Faculty of Electrical Engineering

TUBULAR LINEAR SWITCHED RELUCTANCE ACTUATOR: DESIGN AND CHARACTERIZATION

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**TUBULAR LINEAR SWITCHED RELUCTANCE ACTUATOR:
DESIGN AND CHARACTERIZATION**

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in fulfillment of the requirements for the degree of Master of Science in
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DECLARATION

I declare that this thesis entitled "Tubular Linear Switched Reluctance Actuator: Design and Characterization" 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.

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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 Master of Science in Mechatronic Engineering.

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DEDICATION

To my parent

ABSTRACT

The linear electromagnetic actuator is receiving significant attention due to recent advances in power electronics and modern control method. Besides that, the manufacturing industry is relying on faster and more accurate positioning system in machine tools to meet the increasing demand for higher machining tolerances. Compare to the pneumatic and hydraulic actuator, the linear electromagnetic actuator has a fast dynamic response, high energy efficiency, and high positioning accuracy. In this thesis, a three-phase tubular linear switched reluctance actuator (LSRA) is proposed for the application in semiconductor fabrication industry. The LSRA with tubular structure seems to be attractive for industrial purposes due to both its closed form and inherently absence of normal force compared to the planar type LSRA. In addition, the tubular LSRA has robust construction, low manufacturing and maintenance cost, good fault tolerance capability and high reliability in the harsh environment make it an attractive alternative to permanent magnet linear actuator. However, the tubular LSRA has a long mover which increases the possibility of the mover to deform during fabrication. So, a new mover design is proposed to overcome the problem by separating the mover into mover shaft, magnetic ring and non-magnetic ring. Subsequently, the proposed mover design allows the travelling distance of the actuator to be modified by adding or removing the rings without changing the shaft. In addition, the design procedures, ranging from design specification and structure determination to optimization of actuator parameters is demonstrated in this thesis. The investigation is achieved through the simulation using the Finite Element Method (FEM) analysis and the performance is evaluated based on the generated thrust force. Then, the tubular LSRA prototype is fabricated according to the optimized design. In order to drive the tubular LSRA, three different high current amplifiers together with the switching algorithm are used to provide the correct switching signal due to this method is simple and straightforward while no extensive knowledge of power electronic converter is required. Next, the force and motion characteristics of the tubular LSRA are evaluated to verify the actuator design and the behaviour of the tubular LSRA is obtained through the open loop experiment. The developed tubular LSRA is capable of generating a maximum static force of 0.65 N which is within the required range needed to be operated in semiconductor fabrication process. Through the open loop reciprocating motion, the dynamic responses of the tubular LSRA are capable of achieving a maximum velocity of 210 mm/s and maximum acceleration of 8 m/s^2 which are in the performance range for precision mechanism.

