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Jiles-Atherton-Parameter Identification for Electromagnetic Hysteresis Simulation in Solenoid Design

ABSTRACT

Solenoid actuators are products of mass production. They are applied in large numbers in automotive engineering and industrial automation. Due to the requirement of short development times, a reliable, model-based design process is necessary. To match all those issues, more and more detailed modelling of the actuator has to be done.

Electromagnetic hysteresis affects the static and dynamic behaviour of solenoids. Therefore hysteresis models such as the one by Jiles and Atherton [1] have to be included in the design process. The Jiles-Atherton model is a fast calculating and accurate model based on physical material properties. Another huge benefit for the computation is the easy invertibility. With these qualities it is suited for simulation tasks. However, the Jiles-Atherton model is not yet commonly used for design simulations, due to the issue of its parameter identification. The required five model parameters cannot be determined directly and need to be derived by optimisation.

In this paper a general approach to identify the required parameters from a measured hysteresis loop will be presented. A stand-alone software tool using four different optimisation algorithms will be introduced. It is appropriate to serve as a template for the implementation of an automated Jiles-Atherton parameter identification process.

INTRODUCTION

The Jiles-Atherton (J-A) model of hysteresis is a well known and proven approach to describe magnetic hysteresis. The main equation of this model is [1]:

$$\frac{dM}{dH} = (1-c)\cdot\frac{M_{an}(H_e)-M_{irr}}{k\sigma-\alpha\cdot\left(M_{an}(H_e)-M_{irr}\right)} + c\cdot\frac{dM_{an}(H_e)}{dH}, \qquad (1)$$

with

$$M_{an} = M_s \cdot \left(\coth \frac{H + \alpha M}{a} - \frac{a}{H + \alpha M} \right). \tag{2}$$

With these equations (1) and (2) all five parameters (M_s, α, a, c and k) are linked to each other. So determine the parameters separately will not do the job. Only considering all parameters as a whole parameter set will lead to sufficient accuracy. Therefore the goal is to identify that parameter set which causes the smallest differences between a measured and a calculated hysteresis curve. If this can be achieved, this fast and reliable model can be used for considering magnetic hysteresis effects in the design process of solenoids. Because of its easy invertibility, the adoption in FEA software and circuit simulations is feasible.

PARAMETER IDENTIFICATION PROCESS

In order to identify the parameters of the J-A model a measured hysteresis branch is needed. This branch is the basis for the evaluation of the generated parameters. In this approach only one (the upper or the lower) sector has to be provided. First of all, a parameter set to begin the computed optimisation process is required. Although such a start set contains a high error value it still supports the following optimisation by placing the start parameters in a comparatively beneficial area of the solution space.

To gain such a suitable start parameter set certain points of the hysteresis loop that are related to the J-A model parameters are used [2]:

- saturation M_S: Corresponds to the positive magnetisation maximum.
- interdomain coupling α: $$\alpha = \frac{H_c}{M_r} \tag{3}$$
- domain thermal coefficient a: $$a = \frac{M_s}{3} \cdot \left(\frac{1}{\chi_{an}} + \alpha \right) \tag{4}$$
- reversible coefficient c: $$c = \frac{3 a \chi_{in}}{M_s} \tag{5}$$
- pinning coefficient k: $$k = H_c \tag{6}$$

χ denotes the magnetic susceptibility which describes the relation between magnetisation M and magnetic field strength H in a certain working point ($M = \chi H$). These relations lead to a first approximation of the model parameters.

However, this set of parameters needs to be optimised and this process is divided in two steps. The first step consists of a stochastic algorithm in which a possible global optimum is narrowed down. In the second step a determined optimisation process enhances the parameters and minimises the remaining error. This distribution makes sure that the best set is found.

There are two different optimisation algorithms implemented, which can be selected separately for each optimisation step. The user can choose between an evolutional and a threshold accepting process as stochastic step and a simplex or special adapted algorithm for the deterministic step. (Fig.1) Every combination of these four methods is possible. In the following the methods will be presented more in detail.

