Simulation and Optimization of Variable Capacitance (VC) Micromotors, Using Modified Parallel-Plate Model

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ABSTRACT

This paper presents a new approach for finding the optimal configuration and geometrical dimensions of very small variable capacitance (VC) side drive micromotors based on a modified parallel plate capacitance model The electrostatic drive torque, and friction drag torque terms are estimated by using this proposed model. The effect of all micromotor geometric variations on these terms will be discussed, in order to find the highest average output torque with minimum torque ripple, and minimum frictional torque to determine the optimal operational micromotor. Using a modified parallel-plate model a large number of designs can be easily simulated, for different geometric variations and pole configurations. In this model simple analytic calculations are employed, taking into account the side effects of both stator and rotor poles, to include the effect of rotor-stator fringing fields in actual estimation of total equivalent capacitance in this plane, which leads to fast and accurate estimations

***Keywords*:** Micromotor optimization, Variable capacitance micromotor, Modified parallel-plate model.

INTORODUCTION

Much research recently has been performed to improve understanding the design rules and optimization process of many types of electrostatic micromotors, including in particular works on rotary variable capacitance micromotors (VCM). The initial work on the micromotor design was reported in [1,2] provided the first perspective on design process and fabrication limits of surface-micromachined actuators, and evolved into the development of design rules in [3,4]. In addition, several models for calculation of the electrical drive torque have been addressed [5,6,7,8]. Most of these design models are generally based on the use of numerical finite-element methods to simulate the output drive torque. Because of numerous possibilities of geometrical combinations and variations of micromotor, the optimization technique based on a numerical method will be very time consuming [9,10]. In this paper we propose an optimization design method based on a modified parallel plate capacitance model to simulate the effects of all geometrical variations not only on drive torque production but also on friction drag mechanism. For each pole configuration, the design procedure allows the determination of the optimal micromotor geometric shape that leads to the highest average torque with the minimum torque ripple and minimum friction torque. In this method the initial values of micromotor geometry are chosen and determined (systematically) depending on the electrical and the electromechanical performance requirements. A simple modified parallel model is set-up automatically to simulate a large number of designs. This model will provide a good approximation for drive torque predictions as compared with 2-D FEM methods [5,6,8], and it also takes much less time to perform each application.

MICROMOTOR DESIGN AND ANALYSIS

Geometrical Design Parameters

For any pole configuration, the geometrical structure of micromotor can by defined by the following number of independent parameters, as shown in figure.1.

i) R_o, rotor radius.
ii) d, stator-rotor air-gap spacing .
iii) T_s, T_r, the stator and rotor pole width angles.
iv) T_{ps}, T_{pr}, the stator and rotor pole pitch angles.
v) H_s, H_r, the stator and rotor pole height.

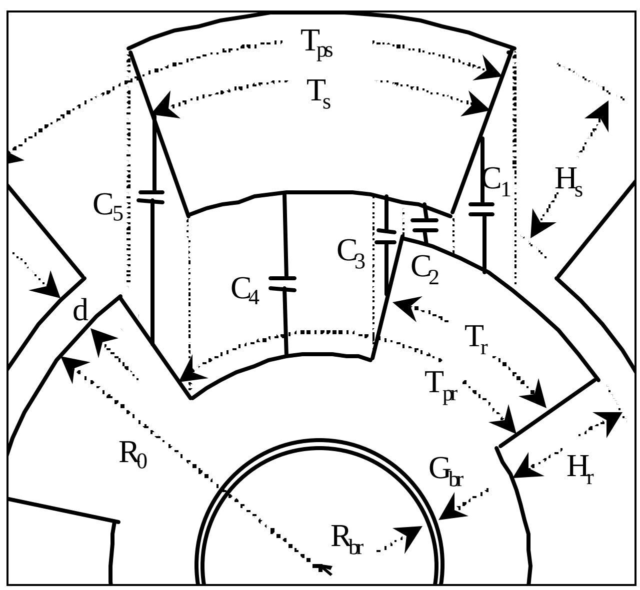

Figure 1: Geometrical design parameters with the equivalent capacitance circuit in the rotor-stator plane.

Modified Parallel-Plate Capacitance Model

The micromotor drive torque and electrically based rotor side pull force, including their angular dependence, are modeled here using an analytic modified parallel-plate capacitance model. This type of simulation provides a good approximation for quite accurate prediction of maximum torque magnitude and torque shape angle, as compared with two-dimensional FEM simulation neglecting axial fringing field and using full thickness of rotor-stator pole face. In this analysis simple calculation are employed taking into account the side effect of both the stator and rotor poles, to include the effect of the rotor-plane fringing field, for actual estimation of total equivalent capacitance as shown in figure 2. For each rotor position of step 0.5^{o}, the total equivalent capacitance can be calculated as follows.

$$C_T(q) = \sum_{i=1}^{5} C_i(q)$$

Where $C_1(q)$, $C_3(q)$, $C_5(q)$, represent the capacitance due to the stator and rotor side effects in the rotor-plane, as shown in figure1, and can be modelled for each rotor position from aligned position to missaligned position.

