A New 3D Analytical Design Model of an Electrostatic Micromotor using Multi-objective Approach

A. Salman*, A. Napieralski*, S. Wiak*, P. Di Barba**, and A. Savini**

*Department of Microelectronics & Computer Science,
Technical University of Lodz, Al.Politechniki 11, Lodz 93-590, Poland.
**Department of Electrical Eng., University of Pavia, I-27100 Pavia, Italy.
salman@dmcs.p.lodz.pl, napier@dmcs.p.lodz.pl, wiakslaw@ck-sg.p.lodz.pl,
di_barba@etabeta.unipv.it, savini@unipv.it

ABSTRACT

This paper presents a new design technique for finding the optimal structures of small size variable capacitance (VC) side-drive micromotors, based on a new 3D analytical micromotor design model. Two objective functions in mutual contrast, depending on the most important design parameters have been considered, giving rise to a multi-criteria design problem. In order to obtain as many optimal solutions as possible a non-dominated sorting algorithm (NSA) has been set up; different solutions are distributed both in the objective space and variable space giving rise to different possible optimal geometries. On one hand, these solutions are characterized by equal values of rotor and stator pole widths and by small values of bearing clearance to air gap spacing in order to maximize the net-average torque; on the other hand, the solutions found are featured by a small value of rotor pole widths in order to minimize the torque ripple. Due to the huge number of objective functions evaluation requested by the NSA we adopted the idea of using a 3D analytical simulation that has the advantage of a low computational cost and the drawback of smaller precision as compared with 3D finite element numerical solution. This new model has been considered to simulate the net-drive torque and torque ripple as two objective functions of the design process. This type of simulation takes into account the effect of both rotor-plane fringing fields and out-off axial fringing fields in actual estimation of total equivalent capacitance in the (r-θ-z) plane. Using such modeling in combination with the proposed design method provides a very powerful optimization tool to obtain many optimal solutions, distributed on the Pareto optimal front.

***Keywords*:** Non-dominated sorting algorithm (NSA), 3D electrostatic analysis, shape design, Pareto optimal front.

1 INTRODUCTION

The main challenge for electrostatic VC micromotors among other electrostatic micromechanical devices is still to achieve enough torque to overcome the friction forces due to their small dimensions. This is why optimization of each micromotor design is a necessity to ensure, or even enable, good operation. Several design models and optimization techniques, for finding the optimal geometrical dimensions of a very small size variable capacitance micromotor, have been reported and recently addressed in literature [1-5]. Most of these design methods or models are generally based on the use of finite-element method (FEM) to simulate the output drive torque. Because of numerous possibilities of geometrical combinations and variations of VC micromotor, the optimization technique based on a numerical method is a time consuming one [1,9]. Moreover, most of these design models are used to simulate either the output drive torque, or frictional drag torque separately, and no attention have been paid to simulate the total net-drive torque and other operational characteristics as well [1-5].

The optimal design of electrostatic micromotors usually is characterized by objectives in mutual contrast, giving rise to a multi-criteria optimization problem [1,5]. There are two different ways to solve such a problem. The first one consists of building a single scalar objective function by combining the single objectives in a suitable way. This approach leads to classical multi-objective optimization methods and results in a solution, which is supposed to be optimal. This procedure seems to be arbitrary in the choice of both the scalarization criterion and the weighting coefficients that the latter implies. The second way to solve the problem consists of applying the Pareto optima theory [7,8]. The result is a family of non-dominated solutions and the procedure does not imply any subjective choice. In this paper we present a new design technique for finding different optimal structure of very small size micromotors. This design is based on the use of a new analytical 3-D equivalent circuit model to simulate the electromechanical operation characteristics for such types of micromotors.

2 NEW 3-D ANALYTICAL MODEL

Although 2D and 3D FEM numerical methods can provide accurate calculations of stored electrical energy and drive torque as a function of the rotor position, performing with these methods is a time consuming process, because a large number of micromotor design models, slightly different from one another, must be built and analyzed. Moreover, for each micromotor design the field analysis must be carried out for a number of rotor positions, in order to obtain the torque and the capacitance as a function of rotor position. For most 3D FEM packages a new rotor position requires a new mesh generation, which in turn requires a considerable runtime to perform the field simulation.

In this paper we present a fast, reliable and more accurate new 3D analytical model based on parallel-plate rotor-stator capacitance formulation [9,10] in the three dimensional space. This model does not takes into account only the effect of the rotor-stator plane fringing fields, but also the effect of the out-off axial fringing fields (in the axial direction) for actual estimation of the total equivalent capacitance in the (r-θ-z) plane shown in Figure 1. This type of simulation provides good approximations for quite accurate predictions of maximum drive torque value and torque shape angle, as compared with three-dimensional FEM simulation [1].

