Strengths and limits of Magnetic MEMS modeling tools

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Abstract:
Thanks to the help of intensive modelling, the two first prototypes realised in the framework of the M^{2}EMS project are functional. It consists of prototypes of single-phase stepper motor whose structure has been transformed from the Lavet motor so as to take into account collective production of the magnet film layers, which are developed in the M^{2}EMS project.
After a short characterisation of design particularities of magnetic MEMS devices, the article explains in detail different steps and way of using a FEM magnetic modelling tool like FLUX to lead the project up to final achievements. Through the description of numerous development work tasks, the interest of using FLUX magnetic computation tool is exhibited. The article ended by an evaluation of limits and strength of such tool for the design of magnetic MEMS.

Keywords: *Magnetic, MEMS, FEM, Permanent magnet, , Modelling, Stepper motor.*

Introduction

The European project M^{2}EMS (Magnetic MEMS) has ended with the realisation of several prototypes among them a mini motor originally from a totally new design specially adapted to the purpose of the M^{2}EMS project and widely inspired for the kind of application from Lavet motors used in Watch industry. Like the Lavet motor our prototype is a single-phase motor designed for one way rotational step actuation.

The motor has been designed with CAD model and the same design has been applied for both bulk and thick film magnet versions. The point that seems the most important to point out is the fact that both prototype versions have been FUNCTIONAL AT THE FIRST ASSEMBLY! It means that a predictive model has been used to design these prototypes and the model was pertinent enough to get a 100% success with the realisation. The first prototype with bulk magnets allowed validating the design of the motor and the second prototype has been used to integrate and test magnet film layers developed by partners of the project.

This success can only be performed thanks to the association of powerful and accurate magnetic models with technological experience. Teams have been able to put in concrete form the model up to the prototype building and the realisation of the tests. About the model, we have mainly used the FEM software FLUX commercialised by Cedrat. Concerning realisation, Cedrat Technologies is now known as an engineering company in the field of mecatronic including the means for mechanical study and laboratory for assembly and tests.

The present article will describe the strength and limits of magnetic modelling tools and statements results from the experience gathered during the M2EMS project and many others.

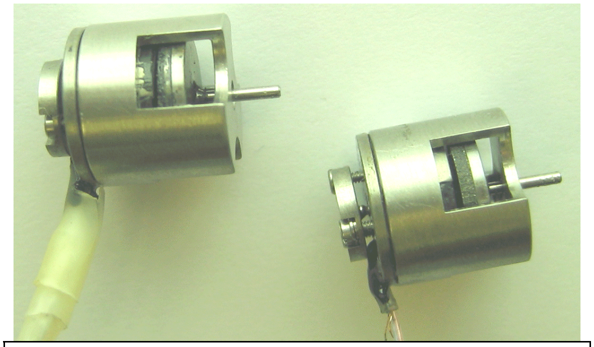

Fig. 1 : The two prototype of Single phase stepper motor
Thick film magnets version (left)
Bulk magnet version (right)

MEMS Specificity

Solving a magnetic problem by FEM tools means extracting out of the Maxwell equations a mathematical formulation (differential equation with partial derivatives) which represents the physics of the device. This formulation remains true whether the device is macro size or micro (µm) dimensions. The result is intrinsic to Finite Element Models (FEM) tools for which size particularities are taken into account through the geometric model of the device.
However, MEMS have their own generic characteristics through the technology of fabrication. It implies, as far as the geometry is concerned, the description of planar shapes with many layers deposited the ones on to the others. It implies also dimensions of micro-metric size which means that the accessibility for control, measurements and characterisation requires adapted sensors and may be not always available without developing an other

sensor system as complex as the concerned device. Finally it involves special processes for material generation and thus the magnetic characteristic of these materials is often not available on catalogues as conventional macro materials.

The use of modelling tools

The use of modelling tool is actually not restricted to the description and computation of a device. In fact modelling tool may be used in many different ways according to the step in the design process. We will present here the different way to use the modelling tool according to the kind of design in process.

Designing a new device starting from a white paper requires to gather and to evaluate very different solutions in order to select ideas and structures the most adapted to the goal. The ideas like a schematic magnetic circuit can be materialised thank to the FEM tool.