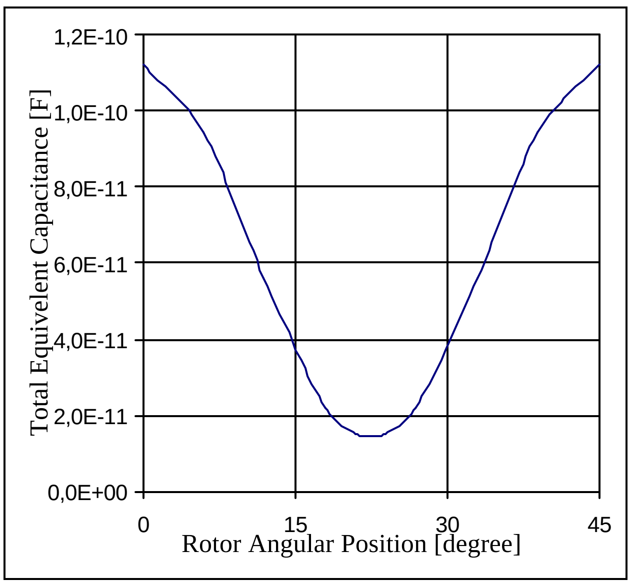

Figure 2: Simulated total equivalent rotor to stator phase capacitance as a function of rotor position.

Once the equivalent capacitance for each rotor position has been determined, the output drive torque versus rotor position characteristic can be easily calculated by the partial derivative of co-energy of the electrostatic field in the rotor-plane with respect to the angular displacement q [6,7,8,9].

$$T(q) = \frac{\partial W(q)}{\partial q} = \frac{\partial (CVdV)}{\partial q} = \frac{1}{2} \cdot V^2 \cdot \frac{dC}{dq}$$

Micromotor Drive Torque Optimization

The variable capacitance micromotor is an electrically linear system [9,10], the characteristics for any other scale can readily be derived from the reference scale. The design process allows selecting and determining of all the initial values of the geometrical parameters, depending on the electrical and electromechanical initial performance requirements. Following guidelines and design rules used in the design of magnetic variable-reluctance micromotor [3,4.9], the pole separation angle (T_{pr}-T_r) must be greater than the stator pole width angle T_s to insure a low minimum opposition capacitance, and hence to find the maximum average torque. Assuming a simple three-phase excitation scheme, each phase is supplied separately, and excitation is made during $T_{pr}/3$; the initial value of the stator and rotor pole widths are selected to be within the following limits.

$$T_{pr}/3 \le T_r \le T_{pr}(1-1/3)$$

$$T_{pr}/3 \le T_s \le (T_{pr} - T_r)$$

Therefore, by varying these geometrical design parameters independently within these limits, a large number of micromotor designs can be created. The optimal geometrical dimensions can be determined by means of successive sampling of the dimensional space describing the main geometrical design parameters in the stator-rotor plane, in order to find the highest average torque with minimum torque ripple. Figure 3, shows the simulated drive torque characteristic for 12/8 pole configuration with rotor radius of 50μm, and air-gap spacing of 1.5μm, using different pole width angles.

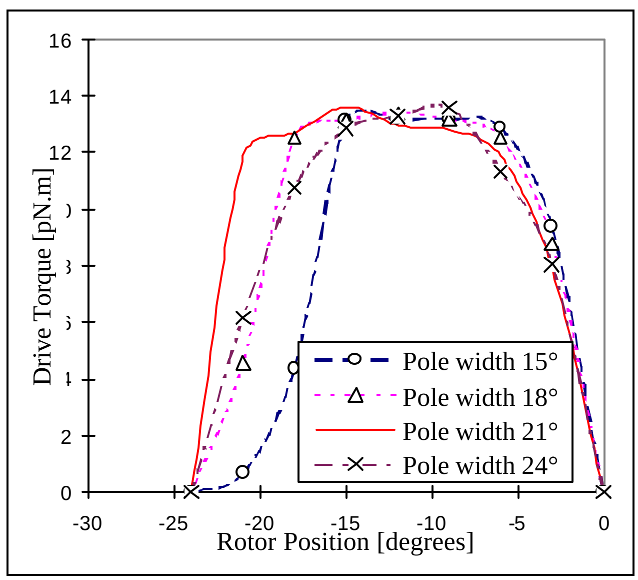

Figure 3: Simulated torque curve, using modified parallel plate approximation for 12/8 pole configuration with R_0= 50μm, and G=1.5μm, using different pole pitch ratio.

