Faculty of Electrical Engineering

POSITIONING CONTROL OF AN IRONLESS LINEAR MOTOR WITH CONTINUOUS MOTION NOMINAL CHARACTERISTIC TRAJECTORY FOLLOWING CONTROLLER

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POSITIONING CONTROL OF AN IRONLESS LINEAR MOTOR WITH CONTINUOUS MOTION NOMINAL CHARACTERISTIC TRAJECTORY FOLLOWING CONTROLLER

FOO JIA EN

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

Faculty of Electrical Engineering

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

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DECLARATION

I declare that this thesis entitled "Positioning Control of an Ironless Linear Motor with Continuous Motion Nominal Characteristic Trajectory Following Controller" 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 : Foo Jia En

Date : 26 / 10 / 2017

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 Electrical Engineering.

Signature	:……………………………………………….
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Date	: 26 / 10 / 2017

DEDICATION

To my beloved father and mother

ABSTRACT

Ironless Permanent Magnet Linear Motors (IPMLM) are abundantly applied in various automated industries due to its capability of achieving high speed and high accuracy motions. Through the removal of transmission elements, the positioning performances of IPMLM are subjected by parameter changes and external disturbances, which is relatively difficult to model accurately. Besides that, since the IPMLM are often used in long working range applications, they are easily influenced by the saturation effect of the system, and may cause large overshoot. Therefore, in this research, a Continuous Motion-Nominal Characteristic Trajectory Following (CM-NCTF) controller is proposed for positioning control of an IPMLM. While the CM-NCTF controller was applied in various mechanism, the performance of CM-NCTF controller has yet to be validated for positioning control of IPMLM. The proposed controller consists of two components: A Nominal Characteristic Trajectory (NCT) and a proportional-plus-integral (PI) compensator. The NCT works as a motion reference for the IPMLM, where the PI compensator makes the system motion follows the constructed NCT. The NCT is constructed on a phase plane using the decelerating velocity of the IPMLM and its corresponding displacement in open loop configuration. This step enables the NCT to capture the nonlinearities of the IPMLM, without having to model the nonlinearities additionally. The PI compensator is designed using information from the NCT and open loop response of the IPMLM. A conditional freeze anti-windup is added to the PI compensator to eliminate actuator saturation effect, particularly due to the large integral gain, and due to large working range motion. The positioning performance in point-to-point and tracking motion is examined and compared to a Proximate Time Optimal Servomechanism (PTOS) controller experimentally. Experimental results show that the CM-NCTF controller does not exhibit any overshoot or steady state error at all, and has 370 % faster rise time than the PTOS controller at smaller displacement. In tracking motion, the CM-NCTF controller performs better than the PTOS controller, with at least 530 % improvement of tracking accuracy at small displacement, and 2400 % improvement of tracking accuracy at large displacement. In the evaluation of robustness against mass changes, experimental results and sensitivity analysis show that the CM-NCTF controller is robust towards mass variation as compared to the PTOS controller. In conclusion, the positioning performance of the CM-NCTF controller is validated on an IPMLM with high positioning and robust performance in the presence of mass variation as compared to PTOS controller, with no occurrence of actuator saturation problem.