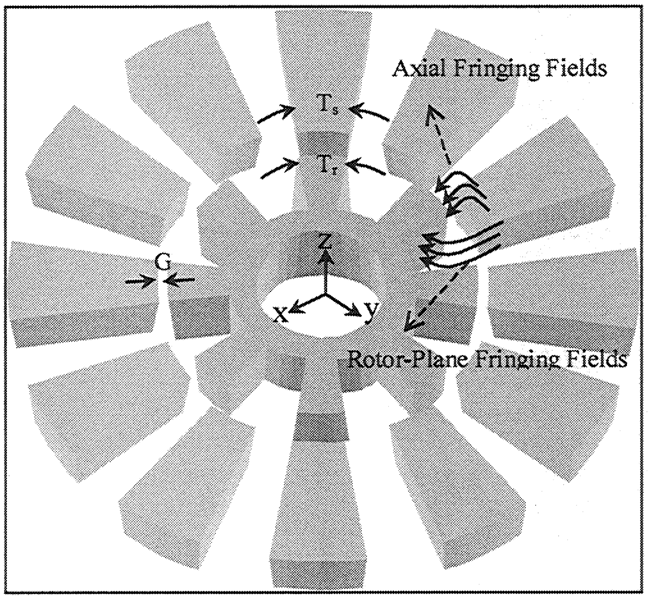

Figure 1. The main micromotor geometry (12/8 pole configuration) with rotor-plane radial and out-off axial fringing fields.

Using 3D analytical model a large number of micromotor designs can be easily simulated using different geometrical variations, with a fully arbitrarily choice of the rotor position. For each rotor position the total equivalent circuit capacitance, describing the micromotor geometry, consists of 10 capacitances. The total equivalent circuit capacitance for the geometry of the micromotor shown in Figure 1 can be calculated as a function of two geometric design parameters

$$C_{eq}(x_1,x_2)=\sum_{i=1}^{10}C_i(x_1,x_2) \tag{1}$$

where $C_1(x_1,x_2)$, $C_3(x_1,x_2)$, $C_5(x_1,x_2)$ represent the capacitances, due to the rotor plane fringing fields, between the stator and rotor edges in the rotor-plane, as shown in Figure 1, and $C_6(x_1,x_2)$, $C_8(x_1,x_2)$, $C_{10}(x_1,x_2)$, represent the capacitances, due to the out-off axial fringing fields, between the stator and rotor edges in the third dimension, which can be modeled for each rotor position from aligned position to misaligned position.

Following the guidelines and the design rules used in the modeling and design of magnetic variable–reluctance micromotors [9,10], the geometry of the micromotor depicted in Figure 1 is modeled by two design variables, namely: the angular width x_1 of the rotor pole and the air-gap spacing x_2. In particular, the rotor pole width is assumed to be equal to the stator electrode width.

If V is the phase supply voltage and W the co-energy due to the electrical field, the basic formula for computing static torque becomes

$$T(x_1,x_2)=\frac{\partial W(x_1,x_2)}{\partial\theta}=\frac{1}{2}V^2\frac{\partial C_{eq}(x_1,x_2)}{\partial\theta} \tag{2}$$

where θ is the angular position of the rotor.

Now we are able to set up two analytical objective functions, as shown in Figures (2), and (3). The first one is the total net-drive torque, which must be minimized during the optimization process.

$$F_1(x_1,x_2)=T_{av}(x_1,x_2)-T_f(x_1,x_2) \tag{3}$$

where $T_{av}(x_1,x_2)$ is the average drive torque, which can be calculated by integrating the area under the torque-angle curve and $T_f(x_1,x_2)$ is the average frictional torque corresponding to the same electrical supply.

The second objective function is the percentage torque ripple T_{rp}, which measures the oscillation of the motive torque, and can be calculated as follows:

$$F_2(x_1,x_2)=\frac{T_{\max}(x_1,x_2)-T_{\min}(x_1,x_2)}{T_{av}(x_1,x_2)} \tag{4}$$

where $T_{max}(x_1,x_2)$ is the maximum value of the drive torque and $T_{minx}(x_1,x_2)$ is the minimum value of the drive torque when the supply voltage has been switched to the next adjacent phase.

3 SHAPE DESIGN OF THE MICROMOTOR

During the design process, the rotor pole width has been allowed to vary from 30% to 75% of the rotor pole pitch. The optimal geometries can be determined by means of successive sampling of the dimensional space describing the main geometrical design parameters in the cross-section of the device, taking into account the fringing fields both in rotor plane and in the axial dimension.

Figure 2 shows a 3D surface fit of the maximum net drive torque, while Figure 3 shows a 3D surface fit of the torque ripple for the same selections of the design parameters. Both figures refer to optimization of 12/8 pole configuration micromotor, using 3D analytical micromotor design model.

