A PARAMETRIC ENVIRONMENT FOR THE OPTIMIZATION OF ELECTROMAGNETIC DEVICES

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Abstract:

A parametric pre-processor and a general purpose optimization environment are presented. Both are implemented in MATLAB, providing the graphical interface and controlls external processes. Due to the open architecture of the package, finite element models can be controlled as well as analytical models. Two optimization tasks are discussed to underline the general application range of the tools. While the first task deals with the optimal design of an inductor used in a traction drive system, the second task focuses on the design of a Superconducting Magnetic Energy Storage (SMES). Special attention is paid to the formulation of the quality function.

INTRODUCTION

The optimization of electromagnetic devices is one key to enhance product quality and manufacturing efficiency. As each device has different specifications, the goal of the optimization is be largely device dependent. Real life optimizations of electromagnetic devices require firm constraints and highly non-linear calculations. This demands for optimization procedures which have a general applicability, allow a high number of independent parameters, as well as a simple implementation of a wide range of constraints and the formulation of multiple objectives. Stochastic optimization algorithms like Evolution Strategy, Simulated Annealing and Genetic Algorithms offer all these specifications. The disadvantage of a larger number of quality function evaluations compared with optimization algorithms based on derivatives is largely compensated by the simplicity of the implementation of constraints and multiple goal quality functions [1,5]. This disadvantage will decrease with the further development of computer hardware.

Finite element analysis (FEA) of electromagnetic devices, on the other hand, has proven to be a reliable tool for the evaluation of new designs. Combining stochastic optimization algorithms and finite element techniques to an optimization environment allows the creation of an easy to use design tool.

PARAMETRIC PRE-PROCESSOR

A key requirement for the combination of FEA and optimization algorithms is a pre-processor which provides the tools to parametrise 2D and 3D finite element models. This includes, apart from the parametrization of the geometry, the parametric definition of material properties, problem definition data and post-processing algorithms. *MATLAB* has been chosen as the environment to implement an interactive graphical pre-processor. Starting from a sketch of the device geometry, the entire analysis procedure for the model can be defined in this environment. The resulting parametrized sketch file contains all data to describe the steps of the finite element analysis, constraints checking and the post-processing algorithm (quality function). Once the analysis procedure of the finite element model is defined, simple parameter variation runs can be performed. The pre-processor controls the full procedure out of *MATLAB* by calling external programs, such as the mesh generator, solver and post-processor routines. Figure 1 shows the structure of the parametric pre-processor.

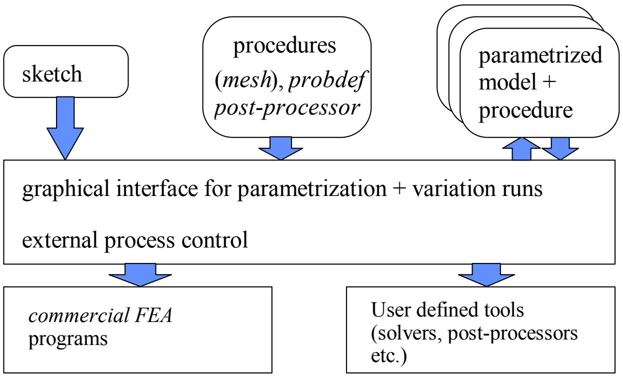


Figure 1. Structure of the parametric pre-processor implemented in *MATLAB*.
Its open architecture allows the combination of different analysis tools.

OPTIMIZATION ENVIRONMENT

The developed optimization environment provides the following features:

1. Different optimization algorithms.
2. Monitoring the optimization process at run-time.
3. Defined stop and restart procedures in case of problems during execution.
4. Handling parametrized procedures provided by the parametric pre-processor to optimize finite element models.
5. Open architecture allowing for the optimization of non-FEA models.
6. Implementation of additional optimization algorithms without changing the whole structure of the environment.

