UNIVERSITI TEKNIKAL MALAYSIA MELAKA

Faculty of Manufacturing Engineering

SUPER TWISTING SLIDING MODE CONTROLLERS AND KALMAN-BUCY FILTER FOR SINGLE AXIS POSITIONING SYSTEM

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CHIEW TSUNG HENG

A thesis submitted
in fulfillment of the requirements for the degree of Doctor of Philosophy

Faculty of Manufacturing Engineering

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DECLARATION

I declare that this thesis entitle "Super Twisting Sliding Mode Controllers and Kalman-Bucy Filter for Single Axis Positioning 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.

Signature : …………………….

Name : …………………….…

Date : ……………………..

DEDICATION

To my beloved father and mother

Their loving and unconditional support throughout my life

and

For those I love very much

ABSTRACT

Demands for accuracy and precision in machine tools have generated great interests for development of high performance drive control system with excellent characteristics in reference tracking, chattering, and robustness against input disturbance and load variation. Recently, a nonlinear control approach named super twisting sliding mode controller (ST-SMC) becomes attractive for its ability to meet complex demands on system performance where classical controllers have failed to meet. ST-SMC provides good tracking quality and effectively proven disturbance rejection property. However, chattering still exist as an issue in application of ST-SMC. To-date, there exists a knowledge gap in in-depth analyses on optimal design of gains parameters in control laws of ST-SMC constituting trade-off between tracking accuracy and effect of chattering. This thesis presents optimal design of ST-SMC with enhanced smoothening functions for precise tracking performances and reduced chattering; validated on a single axis sliding unit with direct driven linear motor. In addition, a Kalman-Bucy filter (KBF) was designed and applied to estimate velocity signal for the control system thus eliminating effect of noise amplification normally associated with numerical differentiation of position signal. A Taguchi optimization method was applied to optimize the control laws gain parameters of ST-SMC based on three performance indexes, namely; root mean square of tracking error (RMSE), chattering amplitude reduction in frequency domain, and variations in RMSE values from exposure to input disturbance. The optimal values of the gain parameters L and W were 0.7 and 10×10^{-5} respectively; with a confidence level of 95%. Two variants of ST-SMC were formulated based on modifications of the control laws of original ST-SMC; where the signum function was replaced by either a hyperbolic tangent function or an arc-tangent smoothening function to a form hyperbolic ST-SMC (HST-SMC) and an arc-tangent ST-SMC (Arc-ST-SMC) respectively. Five controllers were designed and validated experimentally, namely; cascade P/PI controller, pseudo-SMC, optimized ST-SMC, HST-SMC, and Arc-ST-SMC. The control performances of each controller were analyzed with respect to tracking accuracy, chattering suppression, and robustness against input disturbance and system dynamics variation. The optimized ST-SMC produced the best overall control performance with 9.6% (RMSE), 3.9% (disturbance rejection), and 13.4% (robustness) superior results compared to the other variants of SMC-based controllers. On the other hand, HST-SMC produced a comparable tracking performance to optimized ST-SMC with minimal difference of 7.3% (RMSE), 0.4% (disturbance rejection), and 0.7% (robustness). HST-SMC offers a fair trade-off in control performance between tracking accuracy, disturbance rejection and chattering attenuation. Arc-ST-SMC showed its strength with a significant 71.4% reduction in chattering effect. Finally, this thesis has demonstrated outstanding control performances of ST-SMC-based controllers that produced tracking accuracy that was 96.0% better than classical cascade P/PI controller.