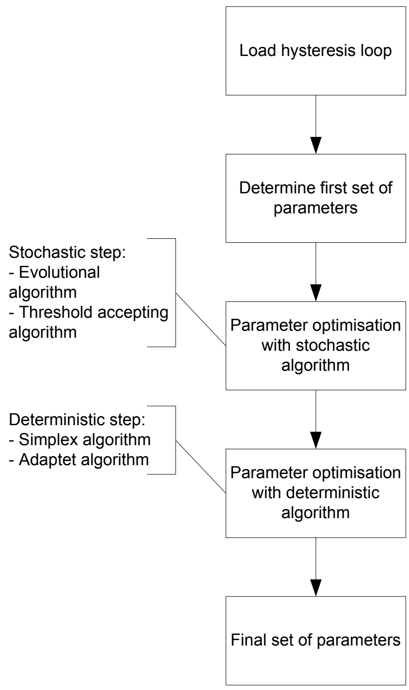

Figure 1. Automated optimisation process

Evolutional Algorithm:

The implemented evolutional method is based on the process presented by [3] and has been successfully applied to the task of parametrisation by [4]. The main structure of this algorithm can be seen in Fig. 2. It begins with the generation of the start population. In order to enhance the convergence speed, a sufficiently good start parameter set is needed. Therefore the approximated set is used as a seed. After that step a random selection and combination of this parent population is performed and the children population is generated. Then this children generation is mutated. Thereby special strategy parameters are applied to support the development towards the optimum. Thereafter the quality (sum of differences between each given reference point and the corresponding calculated one) of the parameter set represented by one child is determined and the top ones will be used as the new parents for the next generation. To avoid stagnation during the optimization, the current population can be reseeded around the best parameter set at that point of time.

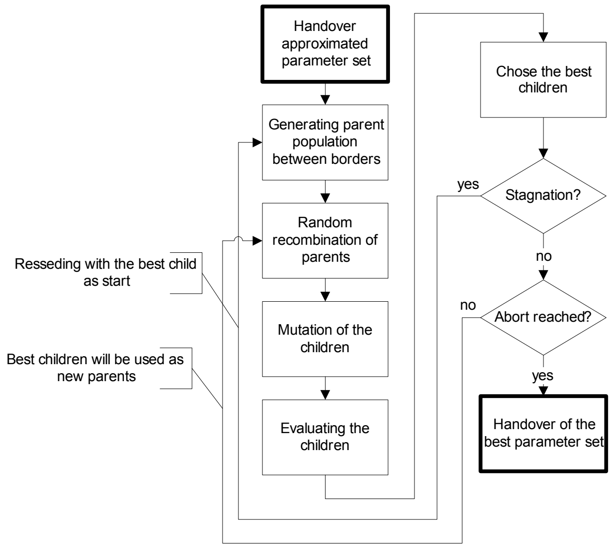

Figure 2. Overview for the evolutional optimisation

For robust convergence behaviour some of this method's parameters can be adjusted: For instance the size of the parent and children population, the maximum number of generations, the initial range for the first parent generation and how this start population is generated (by equal or random distribution).