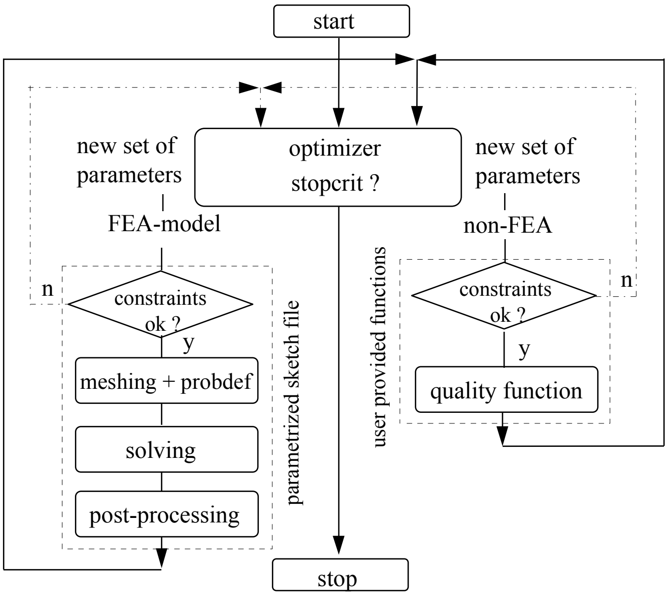


Figure 2. Structure of the optimization environment

Four optimization algorithms have been implemented into the optimization environment: Evolution Strategy, Simulated Annealing, a combination of both and Adaptive Simulated Annealing [2]. In case of an optimization of a finite element model, the parametrized sketch file includes all information necessary to start the optimization. The environment controls the external process calls for the FEA. Whereas the parametric pre-processor is an interactive graphics tool, the optimization process is entirely automatic and can be run as a background process without any graphics. The optimization can be stopped at any time and restarted from the previous position. This feature has been found very useful in a network environment, when a long lasting optimization should be stopped to allow for the maintenance of the network. The progress of the optimization can be monitored by a graphical tool. Depending on the optimization algorithm, key data may be visualized together with the variation of all parameters. Due to the open architecture of the optimization environment, non-FEA models can be processed as well. The user has to provide the constraints checking algorithm and the quality function, that may be external programs or *MATLAB*-macros (figure 2).

OPTIMIZATION OF AN INDUCTOR - AN ANALYTICAL APPROACH

The objective of the first optimization example is the design of an inductor used in a traction drive system. Apart from the required electrical characteristics, minimum weight is desired. The inductor must have an inductance of 3 mH up to a maximum current of 1350 A. The current density in the copper windings should not exceed 10 A/mm^2. Maximum dimensions for the inductor are given.

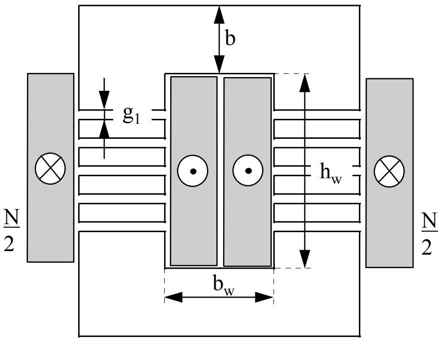


Figure 3. Geometry of the inductor

Set of parameters:		**Constraints:**	
b	- yoke width	$d+b_w$	< 500 mm (depth)
d	- yoke thickness	$2*(b+b_w)$	< 750 mm (width)
b_w	- window width	$2*b+h_w$	< 660 mm (height)
h_w	- window height	g_0	$< h_w/2$
g_0	- total air gap	J	< 10 A/mm^2
N	- number of turns	B_{max}	< 1.5 T (no saturation)

The total air gap is subdivided into multiple gaps with a length less than 1/6 of b and d to minimize leakage flux. An (4,4-20)-Evolution Strategy was chosen.

Special attention has to be paid to the formulation of the quality function (1). Two approaches have been tested in this example. The first one rejects all set of parameters which do not fulfill the constraints, thus narrowing the search space for the optimizer. The second formulation implements a combination of rejecting parameter sets and penalty functions to produce a higher acceptance rate of generated parameter sets.

formulation 1:

Constraints check:

- all parameters > 0
- $N = f(L_0, R_i)$
- $J_{max} < 10$ A/mm^2
- width, height and thickness < maximum dimensions
- $B_i < B_{max}$

Quality function:

- weight m_i

formulation 2:

Constraints check:

- all parameters > 0
- $J_{max} < 10$ A/mm^2
- width, height and thickness < maximum

Quality function:

- weight m_i
- inductance L_i
- flux density B_i
  if $B_i > B_{max}$ set $B_{penalty}$

$$B_{penalty} = \frac{|B_{max} - B_i|}{B_{max}}$$

$$q = \frac{m_i}{1000} + \frac{|L_{given} - L_i|}{L_{given}} + B_{penalty}$$

(1)

Both optimization runs are started with an initial set of parameters not matching the constraints criteria. One of the first accepted parameter sets describes an inductor with a weight of 650 kg (figure 4.).

