321. Design Considerations of a Microelectrostatic Motor

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Abstract. This work analyses influences of geometry of the micromotor on its performance. Using finite element modeling (FEM) a detailed study of electrostatic force fields between two interacting poles and developed moment of rotation is done. The results received are expanded to the whole motor design where its control and torque characteristics are evaluated. Finally, optimal motor construction conclusions are drawn and new motor is produced by UV lithography.

Keywords: MEMS, micromotor, microelectrostatic, electrostatic, modeling, FEM, simulation.

Introduction

Microelectromechanical systems (MEMS) are devices, ranging in size from a micron to a centimeter that combine mechanical and electrical structures. MEMS are the next logical step in the silicon revolution that began over three decades ago, with the introduction of the first integrated circuit. As the smallest commercially produced "machines", MEMS devices are similar to traditional sensors and actuators although much, much smaller. Complete systems are typically a few millimeters across, with individual features of the order of 1-100 micrometers across [1].

One of the more common MEMS devices is micromotor which is analyzed here. The first variable capacitance electrostatic motors with diameters of 60–120 μm were developed by Fan et al. in 1989 at the University of California at Berkeley [3]. Micromotor is an important mechanism capable of creating rotary motion at microscale. Though this type of actuator is not very popular, because it has complicated dynamics and there are very few publications about its research.

Simplified electrostatic – mechanic scheme

First, an interaction between two oppositely charged bodies (micromotor poles) has to be analyzed. A 2D Cartesian space will be used, where one pole is immovable (stator pole) and the other one (rotor pole) can move along an axis without energy losses.

If the poles were point charges, the movable body would tend to get as close as possible to the unmovable body, fig. 1. Similar results happen when two comparable size poles interact: their equilibrium point is reached when centers of both poles align, fig. 2. Normal force F_y does not create motion in the system, whereas tangential force F_x is responsible for lateral movement.

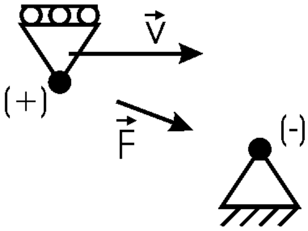

Fig. 1. A force created between two oppositely charged point masses

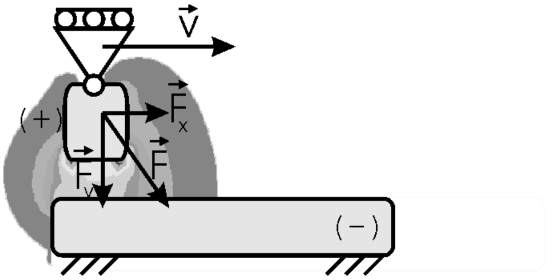

Fig. 2. A simplified electrostatic – mechanic scheme of two oppositely charged poles

Increase in size of poles does not increase tangential force. This is proved by splitting bodies into finite elements. Each element attracts opposite element with force that depends on the square distance between them, according to Coulomb's law. Thus, the bigger is the distance, the smaller is the force. Elements A1 and A2 are attracted to all B elements with some specific tangential forces, fig. 3. But tangential forces between A3, A4, A5 and all B elements cancel out, fig. 4. Though normal force increases between bigger poles, tangential force remains nearly the same. Tangential force can be increased only by increasing potential difference or by decreasing the distance between poles. In a 3D space tangential force can be increased by increasing the area of interacting planes.

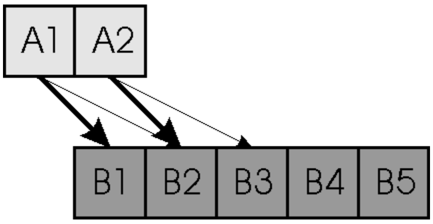

Fig. 3. FEM modeling of poles of different sizes. B4 and B5 segments are attracted with only very small force as compared to B1 and B2

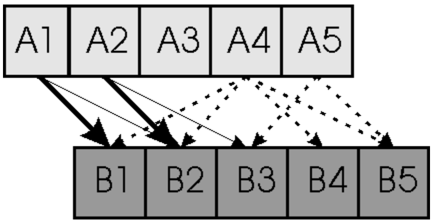

Fig. 4. Attraction between equal size poles. Segments A1, A2 create most tangential force, while the other ones cancel out or act oppositely

Motor geometry

Different micromotor designs are possible depending on required accuracy, speed of rotation, power, etc. Theoretically, a motor can work using any number of stator and rotor poles, but practically the best solution is to interconnect stator poles to produce three phases. Two phases are not enough to determine the direction of rotation. Four phases are not necessary because they make control electronics and motor design complicated without any obvious advantages. Thus, the number of stator poles needs to be a multiple of three: 3, 6, 9, 12, etc.

