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# System design and simulation in electromagnetics

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## Abstract

The system concepts desired by the everyday user of commercial finite element software packages for electromagnetics is described. If such concepts meet the basic user requirements and the package is open via data interfaces to include external program parts, this gives the opportunity for the user to complete the existing commercial software with his own software tools to match specific tasks. By using such pre- and post-process operators a remarkable increase of efficiency of the overall software package can be realised.

## 1 Introduction

Nowadays, the finite element method (FEM) is applied to compute a variety of field problems. To solve problems in electromagnetics a number of commercial field computation packages are available on the market. All those packages in general are very good suited to obtain satisfactory solutions of standard problems as there are the electromagnetic fields in energy converters. Effects like the linear or non-linear characteristics of material and the inclusion of the presence of permanent magnet material inside the device are considered. Field computations in two and in three dimensions are possible via extrusion based or solid model operators in the pre- and post-process.

In this paper examples will be given how to solve special problems suitable in the pre- and post-process. Advantages and disadvantages of the different methods and approaches will be discussed. It will be reported from own experiences using tools for the modelling of electromagnetic devices.

Applications of numerical optimisation algorithms in combination with the finite element method and the necessary tools to parameterize a geometry discussed as well. The methodology of user programmed software and lementation to the electromagnetic field package to enable a coupled /electromagnetic analysis will conclude the paper.

## ıerical field computation

: a brief inside into the numerical field computation fig. 1 illustrates the e of activities necessary during a design session using the finite element . To point out possibilities to enhance an existing FEM program : with own software routines the single steps on the way to the field ı will be described in the following sections.

### -processing

ole FEM procedure can be divided up into three main parts. The first the pre-process, consists out of the problem definition. The geometry,

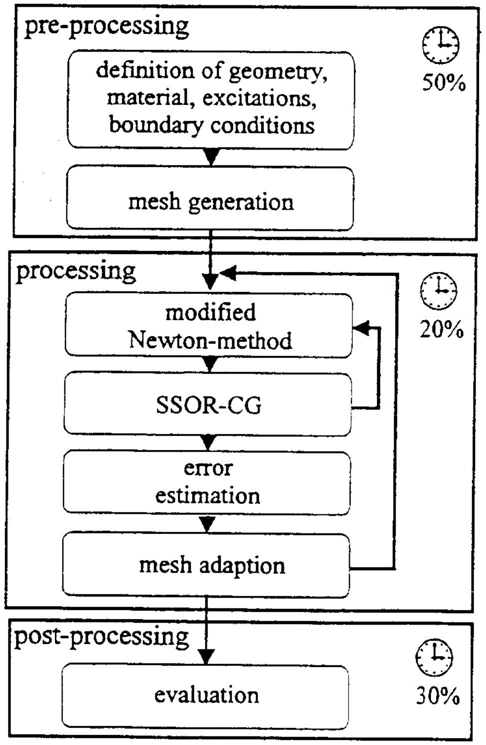


Figure 1: Schedule of the finite element method.

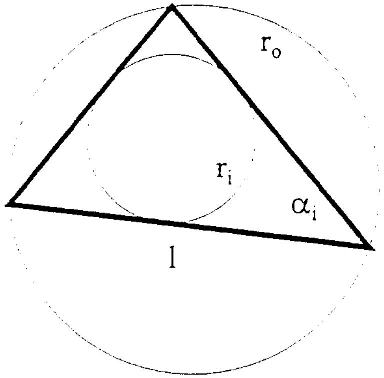


Figure 2: Geometrical definition of a standard triangular element.

the different materials used, excitations and boundary conditions have to be determined to model the physical device. The following step is the mesh generation. The user of the field computation package has to supply the program with some quantities to control the quality of the finite element discretisation. This step demands an experienced design engineer because the quality of the mesh for the specific field problem directly influences the accuracy and the convergence behaviour of the desired solution. Mainly all commercial available finite element packages supports an apriori error estimator to automatically generate an uniformly distributed discretisation. If this is not the case and all the mesh data are available, the geometrical criteria are only given at this place to be included in an existing FEM package and are not discussed further.