Frictional Torque Minimization

The most important friction mechanism is that based on normal forces acting on the rotor plane [5,6]. A lateral force, often termed “side- pull”, tends to pull the rotor into contact with the bearing pin causing friction drag. The bearing force or the lateral side-pull force would also depend on the square of the drive voltage and on the rotor-stator overlap area, and hence on the rotor angular position (similar to the drive torque). In order to create an optimal operational micromotor this frictional torque must be minimized by the design. Therefore, it is necessary to keep the ratio of bearing clearance to air-gap spacing as small as possible, which requires a minimized bearing clearance to the fabrication limit, or increased air-gap spacing. However, the small air-gap spacing is the prerequisite of micromotor operation. Using a modified parallel plate capacitance model, the friction torque can also be easily simulated as a function of air-gap spacing and bearing clearance, as shown in figure 4.

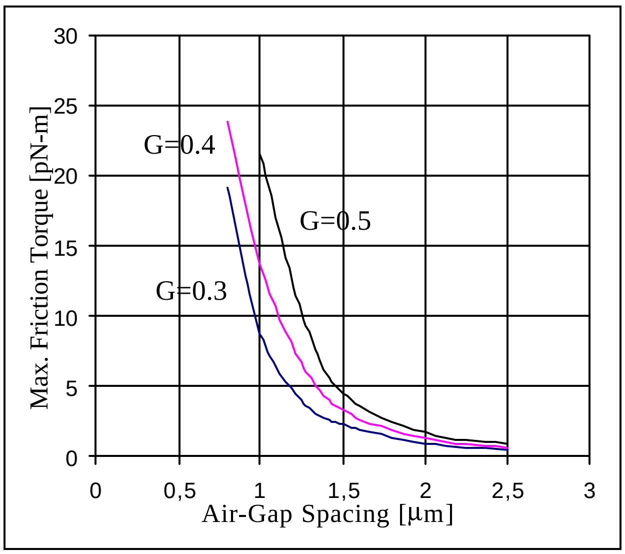

Figure 4: Simulated Max. friction torque as a function of air-gap spacing, using modified parallel plate model for 12/8 pole configuration, with different bearing clearances.

Net Torque Maximization

The maximum resulting drive torque can be obtained by simulating the effects of all micromotor geometry variations on output drive torque, and frictional drag torque characteristics, using a modified parallel plate capacitance model. Optimal micromotor geometrical dimensions, producing maximum net torque are also determined by fabrication limits. In order to minimize the frictional torque, which is electrical in origin, the bearing clearance should be minimized, and the bearing radius should be reduced to the fabrication limit. Figure 5 shows the maximum net-drive torque as a function of air-gap spacing for 12/8 pole configuration micromotor with 50 µm rotor radius, using different bearing clearances.

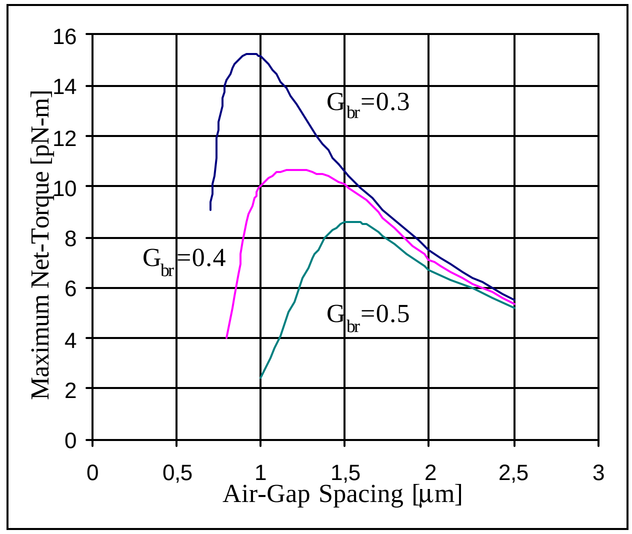

Figure 5: Simulated max. net-drive torque as a function of air-gap spacing, using different bearing clearances.

THE DESIGN PROCEDURE

The optimization procedure may be structured to contain three nested loops controlled by a main shell. For each loop in the main shell one pole configuration or one geometric parameter is analyzed. The design process also allows setting the constraints on the fabrication limits on these geometric parameters. Once the initial values of geometric parameters are selected properly, the modified parallel plate capacitance model is set-up automatically to simulate the output drive torque and friction drag torque characteristics for all possible micromotor geometric variations. For a given pole configuration the design algorithm can be performed to examine the simulated values of friction drag and net drive torque towards finding the optimal operational characteristics. Also the design procedure allows the examination of all the possible types of pole configuration with different pole ratios of 3:1, 3:2, 2:3 in order to select the pole configuration which provides the highest coverage torque.

