INCREASING PERFORMANCE OF ROTARY ULTRASONIC MOTOR THROUGH STATOR MODIFICATION

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ABSTRACT

This thesis concerns with the performance of the travelling wave ultrasonic motor (TWUSM). The performance of TWUSM is mainly constraint by the quality of the piezoceramic material, the electrical driving signal synchronisation and optimization, the heat dissipation system during the operation and the stator-rotor interface designed. One of the factors in the stator-rotor interface design is the deflection amplifier mechanism. Under travelling wave electrical excitation, the piezoceramic layer of the stator vibrates by expanding and compressing. The amplitude of the vibration is amplified by the metal attached on the top of the piezoceramic layer. The metal vibration is in contact with the rotor and through a frictional layer, torque is generated and the rotor rotates. This mechanism of transferring the piezoceramic vibration to the rotor motion is called deflection amplifier. Current TWUSM utilises the comb-teeth structure as the deflection amplifier. One of the factors that influence the deflection amplifier is the position of the stator neutral axis to the contact surface of the stator. Thus, the objective of this thesis is to modify the design of the comb-teeth stator so that the neutral axis position is further distance from the stator top contact surface. The proposed solution is to remove selected mass element from the comb-teeth structure. Modelling and simulation of the proposed concept were carried out under Marc Mentat FEM software utilising Shinsei USR60 as the chosen TWUSM. Results from the modal, harmonic, transient and stress analyses indicate that the modified comb-teeth stator increases the position of the neutral axis from the stator top surface. Due to the neutral axis shifting, simulation results also confirm that the stator speed increases for the modified stator. To observe the performance of the modified stator, experiments were conducted using Shinsei USR60 as the test platform. One set of Shinsei USR60 motor was modified by drilling hole to the comb-teeth structure. Results from experiments confirm that the motor with the modified stator produced better speed, torque and power consumption.

ABSTRAK

Tesis ini adalah berkaitan prestasi rambatan gelombang motor ultrasonik (TWUSM). Prestasi TWUSM secara keseluruhannya bergantung kepada kualiti bahan piezoseramik, pengoptimuman dan penyeragaman isyarat kawalan elektrik, sistem pembebasan haba ketika operasi dan rekabentuk antaramuka stator-rotor. Salah satu faktor rekabentuk antaramuka stator-rotor adalah mekanisma penganda lenturan. Ketika rambatan gelombang elektrik dibekalkan, lapisan piezoseramik stator bergetar secara mengembang dan mengecut. Amplitud getaran digandakan oleh logam yang melekat di atas lapisan piezoseramik. Getaran logam tersebut menyentuh rotor, melalui lapisan geseran, tork dihasilkan dan seterusnya memusingkan rotor. Mekanisma yang menukarkan getaran piezoseramik kepada pergerakan rotor ini dipanggil sebagai pengganda lenturan. TWUSM terkini mengunapakai struktur gigi-sesikat sebagai pengganda lenturan. Salah satu faktor yang mempengaruhi pengganda lenturan adalah posisi paksi neutral struktur stator tersebut dari permukaan atas sentuhannya. Oleh yang demikian, objektif tesis ini adalah untuk mengubah rekabentuk struktur gigi-sesikat stator supaya posisi paksi neutral dijauhkan dari permukaan atas sentuhannya. Cadangan penyelesaiannya adalah dengan membuang sebahagian jisim struktur gigi-sesikat pada bahagian yang telah dikenalpasti. Permodelan dan simulasi terhadap konsep yang dicadangkan, dilakukan menggunakan perisian kaedah berangka Marc Mentat dengan menggunapakai TWUSM yang pilih iaitu USR60 Shinsei. Hasil simulasi yang diperolehi menerusi analisis modal, harmonik,transian dan tegasan menunjukkan stator gigi-sesikat yang diubahsuai mempunyai kedudukan paksi neutral yang lebih jauh dari permukaan atas sentuhan stator. Disebabkan anjakan paksi neutral ini, keputusan simulasi turut mengesahkan kelajuan stator yang diubahsuai adalah bertambah. Untuk memerhatikan prestasi stator yang diubahsuai, eksperimen dijalankan menggunakan motor USR60 Shinsei sebagai platfom ujian. Satu set motor USR60 diubahsuai dengan cara mengorek lubang pada struktur gigi-sesikatnya. Keputusan yang diperolehi dari eksperimen mengesahkan bahawa stator yang dubah bentuk menghasilkan kelajuan, tork dan penggunaan kuasa yang lebih baik.