Using standard triangular finite elements, the quadratic deviation from the angles of the triangle $\alpha_i$ from the standard angle $\pi/3$ should tend to a minimum:

$$\frac{1}{3}\sum_{i=1}^{3}(\alpha_i-\pi/3)^2 \rightarrow \min \tag{1}$$

The ratio of largest and smallest angle in the mesh should tend to unity:

$$\frac{\alpha_{\max}}{\alpha_{\min}} \rightarrow 1 \tag{2}$$

The ratio of outer to twice the inner radius of a triangle should tend to unity:

$$\frac{r_o}{2r_i} \rightarrow \tag{3}$$

The ratio of maximum to minimum side length of a triangle should tend to unity:

$$\frac{l_{\max}}{l_{\min}} \rightarrow \tag{4}$$

Further details can be found in Babuska[1].

The apriori error estimation, used to control the uniformity of a mesh, not permit a general statement about the accuracy of the field solution se the overall accuracy of the field approximation depends on the precise tisation of the geometry in regions with a large change of the field ities as well. Therefore, an aposteriori error estimator is necessary to ate the relative error of the field solution. By using this second type of estimation an adaptive mesh refinement is possible in the way as ted in fig. 1.

### ocessing

ssemblage of the system of equations and their solution, the processing f a FEM session, can usually be influenced by the user only by ucing parameters like solution tolerances or maximum steps of iterations. end of this procedure potential values computed in the nodes or along ges of the FEM elements are available. An open FEM system will have portunity to store those values in an ASCII file accessible for further ulation in the post-process.

### st-processing

a two dimensional finite element approach, the vector potential $A$ is ted and the interesting magnetic field quantities are derived from this n. The numerical evaluation of derivatives can be troublesome due to off errors during the calculation. The flux density $\boldsymbol{B}$ is determined by the derivatives of $A$.

$$\mathbf{B} = curl\mathbf{A} \tag{5}$$

re, the resulting flux density looses one order in accuracy when ed to the order of accuracy of the vector potential. Using standard linear functions to approximate the continuous vector potential over a ar finite element results in an only piece wise constant magnetic flux As a consequence, the calculated forces from those derived quantities accurate when compared to the vector potential results. This causes al errors due to numerical integration by using the MAXWELL stress o evaluate globally generated forces.

For a more accurate force calculation the aim is to improve the results isting field solution in a local post-process [2]. The idea is to solve the E equation

$$\Delta u = 0 \tag{6}$$

e free and homogenous areas, e.g. in the air gap of an electromagnetic tarting with an existing field solution. As a method, the local potential

on the circumference of a circle placed inside the air gap is approximated by a FOURIER series using the existing solution as boundary values of the local problem formulation [3].

$$u(r,\Phi) = \frac{\alpha_0}{2} + \sum_{n=1}^{\infty} r^n \{\alpha_n \cos(n\Phi) + \beta_n \sin(n\Phi) \tag{7}$$

with its coefficients $\alpha_n$ and $\beta_n$.

$$\alpha_n = \frac{1}{\pi R^n} \int_0^{2\pi} u(R,\Phi) \cdot \cos(n\Phi)\,\mathrm{d}\Phi$$

$$\beta_n = \frac{1}{\pi R^n} \int_0^{2\pi} u(R,\Phi) \cdot \sin(n\Phi)\,\mathrm{d}\Phi \tag{8}$$

The procedure to solve eqn (7) describes the solution of a DIRICHLET problem on a circle with given boundary values on its circumference. The FOURIER coefficients $\alpha_n$ and $\beta_n$ can be calculated by using the known potentials $u = u(R,\Phi)$ on the circumference of a circle with radius $R$. To obtain the potential in points $P_1$ on a given contour inside a finite element domain, multiple circles have to be evaluated. According to fig. 2 a finite number of $N$ equiangularly ordered points is applied onto the circumference of the circle with $u_i(R,\Phi_i) = u(R, i \cdot \frac{2\pi}{N})$ , $i = 1(1)N$. With $N$ boundary potential values $u_i$ known on the circumference and according to the properties of harmonic functions the first term in eq. (7) can be written as:

