Faculty of Electrical Engineering

ROTARY MOTION CHARACTERIZATION OF TUBULAR SINGLE EXCITATION SWITCHED RELUCTANCE ACTUATOR

Izzati binti Yusri

Master of Science in Electrical Engineering

2017

ROTARY MOTION CHARACTERIZATION OF TUBULAR SINGLE EXCITATION SWITCHED RELUCTANCE ACTUATOR

IZZATI BINTI YUSRI

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

Faculty of Electrical Engineering

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

2017

DECLARATION

I declare that this thesis entitled "Rotary Motion Characterization Of Tubular Single Excitation Switched Reluctance Actuator" 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 : Izzati binti Yusri

Date : ………………………………

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	:	……………………………………
Supervisor's Name	:	Dr. Mariam binti Md. Ghazaly
Date	:	……………………………………

DEDICATION

To my beloved mother and father

ABSTRACT

Precision motion system has been widely used in many applications either in industries as a pick and place robotic and semiconductor manufacturing processes or for small machines such as micro-gripper. Conventionally, the tasks are carried out using precision actuator that associates with the suitable controller and sensors to drive these actuators. Recently, the electromagnetic actuator is widely implemented to operate in rotary motion which leads to this research, i.e. rotary motion characterization of Switched Reluctance (SR) actuator using tubular single-excitation. The SR actuator is well known to have a highly non-linear characteristic and it suffers from uncontrolled motion's behaviour. The main concern when achieving high precision motion is to suppress the non-linear characteristics of an actuator. Therefore, in this research, a SR actuator was design and evaluated in order to characterize the rotary motion characteristics. The research was divided into two main parts, i.e. (i) design of actuator through simulation work using Finite Element Method (FEM) analysis and (ii) actuator's characterization through experimental works. In the design phase, four (4) parameters were optimized i.e.: (i) number of winding turns, N; (ii) stator-to-rotor poles ratio, S:R; (iii) air gap thickness, g and; (iv) stator-to-rotor arc angle, βs/βr. The optimization was conducted via simulation work through FEM analysis and the results were evaluated in terms of generated torque, flux density and saturation level. The SR actuator prototype was fabricated accordance to the optimized design with the actuator's outer diameter 60mm and length 36mm, respectively. In this research, only Phase A was excited and called as the tubular single-excitation. This method is useful to obtain the motion characterization of SR actuator. The characterization of the SR actuator was carried out through open-loop experimental works. From the analysis, the rotor initial position at 0° was selected as the best initial position due to its highest generated torque. Based on the rotor initial positions at 0°, the linearizer unit was design namely R_{F0}, where the function of the linearizer unit is to suppress the non-linear characteristics of the SR actuator. In addition, in order to improve the motion characteristics, the effects of three (3) signal waveforms were evaluated; i.e.: (i) step input; (ii) sine waveform and; (iii) pulse input signal. It was concluded that the pulse input signal, with 20Hz and 1:4 duty ratio was the suitable signal, which it was able to improve the SR actuator motion characteristics

