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FORCE OPTIMIZATION OF AN FORCE ARTIFICIAL MUSCLE ACTUATED UNDERWATER PROBE SYSTEM USING LINEAR MOTION ELECTROSTATIC MOTOR

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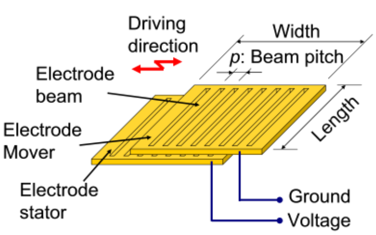
Graphical abstract



Abstract

Two linear electrostatic motors were designed in order to optimize the force characteristics of an artificial muscle actuated underwater probe system. Finite element method (FEM) analyses are used to analyze and optimize the motor's designed parameters. The two structures are designed to be linear-actuated and are compared under similar conditions. The objective of this research is to design, compare and analyze the effect of varying the motor's parameters to the actuation force (Fx). First, the two structures are designed using ANSYS Maxwell 3D; i.e (a) Non-Skew-Type Electrostatic Motor and (b) Skew-Type Electrostatic Motor. Next, the thrust forces were evaluated using Finite Element Method (FEM) analyses in order to optimize the motor's parameters. The FEM analyses are carried out by (i) varying the ratio number of electrode-to-spacer (ii) varying the motor's gap and (iii) varying the motor's size. The FEM analysis shows that the Skew-Type Electrostatic Motor exhibit greater actuation force, 2.7857μN compared to the Non-Skew-Type Electrostatic Motor, 1.7476μN; when the ratio number of electrode-to-spacer is 1.0:2.5.

Keywords: Linear motion, linear motor, electrostatic motor, FEM analysis

Abstrak

Dua motor elektrostatik linear telah direka untuk mengoptimumkan ciri-ciri daya sebuah otot tiruan yang menggerakkan sistem kuar bawah air. Dua struktur direka sebagai penggerak linear dan dibandingkan dibawah keadaan yang sama. Objektif kajian ini adalah untuk mereka, membanding dan menganalisis kesan mengubah parameter motor kepada daya gerakan (F_x). Pertama, kedua-dua struktur direka menggunakan motor elektrostatik. Kemudian, daya tujahan dinilai berdasarkan analisis *Finite Element Method* (FEM) untuk mengoptimakan parameter motor. Analisis FEM dijalankan dengan (i) mengubah nisbah jumlah elektrod kepada peruang (ii) mengubah ruang motor dan (iii) mengubah saiz motor. Analysis FEM menunjukkan bahawa Motor Elektrostatik Condong menghasilkan daya gerakan lebih besar, 2.7857μN berbanding Motor Elektrostatik Tidak Condong, 1.7476μN; apabila nisbah jumlah elektrod kepada peruang ialah 1.0:2.5.

Kata kunci: Gerakan linear, motor linear, motor elektrostatik, analisis FEM

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1.0 INTRODUCTION

Typically, linear motion motors are often utilized in semiconductor manufacturing systems, machine tools, probing systems and scanning probe microscope systems which are often desired to have high positioning accuracy in a short positioning time [1]. The linear motion motors are also desired to generate low heat, have a simple design and are easy to maintain. To date, both piezoelectric motors [2] and electromagnetic motors [1] are typically used for those fine stages. However, the main drawback being that the piezoelectric motors are of a complex structure as they require hinges in order to allow a multiple degree of freedom for the fine stages. Additionally, these hinges become vibration elements. On the other hand, the electromagnetic motors produce a greater thrust force and enable a multiple degrees of freedom motion for the fine stages without utilizing hinges. However, the electromagnetic motors generate high heat [3, 4], which may deform products on the stages and the fine stages themselves. In this paper, the introduction of an electrostatic motor utilized for a fine stage is discussed. The heat generated by the electrostatic motors is essentially much lower than that of the electromagnetic motors. A further benefit is that the electrostatic motors do not require hinges, whereas the piezoelectric motor does.