THE RESULTS AND COMPARSION

The optimization procedure described in previous section has been used to design a typical polysilicon micromotor of 12/8 pole configuration with rotor radius of 50µm, and rotor thickness of 2.2µm. The output drive torque and friction torque characteristics can be simulated using a modified parallel plate model. This model provides a very close approximation to the results obtained by 2-D FEM model, for the maximum drive torque shown in figure 6, and for the torque shape angle shown in figure 7. Moreover Table1 shows the comparison between the simulated optimal performance characteristics and that have been already simulated using 2-D FEM [4,5]. We can see that a great improvement has been achieved to the micromotor average torque as well as minimum torque ripple with the optimal pole width angle ($T_r=21^o$).

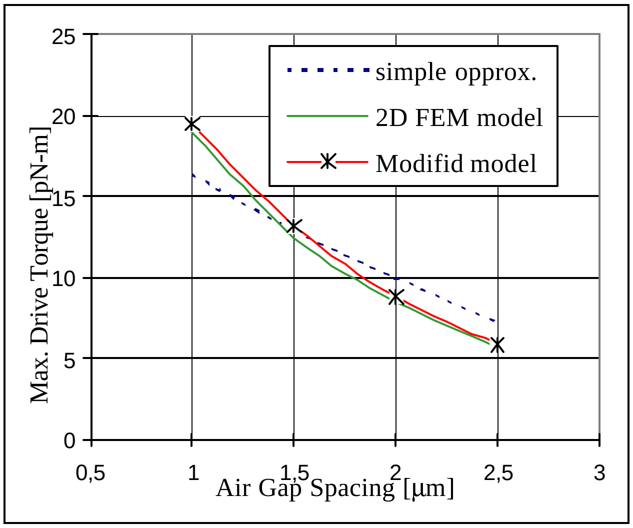

Figure 6: Comparison of the simulated max. drive torque with simple parallel-plate approximation and 2D FEM model for micromotor of 12/8 pole configuration.

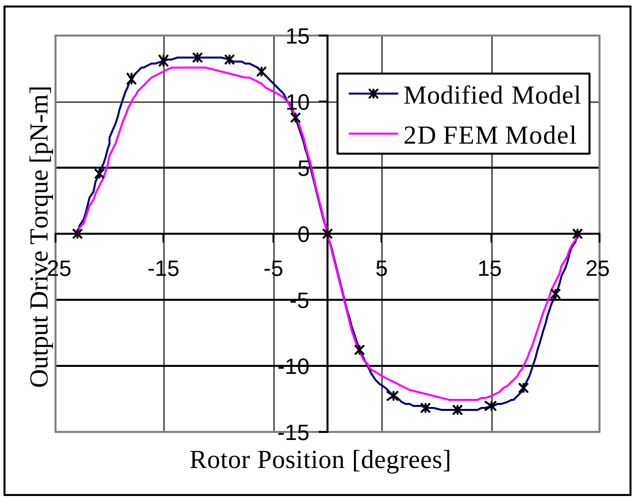

Figure 7: Comparison of the simulated torque shape angle using modified model with 2D FEM model for micromotor of 12/8 pole configuration, with pole width $T_s = T_r = 18^o$.

Table 1: Comparison of the optimal simulated performance characteristics using proposed model with 2D FEM model for micromotor of 12/8 pole configuration.

Micromotor performance characteristics	Simulated optimal value (our model)	Simulated value using 2-D. FEM models
Max. Drive torque (N.m)	$13.3*10^{-12}$	$12.5*10^{-12}$
AVE. Drive torque (N.m)	$12.8*10^{-12}$	$10.5*10^{-12}$
AVE. friction torque (N.m)	$1.4*10^{-12}$	$1.4*10^{-12}$
%Torque ripple	16 %	38 %
%Net. Useful work	90 %	86 %
Max. Ang. Velocity rad/s	$5.2*10^4$	$4.6*10^4$

CONCLUSION

This paper describes an optimization design procedure to select the optimal operational micromotor. For actual calculation of the electrostatic drive and friction torque, a modified parallel plate model has been already used, where a large number of micromotor designs can be simulated using different geometrical dimensions and pole configurations. This type of simulation takes much less time, and it is easier to perform for each application. In conclusion, using such modelling in combination with the proposed optimization procedure will provide a very powerful optimization tool to determine the optimal dimensions for electrostatic micromotors without the need of any numerical simulation.

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