ABSTRAK

Motor limpang bermagnet kekal tanpa teras besi (IPMLM) banyak digunakan dalam pelbagai industri automasi kerana keupayaannya untuk mencapai kelajuan dan ketepatan pergerakan yang tinggi. Akibat penyingkiran unsur-unsur transmisi, pergerakan IPMLM mudah dipengaruhi oleh perubahan parameter dan gangguan luaran terhadap IPMLM yang agak sukar dimodelkan. Selain itu, oleh sebab IPMLM sering digunakan dalam sistem pergerakan jarak jauh, maka IPMLM senang dipengaruhi oleh ketepuan penggerak tersebut, dan menjana pergerakan terlajak yang besar. Oleh itu dalam kajian ini, sebuah pengawal Pengikut Trajektori Ciri Nominal Dalam Pergerakan Berterusan (CM-NCTF) telah dicadangkan untuk mengawal pergerakan IPMLM. Proses untuk mereka pengawal CM-NCTF adalah mudah tanpa pengetahuan kawalan yang dalam, dan ia tidak memerlukan parameter IPMLM yang tepat. Pengawal CM-NCTF mempunyai dua bahagian, iaitu Trajektori Ciri Nominal (NCT) dan pengawal berkadar-dengan-kamiran (PI). NCT berfungsi sebagai sebuah rujukan pergerakan bagi IPMLM, manakala pengawal PI memastikan bahawa pergerakan IPMLM mengikut seperti dalam NCT. NCT ini dilukis di satah fasa dengan menggunakan halaju dan sesaran IPMLM dalam keadaan gelung terbuka ketika ia sedang diperlahankan. Cara pembentukan NCT ini dapat menangkap ciri-ciri tidak lelurus IPMLM, supaya pereka tidak perlu mendapatkan ciri-ciri ini secara khusus. Pengawal PI pula direka dengan menggunakan maklumat daripada NCT dan tindakbalas IPMLM dalam keadaan gelung terbuka. Sebuah struktur anti-memutar beku bersyarat telah ditambahkan ke dalam pengawal PI untuk menghapuskan pengaruh ketepuan penggerak khususnya disebabkan oleh reaksi kamiran yang besar dan pergerakan jarak jauh. Prestasi pengawal CM-NCTF telah diperiksa dan dibandingkan dengan sebuah Pengawal Servomekanisme Masa Optimum Terdekat (PTOS) dalam aspek pergerakan titik ke titik dan pergerakan penjejakan melalui ujikaji. Hasil ujikaji menunjukkan bahawa pengawal CM-NCTF tidak menunjukkan sebarang pergerakan terlajak dan ralat dalam keadaan mapan, dan ia mempunyai masa menaik yang 370 % lebih cepat daripada PTOS dalam pergerakan yang lebih kecil. Dalam aspek pergerakan penjejakan, pengawal CM-NCTF mempunyai prestasi pergerakan yang lebih baik, di mana ralat penjejakannya adalah 530 % lebih rendah daripada pengawal PTOS dalam pergerakan jarak dekat, dan 2400 % lebih rendah dalam pergerakan jarak jauh. Dalam penilaian keteguhan pengawal terhadap perubahan jisim, hasil ujikaji dan analisis kepekaan menandakan bahawa pengawal CM-NCTF adalah lebih teguh terhadap perubahan jisim berbanding dengan pengawal PTOS. Kesimpulannya, pengawal CM-NCTF mampu mencapai ketepatan pergerakan yang tinggi dan teguh terhadap perubahan jisim berbanding dengan pengawal PTOS, tanpa dipengaruhi masalah ketepuan penggerak.

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TABLE OF CONTENTS

	PAGE
DECLARATION	
DEDICATION	
ABSTRACT	**i**
ABSTRAK	**ii**
ACKNOWLEDGEMENTS	**iii**
TABLE OF CONTENTS	**iv**
LIST OF TABLES	**vi**
LIST OF FIGURES	**vii**
LIST OF APPENDICES	**xi**
LIST OF SYMBOLS AND ABBREVIATIONS	**xii**
LIST OF PUBLICATIONS	**xiv**
CHAPTER	
1. INTRODUCTION	**1**
1.1 Background	1
1.2 Problem Statement	3
1.3 Objectives	4
1.4 Scope	5
1.5 Contribution of Research	5
1.6 Thesis Outline	5
2. LITERATURE REVIEW	**7**
2.1 Introduction	**7**
2.2 Permanent Magnet Linear Motor	7
2.3 Motion Control of Permanent Magnet Linear Motor	9
2.4 Background of NCTF controller	27
2.5 Concept of CM-NCTF controller	33
2.6 Summary	35
3. RESEARCH METHODOLOGY	**36**
3.1 Introduction	36
3.2 Experimental Setup	33
3.3 Mathematical Modeling of IPMLM	33
3.4 Design Procedure of CM-NCTF Controller	39
3.5 Stability Analysis	50
3.6 Design Procedure of PTOS Controller	52
3.7 Summary	54
4. RESULTS AND ANALYSIS	**56**
4.1 Introduction	56
4.2 Positioning Performance Analysis	56
4.2.1 Point-to-point Positioning Performance	56
4.2.2 Tracking Performance	61
4.3 Robustness Evaluation	71

	4.4 Summary	88
5.	**CONCLUSION AND FUTURE WORK**	**90**
	5.1 Summary of Work	90
	5.2 Recommendation for Future Work	92
REFERENCES		**94**
APPENDICES		**100**

