THE DESIGN AND ANALYSIS OF A ROTARY MOTION ELECTROSTATIC ACTUATOR

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A report submitted in partial fulfilment of the requirements for the degree of Mechatronics Engineering

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SUPERVISOR'S ENDORSEMENT

"I hereby declare that I have read through this report entitle "*the design and analysis of a rotary motion electrostatic actuator*" and found that it has comply the partial fulfilment for awarding the degree of Bachelor of Mechatronics Engineering"

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STUDENT DECLARATION

I declare that this report entitle "*the design and analysis of a rotary motion electrostatic actuator*" is the result of my own research except as cited in the references. The report has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

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ABSTRACT

Research and development in microelectromechanical systems (MEMS) or most generally defined as miniaturized electromechanical elements, have made outstanding progress. MEMS consist of micromechanisms such as microstructures, microactuators, microsensors and their control circuits. There are two types of microactuator used in MEMS which are linear motion and rotary motion. Both types of actuator consist of electromagnetic, electrostatic, thermal, shape-memory alloy and others. Each type of actuator has its own advantages and drawbacks. This report provides a brief comparison of those actuators and overview of the design of two types of rotary motion electrostatic actuator. It focuses on the thrust force produced when different parameters are manipulated for both designs. Both designs are set to have the same size which is 1.4mm in diameter and thickness is 50 µm; both designs have the same number of electrode for stator and rotor too which are twelve electrodes and sixteen electrodes respectively. To analyse the thrust force produce, Ansys Maxwell3D is used as a tool to design and analyse the two rotary motion electrostatic actuators. Three simulations have been carried out; first, vary the actuator size; second, vary the actuator thickness; third, vary the number of electrode. With the same rotor size, thickness, gap, and number of electrode, the results show that bottom-drive electrostatic actuator has better performance than side-drive electrostatic actuator through simulation.

ABSTRAK

Penyelidikan dan pembangunan dalam sistem mikroelektromekanik (MEMS) atau paling umumnya didefinisikan sebagai elemen elektromekanik bersaiz kecil, telah mencapai kemajuan yang menakjubkan. MEMS terdiri daripada mekanisme mikro seperti struktur mikro, penggerak mikro, sensor mikro dan litar kawalan mereka. Terdapat dua jenis penggerak mikro digunakan dalam MEMS iaitu gerakan linear dan gerakan berputar. Kedua-dua jenis penggerak terdiri daripada elektromagnetik, elektrostatik, haba, aloi bentuk-memori dan lain-lain. Setiap jenis penggerak mempunyai kelebihan dan kelemahan sendiri. Laporan ini memberi perbandingan yang ringkas dari penggerak yang telah dinyatakan dan gambaran tentang reka bentuk dua jenis penggerak berputar elektrostatik. Laporan ini memberi tumpuan kepada kekuatan yang dihasil apabila parameter yang berbeza dimanipulasi. Kedua-dua reka bentuk mempunyai saiz yang sama iaitu 1.4mm diameter dan ketebalan 50µm; kedua-dua reka bentuk mempunyai jumlah elektrod yang sama bagi pemegun dan pemutar iaitu dua belas elektrod dan enam belas elektrod masing-masing. Untuk menganalisis hasil daya tujahan, ANSYS Maxwell3D digunakan sebagai alat untuk mereka bentuk dan menganalisis dua penggerak berputar elektrostatik. Tiga simulasi telah dijalankan; pertama, mengubah saiz penggerak; kedua, mengubah ketebalan penggerak; ketiga, mengubah bilangan elektrod. Dengan saiz pemutar, ketebalan, jurang, dan bilangan elektrod yang sama, keputusan menunjukkan bahawa penggerak elektrostatik *bottom-drive* mempunyai pretasi yang lebih baik daripada penggerak elektrostatik *side-drive* secara teori.

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CHAPTER 1

INTRODUCTION

1.1 Motivation

Microactuator is a subset of microelectromechanical systems (MEMS) that convert electrical energy to mechanical energy. With advance technologies in microfabrication for MEMS, an efficient and reliable microactuator can be built for various microsystems such as mobile microrobots. Microactuators can be used for development in biotechnology, medicine, communication, inertial sensing and so on. In medicine, microactuators are used for developing microsurgery instruments [1, 2], for example cutters, endoscopes [3] and graspers.

The motivation for this project is to analyse and optimize the best rotary electrostatic actuator for the realization of ideal microsystems and become the best solution for more and more applications.