$$u|_{r=0} = \frac{\alpha_0}{2} = \frac{1}{N}\sum_{i=1}^{N} u_i \tag{9}$$

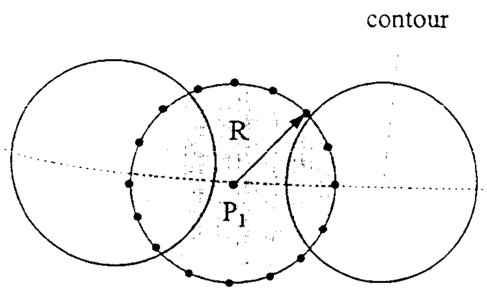


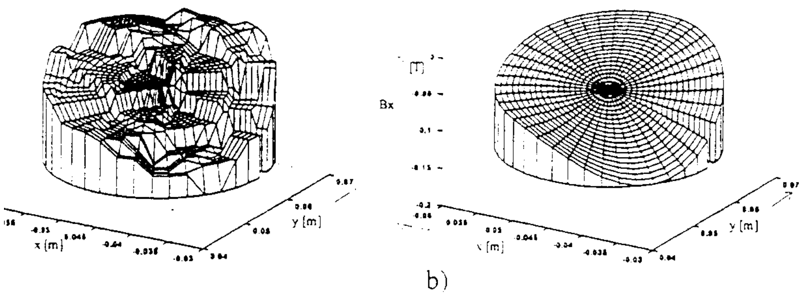
Figure 2: Multiple circles determine the potentials on a contour.

The FOURIER coefficients are rewritten as follows:

$$\alpha_n = \frac{2}{N \cdot R^n} \sum_{i=1}^{N} u_i \cos(n\Phi_i)$$

$$\beta_n = \frac{2}{N \cdot R^n} \sum_{i=1}^{N} u_i \sin(n\Phi_i) \tag{10}$$

With the FOURIER series eqn. (7) and their coefficients eqns.



3: Comparison of flux density distribution using a) $\mathbf{B} = curl\mathbf{A}$ and b) the local post-process operator.

the potential in the centre of a circle can be computed by only knowing ındary potential values on the circumference of the circle. The numerical ›f the eqns. (6, 9, 10) enables an easy implementation of the procedure finite element program package. Overlapping circles guarantee a ıous solution in the considered region after this post-process. Figure 3 as an example the flux density distribution of one circle using eqn. (5) local post-process operator.

## lementation of a thermal FEM analysis module

ıance and rated data of electrical machines are strongly related to the heat transfer and the temperature distribution inside the machine by generated losses. To estimate the heat flux accurately, numerical tools are required. An open FEM package for electromagnetics, that does not support the possibility of a thermal analysis, is suited to fulfil nand. By using the same data structure for a thermal processing module

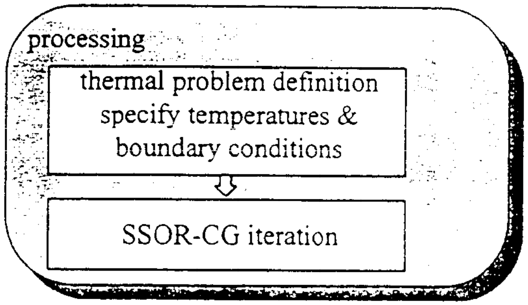


Figure 4: Thermal FEM analysis module.

the pre- respectively the post-processing tools of the magnetic FEM program can be used. Referencing to fig. 1 the processing block must be exchanged for a processing block including a thermal field definition (Fig. 4).

As a consequence, the solution of the thermal field can be obtained by using the data from a magnetic problem definition concerning the geometry and labelled material domains of a previously FEM electromagnetic field computation. Using such data, reduces the efforts for pre-processing the thermal problem. This combined approach is also a step towards an overall solution of the behaviour of an electrical machine. As the losses are linked to the magnetic field distribution and the currents, the calculation of thermal and magnetic quantities has to be linked.

The internal structure of the developed thermal FEM module is given in fig. 5. Input data are the describing parameters concerning the geometry and the material labels generated by the magnetic FEM program. In addition the user has to supply the thermal module with the parameter values defining the thermal field problem. Those parameters are resulting for example from:

- heat sources inside the body
- temperatures set in the nodes of the FEM mesh
- convective boundary conditions
- radiation boundary conditions
- defined heat flux

The structure of the element matrices inside the loop can be taken from the literature [4]. Extensions in the source code to obtain the transient behaviour of the temperature distribution can be implemented without extensive efforts.