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LIST OF SYMBOLS

F_T	Tangential force
F_B	Braking force
F_N	Normal force
μ_s	Static frictional constant
D	Electric flux density
ε_o	Permittivity
P	Polarization performance
E	Electric field
d_{33}	Piezoelectric strain constants in longitudinal direction
d_{31}	Piezoelectric strain constants in transverse direction
F_p	Piezoceramic force
W	Force factor
V	Applied electrical voltage
v	Velocity
I	Electrical current
Z	Mechanical impedance
Y_d	Blocking admittance
b	Width
Y_{11}	x-directional Young's modulus
$\vec{S}$	Strain tensor
s	Elastic compliance
s^E	Elastic compliance of the material in the absence of an electric field
$\vec{T}$	Stress tensor
$\vec{E}$	Electric field tensor
c^E	Stiffness matrix under a zero electric field
e	Piezoelectric stress constant
$i,$	x-axis electric field direction
j	z-axis electric field direction
m	x-axis strain direction
l	z-axis strain direction

^{t}	Transpose
L	Inductance
C	Capacitance
K	Spring constant
m	Mass
ω_o	Natural frequency
Δx	Segmented beam
$d\theta$	Curvature angle
F_S	Shear force
∂M	Changed moment
∂x	Beam local position element on the x-axis
ρ	Density
A	Cross section area
u_z	Stator z-axis displacement
du_z	Changed z-axis displacement
r	Radius
ε	Strain
T	Stress
Y	Young's modulus
M	Moment
I	Moment of inertia
n	Wave number
L	Beam length
β	Eigenvalue
h	Height
ω	Driving frequency
k	Wave characteristic
t	Time
u_x	Stator x-axis displacement
c	Distance between stator top surface to the neutral axis
w_0	Stator maximum z-axis displacement
μ_d	Dynamic friction coefficient

v_{rel}	Relative speed between the stator and rotor
P_r	Rotor power
v_m	Rotor speed
x_{max}	Maximum speed
v_x	Stator tangential speed
λ	Wave length
z	Distance of the stator expansion or contraction
τ_R	Motor torque
r_c	Effective radius of stator-frictional layer contact
T	Current temperature
T_o	Initial temperature
$\vec{U}$	Displacement tensor
L	Sample length
α	Amplification constant
Q	Mechanical quality factor
k_c	Electromechanical coupling factor

LIST OF ABBREVIATIONS

AC	Alternate current
ANSI	American National Standards Institute
CNC	Computer numerical control
DC	Direct current
IEEE	Institute of Electrical and Electronics Engineers
FEM	Finite element method
GDP	Gross domestic product
IMP2	Second Industrial Master Plan
IMP3	Third Industrial Master Plan
LNG	Liquid and natural gas
MITI	Malaysian Ministry of International Trade and Industry
PZT	Lead titanate-lead zirconate
TWUSM	Travelling wave ultrasonic motor
USD	United State Dollar
POI	Point of interest

CHAPTER 1

INTRODUCTION

1.1 RESEARCH OVERVIEW

Manufacturing sector is the major contributing sector that drives Malaysian economy. The manufacturing sector is targeted by the Malaysian government to grow 5.6% annually and to contribute 28.5% to the gross domestic product (GDP) in the year 2020 (Industrial Master Plan 2, 2006). Malaysian manufacturing sector mainly covers electrical and electronic products, palm oil, liquid and natural gas (LNG), chemicals and chemical products, refined petroleum products, crude petroleum, machinery, machine appliances, parts and metal fabrication. Manufacturing sector overall economic growth values from 2005 to 2011 posted a steady increment even though there was a slight decrement in the year 2009. This is shown in Figure 1.1. The export and import values in 2011 posted the highest value which was RM516.8 billion for exports and RM433.1 billions for imports.

According to the Malaysia Third Industrial Master Plan 2006-2020, which was launched on 18 August 2006 by Malaysian Ministry of International Trade and Industry, machine tools industry will be one of the main sub-sectors for the economic growth in manufacturing sector. This is based on the increase of machine tool import and export values in the period of 1996-2011 as shown in Figure 1.2. Based on the report, Malaysian machine tool industry had increased dramatically during the period of the Second Industrial Master Plan (1996-2005) (Industrial Master Plan 2, 2006).

Total exports of machine tools produced by local manufacturers increased from RM5.1 billion in 1996 to RM18.3 billion in 2005.

