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Magnet Shape Optimization Using Adaptive Simulated Annealing

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Abstract: Stochastic methods offer a certain robustness quality to the optimization process. In this paper, the Adaptive Simulated Annealing (ASA) searching techniques are applied to the shape optimization of an electromagnet. The magnetic field is computed using the 2D finite element code FEMM. The aim of optimization is the search for an optimal pole shape geometry leading to a homogeneous magnetic field distribution in the region of interest.

Keywords: Inverse problem, shape optimization, simulated annealing, finite element method.

1 Introduction

For optimal performance of electromagnetic devices, it is necessary to perform design optimization of the shape and parameters of their magnetic circuit, size and position of the current windings, magnetic properties of the used magnetic materials, etc. The traditional optimization methods based on trial-and-error procedures are not very suitable, especially for highly complex and multivariable optimization problems because they are very laborious, time consuming and not accurate enough. Therefore, the development of new and more efficient methods for inverse optimization and automation of the entire optimization process are always desired.

In electromagnetic device optimization the problem of obtaining such devices which will result with desired values of the magnetic flux density at several certain

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points, is a very common problem. However, because the expression of the gradient function can usually not be computed, the usage of deterministic optimization methods is not possible. Consequently, for such optimization problems designers utilize stochastic methods. *Genetic Algorithms (GA), Simulated Annealing (SA), Evolution Strategies (ES), Tabu Search (TS)* or *Particle Swarm Optimization (PSO)* are such stochastic methods which become more and more popular in the computer-aided design of electromagnetic devices [1–4].

In this paper, we apply different versions of the *Adaptive Simulated Annealing (ASA)* searching technique to the shape optimization of the pole shape geometry of a simple electromagnet [5, 6]. The flowchart of Adaptive Simulated Annealing is presented in Fig.1. We are searching for optimal pole shape modifications leading to a homogeneous magnetic flux density in a certain region.

2 Shape Optimization Problem

The test configuration chosen for the evaluation of the Adaptive Simulated Annealing algorithms (Fig. 1) is shown in Fig. 2. It is a simplified 2D configuration of

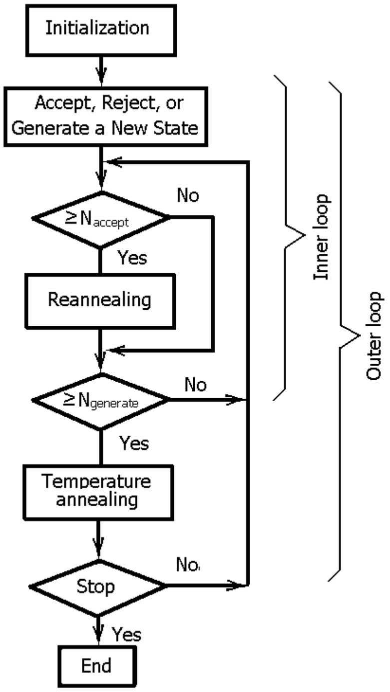


Fig. 1. Flowchart of the Adaptive Simulated Annealing (ASA) algorithm

an electromagnet where the optimization goal is to obtain the magnetic pole shape generating a constant magnetic flux density in a certain part (matching points) of the iron core.

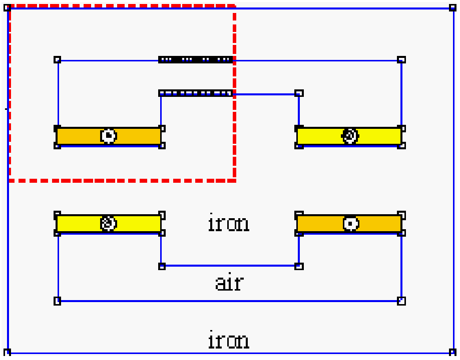


Fig. 2. General layout of considered shape optimization problem (simplified 2D electromagnet system).

