PE-I185-EC-0-03-1998

Design of Very Small Electromagnetic and Electrostatic Micro Motors

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Abstract: The paper describes a general design tool that can be used for small and extra small electric and magnetic devices. Such devices generate micro motions. Due to their dimensions and specially due to the short axial length compared to the radial dimensions a three dimensional analysis of the field is required. Complex geometries recommend a well tuned engineering tool to guarantee reliable results. Here, a standard three dimensional finite element approach is chosen to compute the electric and magnetic field quantities respectively. In combination with a user-friendly computer interface, controlling the necessary finite element procedures, a powerful engineering tool with a general application range is obtained. For that reason it was possible to apply numerical optimization algorithms to realize a fully automated design tool. Various configurations are studied using the same software tools. The paper aims on the application of the finite element method (FEM).

Keywords: electrostatic micro motor, sub-fractional horse power motor, finite element method, 3D field computation, design tools.

I. INTRODUCTION

The paper describes a general design tool that can be used for small and extra small electric and magnetic devices, aiming at producing micro-motions. Micro machines can be defined as very small devices in the millimeter and sub-millimeter range. Due to the dimensions and specially as the dimensions of the diameter of the device is large with respect to its length, a three dimensional analysis of the field is required.

When the dimensions of the electromagnetic devices become smaller, it can be shown that the electrostatic forces scale advantageously when compared to the magnetic forces [1]. Therefore, when dealing with motion systems in the extra small area, one will encounter both electric and magnetic devices to analyze. A design system aiming at assisting the engineer, has to be capable to handle both types of problems.

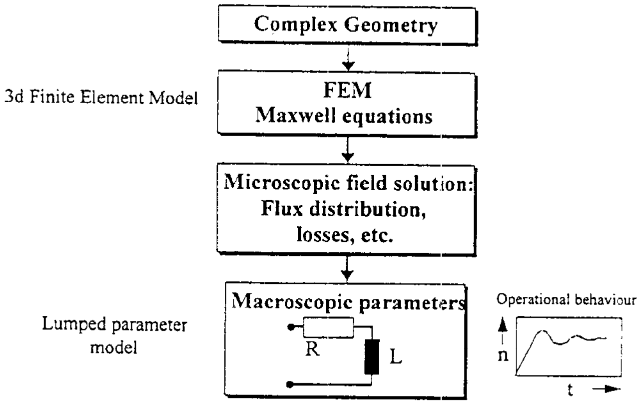


Fig. 1. Micro- and macroscopic field solution yielding the desired overall behavior of the device.

The design tool developed is based on the three dimensional finite element analysis of the field [2]. Rather than using the field solution as such, the designer wants to obtain the macroscopic parameters for a lumped parameter model, calculated from the field solution (Fig. 1). For the electrostatic motors, a capacitance based equivalent circuit is derived. For the magnetic motors, the common inductance based circuit is used.

The torque is evaluated as a function of the position. Specific simulation and design tools to automate the design process are discussed. The designer is not confronted with the finite element method as such, but has to enter only the main dimensions and characteristics of the device. In the post-processing portion of the work, the data are extracted and are introduced in an optimization procedure, leading to a new set of geometric parameters and the process is restarted until an optimum is reached.

Using different types of electrostatic and magneto-static micro devices, it will be shown how the designer can use the field computation methods to obtain the macroscopic parameters that are the basis of dynamic simulation yielding the required behavior of the motor or actuator (Fig. 1).