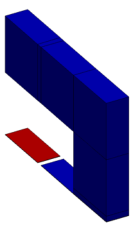
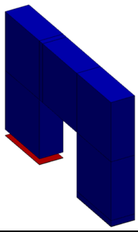

Fig 2 : Parallel magnetisation	Fig 3 : perpendicular magnetisation

Fig 2 : Efficiency comparison of parallel and perpendicular magnetisation

Starting form a white paper, very numerous different structures are candidate for the device. At this stage the FEM tool allows describe series of structures and to evaluate their feasibility from a first evaluation of the performances.

CAD tools are also required for the description and definition of a device. The FEM tool may replace them partly thanks to the modeller (Not specific to magnetism).

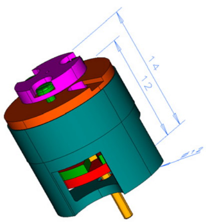

Fig 4 : Motor picture with CAD tool

CAD tools are essential for the detail design of the device. Specialised software may replace them as they take into account the typical planar shape of MEMS components (Not specific to magnetism).

CAF tools are essential on their part for the realisation of the device whose process cannot be manageable by hand (Not specific to magnetism).

The FEM magnetic tool allows computing all magnetic values local or global of the designed device. This is their main role.

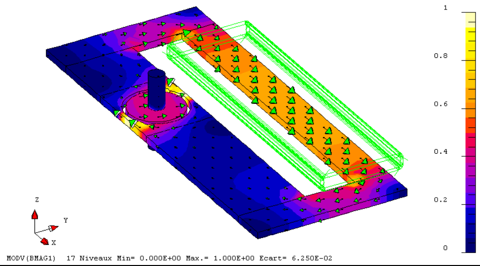

Fig 5 : Flux density on flat shape version of Lavet motor

Their second main role is to perform optimisations in order to fit specifications and goals of the designer.

Once the nominal performances have been reach an additional step left to check all uncertainties and this step is often great resource consuming. It implies to evaluate the sensitivity of the device to variation versus nominal values. When quality procedures are included in the design process it means a certification versus the tolerances.

Finally, the design is theoretically ended. However, the modelling tool is still required for some time because of changes in the device. Mostly when the device is being realised, technological difficulties may bring the designer to correct some parameters. Then the model needs to follow these changes to update performances.

FEM Magnetic models Results

As explained previously, the modelling tool allows characterising a dimensioned device. What are the main results obtained from a FEM tool like FLUX?

A solved FEM model consists in geometry of the device for which physical equations, (Maxwell equation for magnetic systems) have been solved. It means the magnetic field has been solved on each point of the model. This can be done for one case of series of cases when a temporal evolution or a parametric evolution is introduced in the model.

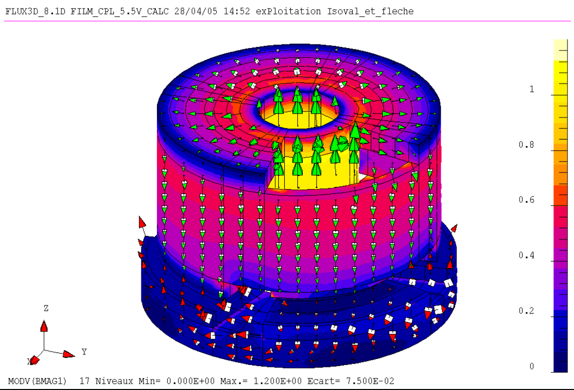

Fig 6 : Flux density representation on motor with colour map (magnitude) and arrows (orientation)