ABSTRAK

Sistem kedudukan tepat telah luas digunakan secara meluas dalam pelbagai aplikasi sama ada di dalam industri sebagai robotik dan pada pembuatan semikondutor atau juga digunakan di mesin kecil sebagai pemegang mikro. Kebiasaannya, tugas ini dijalankan dengan menggunakan penggerak yang disuaipakai dengan pengawal yang bersesuaian bersama sensor untuk memacu penggerak tersebut. Pada masa kini, penggerak elektromagnetik telah banyak digunapakai dalam gerakan berputar yang mana telah mendorong penyelidikan ini dijalankan iaitu pencirian gerakan berputak bagi penggerak Bertukar Keengganan (SR) dengan menggunakan kaedah tiub pengujaan tunggal Penggerak SR telah diketahui mempunyai ciri tidak linear yang sangat tinggi dan pergerakan yang sukar dikawal. Perkara utama yang diketengahkan adalah bagi mendapatkan pergerakan berketepatan tinggi dengan menindas ciri tidak linear penggerak tersebut. Oleh sebab itu, kajian ini dijalankan dengan mereka bentuk penggerak SR dan menilai ciri-ciri pergerakan berputar yang dihasilkan. Kajian ini terbahagi kepada dua bahagian, i.e. (i) reka bentuk penggerak melalui Kaedah Unsur Terhingga (FEM) dan (ii) pencirian penggerak SR melalui eksperimentasi. Dalam fasa reka bentuk, empat (4) parameter yang dioptimumkan, i.e. (i) bilangan wayar gulungan, N; (ii) nisbah tiang stator dan rotor, S:R; (iii) kelebaran jurang angin, g dan; (iv) nisbah sudut ark stator dan rotor, βs/βr. Fasa pengoptimuman dilakukan melalui simulasi yang mana keputusannya dinilai dari aspek daya kilas yang terhasil, rangkaian fluks dan tahap ketepuan. Prototaip SR yang dihasilkan adalah mengikut reka bentuk yang telah dioptimumkan dengan berukuran 60mm diameter dan 36mm panjang. Dalam kajian ini, hanya fasa A dituja dan ia dipanggil sebagai pengujaan tunggal tiub. Kaedah ini penting bagi mendapatkan ciri-ciri penggerak SR dan ia dijalankan menerusi eksperimen fasa tunggal gelung terbuka. Daripada analysis yang dijalankan, posisi 0° dipilih sebagi kedudukan yang terbaik kerana mempunyai daya kilas yang tertinggi. Berdasarkan kedudukan yang dipilih, unit linearizer direka bentuk dan dinamakan sebagai R_{F0} *yang mana fungsinya adalah sebagai menindas ciri-ciri tidak linear penggerak SR. Di samping itu, tiga isyarat pemandu dinilai bagi meningkatkan ciri-ciri penggerak SR iaitu, i.e.; (i) input langkah; (ii) gelombang sinus; dan (iii) isyarat denyut. Berdasarkan analisis, dapat disimpulkan bahawa isyarat denyut dengan konfigurasi 20Hz frekuensi dan nisbah 1:4 adalah isyarat yang paling bersesuaian yang mana dapat meningkatkan ciri pergerakan berputar bagi penggerak SR*

ACKNOWLEDGMENTS

I would like to express my utmost gratitude to my supervisor Dr. Mariam bt. Md Ghazaly for her invaluable support, guidance and encouragement throughout the period of research. My sincere appreciation to Dr. Rahifa bt. Ranom for her continuous help and constructive comments. I would also like to thank Assoc. Prof. Dr. Chong Shin Horng for her helpful suggestion and advice.

My special thanks and acknowledgment are dedicated to UTeM Zamalah Scheme for supporting my master programme for two years in UTeM and following individuals who are contributed to the research at various stages. I wish to thank the technical staff of Motion Control Research Laboratory (Mcon Lab), UTeM for continuous assistance in operating equipments. My appreciation to all my collegues for sharing their research experiences and views.

Finally, I am most grateful to my parents for their morale support and encouragement during my study. Lastly, thank you to everyone who had been associated along with this research.

TABLE OF CONTENTS

			PAGE
DECLARATION			
APPROVAL			
DEDICATION			
ABSTRACT			**i**
ABSTRAK			**ii**
ACKNOWLEDGEMENTS			**iii**
TABLE OF CONTENTS			**iv**
LIST OF TABLES			**vii**
LIST OF FIGURES			**ix**
LIST OF APPENDICES			**xvi**
LIST OF ABBREVIATIONS			**xvii**
LIST OF SYMBOLS			**xviii**
LIST OF PUBLICATIONS			**xx**
CHAPTER			
1.	**INTRODUCTION**		**1**
	1.1	Background	1
	1.2	Research Motivation	5
	1.3	Problem Statement	6
	1.4	Objectives of the Research	7
	1.5	Scopes of the Research	7
	1.6	Research Contribution	8
	1.7	Thesis overview	9
2.	**LITERATURE REVIEW**		**11**
	2.1	Introduction	11
	2.2	Review on the Research Gap	12
	2.3	Comparisons of SRM and SR Actuator	13
	2.4	Past Studies on Electromagnetic Actuator	14
	2.5	Fundamental Operations of Switched Reluctance (SR) Actuator	19
	2.6	Review of varying parameters to Switched Reluctance Actuator	24
		2.6.1 Review of Varying Number of Winding Turns, *N*	25
		2.6.2 Review of Varying Stator-to-Rotor Poles Ratio Configuration, S:R	27
		2.6.3 Review of Varying Air Gap Thickness, *g*	31
		2.6.4 Review of Varying the Stator-to-Rotor Arc Angle, $\beta s/\beta r$	33
		2.6.5 Review of Varying Rotor/Stator Material	37
	2.7	Influences of Rotor Positioning Towards the Generated Torque	42
	2.8	Review of Linearization on Nonlinear SR Actuator Characteristic	46
	2.9	Types of Driving Signal for SR Actuator	51
	2.10	Summary of Chapter 2	57
3.	**RESEARCH METHODOLOGY**		**59**
	3.1	Introduction	59
	3.2	Construction Design of Switched Reluctance (SR) Actuator	61
		3.2.1 SR Actuator Initial Parameters	62

