ATEE – 2004

SALIENT–POLE ELECTROSTATIC MICROMOTOR

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The torque–versus–angle mechanic characteristic of a salient–pole radial–gap electrostatic motor is calculated by an approximate analytical method and by a finite element numerical method.

INTRODUCTION

Microdevices and micromotors are a subject of increasing interest due to their multiple applications in industry, medicine, military, and many other fields. Electrostatic motors appear to be more convenient than motors of a classical type, based on electromagnetic forces: indeed, the structure of microdevices is generally subjected to certain restrictions derived from the manufacturing process which uses integrated circuit technology. The electrostatic micromotor, where both the rotor and the stator present salient–poles, [1], is one of the simplest such realizations.

The design of micromotors starts from a preliminary performance evaluation, with a view to establish the range of the proper design and manufacturing requirements. In this respect, the evaluation of the mechanic characteristic of the micromotor, i.e., the dependence of the active torque on the rotation angle of the rotor, is of foremost importance for both the overall performance evaluation and the design of appropriate driving procedures. The present paper aims at the computation of an approximate mechanic characteristic of the radial–gap salient–pole micromotor, obtained under some reasonable simplifying assumptions.

DEVICE MODEL AND SIMPLIFYING ASSUMPTIONS

The micromotor under study, [1,2], consists in a stator with 12 insulated salient–poles and a rotor with 8 salient–poles, all stator and rotor poles having the same height and being placed at the same elevation above a null potential reference conducting plane (fig. 1). The operation of the motor is quite simple: the conducting rotor is permanently in contact with the zero potential revolving axis, while appropriate stator poles are successively placed at a driving potential V. The energized stator pole attracts the nearest rotor pole until the latter reaches a symmetric position with respect to the former, and thus makes the rotor rotate. By adequately energizing successive stator poles, the rotor can sustain a continuous revolving movement.

Some simplifying hypotheses are supposed to apply:

1°. The radial airgap is negligible with respect to the radii of the stator and rotor pole faces;

2°. The radial airgap is significantly smaller than the pole distance to the null potential reference plane;

3°. The radial airgap is fairly smaller than the height of the stator and rotor pole faces.

The motor geometry is characterized by: $\alpha = \pi/10$ – the angular pole width (for both stator and rotor), $\beta = \pi/6$ – the stator pole pitch, $\gamma = \pi/4$ – the rotor pole pitch, $\delta = \pi/15$ – the stator inter–pole angle, $\varepsilon = 3\pi/20$ – the rotor inter–pole angle, h – the pole height, H –

the elevation of poles above the null reference plane, r – the rotor pole face radius, R – the stator pole face radius, S – the stator outer radius.

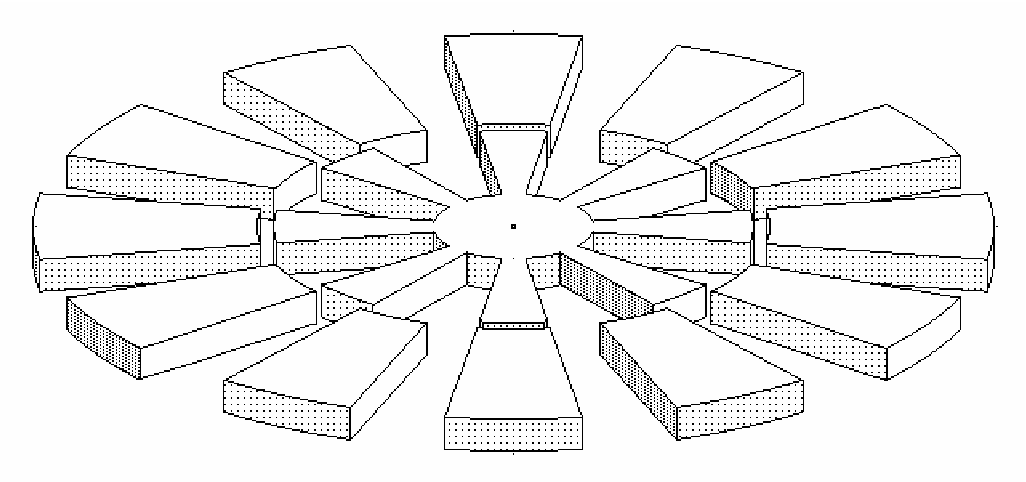

Fig. 1. Device model

The rotational symmetry of the motor structure makes it sufficient to study its mechanic characteristic over a $\gamma/2 = \pi/8$ angle, between two symmetric configurations of null electric torque. The starting configuration is that where two rotor poles are symmetrically placed with respect to the energized stator pole, and the final configuration is that where a rotor pole is face–to–face with the energized stator pole. Moreover, according to the simplifying hypotheses, the computation may assume two-dimensional electric field problems: the problem associated with the radial airgap and field lines in planes transverse to the axis, and the problem associated with the field lines in axial planes, including the presence of the null potential reference plane. Each of the two problems is studied analytically by the field line approximation method and by a finite element numerical method.