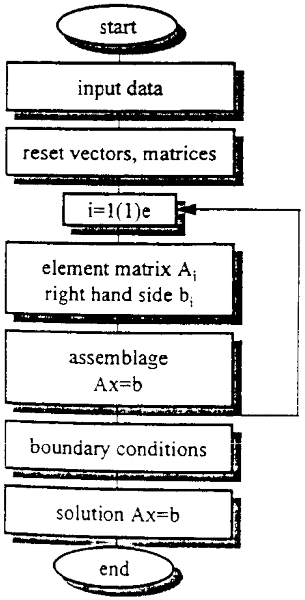


Figure 5: Structure of the thermal FEM module.

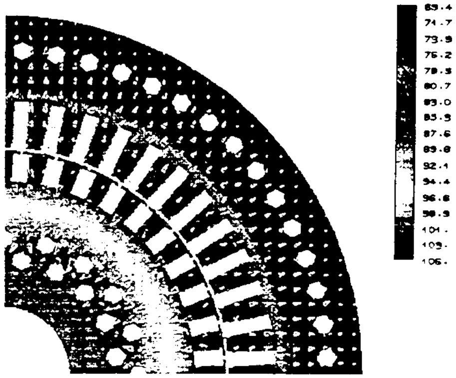


Figure 6: Temperature distribution inside an induction machine under load conditions.

Taking advantage of the equivalence between electrostatic and thermal , the necessary evaluations of the thermal solution can be performed in st-processor of the electromagnetic FEM program (Fig. 6).

## plementation of a numerical optimisation module

levelopment and design of electromagnetic devices reflects a complex ss. Originating from an initial idea, the construction runs through different s. This procedure is terminated when a final concept is selected and lered to be optimised, subject to various targets and constraints. The ination of numerical field computation and optimisation methods enables tomated and structured development procedure and exchanges the former sis tools to a powerful design tool with a general application range. Here, ierical optimisation module is developed to automate the design process to obtain an Automated Optimal Design (AOD) according to given constraints and limitations. To achieve a robust and numerically stable optimisation tool with a general application range a combination of stochastic search algorithms were used [6].

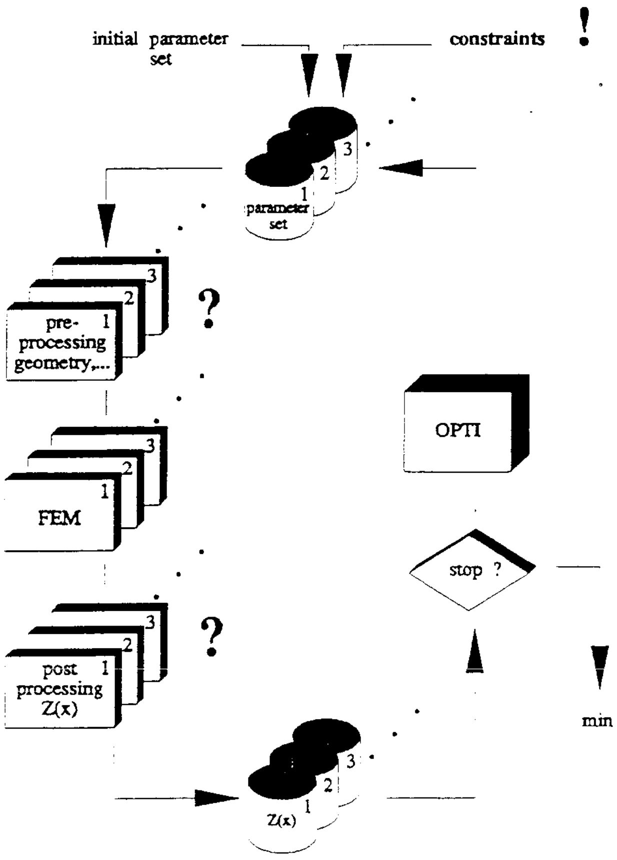


Figure 7: Automated Optimal Design process control.