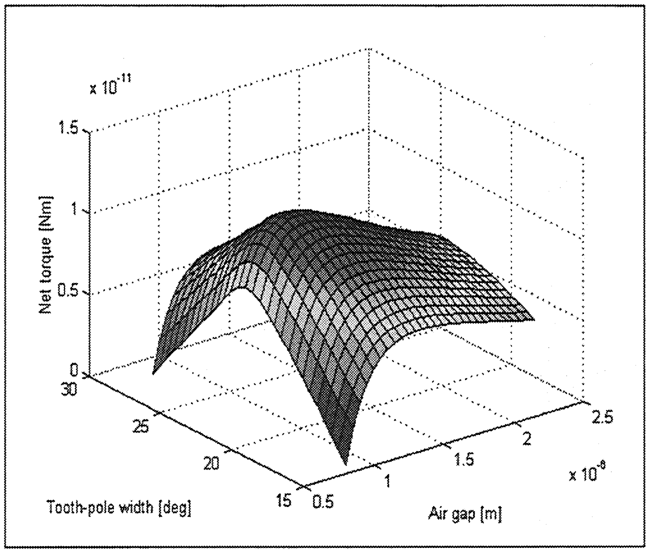

Figure 2. The 3D representation of net torque objective as a function of the design variables.

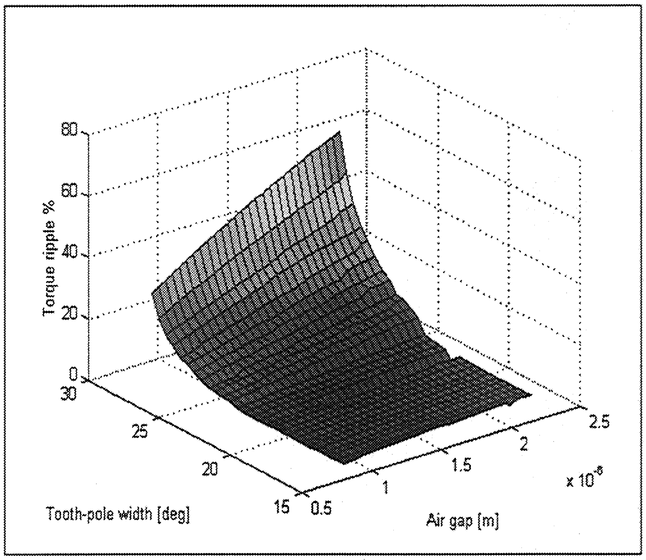

Figure 3. Representation of torque ripple objective as a function of the design variables.

4 MULTICRITERIA DESIGN STRATEGY

When considering a multi-criteria design problem the Pareto optima theory states the existence of the set of non-dominated solutions called Pareto optimal front. The aim of a non-dominated sorting algorithm is to obtain solutions equally distributed in the set. In the first step we generate an initial random population of individuals in the search space. In the second step we classify individuals into Pareto sets using the following definition. An individual X_1 is said to dominate the other solution X_2, if both the following conditions are true.

1. The solution X_1 is not worse than X_2 in all objectives.
2. The solution X_1 is strictly better than X_2 in at least one objective.

The identification of the Pareto optimal front has been achieved by sampling, in a random way, the feasible region in both design and objective spaces. A distribution of 6400 samples fulfilling a uniform probability density in the design space has been considered, constraints and bounds have been taken into account.

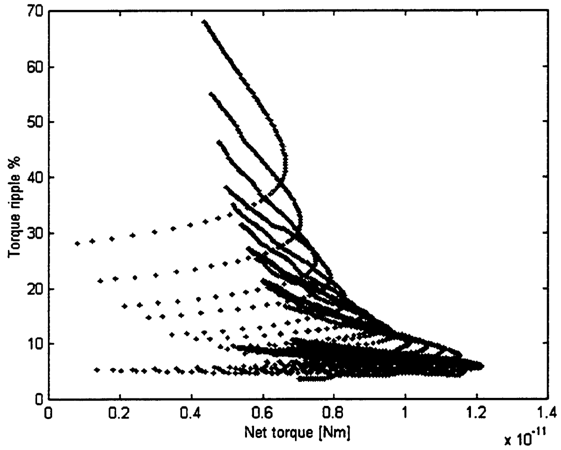

Figure 4. Sampling of the objective space (6400 points).

In Figure 4 the corresponding distribution of samples in the objective space is represented; it can be noted that a quasi-uniform distribution in the design space is mapped into a non-uniform one in the objective space. The Pareto optimal front is approximated by the lower boundary of the latter distribution; it appears to be highly sensitive with respect to the drive torque and poorly sensitive with respect to the torque ripple.

5 RESULTS

In Figure 5 and Figure 6 the points corresponding to the non-dominated samples are represented in objective and design spaces, respectively.