LIST OF TABLES

TABLE	TITLE	PAGE
2.1	Summary of proposed controllers for positioning control of PMLM	26
3.1	Model parameters of IPMLM	40
3.2	Parameters of the IPMLM open loop response	43
3.3	Controller parameters of CM-NCTF controller and PTOS controller	54
4.1	Transient analysis of CM-NCTF and PTOS for 10 times repeatability in different step height	59
4.2	Sinusoidal reference input for tracking analysis	62
4.3	Maximum error and root-mean-square error of CM-NCTF and PTOS for 10 times repeatability in tracking motion	69
4.4	Transient analysis of CM-NCTF controller with different step reference signals with different loads	76
4.5	Transient analysis of PTOS controller with different step reference signals with different loads	77
4.6	Sinusoidal reference input for robustness analysis in tracking motion	78
4.7	Tracking error of CM-NCTF controller with different loads	83
4.8	Tracking error of PTOS controller with different loads	84

LIST OF FIGURES

FIGURE	TITLE	PAGE
2.1	Permanent magnet linear motor	8
2.2	Visualization of linear motor by unrolling a rotary motor	8
2.3	Comparisons of iron-cored and ironless PMLM	9
2.4	Control structure of CM-NCTF controller	34
2.5	Phases on NCT	34
3.1	Experimental setup of IPMLM	37
3.2	Structure and schematic drawing of IPMLM	38
3.3	Dynamic model of the IPMLM	39
3.4	Friction force measured with a load cell	40
3.5	Open loop response of IPMLM	41
3.6	Input signal to drive IPMLM	42
3.7	Time response to proposed input signal	42
3.8	Constructed NCT	43
3.9	Practical stability limit with different safety margins	47
3.10	Stepwise response of 100 μm with PI compensators of different safety margin	48
3.11	Different PI compensators on 50 % safety margin of practical stability limit	49
3.12	Stepwise response to different PI compensators	49
3.13	CM-NCTF controller with anti-windup element	50
3.14	Discrete time CM-NCTF controller	50
3.15	Variation of practical stability limit towards changes of α	52
3.16	Control structure of Proximate Time Optimal Servomechanism (PTOS) controller	53

3.17	Comparative experimental step response of CM-NCTF controller and PTOS controller	53
3.18	Frequency response of CM-NCTF and PTOS	54
4.1	Experimental response of CM-NCTF and PTOS to step height of 100 µm	57
4.2	Experimental response of CM-NCTF and PTOS to step height of 1 mm	57
4.3	Experimental response of CM-NCTF and PTOS to step height of 10 mm	58
4.4	Experimental response of CM-NCTF and PTOS to step height of 50 mm	58
4.5	Experimental tracking response of CM-NCTF and PTOS to sinusoidal reference input of 0.1 Hz, amplitude of 100 µm	62
4.6	Experimental tracking response of CM-NCTF and PTOS to sinusoidal reference input of 0.1 Hz, amplitude of 1 mm	63
4.7	Experimental tracking response of CM-NCTF and PTOS to sinusoidal reference input of 1 Hz, amplitude of 100 µm	63
4.8	Experimental tracking response of CM-NCTF and PTOS to sinusoidal reference input of 1 Hz, amplitude of 1 mm	64
4.9	Experimental tracking response of CM-NCTF and PTOS to sinusoidal reference input of 5 Hz, amplitude of 100 µm	64
4.10	Experimental tracking response of CM-NCTF and PTOS to sinusoidal reference input of 3 Hz, amplitude of 1 mm	65
4.11	Experimental tracking response of CM-NCTF and PTOS to sinusoidal reference input of 3 Hz, amplitude of 5 mm	65
4.12	Experimental tracking response of CM-NCTF and PTOS to sinusoidal reference input of 5 Hz, amplitude of 1 mm	66
4.13	Experimental tracking response of CM-NCTF and PTOS to sinusoidal reference input of 5 Hz, amplitude of 5 mm	66
4.14	Experimental tracking response of CM-NCTF and PTOS to sinusoidal reference input of 0.1 Hz, amplitude of 50 mm	67
4.15	Experimental tracking response of CM-NCTF and PTOS to sinusoidal reference input of 1 Hz, amplitude of 50 mm	67