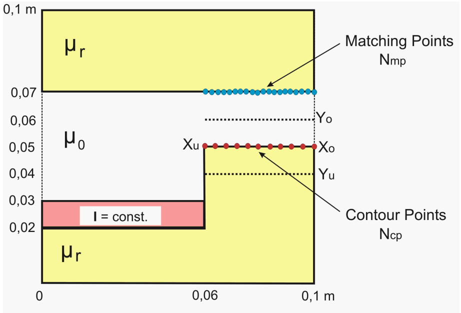


Fig. 3. Fild problem used for shape optimization, with iron core, impressed current I, contour point (N_{cp}) and matching points (N_{mp}).

The magnetic flux in the iron core, which is assumed to be linear or nonlinear, is driven by the current density $\boldsymbol{J}$ indicated in Fig. 1. Because of the symmetry only a part of the magnet has to be taken into account. This region of interest is indicated by the dashed line. Extracting this region of interest we get the configuration to which the stochastic optimization methods were applied (Fig. 3).

To realize a homogeneous magnetic flux density B0 in the matching points first the required current density in the coil has to be estimated. Different cases of magnetic material were considered: linear cases with $\mu_r = 5/20/1000$ and a nonlinear one where a material characterictic of steel M19 was assumed. The magnetic field was computed using the finite element software code FEMM 3.3 [7, 8].

3 Optimization using SA searching technique

Annealing is actually a term from metallurgy. If a metal is heated to a very high temperature, the atoms about at high speed. Yet, if they are cooled very slowly, they settle into patterns and structures, rendering the metal much stronger than before. This principle can be employed as an optimization technique in computer science and engineering.

Simulated Annealing (SA) is a stochastic relaxation technique which is based on the analogy to the physical process of annealing a metal: at high temperatures the atoms are randomly distributed. With decreasing temperature they tend to arrange themselves in a crystalline state which minimizes their energy. Using this analogy, the algorithm generates randomly new configurations by sampling from probability distribution of the system. New configurations are accepted with a certain acceptance probability depending on the temperature. Since increases of energy can be accepted, the algorithm is able to escape local energy minima. It has been shown that the algorithm converges to a global energy minimum if the temperature is reduced slowly enough [4, 6].

In this study we applied Adaptive Simulated Annealing (ASA) which is a C-language code developed to statistically find the best global fit of a nonlinear constrained non-convex cost function over a D-dimensional space [5]. This algorithm permits an annealing schedule for "temperature" T decreasing exponentially in annealing-time k,

$$T = T_0 e^{-ck^{1/D}}. \tag{1}$$

The introduction of re-annealing also permits adaption to changing sensitivities in the multi-dimensional parameter space. This annealing schedule is usually faster than fast Cauchy annealing, where $T = T_0/k$, and much faster than Boltzmann annealing, where $T = T_0/\ln k$.

4 Simulation results

The aim of the simulation study is the investigation of the effects of modified stochastic operators on the shape optimization process. We minimized the cost function

$$C_F = \sqrt{\sum_{i=1}^{N_{mp}} \left(\sqrt{B_{x_i}^2 + B_{y_i}^2} - B_0 \right)^2} \tag{2}$$

where B_0 is the desired constant magnetic flux density in the matching points (N_{mp}). The current density impressed to the coil to get a value of $B_0 = 0.1$ T was first estimated in some test runs. For the dimensions given in Fig. 3 we have chosen a current density $\boldsymbol{J}$ of about 7 A/mm^2.

Fig. 4 shows the start configuration, the start mesh, and the corresponding magnetic flux density in the region of interest computed with FEMM 3.3 [8].

The results of Adaptive Simulated Annealing optimization for linear case with $\mu_r = 20$ when number of contour points is 11 are shown in Fig. 5 (free y - coordinate of contour points) and Fig. 6 (free x, y - coordinates of contour points). By that is $C_F = 0.05188635$ (optimization results from Fig. 5) and $C_F = 0.120271$ (optimization results from Fig. 6).