II. DESIGN OF ELECTROSTATIC MICRO MOTORS

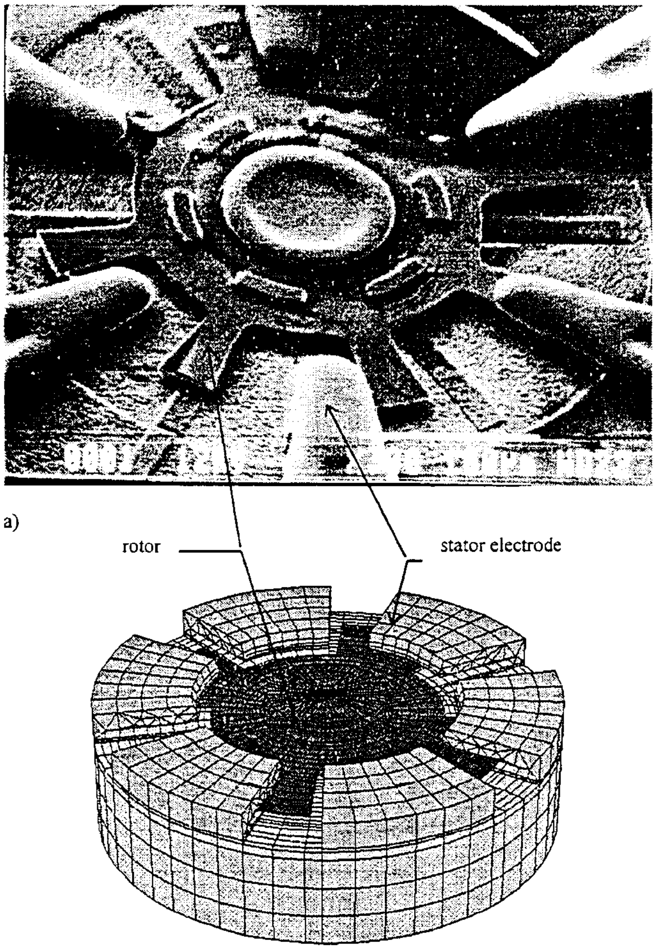
Scaling analysis shows that as size is reduced electrostatic designs become advantageous over the electromagnetic versions that dominate at dimensions starting in the millimeter range. In contrast to for example the wobble design [6], the

PE-I185-EC-0-3-1998 A paper recommended and approved by the IEEE Electric Machinery Committee of the IEEE Power Engineering Society for publication in the IEEE Transactions on Energy Conversion. Manuscript submitted August 27, 1997; made available for printing March 9, 1998.

electrostatic micro motors that were investigated here are based on the principal of variable capacitance. This type of motors is more promising as the wobble motor is difficult to connect with his load. The operation principal is very simple. A voltage on the stator electrodes induces a charge on a conducting rotor that then moves to minimize the field energy.

The cheapest fabrication technology of electrostatic micro machines being a thin film process, infers planar structures [3]. Therefore, such rotating actuators are extremely flat and the generated forces are very low. Fig. 2 shows an axial field electrostatic micro motor and the corresponding three dimensional finite element model. Radial field type machines are also feasible. When the same height of the machine is installed, the surface that contributes to the interaction between stator and rotor is much smaller. However, the problem is that only very limited torques can be obtained. Using a radial type of interaction and the LIGA production technique, allowing to generate a higher microstructures, results in higher torque values [4]. This technique is very expensive. Cheaper alternatives are developed but are not capable of supplying the same depth of the rotor [5]. Fig. 3 shows the three dimensional finite element model of an radial field micro motor.