In order to analyze physics between stator and rotor poles, a complete 2D ANSYS model of the system was created, where potential difference, distances and geometry of rotor and stator can be easily varied. The program simulates developed electrostatic field at any specified angular step between the rotor and an active stator pole and outputs quantitative value of produced torque, fig. 5.

Moment of rotation produced by a pole

In order to obtain moment of rotation as a function of rotor position, the electrostatic energy must first be calculated. It can be found by performing electrostatic field analysis for each rotor position where the stored energy in the electric field is evaluated by

$$W(\theta) = \frac{1}{2}\varepsilon \iiint E^2 dV \qquad (1)$$

where ε is electric permittivity of surrounding medium, E is the electric field intensity and V is the potential difference between the stator and rotor conductors [6].

Each new rotor position requires a new mesh generation. After a set of energy-angle points is obtained, a continuous curve is fitted to them by interpolation techniques, and then the energy vs. angle curve is found.

If centers of stator and rotor poles are aligned, no moment of rotation is produced. This position is assumed to be of a zero degree angular difference. As the angular difference is increased, the moment of rotation increases and then gradually drops down. The drop is a result of an interaction between the stator pole and adjacent rotor pole, fig. 6. A full pole cycle starts at zero tangential force when poles are aligned and ends also at zero tangential force in a middle between two rotor poles. Thus, the cycle of a single pole is always equal to $360°/RotorPoles$. The angle taken by a rotor pole is designated by $\angle\mu$, rotor pole gap - $\angle\rho$ and stator pole - $\angle\sigma$, fig. 7. All stator and rotor radiuses are kept constant in further analysis if not specified expressly.

Torque curve is different depending on the ratio between sizes of rotor pole $\angle\mu$ and rotor pole gap $\angle\rho$. In order to get maximum torque, the integral of the curve needs to be as big as possible.

When the pole cycle is kept constant and the size of rotor pole is varied, FEM analysis shows that the highest moment of rotation integral curve is created when

$$\angle\mu / \angle\rho \approx 0.9 \ldots 1.0 . \qquad (2)$$

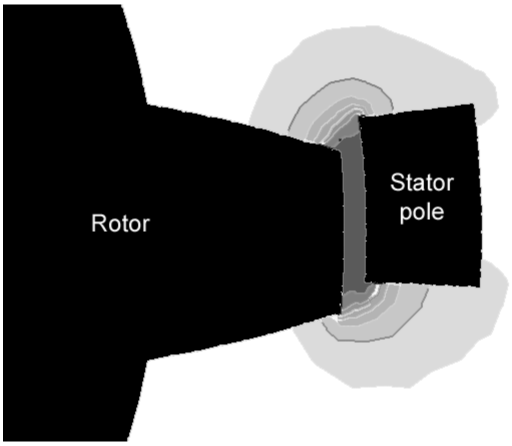

Fig. 5. FEM modeling of electrostatic field between rotor and stator poles

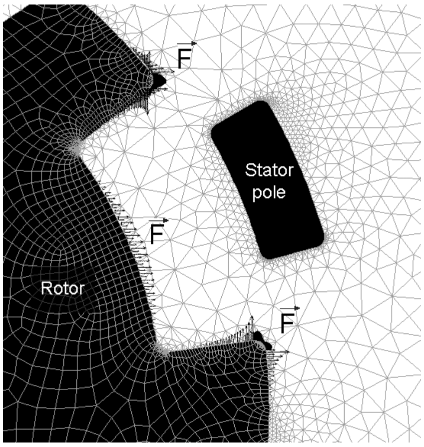

Fig. 6. Electrostatic forces developed when stator pole is in the middle of two rotor poles

Based on previous results $\angle\mu = \angle\rho$. In this case, when rotor size is varied the pole cycle is no longer constant. Once again, the best results are achieved when all three angles are nearly equal, fig. 9. It is important to note that though integral is biggest for the last curve *("2.0")* its average value is lower than the others. The optimal curve should have highest average and integral values.

