DESIGN OF VERY SMALL ELECTROMAGNETIC AND ELECTROSTATIC MICRO ACTUATORS

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Abstract:
The paper describes a general design tool that can be used for small and extra small electric and magnetic actuators. Such devices are aiming at the generation of micromotions. A three dimensional analysis of the field is required to obtain reliable simulation data. Here, a standard three dimensional finite element method is chosen to compute the electric and respectively magnetic field quantities. In combination with a user-friendly computer interface, controlling the necessary finite element procedures, a powerful engineering tool is obtained. Various configurations are studied using the same software tools. The paper aims on the application of the finite element method (FEM) to micro actuators.

Introduction

The design tool developed is based on the three dimensional finite element analysis of the force generating fields. 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 actuators, 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.

Discussing different types of electrostatic and magneto-static micro actuators, 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).

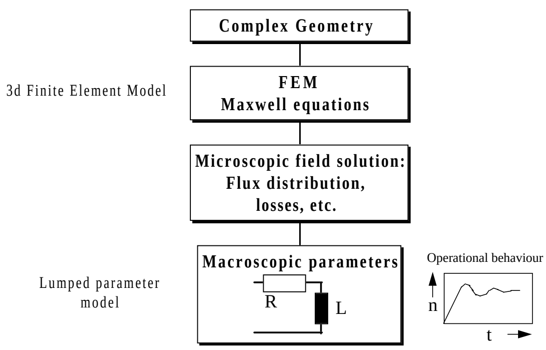
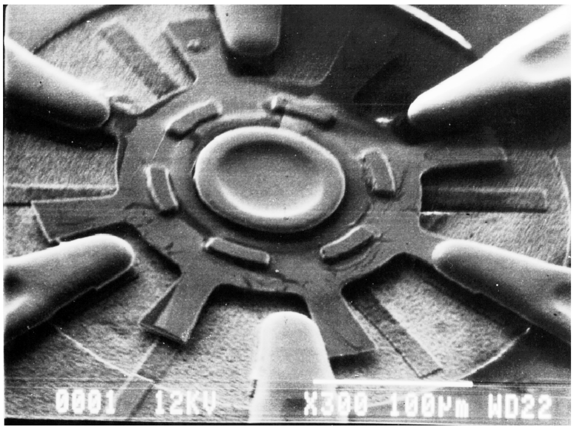


Fig.1 : *Micro- and macroscopic field solution yielding the desired overall behavior of the actuator*

Design of electrostatic micro motors

Scaling analysis shows that as size is reduced electrostatic designs become advantageous compared to electromagnetic devices. Electromagnetic energy converter dominate at dimensions starting in the millimeter range. The electrostatic micro motors studied here, are based on the principal of variable capacitances. Its working principle is very simple. A voltage on the stator electrodes induces a charge on a conducting rotor that then rotates to minimize the electric field energy.

The most inexpensive fabrication technology of electrostatic micro actuators is the thin film process [3]. Such rotating actuators are extremely flat and the generated forces are low. Different principles are possible. Fig. 2 shows an axial field electrostatic micro motor and the corresponding three dimensional finite element model. Radial field type actuators are possible as well (Fig. 3). Assuming here the same height as of the axial field actuators, the surface contributing to the interaction between stator and rotor is smaller and a very small torque can be obtained only. Using the LIGA production technique for the radial type to allow the generation of higher microstructures larger torques can be obtained [4]. This technique is very expensive. More inexpensive alternatives are developed but are not capable of supplying the same depth of the rotor [5].



a)