The active electric torque is computed as [3,4,5]

$$T = \frac{\partial W^*}{\partial \theta} = \frac{\partial}{\partial \theta} \frac{C V^2}{2} \bigg|_{V=\mathrm{ct.}} = \frac{V^2}{2} \frac{\partial C(\theta)}{\partial \theta} \quad ,$$

where W^* is the electric co–energy, V is the potential of the energized stator pole, θ is the rotor position angle, i.e., the angle between the approaching rotor pole and the energized stator pole, and $C(\theta)$ is the rotor–stator capacitance.

ANALYTICAL COMPUTATION OF THE MECHANIC CHARACTIRISTIC

The computation of the electric torque is reduced to the computation of the electric rotor–stator capacitance as a function of the rotation angle θ.

In accordance with the simplifying assumptions, the analytical treatment of the electric field problem associated with the field lines in transverse planes can approximate the pole faces as plane faces and consider a local translation movement of the rotor with respect to the stator. The spectrum of the field lines, approximated by straight segments and circular arcs, [6] , changes when the rotor moves, so that six different spectrum patterns have to be considered, separated by five limit cases. As an example, the second spectrum pattern is suggested in fig. 2, for which the capacitance per unit length results as

$$C_{\mathrm{II}} = \varepsilon_0 \left[\frac{R(\alpha+\theta)}{d} + \frac{2}{\pi}\ln\left(1+\frac{\pi y_1}{2d}\right)\left(1+\frac{\pi x_1}{2d}\right)\left(1+\frac{\pi y_2}{2L}\right)\left(1+\frac{\pi x_2}{2L}\right) + \right.$$

$$\left. + \frac{1}{\delta}\ln\frac{S^2}{(R+y_1)(R+y_2)} \right] \quad , \qquad -\alpha \le \theta \le \sqrt{\frac{R^2\delta^2 - d^2}{r^2}} + \alpha - \gamma < 0 \quad ,$$

where

$$d = R - r \quad , \quad L = R\delta \quad , \quad y_1 = \frac{R\delta - d}{\pi/2 - \delta} \quad , \quad y_2 = \frac{R\delta - L}{\pi/2 - \delta} \quad ,$$

$$x_1 = \frac{1}{2}\left[-R\theta + \frac{2}{\pi}(L-d) \right] \quad , \quad x_2 = \frac{1}{2}\left[-R\theta - \frac{2}{\pi}(L-d) \right] \quad .$$