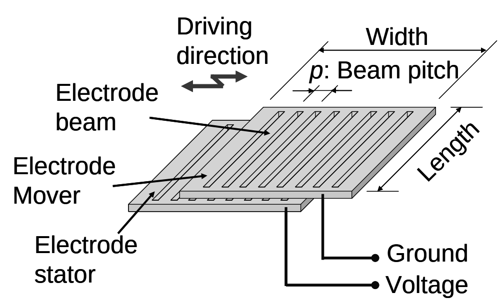
Several types of electrostatic motors i.e. varying capacitance motors have been developed to date [5, 6]. Others include induction motors [5]. For these motors, precise balls are utilized to reduce the frictional effect and also assist in the maintenance of the gap between the electrodes [6]. Ghodssi *et al*. [6] designed and developed a flexible capacitance motor with the use of micro ball bearings in order to maintain a precise gap between the mover and stator layers. These motors show good performances, however the drawback with these methods are that these precise balls typically are more expensive and the system becomes more complex. Industrial utilized systems should be simple and easily maintained as well as cost effective.

The purpose of this research is to optimization the force characteristics of a fish-like artificial muscle actuated underwater probe system using linear motion electrostatic motor, which has a simple structure, is easy to maintain and cost effective. The reciprocating motion of the linear motor, acts similar to fish swimming motion which able to control the probe direction. For the electrostatic motor, the ratio number of electrode-to-spacer, the motor's gap, size of the motor and the applied voltage will effect the generated thrust force. The aim of this paper is to optimize the motors parameters that would generate the best actuation force based on two different linear motor designs. Section 2 deals with the description of the electrostatic motor design, the basic working principle and the comparison of two motor structures; both linearly actuated. Section 3 discusses the comparison of the force characterization and design optimization using FEM analysis when the motor parameters are varied. An overall conclusion is provided in Section 4.

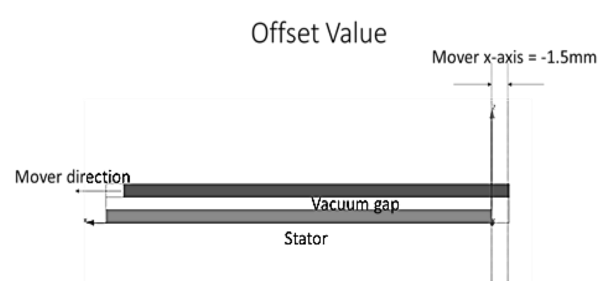
2.0 EXPERIMENTAL LINEAR MOTION ELECTROSTATIC ACTUATOR

2.1 Actuation Principle Variable Capacitance Motor

The type of electrostatic motor in this research is the variable capacitance motor that is useful for a short working range motion, which is suitable to be applied for underwater probing system [7, 8]. The left-right motion of the motor will able to generate forward and backward motion when it's controlled. A general schematic of the motor's structure is shown in Figure 1 (a). The motor consists of a pair of electrodes that have several parallel beams. To realize a bi-directional motion, voltages namely V_1 and V_2 are alternately applied to the Stator A and Stator B, whilst the mover is set to zero (grounded). As the motor is of a simplified structure, it is easy to manufacture. Based on Figure 1(a), the motor structure is drawn using Maxwell 3D. Initially, the offset of mover is set to -1.5mm from the stator in order to generate motion as shown in Figure 1(b). As a basic principle, the overlapping area will increase when voltage is applied, thus generating thrust force or forward motion.