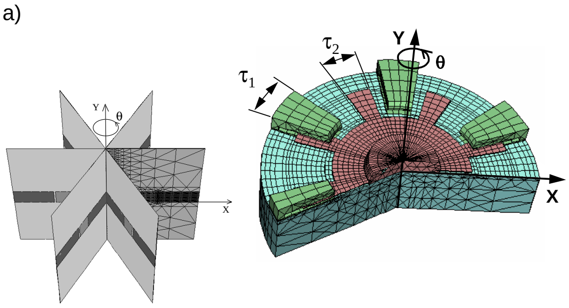


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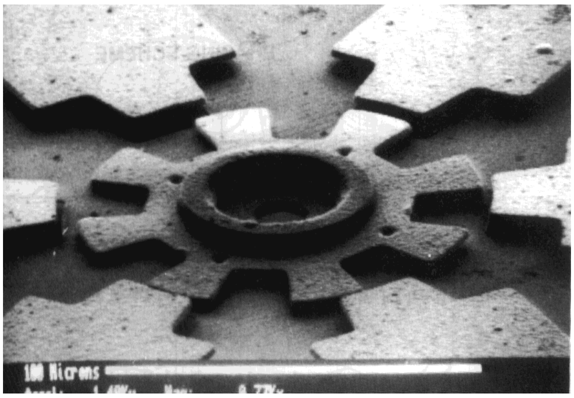
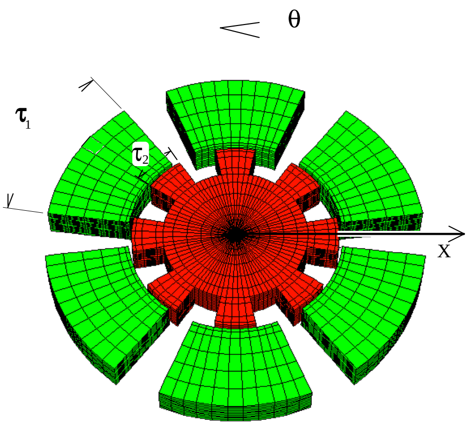
Fig. 2: *a) 6/4 pole Axial field electrostatic micro motor (ESIEE, Paris) and b) the construction of the three dimensional finite element model.*



a)



b)

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

To generate the 3D finite element model, an extrusion process around the machine shaft is developed. A number of planes of symmetry are defined and rotated around the shaft of the actuator (Fig. 2b). This procedure is automated by using a parametrized input interface and leads to a symmetrical three dimensional mesh. Due to the parametrization of the geometry various models can be simulated without additional 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.

The electrostatic energy $W_{electrostatic}$ stored in the model is evaluated (1) and serves as the input quantity to calculate the parameters of the equivalent circuit for this actuator. The desired parameters are the capacities *C* between the single stator and rotor electrodes of the geometry as indicated in Fig. 4.

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

This resulting equivalent circuit of the micro actuator from the model in Fig. 3, consists of 12 capacitances. This is two times the number of stator electrodes. The values of each capacitor varies with the rotor position.

To avoid radial forces on the rotor shaft, resulting in friction or cogging forces, the actuator has to be excited symmetrically. The rotor potential is set to zero. By applying different symmetrical excitation cycles to the equivalent circuit, the torque characteristic versus the rotor position can be calculated. With this simple equivalent circuit several excitation sequences are studied in order to find the maximum torque. Using the principles of virtual work, the torque is found by:

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

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 The generated torque is as a function of the rotor position and is split into an average and a torque ripple component. These results are supplied to numerical optimization strategies [2]. The optimal dimensions of the micro motor are determined by maximizing the generated average torque by simultaneously minimizing the torque ripples. The results of an optimization are given here for the axial flux motor (Figs. 2, 5). The to design parameters

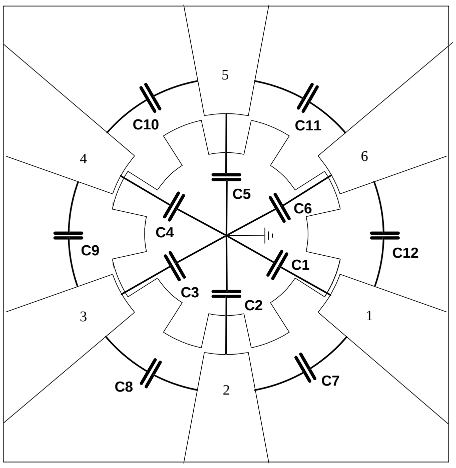


Fig. 4: *Equivalent circuit for a 6/8 pole radial field type.*

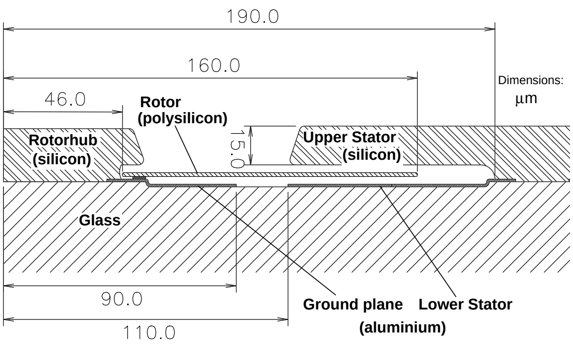


Fig. 5: *Dimensions of the studied axial field type. (the dimensions are given in µm)*

are the angles of the stator and rotor pole pitch τ_1 respectively τ_2 (Fig. 2). For this motor design and pole configuration the optimum combination of τ_1 and τ_2 and was found to be 44.5º and 38.0º. Details on the numerical optimisation can be found in [2] and [7].