1.2 Problem Statement

The growth of interest in Micro Electro Mechanical System (MEMS) is rapid nowadays. MEMS consist of micromechanisms such as microstructures, microactuators, microsensors and their control circuits. Types of microactuator used in MEMS include electrostatic, electromagnetic, piezoelectric, shape memory-alloy and so on. Although electromagnetic actuator is widely used in industry, but when in small size scales, electrostatic actuator has the advantages. The fabrication of the electrostatic actuator is simpler than electromagnetic actuator. On the micro scale, the energy densities of electrostatic and electromagnetic actuators are comparable. Therefore, from the performance point of view, the micro scale electrostatic actuators are comparable to the electromagnetic actuators and in particular cases the electrostatic actuators may be better.

1.3 Objectives

The aim of this thesis is the generation of electrostatic force between two different types of rotary motion electrostatic actuator. Therefore, the objectives of this thesis are set as below:

1. To design two types of rotary motion electrostatic actuator.
2. To analyse and optimize the performances of both electrostatic actuator designs in different parameters.

1.4 Scopes

The central focus of this thesis is to figure out which types of rotary motion electrostatic actuator produce the greatest thrust force using Finite Element Method (FEM). To achieve the aim, the task is divided into three main parts:

1. Design two types of rotary motion electrostatic actuator; side-drive electrostatic actuator and bottom-drive electrostatic actuator.
2. Analyse the thrust force and working range of these two designs by using FEM.
3. Optimize the thrust force and working range for both designs by manipulating the size of actuator, actuator thickness, and the number of electrode with FEM.

1.5 Thesis Overview

This thesis is catergorized into five chapters as listed below. The main body of work is included in Chapter 3 and 4, continued by conclusion in Chapter 5.

Chapter 1: The motivation and problem statement of this research are stated which inspired this research issue. In addition, the objectives and scopes of this research are also included.

Chapter 2: This chapter shows the information found in the literature that related to this research. The review of those literatures is evaluated, managed, explained, and summerized. An assessment is then written.

Chapter 3: The mathematical theory of electrostatic force is discussed followed by the working principle of electrostatic actuator and the design structure for two different types of rotary motion electrostatic actuator.

Chapter 4: The simulation results for both side-drive electrostatic actuator and bottom-drive electrostatic actuator are shown in this chapter and the results are discussed.

Chapter 5: This chapter states the summary, relavant conclusions, and some further research of this thesis.

CHAPTER 2

LITERATURE REVIEW

2.1 Electric Machines

Electric machines are the equipment that converts electrical energy to mechanical energy in rotary motion or linear motion. According to Trimmer and Gabriel, Gordon and Franklin built the first electrostatic motors in 1750s, 100 years before magnetic motors [4]. The first capacitive electrostatic motor was developed during Edison's era in 1889 by Zipernowsky [5].

Several types of microactuators have been studied widely such as electromagnetic, piezoelectric, electrostatic, and so on; Table 2.1 shows the working principle of those microactuators that are widely used in industry while Table 2.2 shows the comparison for the drive type of those microactuators.

The operating principle of variable-capacitance is synchronous machines that produce torque due to spatial misalignment of electrodes on the stator and salient poles on the rotor. Trimmer and Gabriel proposed the concept of linear and rotary variable-capacitance micromotors in 1987 [4].

2.2 Actuation Systems

A brief description will be given for each of the classes of actuators and the detail operating principles is shown in Table 2.1.

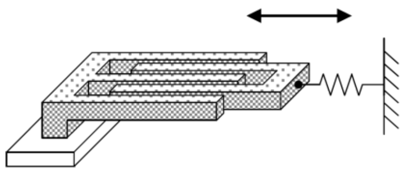
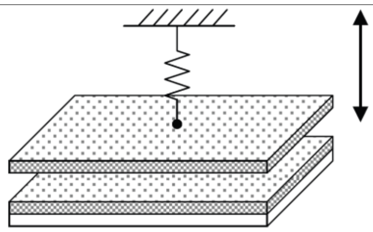
Piezoelectric actuator: The materials of piezoelectric will strain when external electric field is applied. Therefore electric field levels are always limited to a lower value to avoid electrical and mechanical fatigue.