The result of Adaptive Simulated Annealing optimization for the same linear case ($\mu_r = 20$) with free y-coordinate and spline interpolation of countour points (5

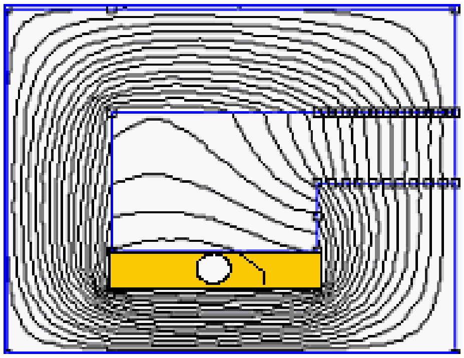
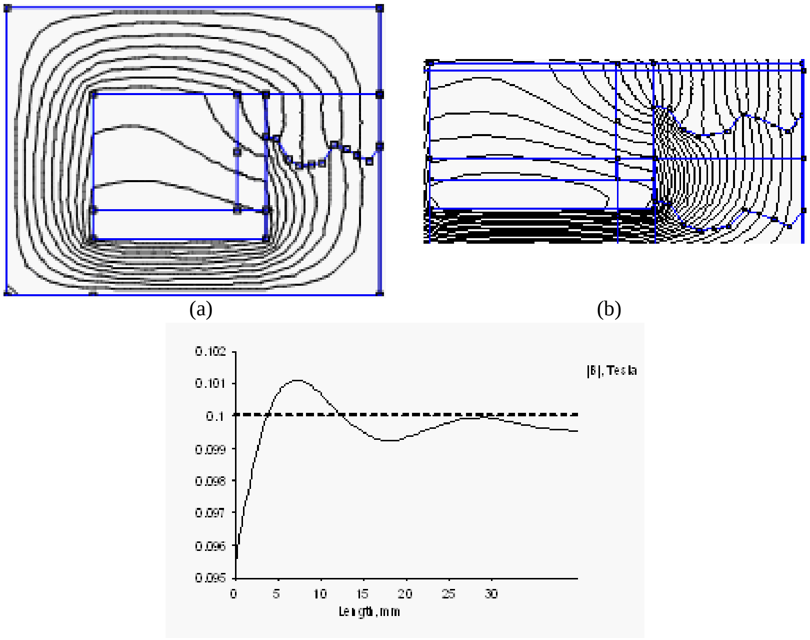


Fig. 4. Test configuration with magnetic field distribution at the beginning of the optimization.

spline nods, 16 interpolation points) is presented in Fig. 7. Cost function value in that case is 0.07902323.

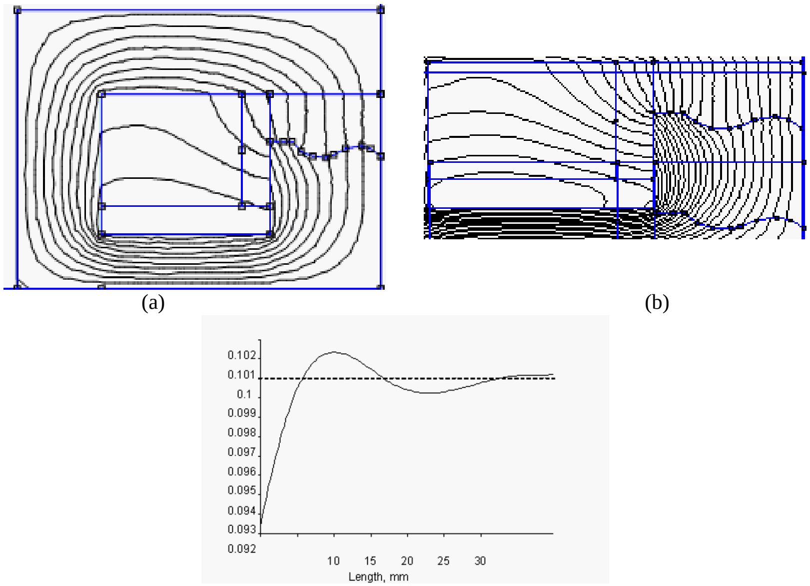


(a) (b)

(c)

Fig. 5. The results of Adaptive Simulated Annealing optimization for linear case ($\mu_r = 20$) and 11 contour points, with free y-coordinates.

For non-linear case (steel M19) with free y- coordinate of contour points optimization result is shown in Fig. 8. By that number of contour points is 11 and C_F value is 0.06708068.



