Design and Simulation of a Three-Phase Electrostatic Cylindrical Rotary Micromotor

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ABSTRACT
Nowadays the electrostatic motor finds frequent use in micro-electro-mechanical systems (MEMS) where their drive voltages are below 100 volts. Using moving charged plates in capacitor motors are far easier to fabricate than coils and iron cores. This paper presents a novel design of a three-phase electrostatic rotary motor. It is shown that the angular velocity of the cylindrical type motor is almost 1.8 times greater in comparison with parallel plate type and as the voltage increases the enhancement of slope rate in the angular velocity of the cylindrical type is more tangible compared to the parallel plate type. The effect of changing the gap between rotor and stator on the angular velocity is also studied.

Key words: Cylindrical capacitors, Electrostatic, Micro-motors, MEMS, Design, Angular velocity

1. INTRODUCTION
Since 1980 several kinds of electrostatic motors have been studied and fabricated. Electrostatic motors are introduced as one of the most promising micro-electro-mechanical actuators for some reasons. Firstly, the planar structure in these motors is highly compatible with lithography processes in integrated circuits. Secondly in the micro scale, the electrostatic motors are stronger than electromagnetic actuators because the force per volume ratios of electrostatic actuators increases as their dimension decrease [10,1,3,7].

In modern technology we are facing an increasing demand for MEMS technology. Micromotors and microgenerators are power MEMS systems for energy conversion between mechanical and electrical domains [4]. Various types of electrostatic micromotors have been introduced in the past. Vinhais et al. proposed an electrostatic side drive motor. They demonstrated that the torque increases with larger rotor radius, smaller gap between rotor and stator and bigger rotor teeth and stator electrodes widths [11]. Ghalichechial et al. reported the design, fabrication and characterization of a rotary micromotor supported on microball bearings. The microball bearing technology provides a uniform and small air gap and a robust mechanical support for the rotor. It must be fabricated with a coating of silicon carbide film to reduce the friction otherwise the operation is not possible [4]. Sarros et al. described the cylindrical and conical electrostatic wobble micromotors and their advantages. Conical design eliminates the need for a long pivot bearing and substantially reduces the size of the motor [9]. Rotor pole shaping (RPS) design technique is also used to optimize the rotor pole slope to maximize the driving torque. The significant low driving voltage makes the integration of electrostatic micromotors possible with CMOS as a driving voltage circuit [2]. To avoid any frictional contact during operation, providing precise, repeatable and reliable bidirectional stepping motion without
feedback control, a flexural suspension of the rotor is employed in a three-phase rotary stepper micromotor [8].

Even though, manufacturing of the micromotors has received a great deal of attention, there are only a few studies about cylindrical design of electrostatic rotary micromotor. Thus, in this paper, for the first time we proposed a novel cylindrical design for micromotors to increase the angular velocity for high speed applications. To investigate the advantages of cylindrical capacitors, the mechanical characteristics of our proposed design is compared to the conventional parallel plate capacitors. The rest of the paper is organized as follows: in section II the mathematical modeling of cylindrical design is discussed. In the next sections the simulation results for the proposed design and comparison study between two models is presented.

2. MATERIAL AND METHODS
2.1 Mathematical Modeling
2.1.1 Cylindrical Capacitors
In the proposed design for micromotor, cylindrical capacitors are used instead of parallel plate capacitors. Figure 1 depicts a cylindrical capacitor with a solid cylindrical conductor of radius $a$ and charge $q$ that is coaxial with a cylindrical shell of negligible thickness that has radius $b > a$ and charge $-q$. In this case the lengths of the capacitors $L$ should be much greater than radius $b$, thus we can neglect the fringing effect of the electric field that occurs at the end of the cylinder [5]. In the following formulation $\varepsilon_r$ is the relative permittivity of the material.

$$E = \frac{q}{2\pi \varepsilon_r \varepsilon_0 r L}$$

The potential difference between the two cylinders is calculated by:

$$V = \int \limits_a^b \left[ E ds = -\frac{q}{2\pi \varepsilon_r \varepsilon_0 L_a} \right] dr = \frac{q}{2\pi \varepsilon_r \varepsilon_0 L} \ln \frac{b}{a}$$

Capacitance is calculated by:

$$C = \frac{q}{V}$$

Thus we have:

$$C = 2\pi \varepsilon_r \frac{L}{\ln \frac{b}{a}}$$

Electric potential energy can be expressed as [6]:

$$U = \frac{1}{2} CV^2$$

So it can be calculated as:

$$U = \frac{1}{2} \left( 2\pi \varepsilon_0 \varepsilon_r \frac{L}{\ln \frac{b}{a}} \right) W^2$$