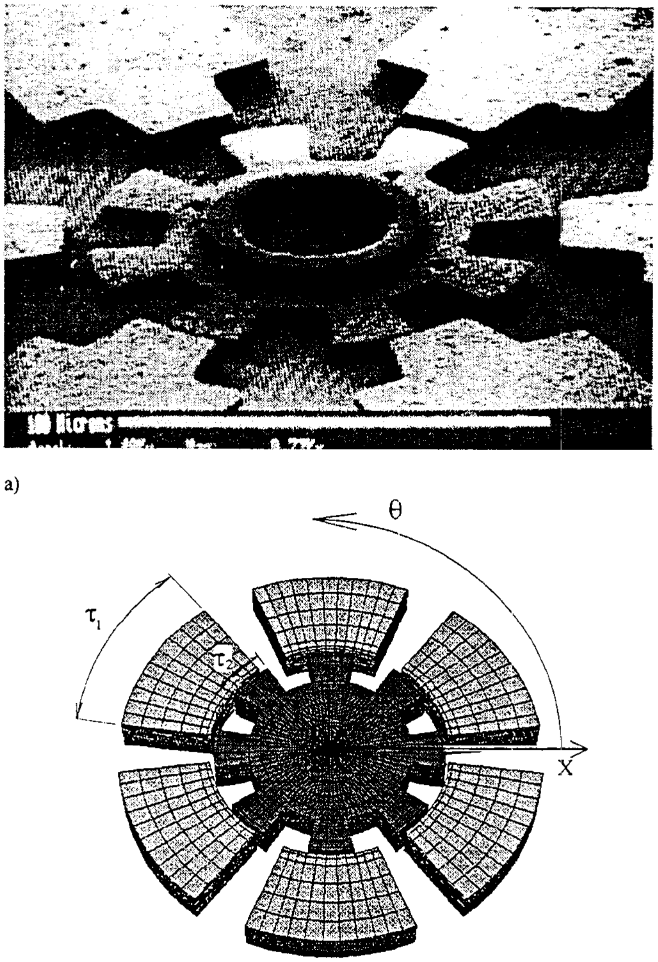
The computed values of the generated torque are in the range of 0.06 pNm/V^2 [6]. The torque is referenced to the square of the supplied voltage. In order to apply numerical optimization algorithms an automated finite element modeling is recommended and therefore, is implemented into the design process. An extrusion process around the machine shaft is developed. A number of planes of symmetry are defined and rotated around the shaft of the motor (Fig. 4a). This procedure is automated via an parametrized input user interface and leads to a symmetrical three dimensional mesh. Due to the parametrization of the geometry various dimensions can be tested without efforts. The number of stator and rotor poles, their width and the particular rotor position are the only data necessary for the automated mesh generation. During the meshing procedure the 2D planes are step by step developing to a 3D geometry (Fig. 4b). Control of the mesh quality is required in order to avoid the appearance of torque components which are not present in the actual machine. This is done by monitoring the aspect ratio of the generated tetrahedron FEM elements. To improve this aspect ratio,



a)

b)

Fig. 2. a) 6/4 pole Axial field electrostatic micro motor (ESIEE, Paris) and b) the three dimensional finite element model.



a)

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Fig. 3. a) 6/8 pole electrostatic radial field micro motor and b) the finite element model.

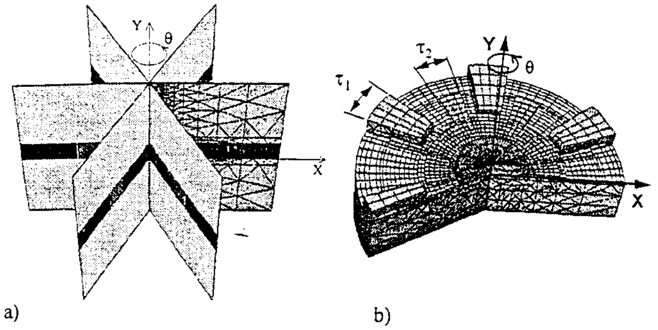

Fig. 4. Axi-symmetrical extrusion based meshing a) planes of symmetry and b) developing 3D FEM mesh.

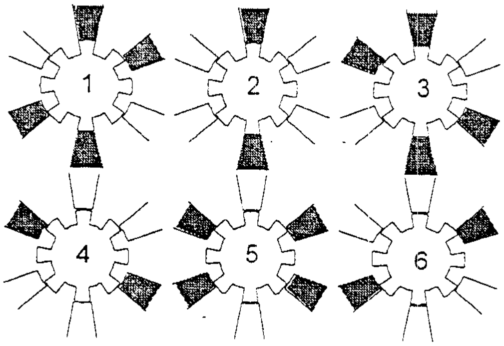

Fig. 6. Possible symmetrical excitation sequence for one revolution.

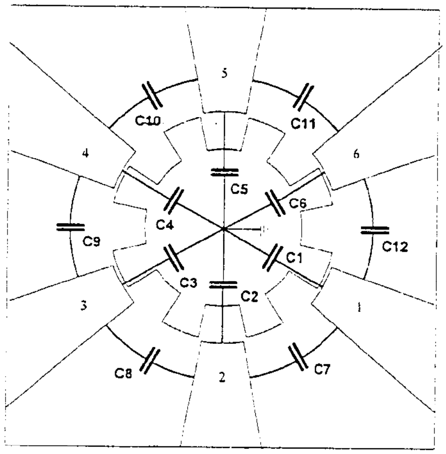

Fig. 5. Definition of the elements of the equivalent circuit for a 6/8 pole radial field electrostatic micro motor.

smaller angular extrusion steps are performed to build the 3 dimensional mesh structure (Fig. 4a).