(a) (b)

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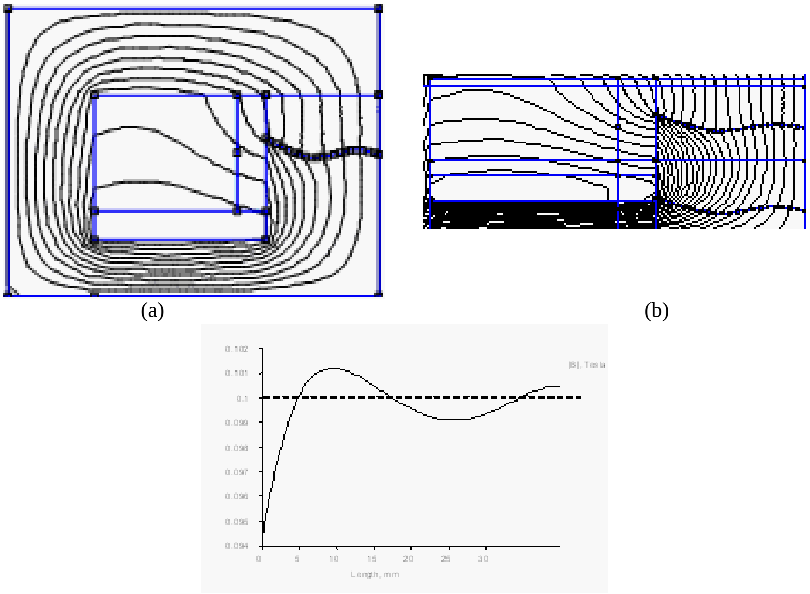
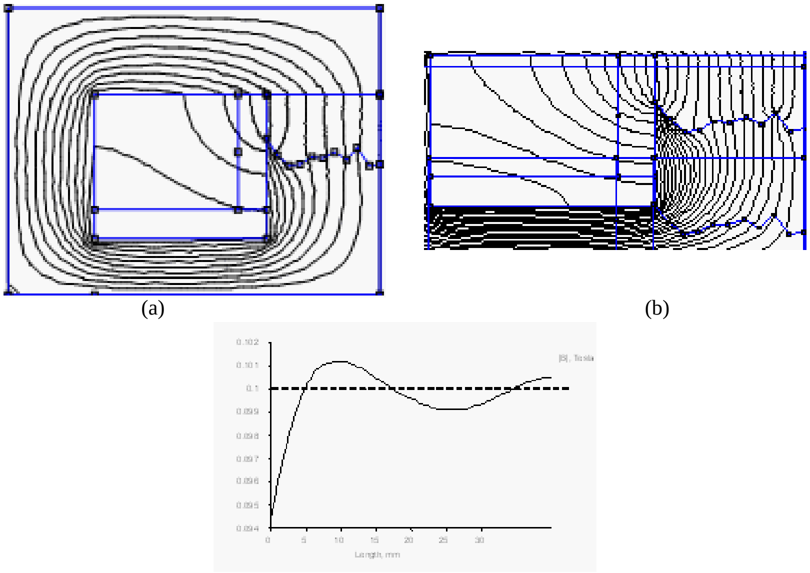
Fig. 6. Results of Adaptive Simulated Annealing optimization for linear case ($\mu_r = 20$) and 11 contour points, with free x, y-coordinates.



(a) (b)

(c)

Fig. 7. Results of Adaptive Simulated Annealing optimization for linear case ($\mu_r = 20$) and 11 contour points, with free y-coordinatex and spline-interpolatted contour.



(a) (b)

(c)

Fig. 8. Results of Adaptive Simulated Annealing optimization for non-linear case (steel M19) and 11 contour points, with free *y*-coordinate.

5 Conclusions

In optimization problems where derivatives of the cost function are not available stochastic methods like Simulated Annealing can be applied. In this paper different versions of the Adaptive Simulated Annealing (ASA) method were used to optimize the pole shape of a simple electromagnet configuration. The algorithms known from the literature were combined with the finite element code FEMM 3.3 to study their performance for shape optimization problems.

The true strength of SA lies in its ability to statistically deliver a true global optimum, but there are no theoretical reasons for assuming it will be more efficient than other stochastic methods. Thus, the evaluation of the performance of a certain Adaptive Simulated Annealing algorithm always depends on the specific characteristics of the considered problem.

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