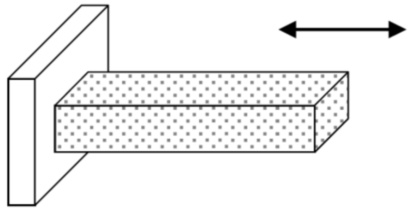
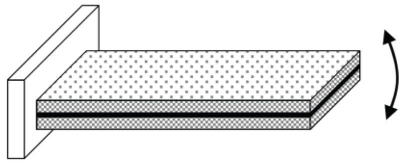
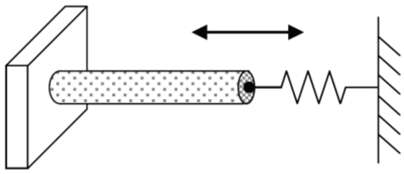
Shape memory alloy actuator: Shape memory alloys are mostly used in form of foil or wire. When shape memory alloys get heated, the length will be reduced; and will back to original length when cooled.

Thermal expansion actuator: The actuation principle for thermal expansion actuator is the opposite way of shape memory alloy actuator. Thermal expansion actuator expands its length when heated and can withstand temperature up to 100 K.

Electromagnetic actuator: Electromagnetic actuator can be divided into three forms: solenoids, moving coil transducers, and motors. Solenoids consist of a high permeability rod and an electromagnetic coil; when the coil is energized, the magnetic field generated will pulls the rod. The actuation principle for moving coil transducers are almost the same with solenoid, the only difference is the moving part is the coil while the rod remains stationary. By using the same principle, motors can produce infinite range of displacements.

Table 2.1: Actuator models

	Actuator	**Geometry**	**Operating Principle**
Electrostatic	Comb drive [11]		Electrostatic force
	Parallel plate [12]		

Thermal	Thermal expansion [13]		Thermal expansion
	Thermal bimaterial cantilever [14]		
Piezoelectric	Piezoelectric bimorph [15]		Converse piezoelectric effect
	Piezoelectric unimorph [15]		
Shape Memory Alloy (SMA)	SMA wire [16]		Thermally induced phase change
	SMA biomaterial cantilever [17]		
	Dielectric elastomer [18]		

After summarizing the actuation principles of different actuator types, the drive range, speed, and response are then compared between linear motion and rotary motion in Table 2.2. From Table 2.2, rotary motion electrostatic actuator has better performances compared with other actuators.

Table 2.2: Comparison of different actuators in different drive types [19]

	Drive type	Drive range	Speed	Response
Electrostatic	**Linear**	Small	Low	High
	Rotary	Large	High	Medium to high
Piezoelectric	**Linear**	Small	Low	High
	Rotary	Large	Low to medium	Low to medium
Electromagnetic	**Linear**	Small to medium	Low to medium	High
	Rotary	Large	Medium to high	Medium to high

In Table 2.3, electrostatic actuator and others actuator are compared from several aspects: maximum deflection, maximum force, speed of actuation and efficiency. The result shows that electrostatic actuator has the minimum deflection, highest speed of actuation, and the highest efficiency.

Table 2.3: Characteristics of various microactuator types [8]

Actuator	Maximum Deflection	Maximum Force	Speed of Actuation	Efficiency (%)
Electrostatic	Low	Low	Very Fast	>90
Piezoelectric	High	Medium	Fast	10-30
Thermal	Medium	Very High	Slow	<5
Shape Memory Alloy	High	Very High	Slow	<5

After a series of comparative studies are presented, it is shown that rotary motion electrostatic actuators have better performance because they can be operated in very high speeds, precise in positioning, large working range and have repeatable movement. However, those research only focus on experimental result of the fabricated electrostatic actuator; therefore this thesis is aim to compare the simulation results of side-drive electrostatic actuator and bottom-drive electrostatic actuator and analyse which drive type of actuator give the better performance.

CHAPTER 3

METHODOLOGY

3.1 Basic Actuation Principle

A fundamental property of electrons and protons is charge. Charged particles can be either positively or negatively charged, and experiments show that same charges repel while different charges attract. The magnitude of the force between the particles is depends on the medium in which the charges are located, and this is taken into account by the factor ε which is known as the permittivity of the medium. The permittivity of a medium is $\varepsilon = \varepsilon_r\, \varepsilon_0$ where ε_0 is a fundamental constant known as the vacuum permittivity which has the value $8.854 \times 10^{-12}\ \mathrm{J}^{-1}\ \mathrm{C}^{2}\ \mathrm{m}^{-1}$ and ε_r is the relative permittivity of the medium. [6, 7]

The tangential force *F* exerted on rotor poles can be estimated using the parallel plate capacitor formula [10]. When a voltage difference is applies between two parallel plates, an alignment force *F* is produced as shown in Figure 3.1.