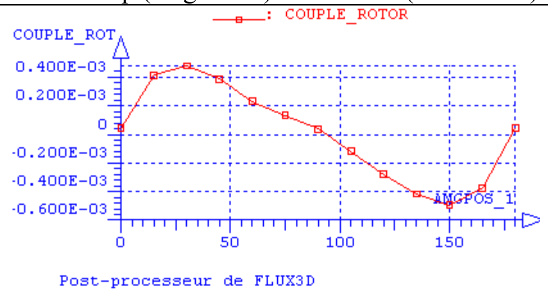

Fig 7a : Torque (Nm) curves according to rotor position and current : I+

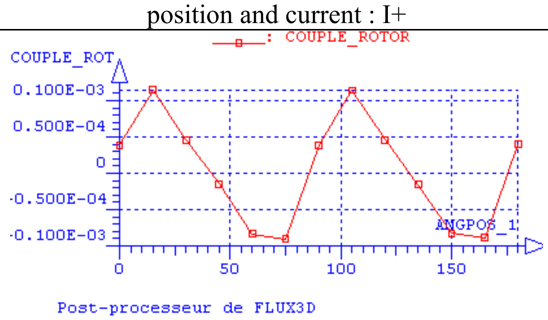

Fig 7b : I = 0 A

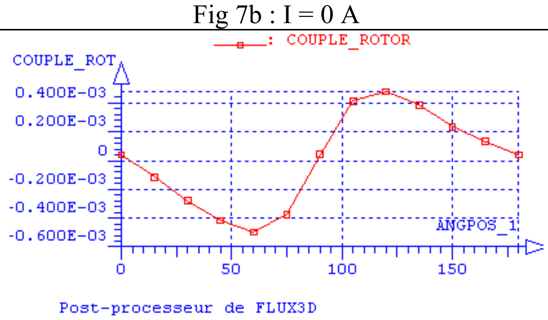

Fig 7c : I-

From each these results the user is able to extract either global values on its system like forces torque, flux, inductance, energy, either local values like magnetic field, flux density permeability for each point of the geometry. Local values can be supplied for set of positions like curves, flux lines, colour maps. Each physical value local or global can be exploited with any evolution

Magnetic computation is not sufficient to fully characterisation. Specialised tools like home tools or generic computation tool like Matlab are then required.

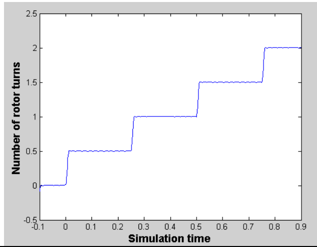

Fig 8 : Evolution of angular position for a specific command (Matlab simulation).

Freedom for open mind and imagination

Starting from white paper, imagination and creativity of the engineer needs to be stored into persistent data - the model - and validated The study feasibility of all of them is feasible with FEM modeller.

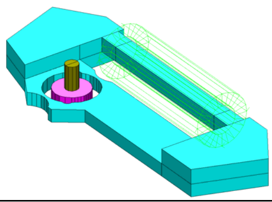

Fig 9 : Initial Lavet motor

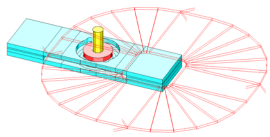

Fig 10 : Flat coil version of Lavet Motor

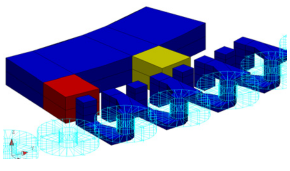

Fig 11 : Parallel magnetisation, Many coils radial air gap generator

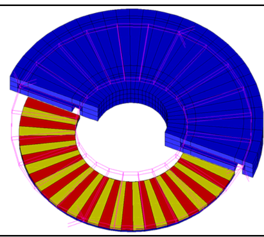

Fig 12 : Perpendicular magnetisation, one coil axial air gap generator

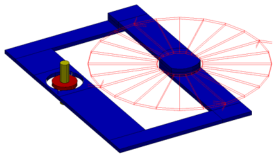

Fig 13 : One of first structure

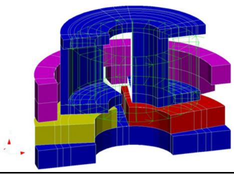

Fig 14 : Final Mini motor structure

Such kind of step concerned the first six-month period of the M2EMS project. The previous table shows different examples of structures evaluated versus the project goal.

Sensitivity studies and optimisation

For each principle of structure a feasibility study more or less advanced is performed to check whether the idea can fit with specifications. This is a first kind of optimisation and is get pre-dimensioning of the device. When a structure is validated further steps can be performed with the dimensioning with more or less optimisation according to the available. Once a nominal version of the device is established, new series of computations complete the model in order to take into account all uncertainties like tolerances, exact material properties, variation of environment like temperature and supply characteristics,....Finally once the model has been fully validated one still needs to follow the impact of variation of properties, solutions, technologies and constraints versus time. Here again the adjustment of the model requires new computations.

All these step in the design of a product are applicable to MEMS and require the evaluation of a great amount case or configurations. Without a model tool it would be never possible to realise the corresponding evaluation. Many uncertainties would remain until the realisation and evaluation. of the prototype. The modelling tools allow fixing many interrogations. It does not means that all problem are fixed, because uncertainties often remain and will need validation trough experiment, but it make the design much smarter.

