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# Hybridizing network reluctance and boundary integral methods: comparisons on an E-core actuator

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**Abstract** — Hybridizing the network reluctance method (NRM) and the boundary integral method (BIM) aims to take advantage of both methods. First for ferromagnetic materials in order to take non linearity into account, and second for surrounding air in order to include fringing and leakages accurately. The automation of such modeling has been done with dedicated software and is compared to the tooth contour method (TCM) and finite element (FEM) simulations, which is applied to an E-core actuator.

**Index terms** — 2D magnetostatic, NRM, MEC, BIM, TCM

## I. INTRODUCTION

Several methods are available to simulate electromagnetic actuators. The choice is made usually for purposes of accuracy or speed. This diversity is explained by the fact that there is no universal method which treats all problems and meets all needs. In fact, all these programs are complementary. For example, the finite element method aims to model objects with complex shapes (2D or 3D) including numerous physical behaviours (saturation, skin effect ...), but it requires significant computing resources. The method of equivalent magnetic circuit (MEC), also called reluctance network method (NRM) is well suited for quick calculations, however the model development is time consuming and requires significant expertise from the user.

The objective of our work is to develop a numerical simulation method, which, like the reluctance network method, is well suited for quick calculations, but whose implementation requires much less time and expertise.

Hybridizing techniques already exists like NRM-MoM [1] but the idea is now to combine NRM and the boundary integral method (BIM). On the one hand NRM is relatively easy to implement in the absence of magnetic leakage in the air, but becomes tedious if leakages are significant. On the other hand, BIM is well known for its effectiveness in fields modelling in the air, but taking into account the method of non-linear materials is more difficult. Hybridizing is then to couple these two methods, ferromagnetic materials will be modelled by NRM and the surrounding air by BIM.

A first method using such a hybridizing is the tooth contour method (TCM) [2] in which leakage flux of a NRM model is identified using a BEM numerical software package. A second method is FVM-BIM, which automates both NRM creation in iron (using finite volumes method) and air (using BIM).

## II. MODELING

### A. Application description

Fig. 1 shows the E-core actuator that is chosen because of its large leakage in order to compare each method.

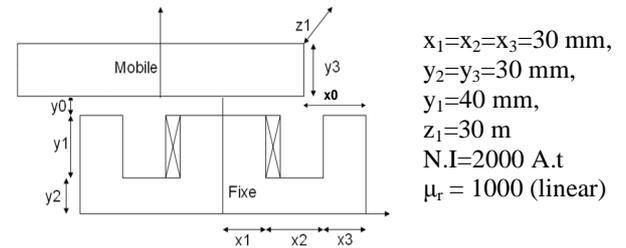


Fig. 1 : Magnetic actuator parameters description

The mobile part is parameterized by its horizontal and vertical translations respectively  $x_0$  and  $y_0$  in order to compute horizontal and vertical forces ( $F_x$  and  $F_y$ ) in several configurations.

### B. FEM simulation

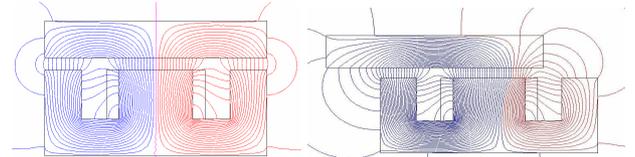


Fig. 2 : The flux lines of the E-core actuator with  $y_0 = 10$  mm and  $x_0 = [0; -45]$  mm

Fig. 2 shows the flux lines obtained with a FEM simulation, in which  $y_0$  has been defined to 10mm. A 2<sup>nd</sup> order mesh is used in Flux2D<sup>TM</sup> with about 3000 nodes for  $x_0 = 0$  mm and 4000 nodes for  $x_0 = -45$  mm. A simulation takes about 1 second. FEM results will be our reference values.

### C. Network Reluctance Method (NRM)

Reluctool software [3] is used to define and simulate a reluctance network. In order to model translation in both x and y directions, the network include parameterized reluctances using analytical formulas. The computation time with linear material is about 10 milliseconds for each position, which is significantly faster than the FEM model.

### D. Tooth Contour Method (TCM)

The TCM is a numerical method to obtain accurate airgap reluctances including leakage and fringing effects.

To obtain the airgap reluctances, the analogy between electric fields and magnetic fields is used. With boundary element (BEM) software (ELECTRO2D) the reluctances in the airgap are obtained. When the reluctances are obtained in- and outside the magnetic material, the calculation time is comparable to original NRM models. Fig. 3 shows the evaluated reluctance network, in which only 12 of the 161 airgap reluctances are shown.

