NOVEL APPROACH FOR REDUCING CHATTERING EFFECTS IN SLIDING MODE CONTROL SYSTEM

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LIST OF ABBREVIATIONS

2-DSMC	**2nd** order Discrete-Sliding -Mode Control
2-SMC	Second-order Sliding Mode Control
ADSMCS	Adaptive Dynamic Sliding-Mode Control System
AFSMC	Adaptive Fuzzy system Sliding Mode Control
BIBO	Boundary Input Boundary Output
BL	Boundary Layer
BLM	Boundary Layer Method
BLSMC	Boundary Layer Sliding Mode Controller
CBL	Conical Boundary Layer
CL	Closed Loop
CMFSMC	Combination Nonlinear Functions with Sliding Mode Controller
CNC	Computer Numeric Control
CSMC	Conventional Sliding Mode Control
CSS	Conventional Sliding Surface
CTSMC	Continuous time Sliding mode controller
DF	Describing Function
DSMC	Dynamic Sliding Mode Control
DSMC	Dynamic Sliding-Mode Controller
DSP	Digital Signal Processing
DSS	Dynamic Sliding Surface
DTSMC	Discrete Time Sliding Mode controller
EQC	Equivalent-Control
FLC	Fuzzy-Logic-Controller

GUI	Graphical User Interface
H-LMN	High-Level Measurements Noise
HOSMC	High Order Sliding Mode Controller
IFO	Indirect Field-Orientation control
IM	Induction Motor
LPFSMC	Low Pass Filter Sliding Mode Controller
LTI	Linear Time-Invariant
ISS	Input to State Stabality
OBM	Observe Method
PID	Integral, Derivative controller
PPESMC	Pre-programmed Exponential Sliding Mode Controller
PPT	Phase Plane Trajectory
RRBFN	Recurrent Radial Basis Function Network
Std	Stander deviation
SDSMC	Sample data Sliding Mode controller
SISO	Single-Input Single-Output
SMC	Sliding Mode Controller
SMCS	Sliding-Mode Controller with a Smooth control law
SMSFC	Sliding Mode with State Feedback Controller
SSE	Steady State Error
STW	Super-Twisting (STW)
TDVC	Two-Dimensional Vector Control
TOC	Time Optimal Controller
TS	Takagi-Sugeno
TS	Taylor Series

TVSG	Time-Varying Switching Gain
UMD	Unmodeled Dynamics
VSCS	Variable Stricture Control System
VSS	Variable Structure System

LIST OF SYMBOLS

$\mathbb{R}^m$	*m-dimensional* control vector
θ	Angle of sliding line
ε	Boundary Layer thickens
k	Constant gain
u	Control input or state velocity vectors $u^{-,+}$
w_c	Controllability Gramian
P	Controllability Matrix
β_1, β_2	Controller parameters
wc	Critical frequency
x_f	Dynamical system around the origin
T	Final time
w	Frequency
M1,M2	Gain Components
K	Gain Matrix of State Feedback
t_o	Initial time
B	Input matrix in state space
$r(t)$	Input signal
δ	Magnitude deflection of controller
A	Matrix states of system in state space
w_o	Observability Gramian
C	Output matrix in state space
α	Parameters of Controllability Matrix

ΔT	Period time of switching function
D	Feedforward Matrix
γ	Reduction filter parameter
sat	saturation function
σ	Sliding function
c	Sliding line parameters (slop)
k_1, k_2	State feedback controller parameter
ψ	Switching Components
X	System state
T	Time
M	m-dimensional order
N	n-dimensional order
$\mathbb{R}^n$	n-dimensional state vector
M_1	Magnitude of switching gain