(a) General schematic of the electrostatic motor

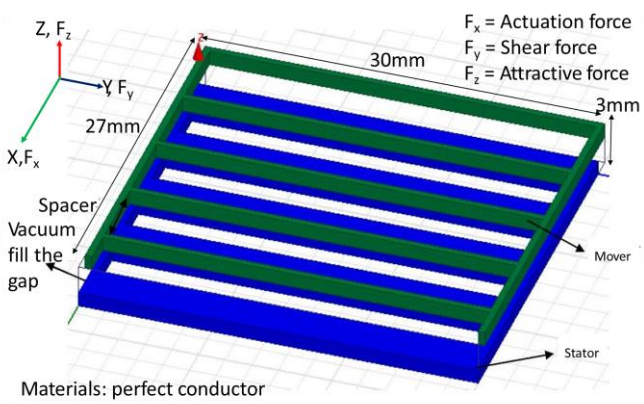


(b) Mover offset distance for actuation

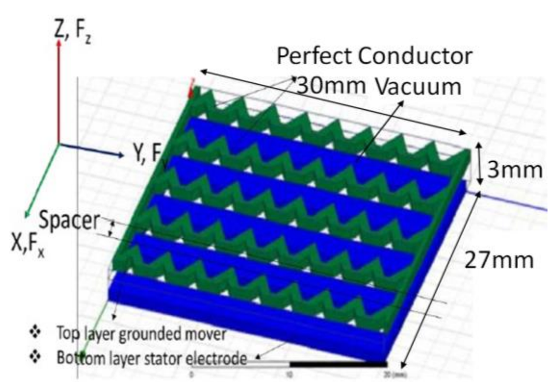
Figure 1 Actuation principle of the linear motion electrostatic motor [7, 8]

2.2 Design Structures: Non-Skew Mover and Skew Mover

In order to compare and analyze the effect of varying the motor's parameters to the actuation force (Fx), two linear structures are designed using ANSYS Maxwell 3D; i.e (a) Non-Skew-Type Electrostatic and (b) Skew-Type Electrostatic Motor. Figure 2 shows the detail structures of the two designs, namely (a) Non-Skew-Type Electrostatic Motor and (b) Skew-Type Electrostatic Motor. The mover of the Non-Skew-Type Electrostatic Motor is design to have a flat pattern compared to Skew-Type Electrostatic Motor which is designed to have a zig-zag pattern for the mover. The skewed design of the electrodes is expected to help reduce torque fluctuation. The x-axis is the desired actuation force direction, y-axis is the shear force, and the z-axis is the attractive force as shown in Figure 2. Initially, for both of the designs the Electrode (E): Spacer (S) ratio is fixed to 1.0:1.0, the size of rotor is fixed to 1.4 mm x 1.4 mm and the gap between the stator and rotor is fixed to 2 μm. The initial dimensions of the two designs are concluded in Table 1.



(a) Non-Skew-Type Electrostatic Motor



(b) Skew-Type Electrostatic Motor

Figure 2 Detail structures of two motor designs

Table 1 Initial design parameters

Parameter	Symbol	Value
Motor size	*r*	1.4mm x 1.4mm
Thickness	*h*	3mm
Electrode: Spacer	*E: S*	1.0:1.0
Gap (rotor-to-stator)	*g*	2μm
Material	-	Bronze

3.0 FORCE CHARACTERISTICS AND DESIGN OPTIMIZATION USING FEM ANALYSIS

In order to optimize the design parameters of the linear motion electrostatic motor, ANSYS Maxwell 3D was used to analyze the electrostatic thrust force of both designs. Simulations are done by varying the motor's parameters using Finite Element Method (FEM) analysis. The parameters varied are (i) motor electrode-to-spacer ratio (ii) motor gap and (iii) motor size.

3.1 Varying Electrode: Spacer Ratio

The Electrode: Spacer ratio of both motors were set to similar six values; i.e 1.0:1.0, 1.0:1.25, 1.0:1.75, 1.0:2.5, 1.75:1:0 and 2.5:1.0 respectively, whilst the gap between the stator and the rotor, thickness and size of motor is fixed to 2 μm, 3 mm and 1.4 mm x 1.4 mm, respectively. The FEM analysis was implemented by applying input voltages to the motor. Figure 3 shows both the structures of the Non-Skew-Type Electrostatic Motor and Skew-Type Electrostatic Motor with different Electrode: Spacer ratio.

Figure 4 shows the relationship between the motor Electrode: Spacer ratio, applied voltage and the generated electrostatic force. From Figure. 4, it can be concluded that for both skew type mover and non-skew type mover, increasing of spacer width will result in larger actuation force, such that ratio of E:S=1.0:2.5 creates larger actuation force. Higher ratio will generates the smaller thrust force; which is an advantage for the motor; i.e stator or mover plates will not easily bent due to attractive force. However, the shear force of the motor at ratio E:S=1.0:2.5 will be largest. The mover will tend to move perpendicularly to the desired direction, thus increasing the friction between the electrodes. This problem may be overcome if the mover surface has a smooth finish surface; i.e. low friction surface. Therefore, it can be concluded that electrostatic force depends on the overlapping area between the stator and the rotor electrodes. By comparing Figure. 4(a) and (b), the electrostatic force of Skew-Type Electrostatic Motor is higher than the electrostatic force of Non-Skew-Type Electrostatic Motor because of the larger overlapping area of the motor.