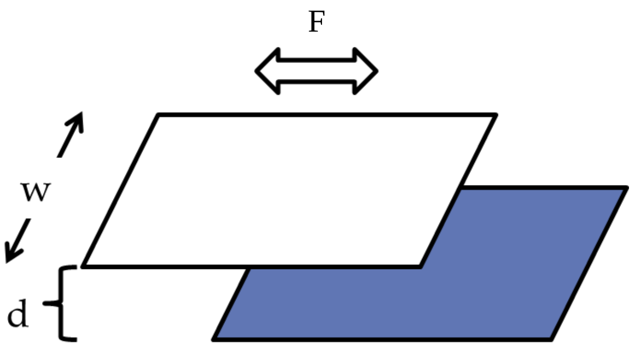


Figure 3.1: Lateral electrostatic force on parallel plate

$$F = n\frac{1}{2}\varepsilon_0\frac{w}{d}V^2 \tag{3.1}$$

Where,

n is the number of active poles in a phase

w is the width of the pole

d is the distance between the rotor and stator poles

ε_0 is the permittivity of air

V is the voltage applied

3.2 Working Principle of Electrostatic Actuator

Stepper microactuator consists of a grounded rotor and a 3-phase stator, both having a large number of teeth-like electrodes. During operation, the rotor electrodes are grounded and the stator electrodes are grouped in three different electrical phases that are symmetrically located around the rotor. Each phase can be activated independently. In the initial position, the electrodes of the first phase are perfectly aligned with the opposite electrodes on the rotor. By applying a voltage difference on one of the misaligned phases, an electrostatic force can be generated. By changing the phase sequences, either clockwise or counter-clockwise stepwise motion of the rotor can be achieved [9].

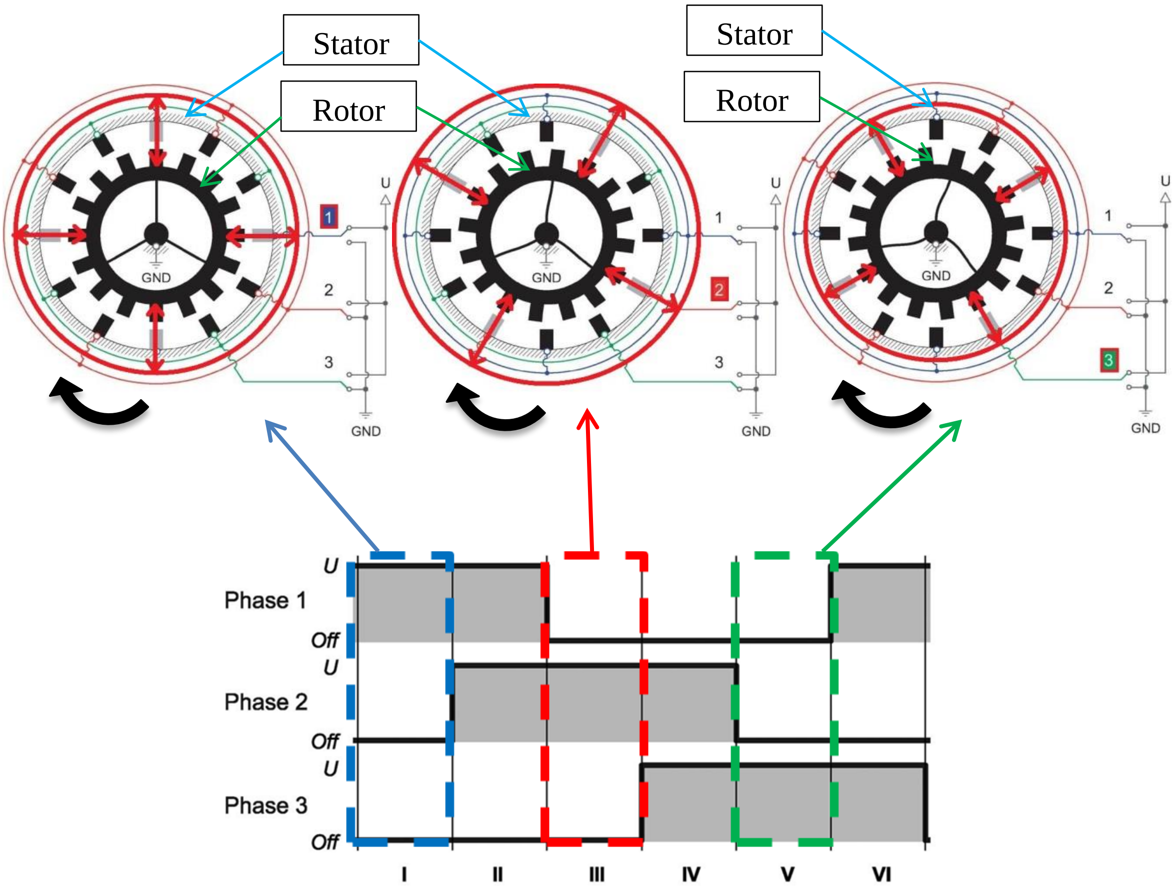


Figure 3.2: Working principle of the three-phase electrostatic rotary stepper motor. In these figures, only a phase is activated at once. (From left to right) Phase 1, phase 2, and phase 3.