Pendekatan Baru Mengurangkan Kesan Chattering Dalam Sliding Mode Sistem Kawalan

ABSTRAK

Alat kawalan mod gelangsar (SMC) ialah sejenis sistem kawalan struktur boleh ubah, yang merupakan alat autoritatif bagi menangani perubahan tak pasti dan gangguan luaran dalam sistem parameter dan sistem tak linear. Walaupun SMC dikaitkan dengan beberapa kelebihan ketara seperti kekukuhan, alat kawalan mod gelangsar konvensional (CSMC) tidak dapat memenuhi kebanyakan keperluan sistem, terutamanya berdekatan titik keseimbangan akibat getaran kuat disebabkan pensuisan berkelajuan tinggi (frekuensi tinggi isyarat kawalan berdekatan garisan gelangsar). Tesis ini tertumpu pada pembangunan alat kawalan baru dan algoritma bagi mengurangkan kesan fenomena getaran dalam usaha mencapai prestasi sistem yang efisien. Ia merangkumi tiga konsep mod gelangsar baru; mod gelangsar dengan pengawal suap balik keadaan (SMSFC), pengawal mod gelangsar eksponen praprogram (PPESMC), dan gabungan fungsi tak linear dengan pengawal mod gelangsar (CNFSMC). Kesemuanya direka berteraskan konsep SMC. SMSFC bertujuan bagi mengurangkan kesan fenomena getaran yang lazim dikaitkan dengan penggunaan CSMCdalam keadaan hingar dan ketakpastian. Ini diperoleh dengan memperhalus amplitud gandaan CSMC dan mencapai keadaan capahan sistem. Pengawal suap balik keadaan akan melaksanakan pemformatan semula dan penggabungan yang lancar dengan CSMC bagi menghasilkan pengawal bersepadu yang dipanggil mod gelangsar dengan pengawal suap balik keadaan (SMSCF), manakala PPESMC bergantung pada nilai isyarat ralat dan menjanakan gandaan eksponen yang berkadaran dengan isyarat ralat tersebut. Akhir sekali, kombinasi fungsi tak linear dengan pengawal mod gelangsar (CNFSMC) boleh dibina dengan menggabungkan kaedah SMSFC dan PPESMC. Kaedah ini bergantung kepada dua ciri keadaan eksponen yang berhubungan dan tak linear. Pengawal baru ini terbukti berkesan sebagai strategi kawalan bersepadu yang kukuh dan efektif untuk sistem linear dan tak linear yang tak pasti dan mengalami perubahan parameter, selain berupaya mengurangkan kesan fenomena getaran. Penilaian, perbandingan dan analisis prestasi ketiga-tiga kaedah ini (SMSFC, PPESMC dan CNFSMC) untuk sistem SMC dibentangkan dalam tesis ini, dan prestasi masing-masing dibandingkan dengan mod gelangsar lapisan sempadan super-berputar dan penapis laluan rendah kaedah SMC (STW, BLSMC and LPFSMC) apabila diaplikasikan dalam motor DC dan robotik. Kesimpulan utama yang dapat diperoleh daripada tesis ini menunjukkan bahawa SMSFC yang dibangunkan dan digunakan seperti diterangkan di atas telah menunjukkan kekukuhan sistem, prestasi yang tinggi serta kawalan pengesanan trajektori yang baik dalam keadaan hingar dan ketakpastian sesebuah model. Penilaian dan analisis dijalankan terhadap indeks prestasi yang berbeza dan di bawah keadaan operasi yang berlainan. Keputusan menunjukkan bahawa di bawah beban luaran dan hingar luaran yang berbeza serta perubahan parameter sistem, prestasi SMSFC, PPESMC dan CNFSMCterbukti lebih baik berbanding STW, BLSMC dan LPFSMC dalam pengurangan kesan fenomena getaran, masing-masing sebanyak 95%, 68%, 78% dan 89%.

Novel Approach for Reducing Chattering Effects in Sliding Mode Control System

ABSTRACT

The sliding mode controller (SMC) is a type of variable structure control system (VSCS), which is an authoritative tool for dealing with uncertainty, variations in parameter systems, nonlinear systems and external disturbances. Although significant advantages are associated with SMC such as robustness, the conventional sliding mode controller (CSMC) does not cover most of the requirements of the system, especially near the equilibrium point because of the high chattering which occurs as a result of high-speed switching (high frequencies of control signal near sliding line). This thesis is concerned with developing a novel controller and algorithms to reduce the effect of the chattering phenomenon, in order to achieve an efficient system performance. It includes three novel sliding mode concepts; sliding mode with state feedback controller (SMSFC), pre-programmed exponential sliding mode controller (PPESMC), and combination of nonlinear functions with sliding mode controller (CNFSMC). These are based on the SMC concept.The SMSFC is designed to reduce the effect of the chattering phenomenon that is present with the use of CSMC when noise and uncertainties occur. This is accomplished by refining the gain amplitude of CSMC, obtaining the convergence states properties of the system. The state feedback controller reformats and combines seamlessly with the CSMC to produce an integrated controller called a sliding mode with state feedback controller (SMSCF), whereas PPESMC relies on the value of an error signal and generates an exponential gain which is proportional to the error signal. Finally, a combination of nonlinear functions with sliding mode controller (CNFSMC) can be constructed from a combination of SMSFC and PPESMC. This method depends on two interrelated and nonlinear state-exponential properties. These new controllers have proved to be a robust and effective integrated control strategy for uncertain, varied-parameter, linear, and nonlinear systems, in addition to reducing the effect of the chattering phenomenon. Performance evaluations, comparisons, and analysis for the three methods (SMSFC, PPESMC and CNFSMC) for the SMC system are presented in this thesis, and their performance compared with the super-twisting (STW), boundary layer sliding mode (BLSMC) and low pass filter (LPFSMC) with SMC methods respectively when applied to a DC motor and robotics. The main conclusion drawn in this thesis was that the SMSFC as developed and implemented exhibited robust and high performance and trajectory tracking control given modeling uncertainties and noise. The evaluation and analysis were performed for different performance indexes and under different operational conditions. The results showed that under various external loads, external noise, and variations in system parameters SMSFC, PPESMC, CNFSMC, STW, BLSMC and LPFSMC with respect to reduction of the effect of the chattering phenomenon by 95%, 94%, 97%, 68%, 78% and 89% respectively.