		3.2.2	Materials of the SR actuator	65
	3.3	Design Optimization Procedures via Finite Element Method Analysis		68
		3.3.1	Effect of Varying Number of Winding Turns, *N*	75
		3.3.2	Effect of Varying Stator-to-Rotor Poles Ratio, S:R	77
		3.3.3	Effect of Varying the Air Gap Thickness, *g*	80
		3.3.4	Effect of Varying the Stator-to-Rotor Arc Angle, $\beta s/\beta r$	83
		3.3.5	Summary of SR Actuator Design Optimization	85
	3.4	Switched Reluctance (SR) Actuator Prototype and Experimental Setup		86
		3.4.1	Fabricated SR Actuator Prototype	86
		3.4.2	Experimental Setup Overview	91
	3.5	Experimental Procedures		94
		3.5.1	Varying Rotor's Position	99
		3.5.2	Varying Driving Signal Type	101
	3.6	Summary of Chapter 3		105
4.	**RESULTS AND ANALYSIS**			**106**
	4.1	Introduction		106
	4.2	SR actuator parameter optimization using Finite Element Analysis (FEM)		107
		4.2.1	Varying the SR actuator parameter	107
			4.2.1.1 Varying number of winding turns, *N*	107
			4.2.1.2 Varying stator-to-rotor poles ratio, S:R	110
			4.2.1.3 Varying the air gap thickness, *g*	114
			4.2.1.4 Varying the stator-to-rotor arc angle, $\beta s/\beta r$	118
		4.2.2	Performance Comparison of Different Type Materials	120
	4.3	SR Actuator Characteristic		123
		4.3.1	SR Actuator Characterization with Difference Rotor Position	125
			4.3.1.1 Generated Torque Characteristic	126
			4.3.1.2 Rotary Motion Characteristics	137
		4.3.2	Performance Comparison of Several Driving Waveform Signal	149
			4.3.2.1 Generated Torque Characteristic	150
			4.3.2.2 Rotary Motion Characteristics	156
	4.4	Summary of Chapter 4		160
5.	**CONCLUSIONS AND RECOMMENDATIONS**			**161**
	5.1	Introduction		161
	5.2	Summary of Research Finding		161
		5.2.1	SR Actuator Parameter Optimizations using FEM Analysis and Prototype's Development	162
		5.2.2	The SR Actuator Characterization and Development of Linearizer Unit	164
		5.2.3	The SR Actuator's Suitable Driving Signal	165
	5.3	Conclusion		166
	5.4	Recommendations for Future Research		167

REFERENCES **168**
APPENDICES **182**

LIST OF TABLES

TABLE	TITLE	PAGE
2.1	Comparisons of Electromagnetic, Electrostatic and Piezoelectric Actuator z	11
2.2	Comparisons of SRM and SR Actuator characteristic	13
2.3	The recommended arc angle for different configuration	36
2.4	Typical Properties of Carbon Steel	41
3.1	Parameter of S:R= 6:5 poles ratio configuration	62
3.2	Initial parameter S:R=6:4 poles ratio configuration	63
3.3	Labelling of the 3-phase system SR actuator's parameter	64
3.4	Chemical Composition of Steel	66
3.5	Mechanical Properties of Steel bar	67
3.6	Parameter of varying the S:R poles ratio configuration	75
3.7	Number of winding turns according to ampere-turns	76
3.8	Parameter of varying the S:R poles ratio configuration	78
3.9	Area of the active region for S:R poles ratio configuration 6:4 and 12:8	80
3.10	Parameter of varying the air gap thickness	82
3.11	Parameter of varying the stator-to-rotor arc angles	83
3.12	Volume and Area of active region for S:R=6:4 poles ratio configuration	85
3.13	SR actuator optimized parameter	85
3.14	Measurement of air gap based on fabricated parts	88

