapati sistem kawalan baru ini telah berjaya untuk mengatasi masalah kesan negatif daya pemotongan (yang dipelbagaikan) terhadap posisi mesin XY. Hasil kerja dalam tesis ini telah berjaya membuktikan bahawa dengan gabungan beberapa fungsi modul (yang ditambah baik) yang digabungkan bersama sistem kawalan "Cascade P/PI" telah berjaya untuk memperbaiki prestasi sistem perkakasan mesin. Hasil eksperimen menunjukkan bahawa sistem kawalan "NCasFF" berjaya membuahkan hasil yang lebih baik sebanyak 33.80 % dari aspek "Root Mean Square Error (RMSE) dan 16.03 % lebih baik dari aspek "Fast Fourier Transform (FFT) Error" serta 20 % lebih baik dari aspek "Surface Roughness, R_a*" berbanding sistem kawalan "Cascade P/PI". Walaubagaimanapun, kajian lanjut dan pembaharuan terhadap kajian ini adalah diperlukan. Tujuan penambaikan ini dilakukan adalah untuk mempertingkatkan lagi kebolehan sistem kawalan tersebut agar ia mampu bertahan pada pelbagai keadaan daya pemotongan. Antara penambahbaikan yang boleh dilakukan ialah untuk memasukkan elemen "adaptive" terhadap sistem kawalan untuk mengatasi masalah daya geseran dan juga untuk merekabentuk sistem kawalan yang boleh mengatasi masalah kesilapan posisi mesin XY pada pelbagai situasi. Contohnya ialah untuk merekabentuk sistem kawalan yang mampu berfungsi dengan baik semasa berlaku perubahan pada diameter alat, kelajuan mesin dan kedalaman semasa proses pemotongan sebenar.*

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R	-	Resultant force
F_c	-	Cutting force
F_t	-	Thrust force
F_s	-	Cutting speed
F_t	-	Thrust force
K_f	-	Motor constant
M	-	Mass
Z_{ref}	-	Reference position
Z	-	Output position
$G(s)$	-	System
$G_m (s)$	-	System model transfer function
$\hat{G} (s)$	-	FRF of the considered system
$G_m^{-1}(s)$	-	Inverse system model transfer function
$G_s(s)$	-	Speed feedforward
$d(t)$	-	Disturbances
$N(t)$	-	Noises
T_d	-	Time delay
$e_p(t)$	-	Position tracking error
$e_v(t)$	-	Velocity tracking error
S_v	-	Sensitivity function of velocity loop
S_p	-	Sensitivity function of position loop
K_p	-	Proportional gain
K_i	-	Integral gain
K_d	-	Derivative gain
K_e	-	Nonlinear gain
f_e	-	Scaled error
KO	-	Rate of variation of nonlinear gain
e_{max}	-	Range value of error variation

LIST OF ABBREVIATIONS

AC	-	Alternating current
CNC	-	Computer numerical control
DAC	-	Digital to analog
DFO	-	Disturbance force observer
DSP	-	Digital signal processor
EDM	-	Electro discharge machine
FFT	-	Fast fourier transform
FLC	-	Fuzzy logic control
FRF	-	Frequency response function
HSS	-	High speed steel
I/O	-	Input/output
ISMC	-	Integral sliding mode control
LTI	-	Linear time invariant
LQG	-	Linear quadratic regulator
MBC	-	Model based compensator
MMI	-	Man machine interface
NCasFF	-	Nonlinear cascade feedforward
NLLS	-	Nonlinear least square
NPID	-	Nonlinear proportional-integral-derivative
P	-	Proportional
PDF	-	Pseudo derivative feedback
PI	-	Proportional-integral
PID	-	Proportional-integral-derivative
RMSE	-	Root mean square error
RPM	-	Revolution per minute
SISO	-	Single input single output
SMC	-	Sliding mode control
V_{est}	-	Estimate velocity

LIST OF PUBLICATIONS

Journals:

1. Abdullah, L., Jamaludin, Z., Salleh, M. R., Abu Bakar, B., Jamaludin, J., Chiew, T. H., and Rafan, N.A. 2014. Theoretical Analysis of Velocity and Position Loop Behaviour of Nonlinear Cascade Feedforward Controller for Positioning of XY Table Ballscrew Drive System. *Advanced Materials Research*, 845, pp. 831 – 836.

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