CHAPTER 1

INTRODUCTION

1.1 Background

Controller systems are dominant in everyday life. Scientific progress and the achievement of consistently outstanding advances in the field of analogue and digital controllers, electronic devices in optical and telecom systems, information networks, local and global activities and controller systems' vital role in the development of the use of advanced control have reached a high level in recent years, especially in the areas of industrial applications, robots, military applications, medical applications and space applications (Boiko 2011, Dorf and Bishop 2011). Such crucial developments require that the control systems must be at the same stage of evolution in all applications. System performance in terms of high precision, speed response, non-chattering, no overshoot and zero steady-state error are the most important and basic requirements for control systems.

The traditional control systems that are applied to linear and nonlinear systems may not be appropriate for all desired system requirements, especially in varied-parameter and uncertain systems (Kundur 2001). Uncertain control systems have been successfully tested, however, by using variable structure systems (VSS) with the sliding mode control (SMC) method (Utkin 1977).

Theoretically, SMC provides powerful stability control systems through a high gain with infinite fast switching (Crassidis and Markley 1996). High-gain control designs, however, suffer from a defective peaking phenomenon. SMC constitutes regular discontinuous control input with infinite switching frequency. This will obviously lead to an undesirable phenomenon called chattering (Huang 2013). This phenomenon has some disadvantages in mechanical and electrical systems such as mechanical wearing and overheating of the electrical components (Piltan, at el. 2011).

The emergence of SMC theory in practical applications gives certain guarantees regarding modelling error and the parameter uncertainties of the system and satisfies most of the demands of these complex systems. Although sliding mode control systems are robust and easy to design and implement (Utkin 1978, Bengiamin and Chan 1982, Utkin, Guldner et al. 1999, Barambones, Garrido et al. 2006, Baburaj and Bandyopadhyay 2012, Ahmed, et al. 2013, Al-Hadithi, et al. 2013), the phenomenon of chattering (which is the implied nature of the control of the discontinuous signal) is a problem; therefore, there is some uncertainty about this approach (Mihoub, et al. 2010, Takhmar, et al. 2012).

The development of the sliding mode control system (SMCS) has addressed the main obstacle posed by the phenomenon by the use of CSMC. Although the implementation of modern SMC has been used to reduce the effect of chattering, most of these methods have weaknesses which emerge in the system output. As a result the harmful chattering that accompanies the conventional sliding mode control has become the focus of a great deal of attention. There are different types of chattering in sliding mode controllers, but this thesis considers only those that can be analysed and addressed as other types may be either harmless or irremediable.

1.2 Problem Statement

There are several approaches to reduce the phenomenon of chattering: for example, the boundary layer method (BLM), the observe method, two-dimensional vector control, the time-varying switching gain (TVSG), the equivalent-control-dependent gain method, the super-twisting method (STW), etc. (Goh, et al. 2003, Liu, et al. 2005, Cupertino, et al. 2008, Min et al. 2008, Ming, et al. 2010, Zaeri, et al. 2012). These methods have disadvantages such as a reduction in the accuracy of the control system, and may be ineffective in the presence of an external load, high level measurement noise (HLMN), parameter system variation, and uncertain systems. As a result, reducing the phenomenon (chattering) may yield weaknesses in other places. Those methods (STW and BLM) lead, however, to weak control signals because the small control signal value reduces the effect of the chattering phenomenon (Yang, et al. 2008, Ming, et al. 2010, Ferreira, et al. 2011, Loukianov, et al. 2011, Zaltni and Abdelkrim 2011, Zhiyu, Gang et al. 2011, Aghababa and Akbari 2012, Al-Hadithi, et al. 2013, Chena, Yangb et al. 2013). Therefore, the most important of the problem statements associated with the use of SMC is as follows:

A small time constant of the system, finite sampling rate in digital sliding mode controller and fast dynamic, which was neglected in the ideal model, causes the chattering phenomenon in sliding mode controllers (Bartolini, et al. 2000, Dal and Teodorescu 2011).

As is it well known the appropriate gain of a sliding controller may ensure the stability of the system; however, this is accompanied by the emergence of the chattering phenomenon. In addition most controller systems suffer from a loss of stability when exposed to external disturbance, high level measurement noise (HLMN) and external loads and variations in the system parameters (Spong and Vidyasagar 1987).

The majority of the offered solutions decrease the value of the gain in order to reduce the chattering phenomenon but the main problem when the system is close to the equilibrium point is that it is possible to lose stability because of the reduction in the amount of gain value. The decrease of gain value (control signal value) of the sliding mode controller in order to reduce the chattering phenomenon has disadvantages for this procedure (Xu, et al. 2004), which lead the trajectory of system states leave the sliding line (Zhao and Jiang 1998). As a result, the controller approach is largely unable to compensate fully for the disturbance. Traditional SMC still provides the closed-loop system with certain characteristics to reduce the influence of external disturbances; however, it is not absolutely foolproof.

Accordingly, a novel approach is needed for designing a sliding mode with state feedback controller (SMSFC) to overcome the most serious weakness of SMC, the chattering phenomenon. The removal of chattering, however, requires precise selection of the gain value to maintain the properties of the sliding mode controller the use of some features of the system itself (property convergence of states in the stable system) in which the states of the system own the property of convergence.