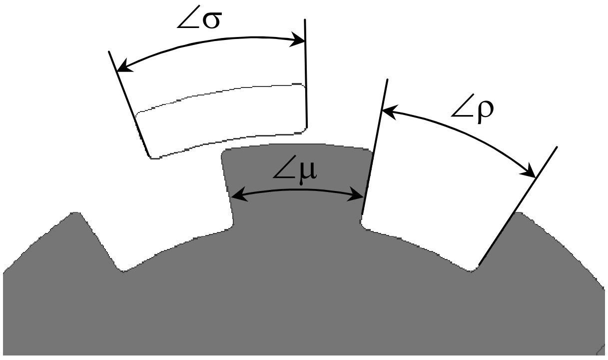

Fig. 7. Dimensions used in analysis

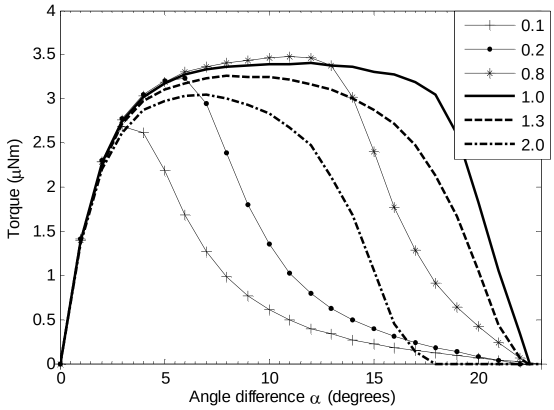

Fig. 8. Torque created by a single pole. Curves represent ratios between rotor pole and rotor pole gaps

Thus the final pole geometry conclusion is that all specified dimensions have to be equal to get the maximum torque:

$$\angle\mu = \angle\rho = \angle\sigma\,. \tag{3}$$

Depending on the number of poles a rotor has, the torque produced by a pole can vary significantly, fig. 10. The integral is directly proportional to the size of pole; also the peak value is slightly higher for bigger poles.

Finally, FEM analysis was carried out to determine the influence of stator-rotor gap, fig. 11. It appears to be inversely proportional, thus by decreasing the gap twice the toque will increase twice, fig. 12.

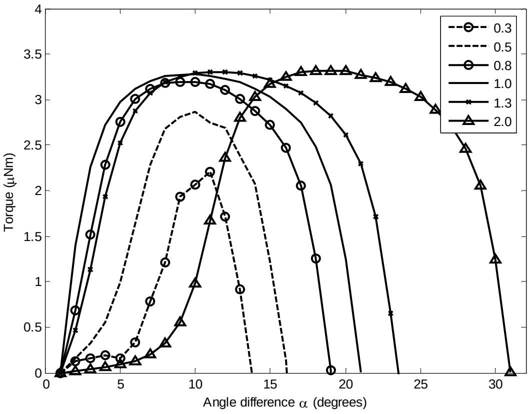

Fig. 9. Torque created by a pole having the defined ratio between rotor and stator pole sizes