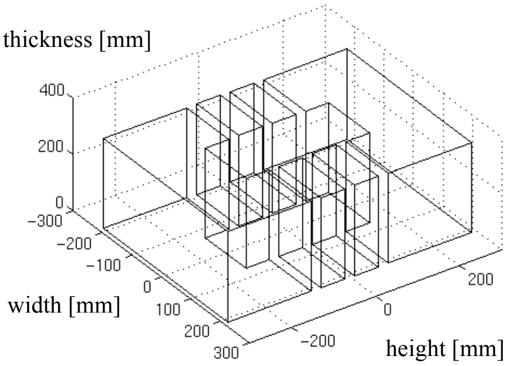


Figure 4. Yoke dimensions of the first accepted model using formulation 1 (total weight 650 kg).

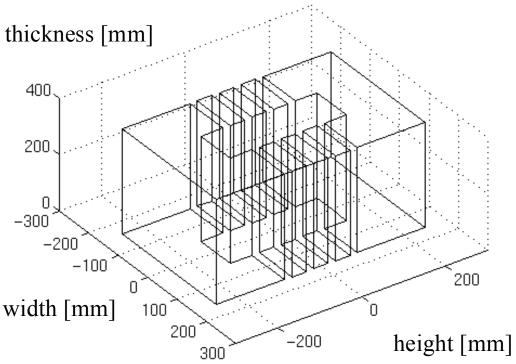


Figure 5. Yoke dimensions of optimal design using formulation 1 with an inductor weight of 472 kg.

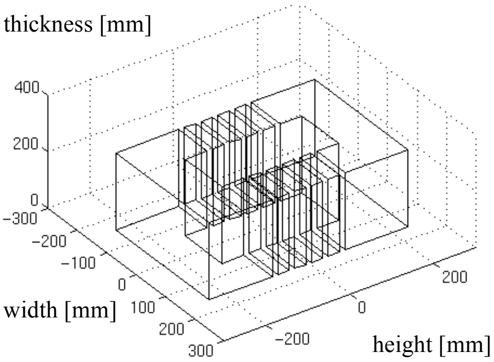


Figure 6. Yoke dimensions of optimal design using formulation 2 with an inductor weight of 349 kg.

Several optimization runs using formulation 1 and 2 have been performed, indicating that formulation 2 results in a more optimal design than formulation 1 (figure 5, 6). Therefore, the use of penalty functions is therefore highly recommended. In other optimizations it might be necessary to apply weighting factors for the different terms in the quality function. Using an Evolution Strategy, the step length of the parameter variation is used as a stopping criterion (figure 7,8). The optimization using formulation 1 stopped after 850 quality function evaluations. The inductance of the inductor is maintained at 3.001 mH and the flux density and the current density did not exceed the maximum values.

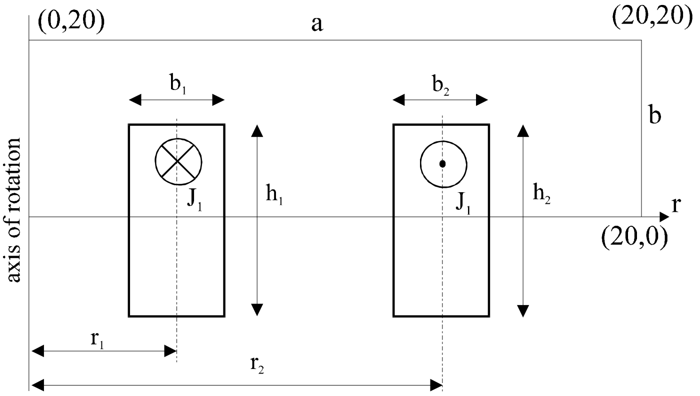
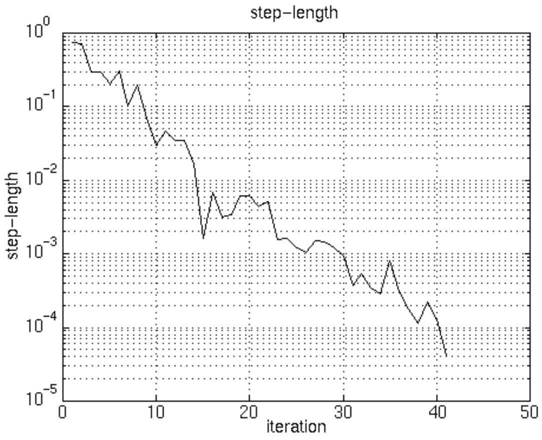


Figure 9. Set of parameters describing the SMES



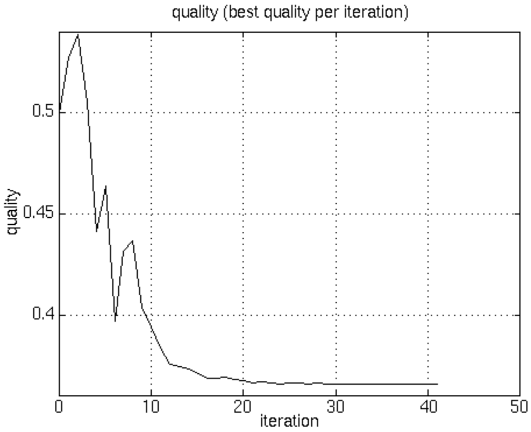


Figure 7. Step length of the best child per generation using formulation 2.