4.16	Experimental tracking response of CM-NCTF and PTOS to sinusoidal reference input of 1.5 Hz, amplitude of 50 mm	68
4.17	Experimental response of CM-NCTF to a step reference signal of 100 µm with different loads	72
4.18	Experimental response of PTOS to a step reference signal of 100 µm with different loads	72
4.19	Experimental response of CM-NCTF to a step reference signal of 1 mm with different loads	73
4.20	Experimental response of PTOS to a step reference signal of 1 mm with different loads	73
4.21	Experimental response of CM-NCTF to a step reference signal of 10 mm with different loads	74
4.22	Experimental response of PTOS to a step reference signal of 10 mm with different loads	74
4.23	Experimental response of CM-NCTF to a step reference signal of 50 mm with different loads	75
4.24	Experimental response of PTOS to a step reference signal of 50 mm with different loads	75
4.25	Experimental tracking response of CM-NCTF and PTOS to sinusoidal reference input of 0.1 Hz, amplitude of 100 µm with different loads	79
4.26	Experimental tracking response of CM-NCTF and PTOS to sinusoidal reference input of 0.1 Hz, amplitude of 1 mm with different loads	79
4.27	Experimental tracking response of CM-NCTF and PTOS to sinusoidal reference input of 1 Hz, amplitude of 100 µm with different loads	80
4.28	Experimental tracking response of CM-NCTF and PTOS to sinusoidal reference input of 1 Hz, amplitude of 1 mm with different loads	80
4.29	Experimental tracking response of CM-NCTF and PTOS to sinusoidal reference input of 0.1 Hz, amplitude of 50 mm with different loads	81

4.30	Experimental tracking response of CM-NCTF and PTOS to sinusoidal reference input of 3 Hz, amplitude of 1 mm with different loads	81
4.31	Experimental tracking response of CM-NCTF and PTOS to sinusoidal reference input of 5 Hz, amplitude of 1 mm with different loads	82
4.32	General closed loop system	86
4.33	Linearized model of CM-NCTF controller	87
4.34	Linearized model of PTOS controller	87
4.35	Sensitivity function of CM-NCTF controller and PTOS controller	88

LIST OF APPENDICES

APPENDIX	TITLE	PAGE
A	Design procedure of PTOS controller	100
B	Determination of low pass filter for CM-NCTF controller	105

LIST OF SYMBOLS AND ABBREVIATIONS

%OS	-	Overshoot percentage
σ	-	Acceleration discount factor
α	-	Inclination of NCT
CM-NCTF	-	Continuous Motion Nominal Characteristic Trajectory Following
D	-	Viscous damping coefficient of IPMLM
e	-	Positioning error
$\dot{e}$	-	Real error rate
e_l	-	Boundary of error
e_{max}	-	Maximum tracking error
e_{rms}	-	Root-mean-square error
f_d	-	IPMLM driving force
F_{max}	-	Maximum static friction
ICPMLM	-	Iron-cored Permanent Magnet Linear Motor
IPMLM	-	Ironless Permanent Magnet Linear Motor
K_i	-	Integral gain
K_p	-	Proportional gain
K_{po}	-	Ultimate proportional gain
K_t	-	Force Constant of IPMLM
k_v	-	Velocity gain
k_y	-	Displacement gain
M	-	IPMLM mover mass
m	-	Linearized slope at origin of NCT
N(e)	-	Virtual error rate reference
NCT	-	Nominal characteristic trajectory
PI	-	Proportional-plus-Integral

PID	-	Proportional-plus-integral-plus-derivative
PTOS	-	Proximate time optimal servomechanism
PTP	-	Point-to-point
SSE	-	Steady state error
T_d	-	Time constant for low pass filter
t_f	-	Total time of motion
t_r	-	Time width of input signal
T_{rise}	-	Rise time
T_s	-	Sampling time
T_{settle}	-	Settling time
u	-	Input current to IPMLM
u_{max}	-	Maximum actuator input
U_p	-	Difference of object motion with NCT
u_r	-	Amplitude of input signal
ω_n	-	Natural frequency
x	-	Displacment of IPMLM
$\dot{x}$	-	Velocity of IPMLM
$\ddot{x}$	-	Acceleration of IPMLM
x_f	-	Final displacement
x_r	-	Reference displacement
ζ	-	Damping ratio
ζ_{prac}	-	Practical stability limit
ZOH	-	Zero order hold

LIST OF PUBLICATIONS

Foo, J.E., Chong, S.H., Nor, R.M., Loh, S.L., 2016. Positioning Control of a One Mass Rotary System with CM-NCTF Controller. *Journal of Telecommuncation Electronic and Computer Engineering*, 8(11), pp. 125-129.

CHAPTER 1

INTRODUCTION

1.1 Background

In modern manufacturing industries, demands on product quality improvement and high productivity have led to the continuous research and development for mechanisms with high positioning accuracy and velocity. Among various actuators, a direct drive linear motor is often opted to fulfil such demands. Unlike conventional machineries such as ball screw mechanisms or conveyor systems, direct drive linear motors do not come with any transmission elements such as gears, screw shafts or belts; the motor is capable of moving in a linear manner directly. With the application of this structure, gear related problems like backlash and mechanical limitation of speed and acceleration are eliminated (Yan & Shiu, 2008). Such advantages have put direct drive motors into extensive area of high speed and high accuracy applications, including robotic manipulators, semiconductor lithography system and transportation system.