2.1.2 Driving Force for Pole Misalignments

The following equation can be used to derive the electrostatic forces in the direction in which misalignment occurs [6]:

$$F_i = -\frac{\partial U}{\partial x_i}$$

Figure 2 is the schematic model of our proposed design for the rotary micromotor. The misalignment of the electrodes is in the $L$ direction, thus by calculating the partial derivative of $U$ with respect to $L$ we obtain:

$$F_L = \frac{\pi \varepsilon_0 \varepsilon_r}{\ln \frac{b}{a}} V^2$$
$F_t$ is the driving force to rotate the micromotor. In the primary design there are 6 poles on the rotor and 8 poles on the stator. The rotor poles are connected in an alternating sequence with three distinct electrical phases. Each phase activates one third of rotor poles independently. When a given phase is activated, a voltage difference between the corresponding rotor poles and the opposing stator poles generates an electrostatic force. However the radial component of the electrostatic force acting on the rotor is canceled due to the symmetry, the tangential component generates a global torque. The electrostatic torque tends to realign the poles of the stator and the activated rotor phase [2].

The tangential force $F_{t,j}$ exerted on a single rotor pole $j$ can be estimated using the cylindrical capacitor as follows:

$$F_{t,j} = \frac{\pi \epsilon_0 \epsilon_r V_j^2}{\ln \left(\frac{b_j}{a_j}\right)}$$  \hspace{1cm} (10)

Where $V_j$ is the voltage applied on the associated phase.

![Figure 2 The schematic model of our proposed cylindrical rotary micromotor](image)

### 2.1.3 Driving Torque for Micromotor Rotation

The electrostatic torque $T_i$, applied on the rotor by one phase is:

$$T_i = \sum_{j=1}^{n} F_{t,j} r = n r \frac{\pi \epsilon_0 \epsilon_r V_j^2}{\ln \left(\frac{b_j}{a_j}\right)}$$  \hspace{1cm} (11)

By putting $T_i = I \alpha$, where $I$ is the mass moment of inertia and $\alpha$ is the angular acceleration of the rotor, the angular velocity of the rotor can be calculated. $n$ is the number of active poles per phase.

### 2.2 Simulation Characteristics

The dimensions of two proposed motors are listed in Table 1. To achieve an implicit comparison, the dimensions of proposed cylindrical motor are assumed equal with the parallel plate capacitor motor. For simulating the real function, 192 poles are placed on the rotors. Silicon is chosen for motor material.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Quantity</th>
<th>Cylindrical capacitor motor</th>
<th>Parallel plate capacitor motor</th>
</tr>
</thead>
<tbody>
<tr>
<td>$r$</td>
<td>Rotor radius</td>
<td>450 $\mu$m</td>
<td>450 $\mu$m</td>
</tr>
<tr>
<td>$b$</td>
<td>Rotor poles radius</td>
<td>50 $\mu$m</td>
<td>-</td>
</tr>
<tr>
<td>$g$</td>
<td>Gap between rotor and stator</td>
<td>1.25 $\mu$m</td>
<td>1.25 $\mu$m</td>
</tr>
<tr>
<td>$n$</td>
<td>No. of active poles per phase</td>
<td>64</td>
<td>64</td>
</tr>
<tr>
<td>$V$</td>
<td>Voltage applied to each phase</td>
<td>100 V</td>
<td>100 V</td>
</tr>
<tr>
<td>$\rho_m$</td>
<td>Motor material density</td>
<td>2330 $kg/m^3$</td>
<td>2330 $kg/m^3$</td>
</tr>
<tr>
<td>-</td>
<td>Ratio of poles in stator to rotor</td>
<td>4/3</td>
<td>4/3</td>
</tr>
</tbody>
</table>

### 3. RESULTS

While some parameters of the motors are changed the angular velocities of both types of motors are calculated and the result is as below:

#### 3.1 Effect of Altering the Voltage on Angular Velocity

The angular velocity of both type of motors for different voltages are calculated. Figure 3 depicts the behavior of motors as the voltage increases. It can be seen that the cylindrical type motor produces a greater value of angular velocity than the parallel plate type. The angular velocity of the cylindrical type motor is almost 1.8 times greater in comparison with parallel plate type. This is due to the difference between magnitudes of constant parameters in cylindrical and parallel plate motor.
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capacitor formulas. Furthermore, it is apparent that as the voltage increases, the angular velocity of the cylindrical type has a sharper increase compared to the parallel plate type.

4. CONCLUSION
A novel design of a three-phase electrostatic rotary micromotor was proposed. The proposed cylindrical type micromotor is compared to the conventional parallel plate type. It was shown that an electrostatic micromotor using cylindrical capacitor produces a larger value of the angular velocity compared to parallel plate capacitors. The angular velocity of the cylindrical type motor is almost 180 percent greater than that of parallel plate type. It is shown that as the voltage increases the angular velocity of the cylindrical type has a sharper increase compared to the parallel plate type. The effect of altering the gap between rotor and stator is also studied. It can be seen that as the gap between rotor and stator increases the angular velocity decreases and the rate of decrement is slower in the parallel plate type. The advantages of our proposed cylindrical capacitance micromotor make it suitable for design optimization of micromotors for high speed applications, namely microdrilling.

5. REFERENCES