3.15	Suitable gain for input current and current monitor	98
3.16	Pulse signal parameter	104
3.17	Average excitation current of different pulse input signal configurations	104
4.1	Area of active region percentage reduction	112
4.2	SR actuator properties for different arc angle, βs/βr configuration	118
4.3	Chemical composition of Low Carbon steel, grade 1008 and Medium Carbon steel, grade S45C	123
4.4	Prototyped SR actuator specifications	125
4.5	Generated torque characteristic equation using non-linear polynomial curve-fit	135
4.6	Output response of 0.25A, 1A and 2A excitation current	141
4.7	SR actuator steady-state error	142
4.8	Steady-state positions standard deviation	144
4.9	Final rotary angle characteristic equation	146
4.10	Assigned pulse input signal parameter for varying frequency and duty ratio	151
4.11	Average excitation current of different pulse input signal configurations	156
4.12	Performances comparison of rotary motion response	159
5.1	SR actuator optimized parameter	163
A1	Summarise of materials and equipment	178
B1	Steady-state error of different position and current	183
B2	Settling time of different position and current	183
B3	Standard deviation of different position and current	184
C1	Output response of different frequency and duty ratio configuration	187
C2	Steady-state positions standard deviation and error	187

LIST OF FIGURES

FIGURE	TITLE	PAGE
1.1	Block diagram of simple closed-loop precision motion system	1
2.1	Flat 3-phase stepper motor	15
2.2	Proposed MSRM with different winding arrangements	16
2.3	Comparison of static average torque versus current	17
2.4	Cross section of proposed MSHSRM	18
2.5	Torque comparison of three SRMs at different excitation current	18
2.6	Model of switched reluctance motor with different S:R poles ratio	20
2.7	Winding Configuration of SR actuator with attached thermocouple	20
2.8	Operation of SR actuator	21
2.9	Magnitude of magnetic flux for different excitation current with respect to rotor position	22
2.10	Average torque for the experimental and FEM model	22
2.11	Direction of flux linkage of 12:8 SRM	23
2.12	The magnetic flux line for a different angle	24
2.13	Comparison of static torque in test machines	25
2.14	Flux distribution at maximum torque	26
2.15	Comparison of torque for SRM1 and SRM2	26
2.16	Comparison of flux linkage to current curves	27

2.17	Flux linkage plot for aligned and unaligned positions	27
2.18	Model of Switched Reluctance Motor of 4/2, 6/4, 8/6 and 12/8 designs	28
2.19	Comparison of measured output torque for 120° conduction angle for poles ratio	29
2.20	Geometrical dimension of 6:10 SRM	30
2.21	Comparison of flux density for arc angle $\beta r > \beta s$ and $\beta s > \beta r$	30
2.22	Comparison of starting torque with 1 phase excitation between general rotor and stepped rotor	31
2.23	Air gap, g measurement at the aligned position of stator and rotor	32
2.24	Air gap flux densities with different air gap length	33
2.25	Geometrical dimension of the arc angle for S:R = 6:4 poles ratio	33
2.26	Variation of average torque with stator and rotor poles arc	34
2.27	Geometrical construction of unequal rotor arc angle	35
2.28	Torque characteristic of single phase winding with different rotor position for varied arc angle	35
2.29	Average torque against rotor pole arc ratio	36
2.30	Comparison of total harmonic distortion	37
2.31	Iron Material Characteristic	38
2.32	Comparison of B-H curves	39
2.33	Mean coil temperature	40
2.34	Engineering stress-strain curves of AISI 1045 carbon steel	42
2.35	Rotor position to derive the inductance profile	43
2.36	Typical overlapping inductance profile	43
2.37	Static torque profile with respect to different rotor position	44
2.38	Relationship of rotor position with the flux linkage and torque profile	44