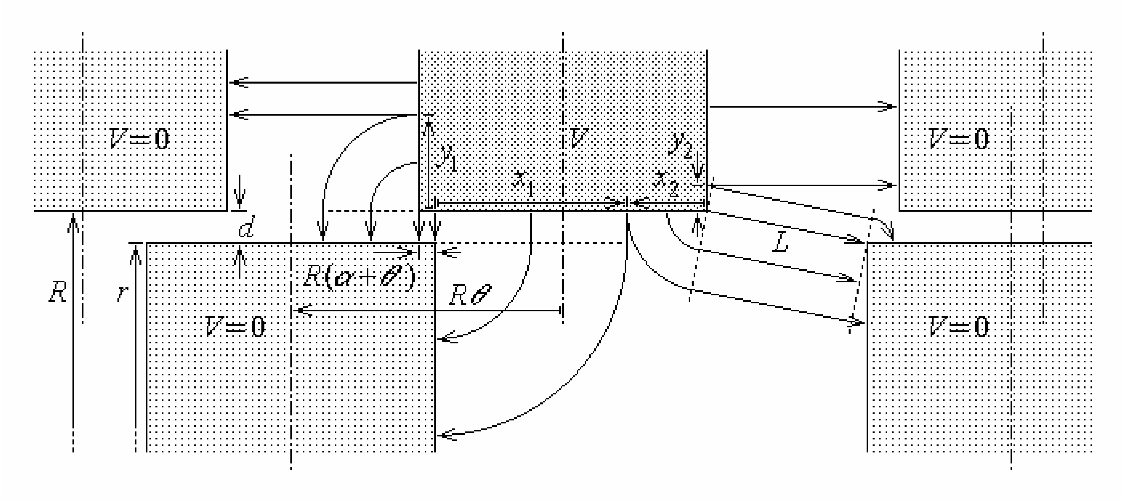

Fig. 2. Approximate field line pattern in transverse planes

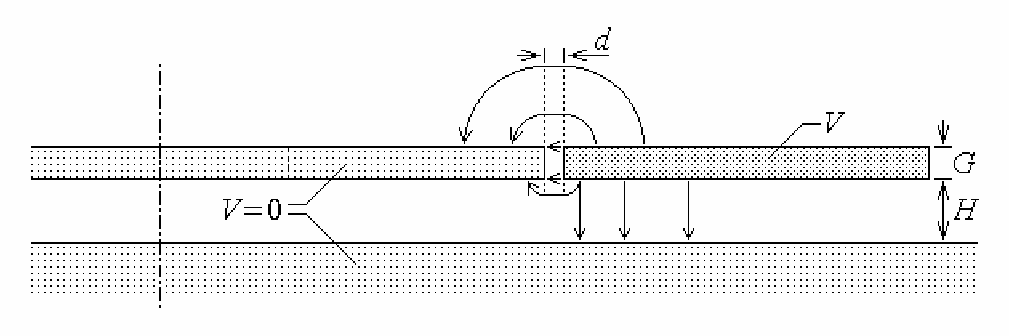

Fig. 3. Approximate field line pattern in axial planes

Under the same simplifying assumptions, the analytical treatment of the electric field problem associated with the field lines in axial planes (fig. 3) remains to apply to the stray field lines only, and add the small correction of the capacitance per unit length

$$C_A = \varepsilon_0 \left[\ln\frac{H}{d} + \ln\left(1+\frac{n\pi H}{d}\right)\right] + C_{\text{stator – plane}} \quad ,$$

where nH is the height of the free space region above the rotor and stator poles, and the last constant term is irrelevant.

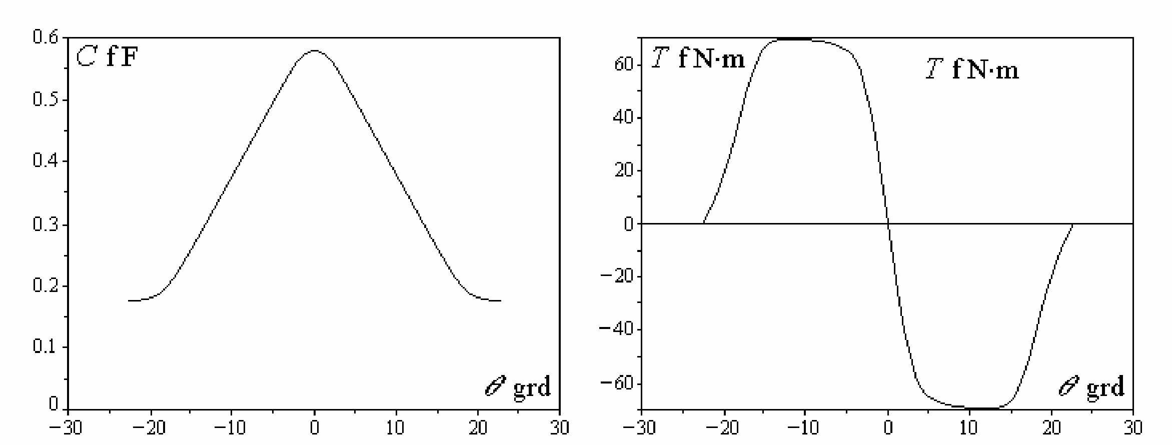

Fig. 4. Capacitance and torque – analytical computation

The capacitance resulted from the plane–parallel problem, completed with the correction given by the axial problem, was computed, according to formulae like those above, for 211 angular positions within the $\pi/8$ range, and smoothed by a sliding average procedure [8] with a 20 entries half–range (fig. 4).

The approximate mechanic characteristic torque–versus–rotation angle is readily computed, according to the above given formula, by using an approximate derivation formula [7], followed again by a smoothing procedure based on a sliding average technique (fig. 4).

