Field simulation of the elevation force in a rotating electrostatic microactuator

P. Di Barba, A. Savini, S. Wiak

Department of Electrical Engineering, University of Pavia, I-27100 Pavia, Italy
IMET, Technical University of Lodz, 90-924 Lodz, Poland

Abstract

During the last decade, a renewed interest has grown about electrostatic motors in the microscopic scale, owing to the impressive developments in the technology of integrated electrostatics. Since friction has a crucial effect on micromotors efficiency, from the designer viewpoint it is important to identify new device geometries able to improve the mechanical response. After discussing the major sources of friction in a rotating microactuator, a case study is presented; in particular, a geometry reducing the dry friction is identified and discussed.

1 Introduction

In principle, if a mechanical system is scaled down by a factor of $10^2$, mass - and hence inertial and gravitational forces - decrease by a factor of $10^0$. Forces scaling as the area of the system, such as electrostatic interaction, will decrease by a factor of only $10^4$. As a result, the ratio of electrostatic forces to inertial ones increases by a factor of $10^2$; this seems a robust motivation to use electric field as the basis for actuation in devices featured by sub-millimetric size. On macroscopic size scale, electromechanical systems based on electric fields are less suited to industrial applications than systems based on magnetic fields, but in the microscopic world this is no longer true. Strong electric fields can be produced by low voltages and exhibit a breakdown field up to $10^8$ V m$^{-1}$ in air. Motion in electric motors is actually created as a result of electric forces acting on mechanical structures; devices of this type have been operated from voltages in excess of $10^3$ V, much higher than those suitable to supply electromagnetic motors, and currents smaller than $10^{-9}$ A.

These considerations show quite clearly that electrostatic micromotors possess a number of attractive properties, that will make such devices increasingly more important in the field of science, engineering and technology in the near future. Electrostatic micromotors, having e.g. rotors with a diameter from 100 to 200 µm, have been fabricated and driven to continuous rotation. The fabrication of these devices is based on processes derived from Silicon integrated-circuit techniques; however, tests on prototypes have shown that friction plays a dominant role in the dynamic behaviour of micromotors. Observed rotational speeds are a small fraction of the speed achievable if only natural frequency
were to limit the mechanical response. Though the fabrication of electrostatic microactuators is technologically feasible, the mathematical modelling of microdevices is likely to be important in the development of new design criteria. The development of accurate models (see e.g. [1]) makes it possible to predict in a quantitative way the electromechanical performance of a micromachined device, so aiming at the optimization of the design.

2 Friction in electrostatic micromotors

In the operation of a micromotor, static friction represents the most important contribution to the mechanical losses [2,3]. Following the equivalent-circuit approach, a friction torque $T_f$ can be defined, summarizing the main mechanisms of drag:

$$T_f = k_1 + k_2 V^2$$

where $V$ is the supplied voltage and

$$k_1 = f (W + f_{a1}) R_a$$
$$k_2 = f (f_{a2} R_a + f_r R_{ax})$$

In relationship (2), representing the voltage-free loss, $f$ is the friction coefficient or the rotor material (polysilicon onto the substrate) while $W$ is the rotor weight and $f_{a1}$ is the axial force due to charges induced by triboelectricity. Both $W$ and $f_{a1}$ are forces applied to the hemispherical bushings that support the rotor at a radial distance $R_a$. On the other hand, relationship (3) accounts for the eddy polarization of the rotor. In particular, $f_{a2}$ is the axial force (p.u. of squared voltage) simulating the effect of a native oxide layer between rotor and substrate; $f_r$, in turn, is the radial force (p.u. of squared voltage) due to the radial displacement of the rotor, namely the side-pull effect. The latter force is applied along the boundary of the motor axle having radius $R_{ax}$.

Identifying the dependence of each friction terms on the device geometry is actually a challenging and difficult task for the designer.

3 Case study: the Berkeley prototype

The device considered [4] is a variable-capacitance side-drive micromotor, characterized by twelve stator poles (electrodes) and four rotor teeth. The electrical supply provides a three-phase system of rectangular voltages equal to 200 V, so that every third stator pole is electrically connected to the same phase; the rotor is internally connected to the ground. Two dielectric layers are attached to the boundary of both rotor teeth and stator poles along the air gap. These layers - made by $Si_3N_4$ and 340 nm thick in the radial direction - exhibit a
relative permittivity equal to 3.8; they act as dielectric spacers providing wear protection for rotor and stator. In Fig. 1 the cross-section of the device is represented.

![Symmetry axis diagram](image)

Figure 1: Simplified cross-sectional view (one quarter) of the motor (linear dimensions in \(\mu m\)).

4 Axial field geometry and elevation force

Since dry friction influences in a dramatic way the mechanical performance of the micromotors, from the designer viewpoint it is important to improve the geometry of the device in order to reduce frictional losses, so increasing its starting torque. A kind of configuration has been proposed [4] in which the stator electrodes are slightly displaced in the upper axial direction; in this way an axial component of electric field takes place and gives rise to a force pulling up the rotor body. By varying the axial displacement of electrodes, the electrostatic interaction between stator and rotor also varies so that, in principle, identifying an optimal configuration could be possible.

To obtain the numerical simulation of the electric field, the region represented in Fig. 2 has been considered and the finite-element method was used to solve the Laplace equation of electric potential \(v\), subject to the following boundary conditions:

\[
\begin{align*}
v &= 0 \quad \text{along } \Gamma_1 \\
v &= 200 \text{ V} \quad \text{along } \Gamma_2 \\
\frac{\partial v}{\partial n} &= 0 \quad \text{along } \Gamma_3
\end{align*}
\]
It may be useful to note that there is no groundplane underneath rotor and stator; two dielectric layers are present with relative permittivity equal to 3.8 (Si$_3$N$_4$) and 3.9 (SiO$_2$), respectively.

A dense axisymmetric grid, composed of nearly 1100 triangular elements, was then generated simulating a pair stator electrode - rotor tooth. The procedure of field analysis has been repeated, for different axial displacements of the electrodes with respect to the rotor. At each relative position the corresponding value of total energy stored in the field region has been evaluated; this way, the force-displacement curve shown in Fig.3 has been obtained by means of the virtual work principle (the absolute value of the attractive force is represented).

![Figure 2: Simplified longitudinal view (one half) of the motor: dimensions (μm), materials and boundary conditions.](image1)

![Figure 3: Force-displacement curve.](image2)
Despite the numerical oscillations, the curve seems to show the expected maximum of force for an axial displacement equal to 1.9 µm. For the sake of validation, the calculation of the axial force has been repeated using the method of the Maxwell stress tensor, taking an integration surface surrounding the energized electrode; a slightly bigger value has been found (discrepancy within 3%). In principle, the new device configuration should reduce friction between rotor and ground plane at the expenses of a small decrease of driving torque. On the other hand, the major disadvantage of this design is the more complicated technological process of electrode shaping.

5 Conclusion

Thanks to the technology of Silicon integrated-circuit, nowadays electrostatic micro-motors find broad applications as sophisticated actuators in systems where sub-millimetric movements are required. The designer, consequently, is concerned with the numerical simulation of the device in order to fulfil the prescribed electromechanical performance. The work represents a contribution to identify device geometries well suited for reducing frictional losses in static conditions.

Acknowledgement

The work has been partially supported by a NATO research grant (ref. HTECH.CRG 931352) and by Polish State Committee for Science (Grant 0588) as well.

References