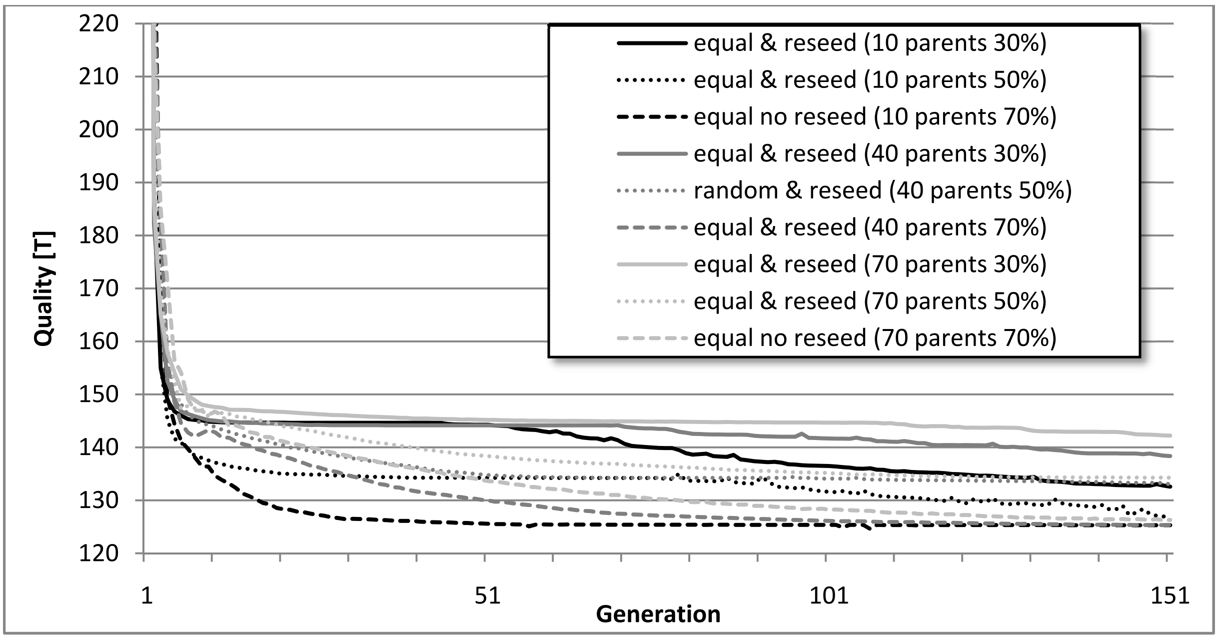

Figure 3. Influence of the evolutional optimisation parameters

Fig. 3 shows that a combination of only few parents and a widely spread start population lead to a better quality after a low number of generations. The evolutional algorithm is perfectly suited to narrow down a quite good parameter set but due to its stochastical background, a refinement step is needed.

Threshold Accepting Optimisation:

The stochastic threshold accepting optimisation is very similar to the well known simulated annealing (SA). Its main structure has been described in [5] and is displayed in Fig. 4.