ABSTRAK

Penggerak elektromagnetik lelurus mendapat perhatian yang ketara disebabkan oleh kemajuan terkini dalam elektronik kuasa dan kaedah kawalan moden. Selain itu, industri perkilangan bergantung pada sistem kedudukan yang lebih cepat dan tepat dalam alat mesin bagi memenuhi permintaan toleransi mesin yang semakin meningkat. Berbanding kepada penggerak pneumatik dan hidraulik, penggerak elektromagnetik lelurus mempunyai tindak balas dinamik yang pantas, kecekapan tenaga yang tinggi, dan ketepatan kedudukan yang tinggi. Dalam tesis ini, penggerak bertukar keengganan lelurus (LSRA) tiga fasa yang berbentuk tiub dicadangkan untuk aplikasi dalam perusahaan pembikinan separuh pangalir. Struktur tiub LSRA seolah-olah menjadi struktur yang menarik bagi tujuan perindustrian kerana bentuknya yang tertutup dan ketiadaan daya normal berbanding dengan jenis LSRA yang berbentuk satah. Di samping itu, LSRA tiub mempunyai pembinaan yang tegap, kos pembuatan dan penyelenggaraan yang rendah, keupayaan tolerasi kegagalan yang baik dan kebolehpercayaan yang tinggi dalam persekitaran yang kasar menjadikannya alternatif yang menarik kepada penggerak lelurus magnet kekal. Walau bagaimanapun, LSRA tuib mempunyai penggerak yang panjang menyebabkan peningkatan kemungkinan ubah bentuk berlaku pada penggerak semasa pembikinan. Oleh itu, reka bentuk penggerak baharu dicadangkan untuk mengatasi masalah tersebut dengan memisahkan badan penggerak kepada aci penggerak, tuib magnet dan tuib tanpa magnet. Tambahan, reka bentuk penggerak tersebut turut membolehkan jarak beroperasi diubah dengan menambahkan atau mengeluarkan tuib pada aci penggerak tanpa mengubah aci penggerak yang sedia ada. Kemudian, tatacara rekabentuk dari spesifikasi reka bentuk dan penentuan struktur sampai ke pengoptimuman parameter penggerak ditunjukkan dalam tesis ini. Kajian ini dicapai melalui simulasi dengan menggunakan analisis Kaedah Unsur Terhingga (FEM) dan prestasinya dinilai berdasarkan daya tujah yang dihasilkan. Prototaip LSRA tiub yang dibikin adalah mengikut reka bentuk yang telah dioptimumkan. Untuk memacu LSRA tiub ini, tiga penguat arus tinggi yang berbeza bersama-sama dengan algoritma pensuisan digunakan untuk menghasilkan pensuisan isyarat yang betul kerana kaedah ini adalah mudah dan ringkas sementara pengetahuan yang luas mengenai penukar kuasa elektronik tidak diperlukan. Seterusnya, ciri-ciri daya tujah dan gerakkan LSRA tiub dinilai untuk mengesah reka bentuk penggerak dan menentu kelakuan LSRA tiub menerusi eksperimen gelung terbuka. LSRA tiub yang dibina berkebolehan menghasilkan daya tujah maksimum sebanyak 0.65 N yang mana daya hujahnya berada di dalam julat yang diperlukan untuk beroperasi dalam tujuan pembikinan separuh pengalir. Dengan menggunakan gerakan salingan gelung terbuka, tindak balas dinamik oleh LSRA tiub mampu mencapai halaju maksimum sebanyak 210 mm/s dan pecutan maksimum sebanyak 8 m/s di mana prestasinya berada dalam julat prestasi bagi mekanisme kepersisan.

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AC	-	Alternating-Current
DC	-	Direct-Current
DSP	-	Digital Signal Processor
FEM	-	Finite Element Method
LEA	-	Linear Electromagnetic Actuator
LIA	-	Linear Induction Actuator
LRSA	-	Linear Reluctance Synchronous Actuator
LSA	-	Linear Synchronous Actuator
LSRA	-	Linear Switched Reluctance Actuator
RSRA	-	Rotary Switched Reluctance Actuator
SRM	-	Switched Reluctance Motor / Machine

LIST OF SYMBOLS

μ_i	-	Permeability of material
μm	-	Micrometre
μ_o	-	Permeability of air
a	-	Acceleration
A	-	Ampere
A_{coil}	-	Area of coil winding
A_{Cu}	-	Area of copper wire
A_i	-	Overlapping area of material
A_{ins}	-	Area of insulation
Al	-	Aluminium
A_o	-	Overlapping area of air gap
A_s	-	Area of stator
A_{slot}	-	Area of stator slot
B	-	Magnetic flux density
B_g	-	Flux density of air gap
B_s	-	Flux density of stator
C	-	Carbon
d	-	Diameter of enamelled copper wire
d_1	-	Mover shaft diameter
D_1	-	Stator outer diameter
D_2	-	Stator inner diameter
D_c	-	Coil diameter
F	-	Generated thrust force
F_f	-	Fill factor
$F_{generated}$	-	Generated force
$F_{measured}$	-	Measured force

$F_{per\ unit\ volume}$	-	Force per unit volume
fr	-	Friction force
g	-	Air gap thickness
g_m	-	Gap between end of mover tooth and linear bushing
H	-	Magnetic field strength
h_1	-	Stator tooth width
h_2	-	Stator slot width
h_3	-	Mover tooth height
h_4	-	Mover tooth width
h_5	-	Stator tooth height
h_{ins}	-	Insulation height
Hz	-	Hertz
i	-	Excitation current
I.D.	-	Inner diameter
kg	-	Kilogram
L	-	Phase inductance
l_{ins}	-	Insulation width
m	-	Number of phases
mm	-	Millimetre
Mn	-	Manganese
mN	-	Milli newton
N	-	Newton
n	-	Number of winding turns
N_M	-	Mover pole number
n_m	-	Number of mover pole of respective configuration
N_S	-	Stator pole number
O.D.	-	Outer diameter
P	-	Mover tooth pitch
P_g	-	Air gap permeance
Ph	-	Phosphorus
P_S	-	Stator tooth pitch
R	-	Magnetic reluctance
r_g	-	Radius of air gap