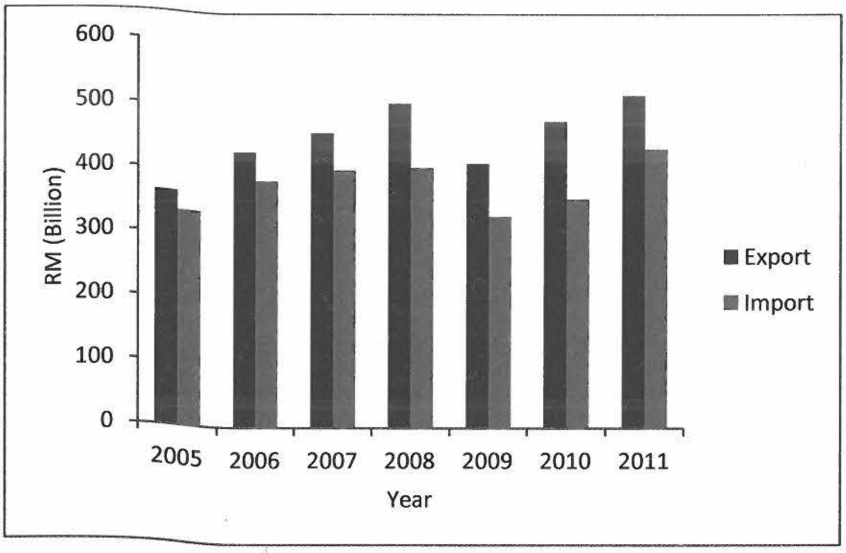

Figure 1.1: Economic growth of the manufacturing sector (2005 -2011)

Source: Ministry of International Trade and Industry, Malaysia (2012)

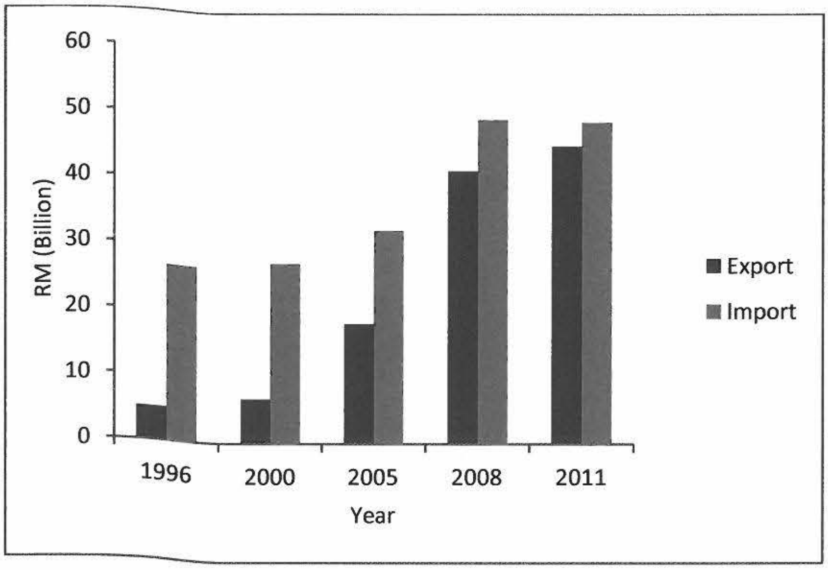

Figure 1.2: Exports and imports of Malaysian machine tools industry (1996 – 2011)

Source: Ministry of International Trade and Industry, Malaysia (2012)

Under the Industrial Master Plan Three (IMP3), the machine tool exports in 2008 are highest with RM 41 billion almost doubling the exports in the year 2005. Most of the export countries were China, Singapore, Thailand and the United States. This shows the potential of machine tools industry in Malaysia. On the other hand, Malaysia still depends on imports of machine tools from overseas. Average rate of yearly growth for imports of machine tools is 1.5%, which was from RM26.7 billion in 1996 to RM32.4 billion in 2005 and to RM46.1 billion in 2011. This is due to Malaysia lack of expertise in high-tech machine tool industries (MITI, 2006).

Malaysia government is trying to support the machine tool industry by focusing on the high technology and customised machine. The government has listed four main categories in IMP3 which are:

1) Machine tools for power generator including turbine and power plant.
2) Machine tools for specific industry such as for agriculture, electric and electronic, oil and gas and plastic processing.
3) Computer numerical control (CNC) machine for steel working process and steel making which involves of conventional and non-conventional cutting process.
4) Machine tools for general purposes including air-conditioning, pressure vessel and construction equipments.

Based on the third category, research on CNC machine tools is highly in line with Malaysian's aspiration to be a high technology country beyond 2020. Expertise in CNC machine is essential in reducing the imports while increasing the exports of machine tools.

In machine tool industry, one of the important technologies is precision engineering technology. The technology is applied in vast area such as medical equipment, medical implant and device, micro-process instrumentation and control system, micro-electro-mechanical system, computer numerical control (CNC) of micro-machine tools, telecommunication and satellite.