The electrostatic energy stored in the model is evaluated (1) and serves as the input to obtain the parameters of the equivalent circuit. The desired parameters are the values C of capacity between the single parts of the geometry as indicated in Fig. 5.

$$W_{electrostatic} = \frac{CV^2}{2} \qquad (1)$$

The equivalent circuit in Fig. 5 consists of 12 capacitances, two times the number of stator electrodes. The capacitance of each capacitor varies with the rotor position.

To avoid radial forces on the rotor shaft, the motor have to be excited symmetrically. Fig. 6 shows the possible symmetric excitations of a motor with 6 stator electrodes. The grey electrodes are excited by 1 V and the rotor electrodes are set to ground potential 0 V. By applying different excitation series to the equivalent circuit the torque characteristics versus rotor position can be calculated.

With this simple equivalent circuit several excitation sequences in time are studied in order to find the maximum torque. Using the principles of virtual work, the torque is found by partial differentiating of energy with respect to the angle of rotation:

$$T = \frac{\partial W_{electrostatic}}{\partial \vartheta} \qquad (2)$$

The generated torque is as a function of the rotor position and is split into an average component and the torque ripple. These results are supplied to numerical optimization strategies. The optimal dimensions of the micro motor are determined to maximize the generated average torque by simultaneously minimizing the torque ripples. Clearly, several three dimensional solutions are required in order to find the optimum [2].

In general, optimisation means to find the best solution for a given problem formulation under the consideration of prescribed constraints. The correct and functional expression of the objective function is of particular importance. Optimisation algorithms are generally constructed in the way that the desired optimum is reached step by step. This happens through determined rules. Here, the evolution strategy is used [9]. The evolution strategy copies the principles of the biological evolution into the mathematical process of optimisation. The term mutation describes the variability of the objective variables and the term selection is the equivalent of CHARLES DARWIN's (1809-1882) postulate *survival of the fittest*. Stochastic methods do work without the use of derivatives. They are easy to implement and the treatment of constraints is simple.

Here, the results of an optimization run are given for an axial flux motor (Figs. 2 and 8) constructed with 6 stator electrodes and 4 rotor teeth. This specific motor has a rotor diameter of 320 µm, a double air gap of 3 µm and a rotor thickness of 4 µm (Fig. 8). The two design parameters are the angles of the stator and rotor pole pitch τ_1 respectively τ_2 (Fig. 4). For this motor design and pole configuration the optimum combination of τ_1 and τ_2 and was found to be 44.5° and 38.0° respectively.

