COMPUTER MODELING TECHNIQUES FOR MICROSTRUCTURES

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1. 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 one of the dimensions is large with respect to the other, 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, both electric and magnetic devices are found. A design system aiming at assisting the engineer, has to be capable to handle both types of problems.

The design tool 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. 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.

2. DESIGN OF ELECTROSTATIC MICRO MOTORS

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.1 shows an axial field electrostatic micro motor and the corresponding three dimensional finite element model. Radial field type machines are also feasible (Fig.2). 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 higher microstructures, larger torque values are feasible [4]. This technique is very expensive, but cheaper alternatives are developed.

In order to apply numerical optimization algorithms an automated finite element modeling is implemented into the design process. This procedure is automated via an parametrized input user interface and leads to a symmetrical three dimensional mesh. 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 stored is evaluated and serves as the input to obtain the parameters of the equivalent circuit. The desired parameters are the values C of capacity between the individual parts of the geometry:

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

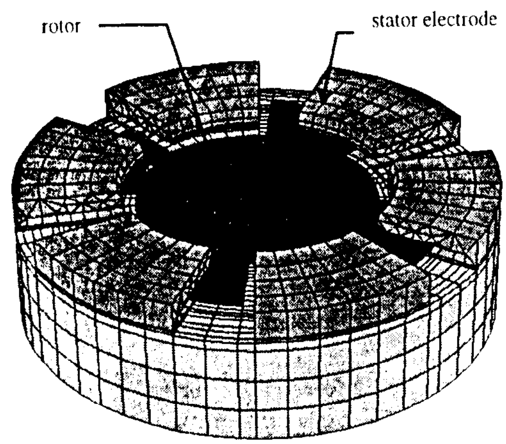

Fig. 1. 6/4 pole Axial field electrostatic micro motor (ESIEE, Paris).

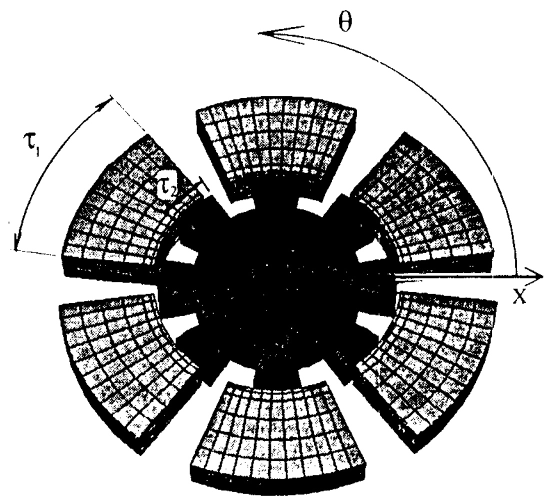

Fig.2. 6/8 pole electrostatic radial field micro motor.

The equivalent circuit 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 motors are excited symmetrically. 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 are studied in order to find the maximum torque. Using the principles of virtual work, the torque is:

$$T = \frac{\partial W_{electrostatic}}{\partial \vartheta} \tag{2}$$

The torque is as a function of the rotor position and is split into an average and a ripple component. These results are supplied to numerical optimization strategies. The optimal dimensions of the micro motor are determined maximizing the generated average torque while minimizing the torque ripple. Several three dimensional solutions are required in order to find the optimum [5]. 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 [6]. Stochastic methods do not require derivatives. They are easy to implement and the treatment of constraints is simple. The results of an optimization run for an axial flux motor will be discussed having 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. The two design parameters are the angles of the stator and rotor pole pitch τ_1 respectively τ_2. For this motor design and pole configuration the optimum combination of τ_1 and τ_2 are 44.5° and 38.0° respectively.

3. 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 millimeter range. The motors are of the axial flux type equipped with etched planar double layer winding in a double stator system (Fig. 3). 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 can not be simulated using superposition. The motor is operated as a brushless dc motor. 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. The high remanence and coercivity at room temperature make this material particularly attractive. However, the sensitivity of the coercivity of NdFeB to high temperatures calls for increased attention to the thermal aspects of a design.

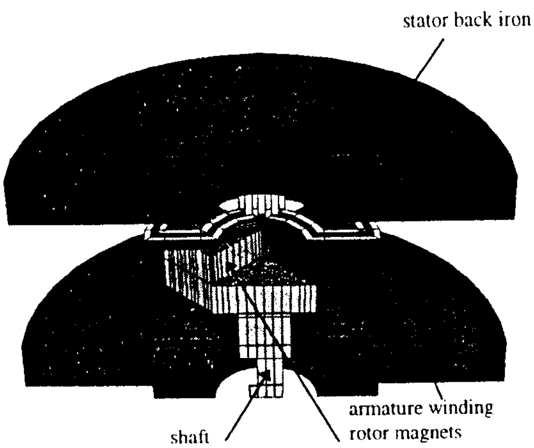

Fig.3. Electromagnetic mini motor

Fig.3 shows an axial flux motor with a rotor diameter of 6 mm including the armature winding layout. Due to symmetry, only one half of the motor is drawn. The air gap windings are fixed to both 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.

In the design stage, the target is to obtain reliable results predicting the operational behavior of this device. Macroscopic parameters are reactances and reluctances. To extract them from the field solution, the same strategy as with the electrostatic micro motor, is followed. The inductance and the torque are found from the stored field energy after replacing the permanent magnets by air and from the virtual work:

$$W_{magnetic} = \frac{LI^2}{2} \qquad (3) \qquad\qquad T = \frac{\partial W_{magnetic}}{\partial \vartheta} \qquad (4)$$

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. The results of this calculation again are fed into a self controlled optimization process. 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.

4. CONCLUSIONS

The design of micro motors requires the use of advanced three dimensional field analysis methods to obtain the field distribution and subsequently 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 input of an optimization process, searching in a multivariable space to find the best design. The search process is designed in a such a way that the best solution is found with a minimum calculation time. Using a combined statistical optimization method, parallel processing may be used to reduce the overall calculation time further.

5. ACKNOWLEDGMENTS

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