Figure 8. Quality of the best child per generation using formulation 2.

SUPERCONDUCTING MAGNETIC ENERGY STORAGE - AN FEA APPROACH

An optimization benchmark has been proposed by [3,4]. The main objective is the design of an Superconducting Magnetic Energy Storage (SMES) with minimum stray field while storing a given amount of magnetic energy (180 MJ). Due to the rotational symmetry, a 2D-axisymmetric FEA is used. Seven parameters are necessary to describe the key dimensions of the device (figure 9,10).

Apart from the geometrical restrictions, the superconducting coil has to be prevented from quenching. The violation of the quench condition can only be tested after the model has been simulated and is treated by adding a penalty term to the objective function. The SMES consists of two circular coils carrying an opposite directed current. The current density in both coils has the same value. The geometrical dimensions are tested directly after a new set of parameters is generated. If the geometry is valid, a 2nd order finite element analysis is carried out. The maximum flux density inside the coils together with the applied current density indicates whether the quench condition is violated. The objective function is the weighted sum of two terms, one regarding the stored magnetic energy and the second regarding the magnetic flux density along the two lines a and b defined in figure 9. Penalty terms are applied if the quench condition is violated, and if generated parameters exceed the prescribed limits but do allow the generation of a model.

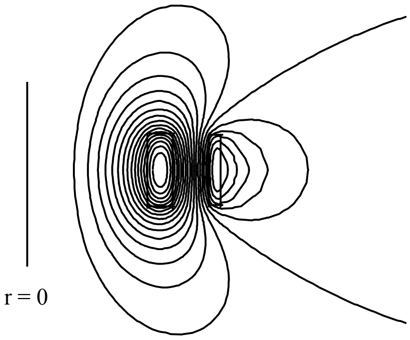


Figure 10. Equipotential plot of the optimal configuration found in [3].

The minimizing objective function is given by

$$q = w_1 \frac{q_B}{q_{B,0}} + w_2 \frac{q_E}{q_{E,0}}, \quad where \quad w_1 = 0.4 \quad and \quad w_2 = 0.6 \tag{2}$$

$$q_B = \sqrt{\sum_i \left(\left|B_{stray,i}\right|^2 - \left|B_{i,0}\right|^2 \right)}, \qquad \left|B_{stray,i}\right| > \left|B_{i,0}\right|, \qquad B_{i,0} = 10\mu T, \tag{3}$$

$$q_E = \left|E_{stored,i} - E_{stored,0}\right|, \qquad q_{E,0} = E_{stored,0} = 180\ MJ \tag{4}$$

Again an Evolution Strategy has been applied to optimize the arrangement. The value of the objective function depends on the initial set of parameters. A comparison with the proposed benchmark model is therefore only possible by comparing the stored energy and the distance along both axes at which the flux density falls below 50 µT. Table 1 lists the results of the optimization.

Table 1. Results of the optimization test.

	Energy (180 MJ)	r < 50 µT	z < 50 µT	calls of q
benchmark (GSA) [3]	180.112 MJ	18.5 m	17.4 m	34000
benchmark (ES) [3]	180.12 MJ	18.9 m	18.0 m	4200
(5,5/20) - Evolution Strategy	179.88 MJ	19.0 m	18.1 m	800

The optimization stopped after 800 quality function evaluations. The optimization results closely match the results found in [3]. The optimum was reached with considerable less function evaluations.

CONCLUSION

A parametrized environment for the optimization of electromagnetic devices has been developed. The emphasis was put on the development of a tool that is easy to use and applicable to both, FEA and non-FEA simulations. The two examples demonstrate the open architecture of the environment, which will be extended in the future, incorporating more optimization algorithms. Another central point in the further research will be the automatic selection of the parameters defining the optimization strategy.

ACKNOWLEDGMENT

The authors are grateful to the Belgian Nationaal Fonds voor Wetenschappelijk Onderzoek for its financial support of this work and the Belgian Ministry of Scientific Research for granting the IUAP No. 51 on Magnetic Fields.

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