NUMERICAL COMPUTATION OF THE MECHANIC CHARACTIRISTIC

In the plane–parallel electric field problem, associated with field lines in transverse planes, the electric potential decreases very rapidly from the energizing V value to zero, so

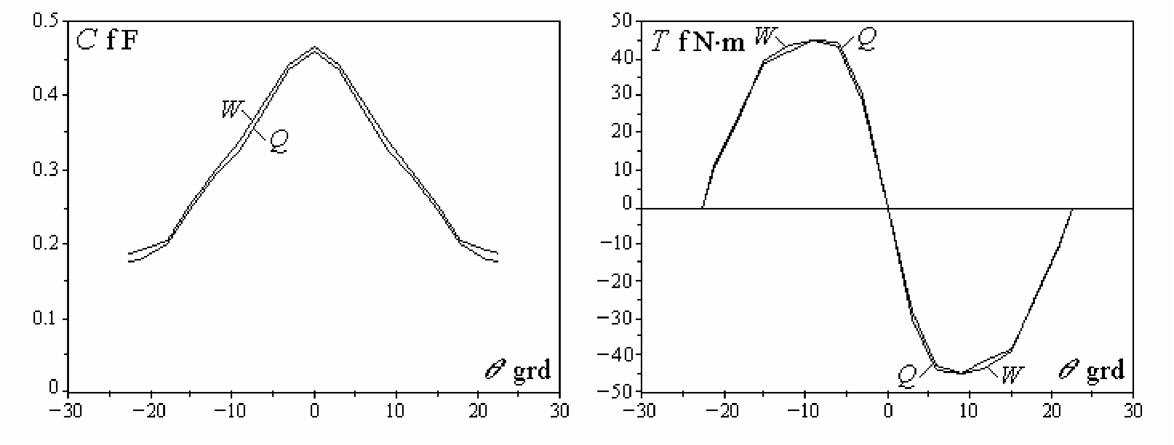

Fig. 5. Capacitance and torque – numerical computation

that a $\pi/2$ sector only of the motor, with the energized stator axis at a $\pi/3$ angle, is sufficient to be studied by the finite element numerical approach, [7]. Nine values are considered for the rotor–stator angle: 0° , 3° , 6° , 9° , 12° , 15° , 18° , 21° , 22°.5 , for which the capacitance per unit length is determined, both in terms of electric charge and in terms of electric energy.

The axial electric field problem, associated with field lines in axial planes, gives the capacitance for the entire cylindrical structure of the given axial cross–section. It is quite difficult to extract from it the contribution of the electric field in the radial rotor–stator airgap, so that the solution is more useful as a confirmation of the analytical computations.

The results of the numerical modelling were processed, for the indicated angular positions, in a similar manner to that of the analytical approach, for both the capacitance–versus–angle dependence and for the torque–versus–angle dependence, i.e., the mechanic characteristic (fig. 5).

The usual mechanic characteristic torque–versus–revolving speed can then be derived with reference to a particular driving procedure, aiming at relating the revolving speed with the switching rate of the energized pole pairs.

CONCLUSIONS

The approximate mechanic characteristic of a radial–gap salient–pole electrostatic motor was calculated, under reasonable simplifying hypotheses. The computations done by using an analytical and a numerical method are in a satisfactory agreement, and allow a valuable evaluation of the motor performance, preliminary to the proper design of the device.

The results presented here are also in good agreement with published results [1], reported for the same constructive data.

ACKNOWLEDGEMENTS

Thanks are due to the staff of the Numerical Methods Laboratory, and to colleagues in the Group of Theoretical Electrical Engineering of the Electrical Engineering Department, "Politehnica" University of Bucharest.

REFERENCES

1. M.P. Omar, M. Mehregany, R.L. Mullen, *Electric and Fluid Field Analysis of Side–Drive Micromotors*, IEEE JMEMS, Vol 1, No. 3, September 1992, pp. 130–140.
2. D. Marta, *Micromotor electrostatic cu poli aparenti*, Graduation thesis, Department of Electrical Engineering, Polytechnic University of Bucharest, 2003.
3. J. Van Bladel, *Electromagnetic Fields*, McGraw-Hill Book Company, New York, 1964.
4. H.A. Haus, J.R. Melcher, *Electromagnetic Fields and Energy*, Prentice Hall, Englewood Cliffs, J.J., 1989.
5. Anca Tomescu, F.M.G. Tomescu, R. Mãrculescu, *Bazele electrotehnicii – Câmp electromagnetic*, MatrixRom, Bucuresti, 2002.
6. Anca Tomescu, F.M.G. Tomescu, *Bazele electrotehnicii – Sisteme electromagnetice* (*Lecture Notes*), Department of Electronics and Telecommunications, Polytechnic University of Bucharest, 1996.
7. Anca Tomescu, I.B.L. Tomescu, F.M.G. Tomescu, *Modelarea numericã a câmpului electromagnetic*, MatrixRom, Bucuresti, 2003.
8. Anca Tomescu, F.M.G. Tomescu, *Transmisia Informatiei* (*Lecture Notes*), Department of Electrical Engineering, Polytechnic University of Bucharest, 1999.