$R_{S:M}$	-	Stator-to-mover pole ratio
s	-	Second
S	-	Sulphur
Si	-	Silicon
T	-	Tesla
v	-	Velocity
V	-	Voltage
V_m	-	Volume of mover
V_s	-	Volume of stator
V_{total}	-	Total volume of the actuator
W_c	-	Magnetic field co-energy
W_e	-	Electrical energy
W_f	-	Magnetic energy stored
W_m	-	Mechanical energy
x	-	Mover position
x_{max}	-	Maximum travelling distance
Δy	-	Overlapping area
Φ	-	Magnetic flux
Ω	-	Ohm

LIST OF PUBLICATIONS

Journal:

1. Yeo, C.K., Ghazaly, M.M., Chong, S.H., Jamaludin, I.W., 2018. Design Optimization of a Three Phase Tubular Linear Switched Reluctance Actuator. *ARPN Journal of Engineering and Applied Sciences*, 13(5), pp. 1600-1607.
2. Yeo, C.K., Ghazaly, M.M., Chong, S.H., Jamaludin, I.W., Ranom, R., 2018. Influence of Materials, Air Gap and Winding Turns for a Tubular Linear Switched Reluctance Actuator (TLSRA). *Journal of Telecommunication, Electronic and Computer Engineering*, 10(2-2), pp. 63-66.
3. Yeo, C.K., Ghazaly, M.M., Chong, S.H., Jamaludin, I.W., 2017. A Review: Design Variables Optimization and Control Strategies of a Linear Switched Reluctance Actuator for High Precision Applications. *International Journal of Power Electronics and Drive System,* 8(2), pp. 963-978.

Conference:

1. Yeo, C.K., Ghazaly, M.M., Chong, S.H., Jamaludin, I.W., 2017. Design of a High Force Density Tubular Linear Switched Reluctance Actuator (TLSRA) without Permanent Magnet. *17th Asia Simulation Conference (AsiaSim 2017)*, pp. 138-148.

CHAPTER 1

INTRODUCTION

1.1 Introduction

This chapter highlights the background of the study, problem statement, objectives and scopes of the project. Background of study is a brief exposition on different types of linear actuators that are being researched and the problem statement dictates the core issue that is to be addressed by this research. Meanwhile, the objectives serve as a benchmark of the research while the scopes define the limits and boundaries of the project in overseeing the project upon completion. Lastly, the thesis outline of the research is described at the end of this chapter.

1.2 Background

A linear actuator is a device that converts different forms of energy into linear motion. The linear actuator has been subjected to research and development for over 100 years and their concept has been known since the time of rotary motors, but the usefulness of linear actuator is not fully realized until many years later. Unlike linear motor, linear actuator focuses on achieving high precision motion performance with compact structure instead of high force performance. Therefore, the development of the linear actuator is focusing on three main aspects which are positioning accuracy, positioning speed and acceleration. However, the force performance of the actuator is not highlighted as long as the actuator met the performance range for precision mechanism (Oiwa et al., 2011; Sato, 2013; Maslan et al., 2019). The linear actuator provides a viable solution to numerous actuation requirements, and it can be rotary, flat, tubular or converting rotary motion to linear motion. The application of linear actuator is wide-ranging from industrial applications to consumer goods such as industrial transportation system, vehicle suspension system, industrial robot and machine tool, industrial of semiconductor fabrication and medical instrument.

The linear actuator can be classified into three major types. There are hydraulic actuator, pneumatic actuator and electric actuator. Hydraulic actuator has the advantages of high power to weight ratio, high reliability and high durability. However, it requires a large time constant and continuous pressurized liquid which increases the energy consumption of actuator operation. Moreover, the hydraulic actuator exhibits highly nonlinearity due to dry friction and subjected to leakage which makes it suitable for non-precision applications that requiring high force performance (Mantovani et al., 2018). Pneumatic actuator, on the other hand is capable of providing high force density with relatively low cost due to cheap power source and easy maintenance. As the air is compressible fluid, the force of the pneumatic actuator is slightly lower than the hydraulic actuator. However, the pneumatic actuator tends to be highly nonlinear due to the air compressor and complex friction in the chamber. This increases the complexity of control and degrades the overall performance of the actuator towards precision applications (Al-Ibadi et al., 2018). Therefore, both hydraulic and pneumatic actuator only applicable for non-precision heavy applications which require high force performance.