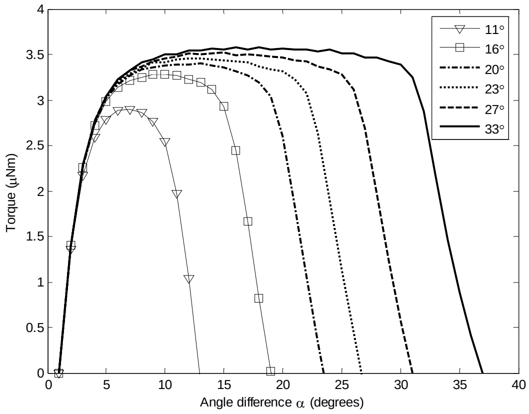

Fig. 10. Torque created by a single rotor pole of a specified angular size

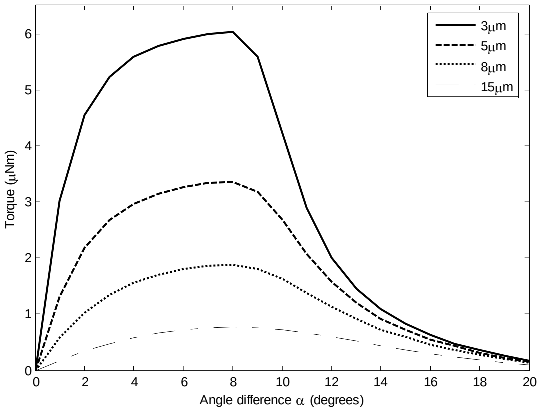

Fig. 11. Torque created by a motor having specified gap between rotor and stator

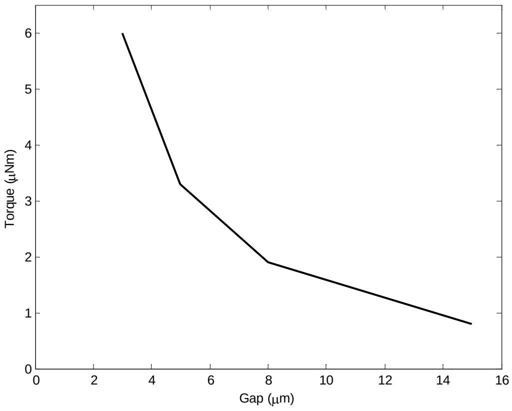

Fig. 12. Dependence between torque and stator-rotor gap

Torque produced by a motor

A MATLAB program was created to evaluate performance of motors having different geometries. The program displays sequence of how stator poles are energized, required number of phases, periods, duty cycles, minimal angular difference graph and finally, momentum and average motor torques, fig. 13. Thus, any motor construction can be quantitatively analyzed.

The following motor construction conclusions were made:

1. By increasing the number of rotor poles, the torque slightly decreases. For example, if the number of rotor poles is increased 2,5 times, the average torque decreases by 15%.
2. A change in stator poles gives a proportional change in torque. For example, by increasing the number of poles twice of a three-phase motor, the torque will increase twice, also.

Thus, irrelevantly of number of phases, the biggest torque is created when the number of stator poles is largest and the number of rotor poles is smallest.

Based on the results of previous FEM analysis, the motor design can have two tendencies:

1. Small number of poles, small torque, simple construction and electronics. This motor would have 3 or 6 rather big stator poles, fig. 15.
2. Large number of poles, high torque, complicated construction and electronics. Such a motor would have 9 and more small stator poles, fig. 16.

Conclusions

MEMS are small devices that perform mostly the same functions as their macroscopic counterparts. There is a big difference in manufacturing and maintenance of these devices.

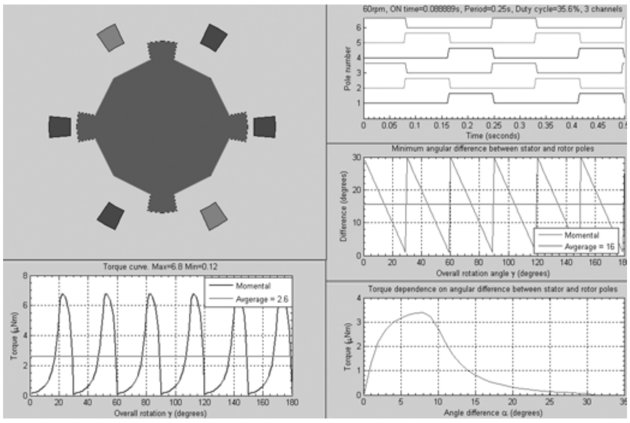

Fig. 13. A MATLAB program for micromotor analysis

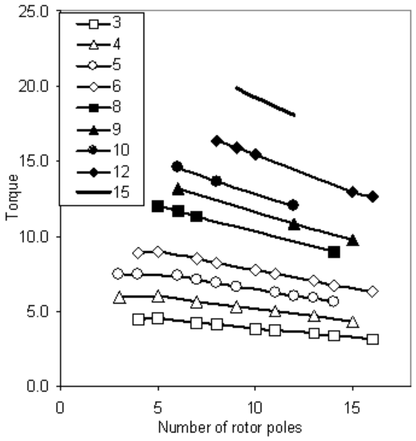

Fig. 14. Torque dependence on the number of rotor and stator poles

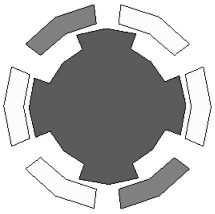

Fig. 15. Simple construction motor: 3 phases, 6 poles. Two opposite poles are energized simultaneously

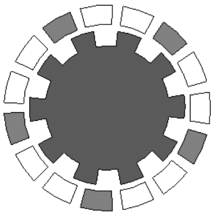

Fig. 16. More complicated construction motor: 3 phases, 15 poles. Five poles are energized simultaneously

Optimal conditions for the motor design were established:

- Angles taken by rotor pole, rotor pole gap and stator pole have to be equal.
- The number of rotor poles should be a factor of 3 and interconnected to three phases.
- Torque increases when the number of stator poles is increased.

- Torque slightly increases when the number of rotor poles is decreased, thus it has to be as small as possible.
- The gap between stator and rotor poles has to be as small as possible.

According to these conditions, new micromotors were produced for further experimental analysis and evaluation of theoretical analysis.

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