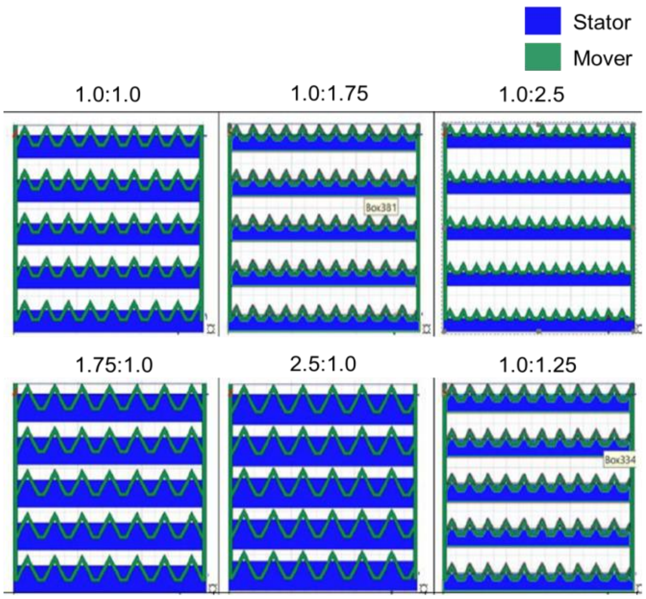
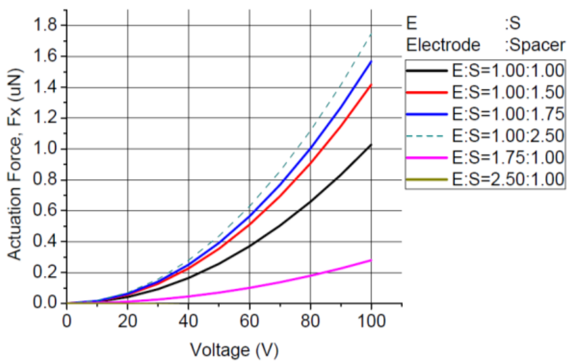
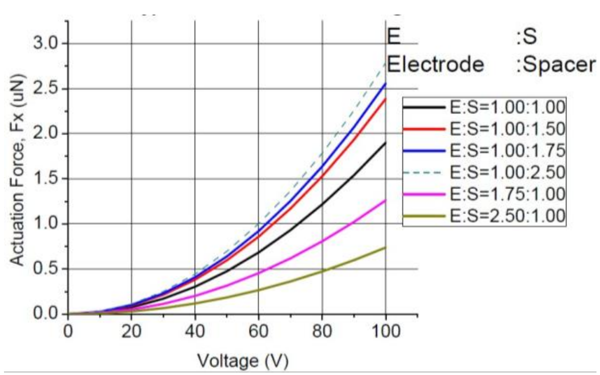


Figure 3 Structure of the skew-type electrostatic motor when the electrode: spacer ratio is varied



(a)Non-Skew-Type Electrostatic Motor

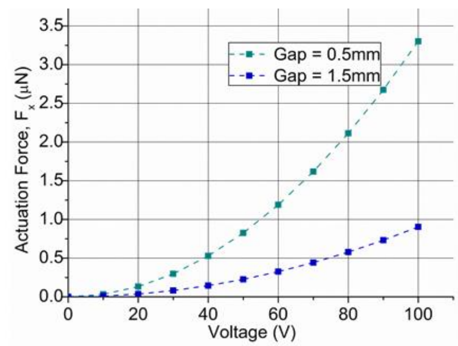


(b)Skew-Type Electrostatic Motor

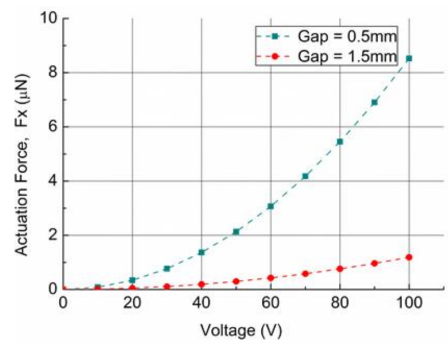
Figure 4 Comparison of the generated thrust force between the two designs when the Electrode: Spacer ratio is varied and evaluated with different input voltages