Inside the precision engineering technology, functional materials play a very important role. One of the functional materials is piezoelectric material that has a special characteristic which can be designed as actuators for ultrasonic welding, cleaning, motors, sensors, transducers, medical imaging, non-destructive acoustic testing, energy harvesting, ceramic resonators, transformers and other types of customised devices. With an excellent characteristic and flexibility in determining the design functions, piezoelectric material exists as a new technology.

According to Innovative and Research Products (2008), the global market for the piezoelectric devices in the year 2010 equals to USD 10.6 billion and projection for the year 2012 is expected to reach USD 19.5 billion. Table 1.1 shows several sectors covered by piezoelectric device market usage.

Table 1.1: Piezoelectric device market

Sector	Market (%)
Information technology/robots	31.7
Semiconductor manufacturing and Precision machines	18.6
Sonar	12.5
Bio/medical	11.1
Ecology and energy harvesting	7.0
Accelerators and sensors	5.8
Non-destructive testing	5.7
Gas igniters, piezo printing heads, telecommunication devices	4.5
Acoustic devices and resonators	3.1

Source: Innovative and Research Products Inc. (2008)

Piezoelectric device has a unique characteristic; it vibrates at a micro level through the excitation of electrical signal. This characteristic enhances the design and development of precision devices. One of the precision motion control device that uses piezoelectric characteristic is an ultrasonic motor. The ultrasonic motor is suitable for the development of precision engineering machine tools or processes. In fact more than 20 years ago, the companies that had immersed into the ultrasonic motor business are shown in Table 1.2 (Uchino 1991). This indicates that ultrasonic motors has played significant role in industrial products.

Table 1.2: Commercialization of ultrasonic motors

Company	Role
Shinsei Kogyo	The pioneering company in marketing ultrasonic motors.
Fukoku	Manufacturer of Shinsei's ultrasonic motors producing 20,000 units per year.
Canon	Utilizing the Shinsei ultrasonic motors for automatic camera lenses with production of 300, 000 units per year.
Toyota	Ultrasonic motor was used for head-rest control for car seat.
Seiko Instruments	Commercializing a miniature ultrasonic motors for watch mechanism
Nasca	Manufacture the ultrasonic motors developed by Matsushita Electric
THK	Axial ultrasonic motors utilizing Shinsei ultrasonic motors
SUN-SYN	Develop precision x-y stages using linear type ultrasonic motors.
Malcon Electronics	Standing wave type ultrasonic motor
AlliedSignal	USA company who is manufacturing the ultrasonic motors.
Rion and Piezotech	Developing various type of ultrasonic motor.

Source: Uchino (1991)

1.2 RESEARCH PROBLEM STATEMENT

In order to improve the performance of an ultrasonic motor, fundamental studies on the behaviour of ultrasonic motor are needed. From the study, the major constraints to the performance of the ultrasonic motor are heat generated, piezoceramic quality, electrical driving signal and stator-rotor interface design.

Firstly, temperature rise causes the piezoceramic characteristic to become non-linear. Excessive temperature change also causes depoling effect to the piezoceramic. Furthermore, wear between the stator and the friction layer of the rotor increases as the temperature increases. Lastly, the optimum driving frequency changes due to temperature changes.

Secondly, the piezoceramic quality is another factor that affects the performance of the ultrasonic motor. High quality piezoceramic has high piezoelectric strain constant and electromechanical coupling. The strain and electromechanical coupling constants determine the maximum stator displacement which directly influences the speed and torque of the motor.

Thirdly, speed and torque performance is also affected by the consistency of the electrical driving amplitude, phase and frequency. The optimum driving frequency is at the natural frequency of the stator and rotor. In the dynamic of stator-rotor interface, factors such as friction variation and holding torque dynamic affect the optimum driving frequency. Hence, an adaptive driving frequency is needed to enhance the motor performance.

Next, the design of the stator-rotor interface is another factor that influences the motor performance. The frictional layer behaviour between the stator vibration and the rotor causes ripples and hysteresis to the rotor speed. Furthermore, the stator geometrical design affects the amplitude of stator vibration.

The design of the so called "deflection amplifier" is critically studied in this research. Deflection amplifier (also called horn) amplifies the stator deflection by acting as "mechanical level". The current design of the travelling wave ultrasonic motor uses a "comb-teeth" structure to increase the stator deflection. The comb-teeth structure functions as a vertical magnitude amplifier (mechanical level) between the piezoceramic vertical amplitude to the stator contact surface amplitude. The rotor speed and torque is directly dependent on the stator-rotor contact surface amplitude. Thus, the goal of this research is to enhance the performance of the ultrasonic motor by increasing the performance of the deflection amplifier. This is achieved by modifying the stator geometry.