Despite having simple construction, it was pointed out that the magnetic structure of linear motor presents a huge non-linear characteristic: the attractive force between permanent magnet and armature coil produces ripple force that causes unwanted vibrations (Tan et. al., 2003). These vibrations affect the positioning accuracy significantly, and may lead to system instability. Apart from the ripple force, the linear motor is also more sensitive towards parameter variations (load changes and external disturbances) due to the lack of mechanical transmissions. Therefore, in order to realize the high positioning performances of linear motor in presence of these characteristics, application of controller is inevitable.

Over the past decades, various controllers were designed for positioning control of linear motors. In 1991, a disturbance observer was designed to estimate and counter the action of disturbances and parameter variations (Komada et al., 1991). Not long after, the design of H∞ (H-infinity) optimal feedback controller was proposed to provide high dynamic stiffness for the linear motor to reduce the effect of external disturbances (Alter and Tsao, 1996). More than half a decade later, an adaptive robust motion control which is capable of adapting the changes of unknown parameters and reduces their effects on the motor was proposed and simulated (Yao and Xu, 2002). In 2010, compensation of force ripple was done by considering the ripple model into the control scheme (Bascetta et al., 2010). In recent years, a two degree-of-freedom controller incorporated with a learning feedforward controller was developed to achieve high precision tracking control in the presence of nonlinearities (Hama and Sato, 2015).

While it is well documented that these controllers are effective in producing top-notch positioning performances in linear motors, it is also observed that majority of the controllers need one to identify and model the nonlinearities of the linear motors to compensate them, which is relatively complicated and time-consuming. Apart from that, some of these controllers involve complex design procedures where deep comprehension of control system theory is essential. Therefore, with the reference of the above mentioned setbacks, it is favorable to produce a controller that is relatively simple and easy to design, while fulfilling desired performance specifications as well as robustness and stability (Dorato, 2000). It is also preferable if the controller is free of the necessity of plant modeling.

To achieve this objective while assuring the above-mentioned controller characteristics are attained, a Continuous Motion Nominal Characteristic Trajectory Following (CM-NCTF) controller is proposed in this research for the positioning control of an Ironless Permanent Magnet Linear Motor (IPMLM). The CM-NCTF controller is a model based controller designed using the open loop response of the system, and it has straightforward design procedures that does not require deep understanding of control knowledge.

1.2 Problem Statement

Linear motors are highly favorable over the conventional transmission machineries due to their structural simplicity, high speed and high accuracy properties. In spite of that, repeated researches have reported the existence of ripple force in the linear motor that lead to vibrations and possible instability, particularly at low velocity motion. Furthermore, linear motors are also subjected to nonlinear frictions, load changes and parameter variations that degrade the positioning accuracy and compromise the stability of the system.

Apart from the classical controllers, various advance controllers were designed to achieve high positioning accuracy in the presence of nonlinearities. However, these controllers have proven their limitations as the dynamics of the system has to be modeled as accurately as possible, else the stability and the positioning performance of the system will be at stake. On top of that, industrial operators might find difficulties in the applying advance controllers in the real plant as they are not familiar with the complex design procedures which require deep understanding of control theory. To overcome the mentioned restrictions of advance controllers, a CM-NCTF controller which does not require the exact model parameters, and has straightforward design procedure is proposed.

While the CM-NCTF controller has been proposed for various mechanism, its application on the IPMLM has yet to be observed. Even though in the past literature it was highlighted that the CM-NCTF controller has already proven its capability on mechanisms driven by voice coil motor (direct drive), however it must be stressed that these mechanisms work in a short range, whereas in this research, the direct drive IPMLM is a long working range linear motor. It is noted that at large displacement motion, actuator saturation problem occurs. Therefore, the CM-NCTF controller is improved to eliminate the occurrence of actuator saturation of the system.

1.3 Objectives

The objectives of this project are:

i. To design a Continuous Motion Nominal Characteristic Trajectory Following (CM-NCTF) controller for positioning control of the linear motor; and

ii. To evaluate the positioning performance as well as the robustness towards mass variations of the CM-NCTF controller and compare to a Proximate Time Optimal Servomechanism (PTOS) controller in point-to-point and tracking motion experimentally.