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 studied motors are from the axial flux type and equipped with etched planar double layer winding in a double stator system (Fig. 6). In order to avoid cogging torques an air gap winding is used.

The rotor is constructed with NdFeB permanent magnet blocks of the dimension 2x2x2 mm. The use of high-energy permanent magnet material leads 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

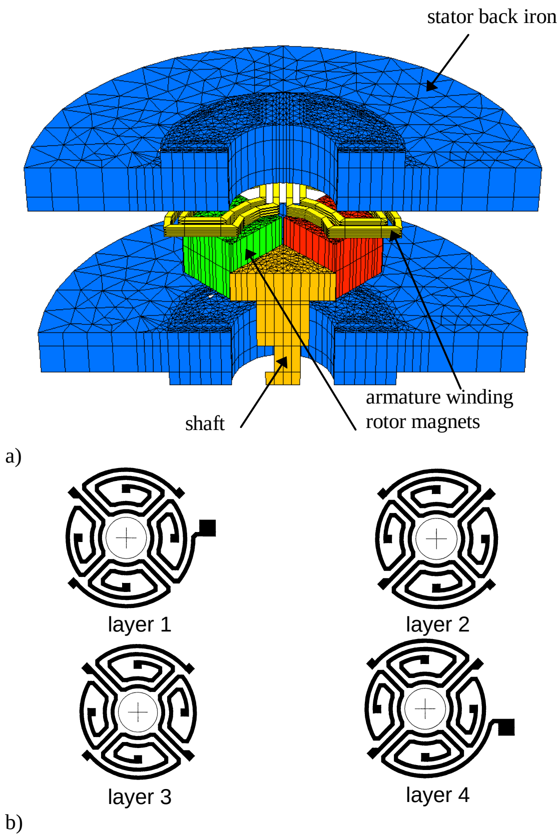


Fig. 6: *Four pole electromagnetic mini motor: a) 3D finite element model and b) armature winding layout..*

sensitivity of the coercivity of NdFeB to high temperatures calls for increased attention to the thermal aspects of a design.

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.

Due to the squared shape of the permanent magnets, the rotational extrusion process as used for the electrostatic motor, is not possible. Here, a translational mesh extrusion in axial direction of the motor has to be applied. Fig. 6 shows an axial flux motor with a rotor diameter of 6 mm. 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. 6b (layer 1-4).

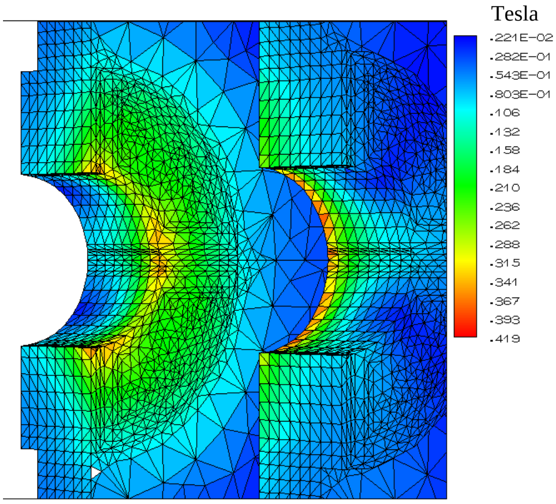


Fig. 9: *Flux density distribution in the ferro-magnetic back iron.*

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. 7 it can be seen that the stator back iron is not saturated but the iron material is recommended for the mechanical construction. The highest values of flux density are found here in the range of 0.4 T (Fig. 7).

To extract the parameters for a simplified equivalent circuit, the same strategy as performed 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:

$$W_{magnetic} = \frac{LI^2}{2} \quad (3)$$

The torque is found from the virtual work.

$$T = \frac{\partial W_{magnetic}}{\partial \vartheta} \quad (4)$$

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].

Conclusions

The design of micro actuators requires the use of advanced three dimensional field analysis methods to obtain the field distribution and subsequently the elements of the equivalent circuit. Using appropriate pre-processing tools, the meshing of the model is automated, requiring no interference of the design engineer.
Three practical designs are used to show the versatility and the flexibility of the approach.

Acknowledgments

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