3.3 Design structure

Figure 3.3 and Figure 3.5 show the three-dimensional view of two different electrostatic rotary motion actuators that having 12 stators and 16 poles rotor so that it will function as a three-phase motor. In the actuators shown in Figure 3.3 and Figure 3.5, the diameter of rotor is 1.4mm, and the gap between the stator and rotor is 2 µm for both designs. The main dimensions of the designs are listed in Table 3.1. The operation of these actuators relies on the electrical energy stored in the variable capacitances formed between the poles of the rotor and the stator. The stator poles are connected in an alternative sequence with three electrical phases, each phase activates a group of stator independently. When a phase is activated, a voltage difference between the corresponding stator poles and the opposite rotor poles generates an electrostatic force. The electrostatic force tends to realign the poles of rotor with the activated stator poles.

3.3.1 Design 1 (side-drive electrostatic actuator)

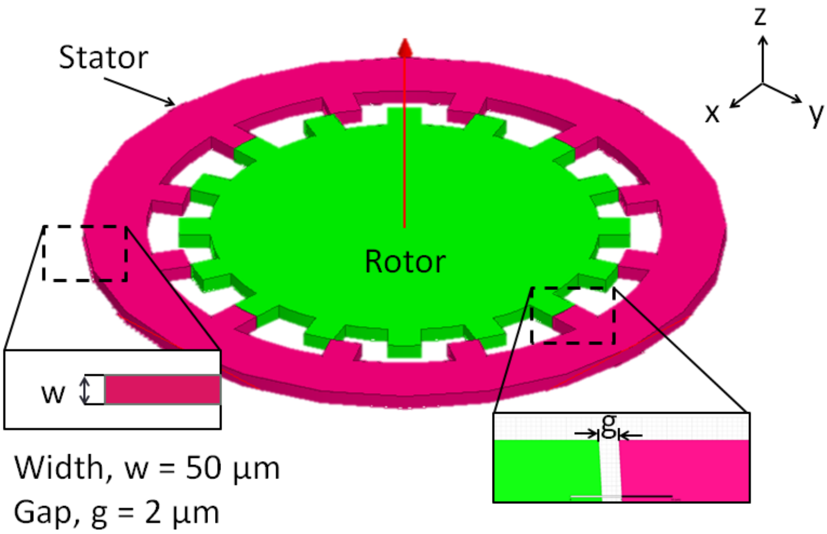


Figure 3.3: Side-drive electrostatic actuator (Design 1)

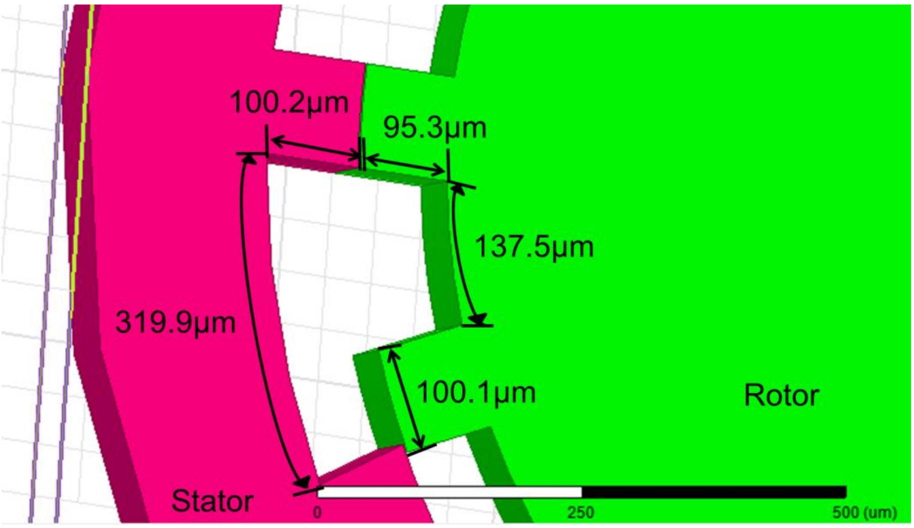


Figure 3.4: Dimensions for Design 1