2.39	Resulted characteristic as a function of rotor for flux linkage and static torque	45
2.40	Relationship of excitation current, input force and the mover position	47
2.41	Control system with the linearizer units	47
2.42	Control system for positioning control of pneumatic actuator muscle	48
2.43	Compensator D and measured experimental results	49
2.44	Block Diagram of the control system	50
2.45	Applied negative impulse signal to the displacement of the actuator with 1kV holding signal	50
2.46	Excitation current for maintaining short flux path excitation	52
2.47	Electromagnetic torque under SFPE and LFPE	52
2.48	Step response for no-load of single and four step	53
2.49	Result of motion responses on different control period driving signals	54
2.50	Frequency characteristics from different input voltage and position	55
2.51	Top view magnetic circuit	55
2.52	Driving signal waveform	56
2.53	Measured reciprocating motion of the prototyped LSRM	57
3.1	Researches flow and development	60
3.2	Geometric view of previous research S:R=6:5 poles ratio configuration	62
3.3	Geometric view of S:R=6:4 poles ratio configuration	63
3.4	Geometric structure of SR actuator S:R=6:4 poles ratio configuration	65
3.5	B-H curve of Low Carbon steel (Steel 1008) and Medium Carbon steel (S45C)	68
3.6	Optimization process sequence	70

3.7	Winding turns configuration	71
3.8	Measurements of poles area	73
3.9	Geometrical structure with solid coil winding	76
3.10	Winding coil space between phases	77
3.11	Geometric design S:R poles ratio configuration for S:R=6:4 and S:R=12:8	79
3.12	Air gap thickness measurement	81
3.13	Coil winding space for increments of 2° stator's arc angle	84
3.14	Technical drawing of optimized SR actuator rotor	87
3.15	Actual prototype of optimized SR actuator	88
3.16	SR actuator prototype full assembly includes insulation and coil winding	89
3.17	SR actuator wire connection	90
3.18	Current direction through coil winding	91
3.19	Experimental Setup	92
3.20	Assembly of experimental setup	94
3.21	Flowchart of experimental work	95
3.22	MATLAB/Simulink block diagram	97
3.23	Measurement setup	98
3.24	Setup for positioning the rotor at initial position using microscope	99
3.25	Initial position of the rotor from 0° to 80° with interval of 10°	100
3.26	1A step input signal	100
3.27	Application of linearizer unit in control system	101
3.28	Position of the rotor based on the pointer measurement	102
3.29	Energized pole of fully unaligned position, 0°	103
4.1	FEM analysis result with varying number of winding turns, *N*	109

4.2	FEM analysis generated torque with varying S:R poles ratio configuration	111
4.3	Area of active region rotor and stator	112
4.4	Magnetic flux distribution for S:R poles ratio 6:4 and 12:8	113
4.5	FEM analysis Phase A flux density with varying stator-to-rotor poles ratio, S:R	114
4.6	FEM analysis generated output torque with varying air gap thickness, *g*	115
4.7	Magnetic flux distribution with varying air gap thickness, *g* 0.2 mm, 0.3 mm, 0.4 mm and 0.5mm	116
4.8	Magnetic flux vector with varying air gap thickness, *g* 0.2 mm, 0.3 mm, 0.4 mm and 0.5 mm	117
4.9	FEM analysis generated torque of varied stator-to-rotor arc angle, *βs/βr*	119
4.10	FEM analysis Phase A flux density with varying stator-to-rotor arc angle, *βs/βr*	120
4.11	FEM analysis results of maximum static torque of material Low Carbon Steel, grade 1008 and Medium Carbon Steel, grade S45C	121
4.12	SR actuator prototype	124
4.13	Position of the rotor from 0° to 80° with interval of 10°	126
4.14	Experimental results of acceleration for 1A excitation current at position 10° and 70°	128
4.15	Comparisons of generated torque result of varying rotor's position	129
4.16	Rotational direction with respect to position (a) 0° and (b) 80°	130
4.17	Magnetic flux flows at aligned rotor position	130
4.18	Stator and rotor plates of the two finger VR gripper	132
4.19	Response of two finger VR gripper for force and current	133
4.20	Direct torque measurement for two finger VR gripper	134