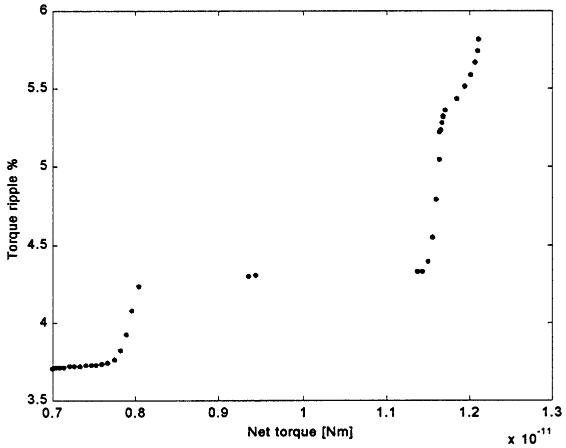

Figure 5. Approximation of Pareto set in the objective space (71 points).

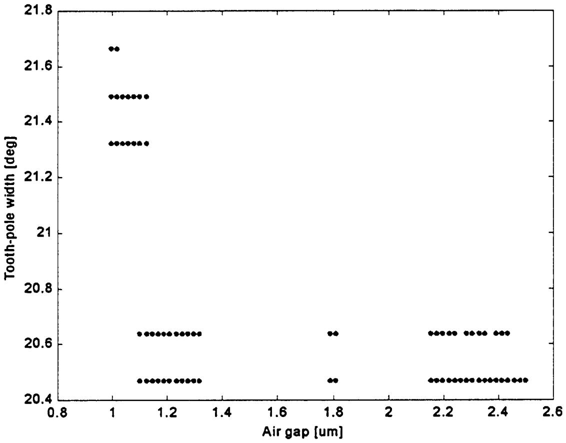

Figure 6. Approximation of Pareto set in the design space (71 points).

In particular, Figure 6 shows a set of non-trivial devices differing both in shape and in performance.

6 CONCLUSION

In the paper, an application of multi-criteria optimality to the electromechanical design of small size electrostatic micromotor is presented. A new 3D analytical capacitance circuit model has been adopted to evaluate the objective functions, taking into account both the rotor-plane and the out-off axial fringing fields, for fast and accurate calculation of total equivalent capacitance. Two objective functions have been considered i.e. the net drive torque and the torque ripple, as criteria of the design process. An efficient non-dominated sorting algorithm and the 3D analytical model are combined to obtain a self-running design process. The proposed approach has proved to be a very powerful design tool in order to identify several optimal solutions, distributed on the Pareto optimal front.

REFERENCES

[1] T. B. Johansson, M. Van Dessel, R. Belmans, and W. Geysen, "Technique for finding the optimal geometry of electrostatic micromotors", IEEE Trans. Industry Applications, Vol. 30, No. 4, July/Aug 1994.

[2] I. Dufour, E. Sarraute, and A. Abbas, "Optimization of the geometry of electrostatic micromotors using only analytical equations", J. of Micromech. Microeng., Vol. 6, pp.108-111, July/Aug 1994.

[3] Y. Lefevre, M. Lajoie-Mazenc, E. Sarraute, H. Camon, "First step towards design, simulation, modeling and fabrication of electrostatic micromotors", Sensor and Actuator A, vol., 47, pp. 645-648, Issues 1/3, March 1995.

[4] P. Di Barba, A. Savini, S. Wiak , "2-D Numerical simulation of electrostatic micromotor torque", Second Int. IEE Conf. on Computation in Electromagnetics, Nottingham, pp.227-230, 12-14 April 1994.

[5] P. Di Barba, M. Farina, A. Savini, "Vector shape optimization of an electrostatic micromotor using a genetic algorithm ", COMPEL vol.19 no.2, 2000.

[6] K. Deb, "Evolutionary Algorithm for Multi-criterion optimization in engineering design", Proceeding of EUROGEN99, Jyvaskyla, 31 May-4 June Wiley, 1999.

[7] Srinivans, N., Deb, K.: Multiobjective Optimization using Non-dominated Sorting in Genetic Algorithms. IEEE Trans. Evol. Comput., Vol. 2 no. 3, pp. 221-248, 1994.

[8] D. E. Goldberg, "Genetic algorithm in search optimization and machine learning", Addison-Wesley publishing company, 1989.

[9] A. Salman, A. Napieralski, G. Jabłoński, "Simulation and Optimization of VC Micromotors using Modified Parallel-Plate Model", in Proc. 2nd Int. Conf. of MSM'99, Pureo Rico, USA, pp.609-612, 19-21 April 1999.

[10] A. Salman, A. Napieralski, G.Jabłoński, "New Analytical Micromotor Design Models for CAD PC-Design Tools", In Proc. of 3rd Int. Conf. of MSM'2000, San Diego, California, USA, pp.692-695, 27-29, March, 2000.