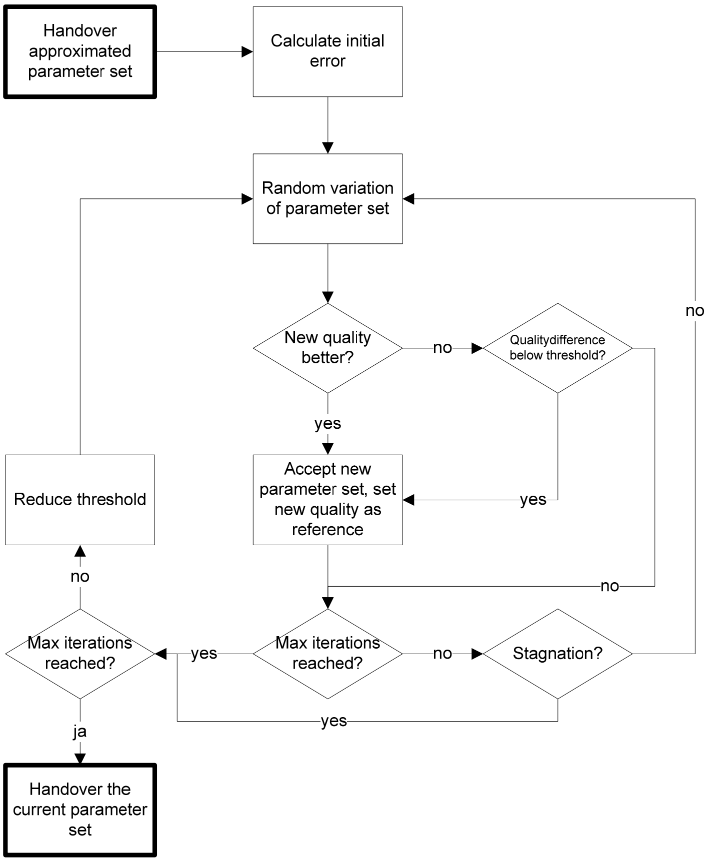

Figure 4. Overview for the Threshold Algorithm

It uses the global error as an indicator of success. This error is very alike to the energy state used by the SA. Another analogy to the SA is the separation into a main and inner loop. The main loop reduces the acceptance threshold and the inner loop performs a minor variation of the whole parameter set and compares the corresponding calculated error is with the initial one. If the current variation leads to a better fitting, it is accepted and a new variation starts using this parameter set. If not, the set of parameters is only accepted, if the difference of its error and the initial error is below the threshold. Otherwise the parameters are discarded. In order to positively pinpoint a good parameter set in a considerably short time some of the algorithm parameters should be adapted. In [6] it is shown that a variation of the maximum number of iterations for the main and the inner loop, the initial threshold and the factor for its reduction improves the convergence performance of the algorithm. Fig. 5 illustrates the effects of these parameters during an optimisation process. It has to be kept in mind that this is a stochastic method so only the average outcome for one specific material is presented. In order to maintain a robust convergence for different materials and therefore different initial parameter sets not the best algorithm parameter combination is chosen, but one close by which showed a similarly good performance at other material samples.

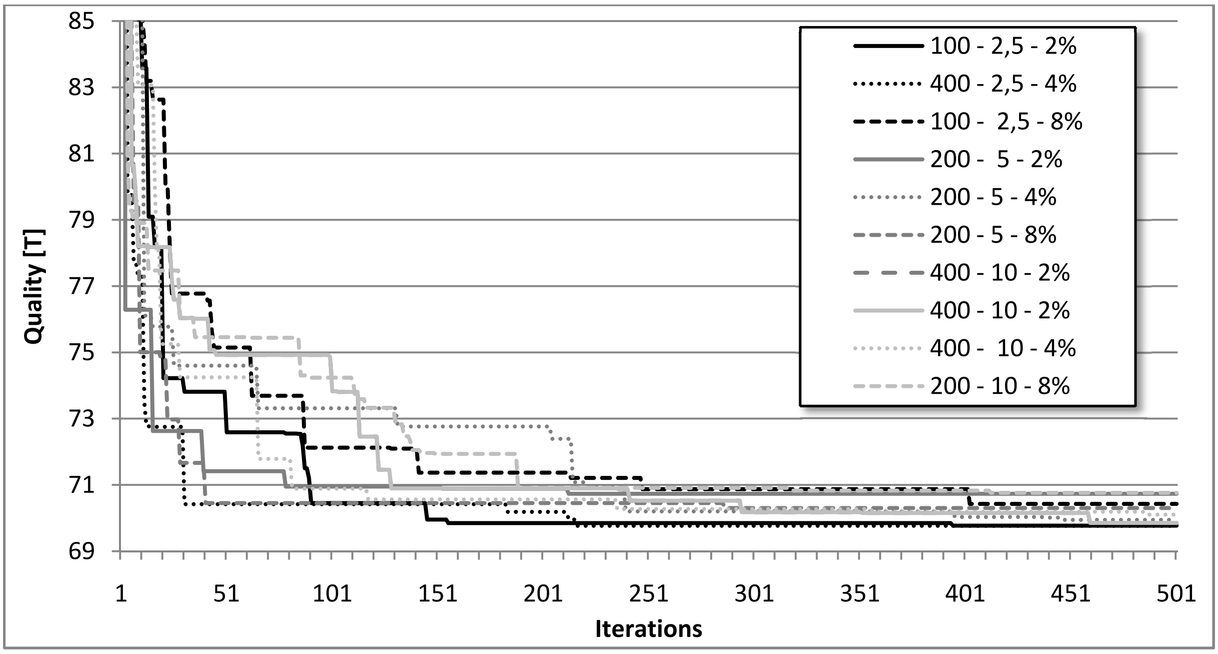

Figure 5. Influence of the threshold accepting algorithm parameters

Adapted Algorithm:

The adapted algorithm is inspired by the process developed by [7] for the inverse J-A model. Like the original it still consists of a major loop and a variation loop (Fig. 6). The major loop is responsible for the sequential order of the parameter variation and the reduction of the parameter's step size, whereas the variation loop alters one parameter at a time according to its own step size and checks if this variation leads to an error reduction. Some of the algorithm parameters can be adjusted to better suit the task of fitting the J-A model parameters: For instance the maximum number of recurrences for the variation loop the initial step size and the reduction of this step size during the optimisation process.