Limits

Despite modelling tools seem to furnish all required data for the design of the device, the efforts of the magnetic device designer is not suppressed! Each parametric evaluation is time consuming so it has its cost. Because it is easy, with parametric FEM software, to study the variation of the impact of a parameter, the designer tends to explore many aspect of his device. Whereas without model only a set of test prototypes is realised, often-intermediate parametric models allow discovering some physical particularities and bring new questions to be cleared. It risks to never ending and the designer needs to forget part of his ideas or interrogations to remain in the frame of project schedule and budget.

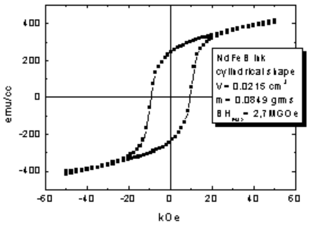

Fig 15 : IMS NdFeB Magnet characteristic

Other a very classic limit for FEM magnetic tools is the accurate knowledge of the magnetic properties of the materials. As general equations are well mastered through the formulation, magnetic state of material is often hard to fix. With conventional special magnetic produced material, the magnetic characteristic is well known if the designer follows strictly the recommendation for machining and thermal treatment. Their characteristics may become very rough or uncertain as soon as magnetic materials not specially designed for magnetic applications are employed. The difficulty stays the same when new processes are used for material production as in M^{2}EMS project. Then one has to rely on a special characterisation of the material employed.

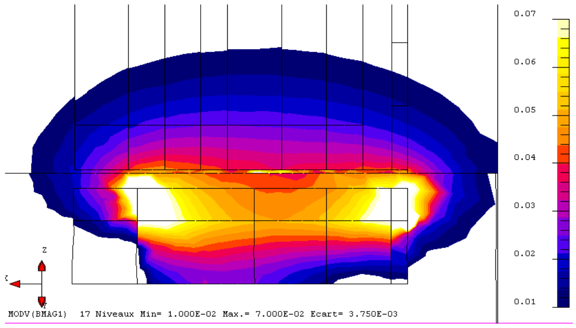

Fig 16 : Section of flux density in the rotor

The same kind of uncertainties may be due to part making tolerances. The dimensions of the prototype parts depend on the machining and are not the one effectively introduced in the model. For some kind of device it may result in an important variation of properties.

Briefly speaking, exact model never happen. The model is always an approximation of the obtained device. In good models few room is left to uncertainties, while sometime when processes, material, characterisation are not fully mastered quite many uncertainties are left.

Strength :

The first strength of the model is the reliability of the result obtained. For pre-dimensioning, simple analytical models are often and still used to try to evaluate the main trends. However, the high difficulty here is to validate all assumptions. This is all the more difficult as the device is design in 3D. Using a F.E.M. model with competence allows being more trustful because we can rely on physical accuracy of results trough the choice of the correct formulation and an active control of the mesh.

As explained previously the adaptation to the micro scale is not a problem for a F.E.M. software. One can however point out on the tendency to use layer shape of material. With non adapted tool this may bring modelling difficulties because huge ratio wideness over thickness may result in huge number of elements and high computational costs. However, in flux a special surface formulation already included in the software can take in charge of a thin material layer. Thus, dimensional aspects of the model are well mastered.

About material properties, even though there would be some specific behaviour of magnetic material due to very small dimensions of parts, Flux software allows the user to supply specific through user subroutine. If these special properties become well know and often used, the software will finally integrate their model in the conventional version. This has already been done for supra conductive materials. Thus even for very specific properties an adapted model can be described.

Other very interesting feature of F.E.M. tool is the ability to check some physical assumptions to understand surprising characterised behaviour. The problem is similar to the one encountered making CND work and is close to the solving of inverse problem.

Shortly speaking, the use of models brings to the designer a much better understanding on his device. This become crucial when the device is so small like MEMS that no measurement can be performed either of forces or flux density in the device. Then when the device is realised, whether it works or not, results particularities are hardly interpretable. With the modelling tool assumption still can be proposed and an adapted model can be described so to check whether it fit with device behaviour.

Conclusion

Cedrat Technologies had already experience for the realisation of devices and prototypes. APA is an actual product range. Realisations are often performed starting from an existing product with an adaptation or an optimisation. This time Cedrat Technologies designed and realised a new motor structure starting from a white paper. And the first realisation work!

The success is due to the process of the design, which has used widely the model to predict performance, problems and physical phenomena.

The use of models for MEMS is all the more important as:

The prototype realisation is expensive, (big devices, device using expensive equipment for realisation (MEMS).

The prototype is not easily accessible for characterisation (dimensions of M2EMS).

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