3.2 Varying Gap

The gap of both motors were set to two values; i.e 0.5 mm and 1.5 mm respectively, whilst the Electrode: Spacer ratio between the stator and the rotor, thickness and size of motor is fixed to 1.0:2.5, 3 mm and 1.4 mm x 1.4 mm, respectively. Figure 5 shows the relationship between the gap of the motor, applied voltage and the generated electrostatic force. From Figure 5, changing the gap thickness of Skew-Type Electrostatic Motor does affect the electrostatic force produced because the area overlapping depends the motor's thickness. By comparing Figure 5(a) and (b), the electrostatic force of Skew-Type Electrostatic Motor is higher than the electrostatic force of Non-Skew-Type Electrostatic Motor.



(a)Non-Skew-Type Electrostatic Motor

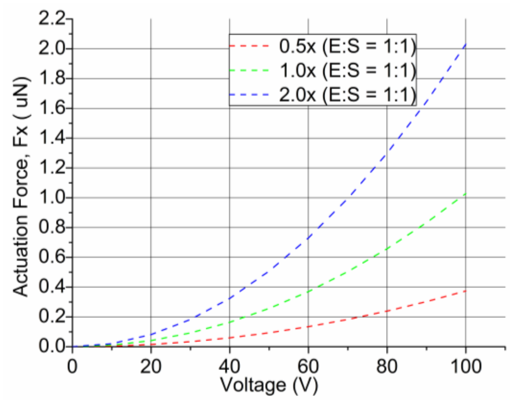


(b)Skew-Type Electrostatic Motor

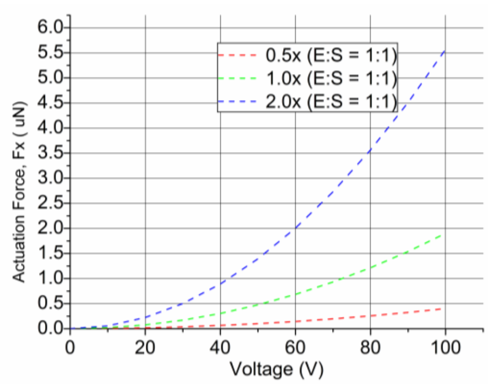
Figure 5 Comparison of the generated thrust force between the two designs when the gap is varied, evaluated with different input voltages

3.2 Varying Size

The size of both motors were set to three values; i.e 0.5x, 1.0x and 1.5x, whilst the Electrode: Spacer ratio between the stator and the rotor, thickness and gap of motor is fixed to 1.0:2.5, 3 mm and 3 mm, respectively. From Figure 6, it can be depicted that, as the size of motors decreases, the overlapping area between the rotor and the stator electrodes will also decreased, which results in lower thrust force. By comparing Figure 6(a) and (b), the electrostatic force of Skew-Type Electrostatic Motor is higher than the electrostatic force of Non-Skew-Type Electrostatic Motor because of the overlapping increases.



(a)Non-Skew-Type Electrostatic Motor



(b)Skew-Type Electrostatic Motor

Figure 6 Comparison of the generated thrust force between the two designs when the gap is varied, evaluated with different input voltages

4.0 CONCLUSION

The overall results show that in terms of the generated electrostatic thrust force, the Skew-Type Electrostatic Motor has more advantages compared to the Non-Skew-Type Electrostatic Motor. Based on the FEM analysis results, both the size, electrode: stator ratio and gap affect the generated electrostatic force of the Skew-Type Electrostatic Motor significantly. As a conclusion based on Table 2 shows the general comparison of Skew-Type Electrostatic Motor and Non-Skew-Type Electrostatic Motor. The force and changes of force during the motor offset equivalent to -1.5 mm. Although skew type mover has lower actuation force, but it moves smoothly; compared to non-skew mover which has high actuation force but moves like stepping motion.

Table 2 Summary of general comparisons of FEM analysis results

Parameters	Skew mover	Non-skew mover
F_x	Small	Large
ΔF (during motion)	Relative small	Quite large
Ripple	High	Low
Smoothness	Best	Low
F_z (attraction between plates)	Small	High

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