Recently, linear direct-drive mechanism rapidly becomes an area of interest in the field of high speed and high precision machine tools because of their potential to overcome the inherent limitations of the traditional electric actuator such as ball screw system. The direct-drive method eliminating the mechanical transmission devices which contribute to low friction, eliminate backlash and reduce the mover mass and thus high precision performance can be achieved (Siadatan et al., 2017). Linear electromagnetic actuator such as linear synchronous actuator and linear induction motor are electric actuators with direct-drive properties. To provide a high speed and high force performance, most of the electromagnetic actuators are utilizing the permanent magnet which has a strong attractive force. However, the utilized of permanent magnet leads to the actuator's cost rises and high cogging force which significantly affects the positioning accuracy in the ultra-precision actuator (Saadha et al., 2018).

Linear switched reluctance actuator (LSRA), on the other hand has a magnet-free structure, thus LSRA is free from the above problems caused by the permanent magnet. Typically, the LSRA is only constructed with several physical parts; i.e. stator, mover and phase windings which are simple and cost-effective (Yusri et al., 2018). Besides that, LSRA offers fast response, low maintenance, simpler and more robust configuration than permanent magnet linear actuator which leads to a reliable and low-cost system (Wang et al., 2018b). These advantages make LSRA a promising alternative actuator to permanent magnet linear actuator. LSRA may have lower force production for approximately 60 % compared to permanent magnet linear actuator, but lighter weight mover compensates for this (Amorós et al., 2015). The efficiency of LSRA is not very important, and the previously described advantages of the LSRA are more significant.

The structure of the LSRA can be divided into planar single-sided, planar double-sided and tubular topology. The simplest structure of LSRA is planar single-sided topology. This structure has a large normal force due to the asymmetrical air gap causes high friction force in the system and thus reduces the force density (Maslan et al., 2017). In high precision positioning applications, the effect of friction force in the system can lead to significant positioning error. On the other hand, planar double-sided LSRA has a balance normal force with twice the air gaps and coils compared to planar single-sided LSRA, which indicates the generated thrust force is expected to be doubled (Wang et al., 2016a). However, planar double-sided LSRA still suffers from low force production compared to the permanent magnet actuator which limits the applications of LSRA. Henceforth, tubular LSRA has been proposed and employed to improve the force performance and increase the diversity of LSRA application. This is because the tubular LSRA fully utilized the actuator volume which contributes to larger force production compared to the planar type LSRA (Chen et al., 2017). Besides that, the symmetrical structure of tubular LSRA in all direction eliminates the normal force as well as radial force. However, tubular LSRA utilizes more material compared to planar type LSRA (Chen et al., 2017).

Several kinds of research reported the design of LSRA which focuses on achieving precision positioning. A planar single-sided micro LSRA with short travelling distance was developed by Liu and Chiang (2004) for micro positioning stages. As the proposed LSRA was designed for precision motion application, the maximum generated force only has 0.34 N. Then, Pan et al. (2009, 2013) designed a planar single-sided LSRA for high precision X-Y table with short travelling distance while the maximum thrust force generated at 3 A was approximately 6 N. Besides that, Maslan and Sato, (2018) proposed a thin and compact planar double-sided LSRA with disposable-film mover for precise positioning control purposes that to be operated in hazardous environment. The developed LSRA has short travelling distance and capable of generating maximum thrust force for approximately 4 mN at 3.33 A. Meanwhile, Saidi et al. (2018) designed a tubular LSRA for actuating the left ventricular assist device with maximum thrust of 4.82 N at 5.9 A. The high precision positioning capability of the proposed LSRA is important to control actuator stroke position and the blood flow to the body.

Based on the background studies, it can be observed that the designs of the LSRA are focusing on short travelling distance range with precision motion performance. According to the Japan Society for Precision Engineering (JSPE), a precision actuator has