ABSTRAK

Permintaan terhadap ketepatan dan kejituan pada perkakasan mesin telah menjana minat yang besar terhadap sistem kawalan pemacu berprestasi tinggi dengan ciri cemerlang berkaitan penjejakan rujukan, gelantuk, dan keteguhan terhadap gangguan input dan variasi beban. Kebelakangan ini, kaedah kawalan tidak lelurus dikenali sebagai pengawal mod gelongsor pemusingan super (ST-SMC) menjadi tarikan kerana keupayaannya memenuhi permintaan kompleks pada prestasi sistem yang gagal dicapai oleh pengawal klasik. ST-SMC menawarkan kualiti pengesanan yang baik di samping keupayaan penolakan gangguan yang terbukti berkesan. Walau bagaimanapun, gelantuk masih wujud sebagai satu isu dalam aplikasi ST-SMC. Hingga kini wujud jurang pengetahuan terhadap analisa mendalam pada reka bentuk optima parameter peraturan kawalan ST-SMC melibatkan keseimbangan antara ketepatan pengesanan dan kesan gelantuk. Tesis ini membentangkan reka bentuk optimum ST-SMC dengan fungsi pelicin yang dipertingkatkan untuk prestasi pengesanan yang jitu dan pengurangan kesan gelantuk; disahkan pada paksi tunggal unit gelangsar pemacu terus motor lelurus. Di samping itu, penapis Kalman-Bucy (KBF) direka dan digunakan untuk menganggarkan isyarat halaju pada sistem kawalan bagi mengelakkan kesan amplifikasi bunyi yang biasanya wujud melalui pembezaan berangka isyarat kedudukan. Kaedah pengoptimuman Taguchi digunakan untuk mengoptimumkan parameter-parameter kawalan ST-SMC berpandukan kepada tiga indeks prestasi, iaitu; ralat purata punca kuasa dua (RMSE), pengurangan amplitud gelantuk dalam domain frekuensi, dan variasi dalam nilai RMSE daripada pendedahan kepada gangguan input. Nilai optimum yang dikenalpasti bagi parameter L dan W adalah 0.7 dan 10×10^{-5} *berdasarkan tahap keyakinan 95%. Dua variasi ST-SMC telah dirumuskan berdasarkan pengubahsuaian terhadap peraturan kawalan ST-SMC; di mana fungsi signum digantikan oleh fungsi tangen hiperbolik atau fungsi arc-tangen untuk membentuk hiperbolik ST-SMC (HST-SMC) dan arc-tangen ST-SMC (Arc-ST-SMC). Lima pengawal telah direka dan disahkan secara ujikaji, iaitu; pengawal lata P/PI, pseudo-SMC, ST-SMC optimum, HST-SMC, dan Arc-ST-SMC. Prestasi kawalan setiap pengawal dianalisa berdasarkan ketepatan pengesanan, pengurangan gelantuk, dan keteguhan terhadap gangguan input dan variasi sistem dinamik. ST-SMC optimum menghasilkan prestasi kawalan keseluruhan yang terbaik iaitu 9.6% (RMSE), 3.9% (penolakan gangguan), dan 13.4% (keteguhan) lebih baik berbanding dengan varian-varian pengawal berasaskan SMC yang lain. Sebaliknya, HST-SMC menghasilkan prestasi pengesanan yang setanding dengan ST-SMC optimum dengan perbezaan minimum sebanyak 7.3% (RMSE), 0.4% (penolakan gangguan), dan 0.7% (keteguhan). HST-SMC menawarkan keseimbangan antara ketepatan pengesanan, penolakan gangguan dan pengurangan gelatuk. Arc-ST-SMC pula menunjukkan kekuatannya dengan penurunan ketara sebanyak 71.4% kesan gelantuk. Akhirnya, tesis ini juga telah menunjukkan kecemerlangan prestasi kawalan pengawal-pengawal berasaskan ST-SMC yang menghasilkan ketepatan pengesanan sebanyak 96.0% lebih baik daripada pengawal klasik lata P/PI.*

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ADC	-	Analog digital converter
ANOVA	-	Analysis of variance
Arc-ST-SMC	-	Arc-tangent super twisting sliding mode controller
AUV	-	Autonomous underwater vehicle
CCC	-	Cross-coupling controller
CNC	-	Computer numerical control
D	-	Derivative
DC	-	Direct current
DOF	-	Degree of freedom
DSP	-	Digital analog converter
EKBF	-	Extended Kalman-Bucy filter
EKF	-	Extended Kalman filter
ESA	-	Ecological system algorithm
FFT	-	Fast Fourier transform
FRF	-	Frequency response function
GMS	-	Generalized Maxwell-slip
GUI	-	Graphical user interface
HOSMC	-	Higher order sliding mode controller
HST-SMC	-	Hyperbolic super twisting sliding mode controller