4.21	Comparisons of FEM analysis generated static torque characteristic	136
4.22	FEM analysis of rotational direction according to the energized rotor's pole at position 0°	137
4.23	Rotary motion characteristic of i =1A at initial position 0°	138
4.24	Experimental works rotational motion result of varying rotor position maximum rotation and final rotation	138
4.25	Experimental work rotary motion response of excitation current 0.25A, 1.0A, and 2.0A for initial position 0° to 30°	139
4.26	Experimental work rotary motion response of excitation current 0.25A, 1.0A, and 2.0A for initial position 40° to 80°	140
4.27	Experimental work standard deviations of final rotary angle at position 10°	144
4.28	Experimental work result of rotary motion characteristic at position 0°	148
4.29	Linearizer unit based on the motion characteristics of the SR actuator with respect to applied step input signal	148
4.30	Application of linearizer unit in the control systems	149
4.31	Experimental generated torque of different driving waveform signal at initial position 0° and initial position 80°	150
4.32	1Hz pulse signal with duty ratio	151
4.33	4Hz pulse signal with duty ratio	151
4.34	Experimental work maximum accelerations time of step input signal	152
4.35	Experimental work resulted accelerations at position 0° for signal	153
4.36	Experimental work resulted accelerations at position 80° for signal	153
4.37	Experimental work resulted acceleration of 20Hz frequency pulse input signal of 1:2 duty ratio and 1:4 duty ratio	154
4.38	Experimental work resulted acceleration of 20Hz frequency pulse input signal 1:8 duty ratio	152

4.39	Experimental work rotary motions of different signal types at the position 0°	157
4.40	Experimental work rotary motions of different signal types at the position 80°	157
4.41	Experimental work rotary motion responses of different off-time period for configuration pulse input	160
B1	Rotary motion response of position 0°	180
B2	Rotary motion response of position 10°	180
B3	Rotary motion response of position 20°	180
B4	Rotary motion response of position 30°	181
B5	Rotary motion response of position 40°	181
B6	Rotary motion response of position 50°	181
B7	Rotary motion response of position 60°	182
B8	Rotary motion response of position 70°	182
B9	Rotary motion response of position 80°	182
C1	Rotary motion response of different input signals at position 0°	185
C2	Rotary motion response of different input signals at position 80°	186

LIST OF APPENDICES

APPENDIX	TITLE	PAGE
A	Summarise of materials and equipment	182
B	Rotary motion response of varying position	184
C	Rotary motion response of varying input signals	189

LIST OF ABBREVIATIONS

SR	-	Switched Reluctance
FEM	-	Finite Element Method
DSP	-	Digital Signal Processing
PC	-	Personal Computer
DC	-	Direct current
CW	-	Clockwise
CCW	-	Counter-clockwise

LIST OF SYMBOLS

g	-	Air gap thickness
N	-	Winding turns
β_s	-	Stator arc angle
β_r	-	Rotor arc angle
D_{So}	-	Stator outer diameter
D_{Si}	-	Stator inner diameter
D_{Ro}	-	Rotor outer diameter
W_{Rt}	-	Rotor thickness
W_{St}	-	Stator thickness
H	-	Stator and rotor height
S_D	-	Shaft hole diameter
N_r	-	Rotor pole number
N_s	-	Stator pole number
N_{ph}	-	Phase number
C	-	Carbon
Mn	-	Manganese
P	-	Phosphorus
S	-	Sulphur
Si	-	Silicone
Hz	-	Hertz
kg	-	Kilogram

m	-	Meter
N	-	Newton
τ	-	Torque
θ	-	Rotor position
T	-	Tesla
^{o}	-	Degree
rad	-	Radian
s	-	Second
Mpa	-	Mega Pascal
t	-	Time
A	-	Ampere
i	-	Current
V	-	Volt
L	-	Inductance
μ_o	-	Permeability of air
K_{fr}	-	Constant fringing inductance
D	-	Stack length
A_p	-	Poles area
Φ_a	-	Flux linkages
M	-	Mutual inductance
I	-	Moment of inertia
α	-	Acceleration
T_s	-	Settling time
e_{ss}	-	Steady-state error
σ	-	Standard deviation