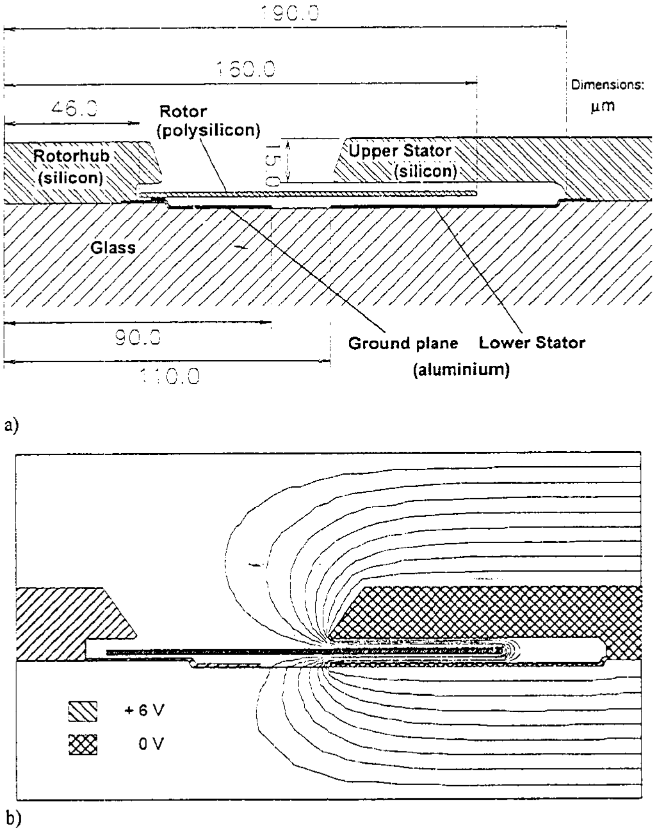

Fig. 8. a) Geometrical dimensions and b) potential solution of a radial cross section of the axial field motor.

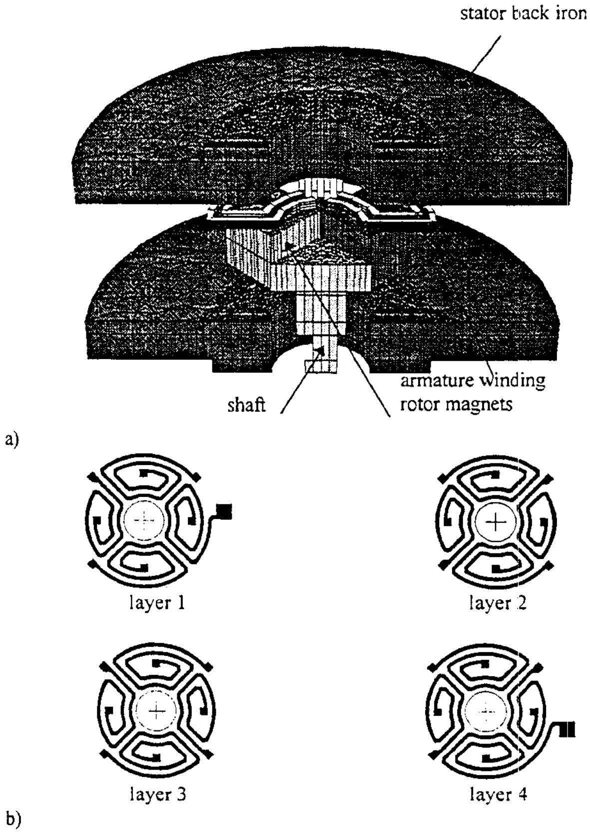

Fig. 9. Electromagnetic mini motor a) 3D finite element model and b) armature winding layout..

III. DESIGN OF ELECTROMAGNETIC MINI MOTORS

The mini motors based on the electromagnetic principle are excited by high energy rare earth permanent material such as NdFeB. The overall dimensions of such motor devices are found in a range of some millimeter. The studied motors are from the axial flux type equipped with etched planar double layer winding in a double stator system (Fig. 9). In order to avoid cogging torques an air gap winding is used.

In this type of application, the supply source is an essential part of the system. Due to the non-linearities of the ferro-magnetic parts of the machine, the link with the time pattern of the supply voltage cannot be simulated using superposition. The motor is operated as a brushless dc motor. Constant dc currents are switched to the armature winding in the stator according to the signals of a position sensing system equipped with hall sensors.

The rotor is constructed with NdFeB permanent magnet blocks of the dimension 2x2x2 mm. The use of high-energy permanent magnet material can lead to significantly improved efficiency and performance of small electrical machines. The high remanence and coercivity at room temperature makes this material particular attractive to this type of machine. However, the sensitivity of the coercivity of NdFeB to high temperatures calls for increased attention to the thermal aspects of a design. Integrated designs using NdFeB magnets are cost-effective for fractional and sub-fractional horse power motors.

Due to the square shape of the permanent magnets, the rotational extrusion process as used for the electrostatic motor, is not possible. Here, a translational mesh extrusion in the axial direction of the motor has to be applied. Fig. 7 shows an axial flux motor with a rotor diameter of 6 mm including the armature winding layout (Fig. 9b). Due to symmetry one half of the motor is drawn only. The air gap windings are fixed to the two stator halves. They are made in thick film technology of four layers on each stator side. As substrate an Al_2O_3-ceramic is used; the conducting material is a palladium, a gold alloy. The four layers are electrically connected in series as indicated in Fig. 9b (layer 1-4).