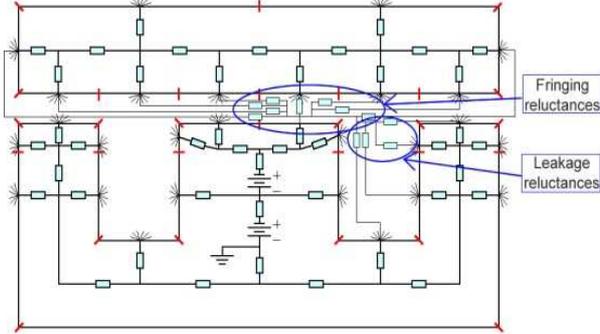


Fig. 3 : Reluctance network including the evaluated airgap reluctances for one segment

### E. Finite Volumes Method – Boundary Integral Method (FVM-BIM)

A new hybrid method is developed in Grenoble, and is implemented in software called MAGOT, in which FVM and BIM are coupled automatically. Like NRM and edge element method equivalence [4], FVM can be considered as equivalent with NRM. Magot software is then able to define a meshing parameter (number of elements in a flux tube cross section,  $n = 2$  in Fig. 4) corresponding to the reluctances in the iron. Fig. 5 shows convergence and computation time regarding this subdivision parameter. The accuracy reaches less than 4% with 5 subdivisions leading to a computation time of 1 second. But a result with about 7% of accuracy can be reached in 30 milliseconds. This FVM is then coupled with BIM, as FEM and BIM can be coupled together [5]-[6].

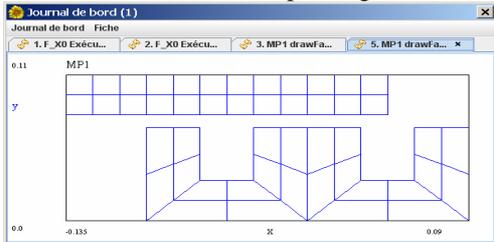


Fig. 4 : Ferromagnetic part meshing in Magot software

### F. Results comparison

Fig. 6 shows that the results for the hybrid methods (TCM and FVM-BIM), which are significantly better than for the NRM. Table I gives the forces for  $x_0$  is 0 and -45mm

The NRM is the fastest method but requires deep knowledge in order to build a correct network topology and to make an accurate parameterization of reluctances. The results for the TCM are better than for the NRM, due to improvement of the leakage reluctances, however a similar network topology must be build in advance. FVM-BIM has been fully automated and reluctances meshing can be configured in order to deal with time/accuracy trade off leading rapidly to good results.

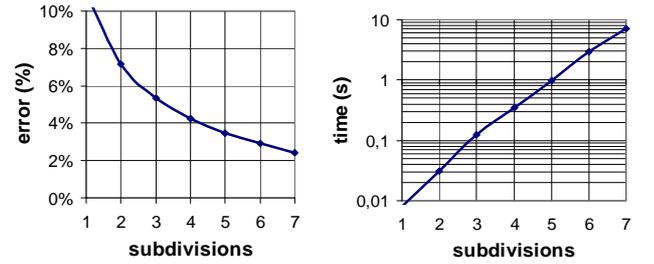


Fig. 5 : Accuracy and computation time regarding the number of subdivisions of the iron

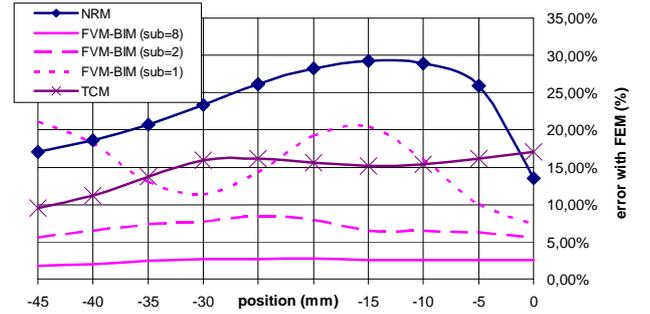


Fig. 6 : Error plot regarding position for reluctance and hybrid method with different subdivisions

TABLE I  
VERTICAL FORCE SIMULATED WITH EACH METHOD

| Fy (N)                    | FEM  | RNM  | TCM   | FVM-BIM |
|---------------------------|------|------|-------|---------|
| Fy (N) $x_0=0$            | 18,4 | 15,3 | 16,64 | 18      |
| Fy (N) $x_0=-45\text{mm}$ | 24,2 | 20,9 | 20,04 | 23,55   |

### III. CONCLUSIONS

The advantage of hybridizing is clear for such an application where leakages and fringing are important. Moreover, the automation of the modeling made with FVM-BIM allows having results very quickly and to do parameterized study with high confidence results since leakages are computed for each new position. In the full paper, details will be given on reluctance networks, modeling procedure of each methods, and comparison results on both vertical and horizontal forces.

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