To link the optimisation module to the FEM package again an open system is recommended. Data and parameter computed by the post-process operators of the FEM program, usually field quantities, energies and forces, must via an ASCII data exchange files be available to the optimisation module and data generated by the optimisation algorithms, usually geometry data, must be read by the FEM pre-processor as well to generate new FEM models. Figure 7 shows the developed AOD procedure. To start the process a valid initial data set of parameters, thus no limitations or constraints are violated, is given to the field computation program. Here, a stochastic search method is used and thus multiple data set are necessary (Fig. 7). The FEM model is automatically generated by the pre-processor, the field problem is solved and with the field solution an external program part, containing the formulation of the single aims of the optimisation, evaluates this objective function Z(**x**) subject to be optimised. The vector **x** contains all the design parameters describing the optimisation problem [6, 7]. Usually those data are the geometry describing parameters. After this procedure the set of results is given to the optimisation module where the achieved quality values of Z(**x**) are judged according to the rules of the optimisation method used. A stopping criterion is tested and if not fulfilled the design parameters are modified by the module and the next step of iteration is initialised. The limitations and constraints are tested before the pre- and during the post-processing operation.

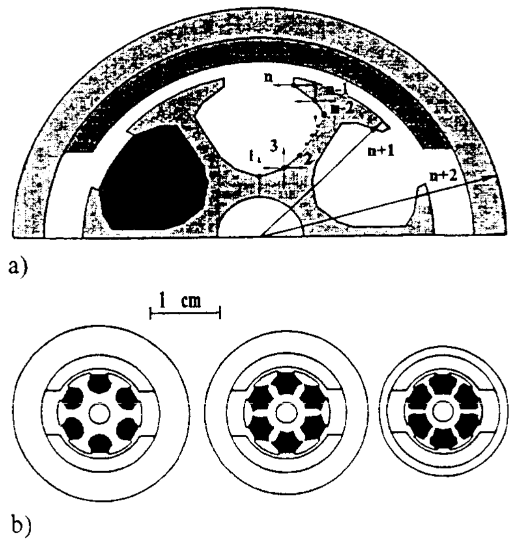


Figure 8: Motor geometry a) objective parameter definition and b) geometry variation.

With the optimisation technique, the shape of a small dc-motor is optimised, aiming to minimise the overall material cost. Quality function evaluation is done with the FEM. Figure 8a illustrates the problem formulation. The free variables are the co-ordinates of the data sample of a polygon describing the rotor slot shape, the rotor- and the outer-radius of the motor. In this example 14 objective variables are tuned [6]. The initial shape of the motor generates 75% of the torque. The quality expressed by the material costs decreased by 10%. ınge of geometry during the optimisation is shown in fig. 8b. Further ation examples can be found in [7].

## clusions

per discusses possibilities and shows already developed software s to extend an commercial FEM package suited for electromagnetics [5] special problems in the pre- and post-process. A thermal FEM and an ation module are introduced. Selected examples demonstrate the ity of the methods.

## ›wledgements

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# Stability analysis of a time-domain MM code for electromagnetic scattering predictions

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## Abstract

It is known that numerical electromagnetic scattering simulators based on a time-domain version of the method of moments may exhibit instability phenomena induced by the joint space-time discretisation of the field equations. In this paper we address the above problem with specific reference to a simulation code which allows evaluating electromagnetic scattering from perfectly conducting bodies of arbitrary shape. The simulator relies on a triangular-patch geometrical model of the exterior surface of the scattering body and operates according to a *marching-on-in-time* technique, whereby the surface current distribution at a given time step is evaluated as a function of the previous distributions. A heuristic stability condition is devised for the simulator, which allows to define a proper time step, as well as a correct geometrical discretisation, ensuring convergence of the numerical procedure. The stability condition is discussed and validated by means of a few working examples.

## 1 Introduction

Numerical techniques for the analysis of scattered electromagnetic fields directly operating in the time domain (TD) have recently received considerable attention. In the classical approach, a TD description of the scattered field is only possible at the cost of running the simulation several times, for a given set of equally-spaced frequencies, and then recovering the TD evolution of the field through an inverse Fourier transform. However, an alternative procedure can be followed, whereby the relevant equations are solved directly in the TD, by using a *marching-on-in-time* procedure. The main advantages of this latter technique can be summarised as follows: *i*) it allows a deeper physical insight in the phenomena involved, *ii*) it permits wideband analyses by executing the TD algo-