1.3 RESEARCH OBJECTIVES AND SCOPES

The research objectives are to:

- Investigate the characteristics of an ultrasonic motor and propose an idea to increase its performance.
- Perform computer modelling and simulation of the proposed idea in order to observe the improved performance.
- Setup and conduct experiments in order to observe the improved performance.

The research focuses on a rotary type which means a linear type motor is not considered. Furthermore, although there are various mechanisms to drive an ultrasonic motor such as flex-tensional, multi-mode vibrations and standing wave concept, ultrasonic motor that utilises travelling wave mechanism is the focus of this research.

For modelling and experimental studies, a specific (commercial) travelling wave ultrasonic motor is chosen. Shinsei USR60 ultrasonic motor is chosen together with its corresponding driver because of its popularity in research literature. Finally, this research focuses on speed-torque performance as well as the motor efficiency. Other performance such as limited operation durability that arises due to the heat generation is not considered.

1.4 RESEARCH METHODOLOGY

Figure 1.3 illustrates the activities conducted for this research.

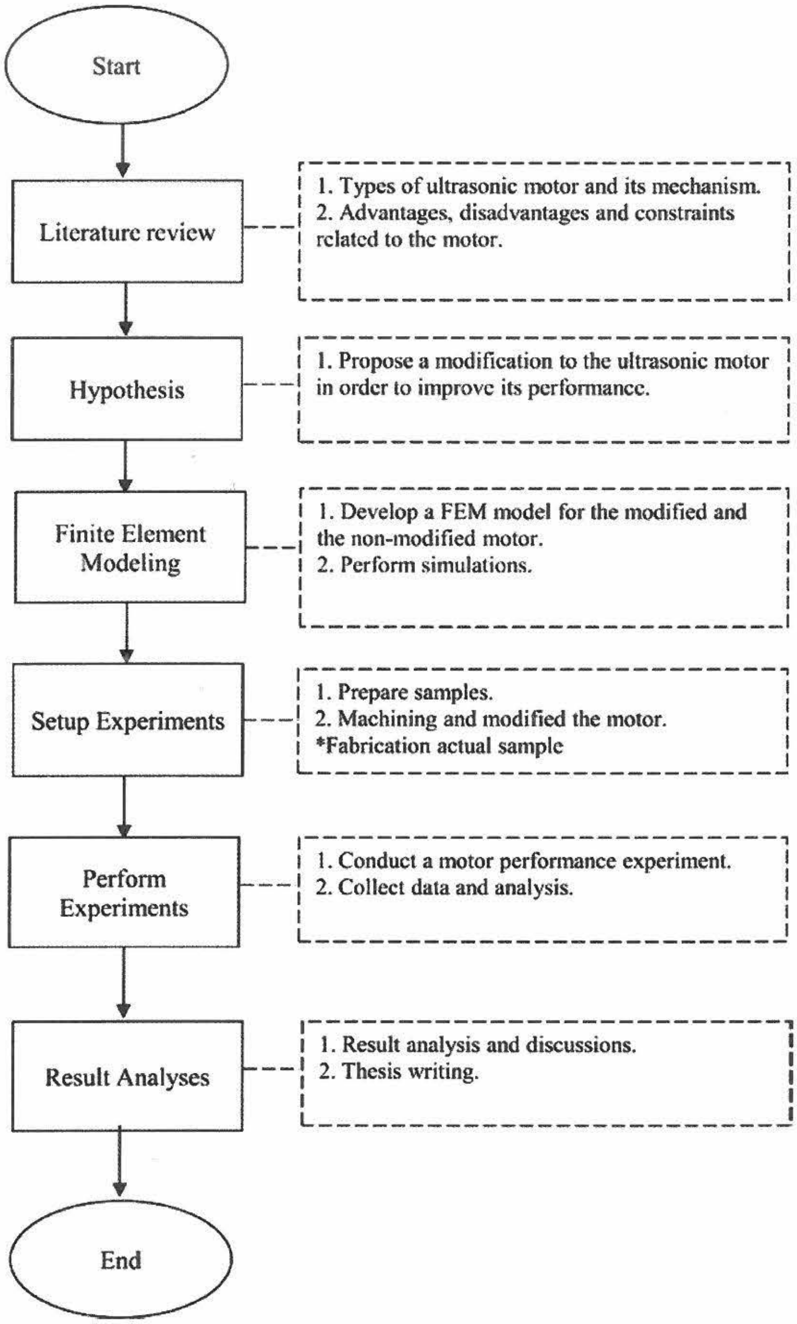

Figure 1.3: Research methodology