In the design stage, the target is to obtain reliable results predicting the operational behavior of this device. Macroscopic parameters, reactances and reluctances, are describing the technical physical properties of the machine. Due to the presence of ferro-magnetic materials, the calculations have to account for the non-linearities. However, from Fig. 9 it can be seen that the stator back iron is not saturated but the iron material is recommended for a stable and reliable mechanical construction. The highest values of flux density are found to be in the range of 0.4 T (Fig. 9).

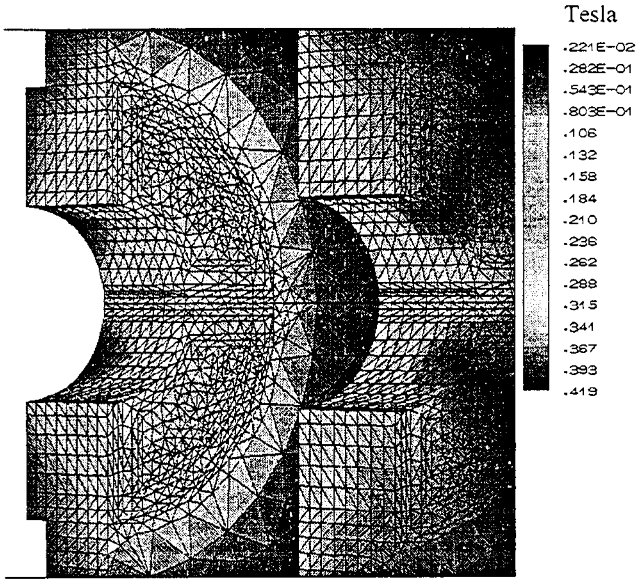

Fig. 9. Flux density distribution in the ferro-magnetic back iron.

To extract the parameters for a simplified equivalent circuit, the same strategy as done with the calculations at the electrostatic micro motor, is followed. The inductance is found from the stored field energy after replacing the permanent magnets by air:

$$W_{magnetic} = \frac{LI^2}{2} \tag{3}$$

The torque is found from the virtual work.

$$T = \frac{\partial W_{magnetic}}{\partial \vartheta} \tag{4}$$

The evaluation of the torque as a function of the rotor position is performed by an automated process.

Once the device dependent parameters are known, the equivalent circuit is modeled and in combination with the characteristic values of the supplying energy source, the overall system is modeled, simulated and analyzed [8].

The results of this calculation again are fed into a self controlled optimization process [9]. Different strategies are combined (simulated annealing and evolution strategy). The implementation of these essentially parallel search techniques can lead to much faster solutions when compared to deterministic methods requiring consecutive solutions. Furthermore, these techniques do not require numerical differentiation and are therefore less sensitive to numerical truncation errors [9].

IV. CONCLUSIONS

The design of micro motors requires the use of advanced three dimensional field analysis methods to obtain the field distribution and subsequently the elements of the equivalent circuit (capacitances or inductances) and the torque. Using appropriate pre-processing tools, the meshing of the model is automated, requiring no interference of the design engineer. The evaluation of the parameters serves as the input of an optimization process, searching in a multivariable space to find the best design. The search process is designed in an appropriate way in order to find the best solution with a minimum of computation time. By using a combined stochastic optimization method, parallel processing can be used to reduce the overall calculation time further.

Three practical designs (axial field electrostatic motor, radial field electrostatic motor and axial field permanent magnet motor) are used to show the versatility and the flexibility of the method. The total process is described and actual prototypes are discussed.

V. ACKNOWLEDGMENTS

The authors are grateful to the Belgian NFWO "Nationaal Fonds voor Wetenschappelijk Onderzoek" for its financial support of this work and the Belgian Ministry of Scientific Research for granting the project IUAP No. P4/20 on Coupled Problems in Electromagnetic Systems.

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VII. BIOGRAPHIES

Kay Hameyer (M' 1995) received the M.S. degree in electrical engineering in 1986 from University of Hannover, Germany. He received the Ph.D. degree from University of Technology Berlin, Germany, 1992.

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