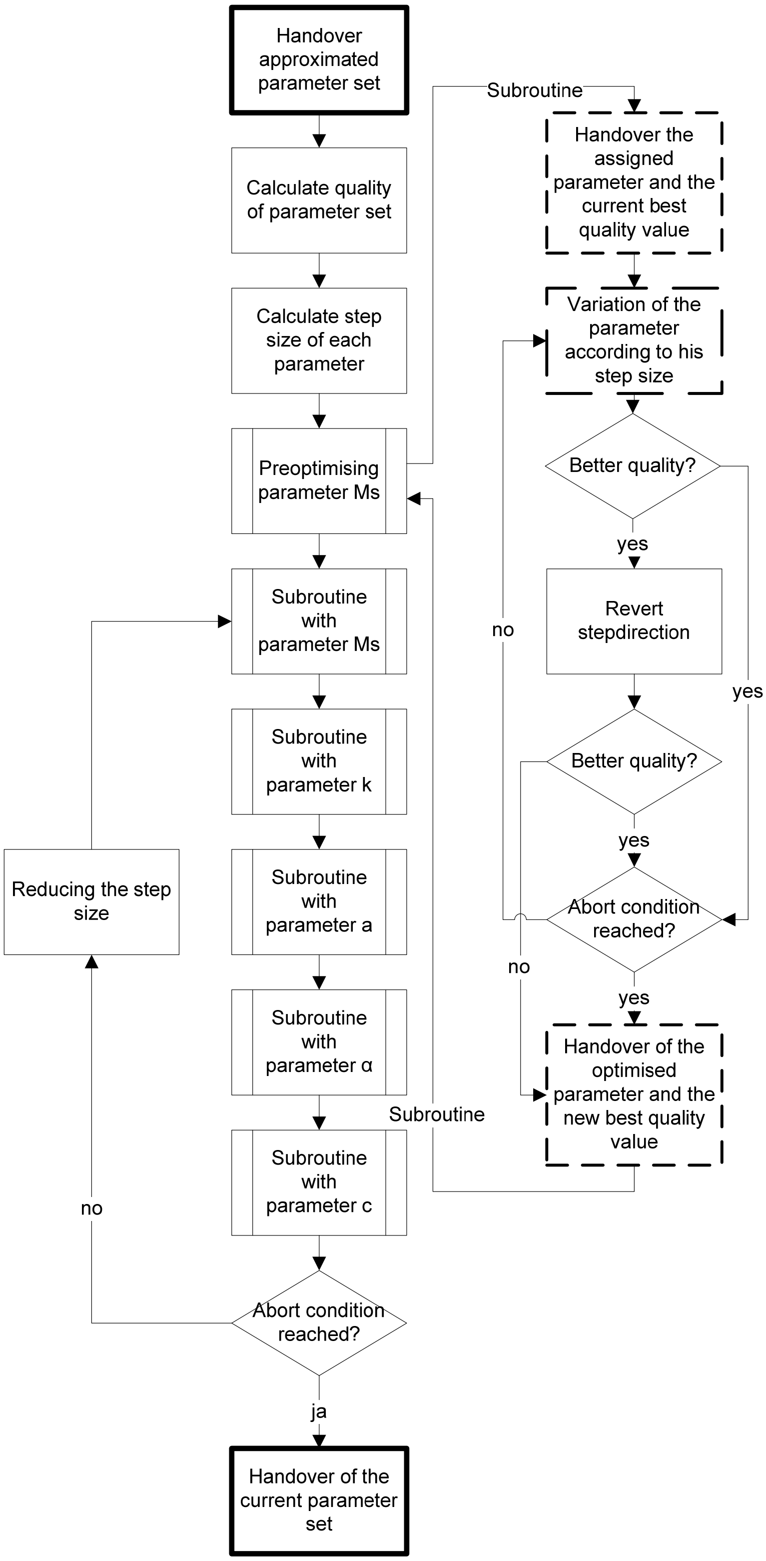

Figure 6. Overview for the adapted algorithm

Fig. 7 shows that the number of variation loops has a major influence on the parameter set’s quality and in combination with a small initial step size at a slow step reduction it leads to the best quality.

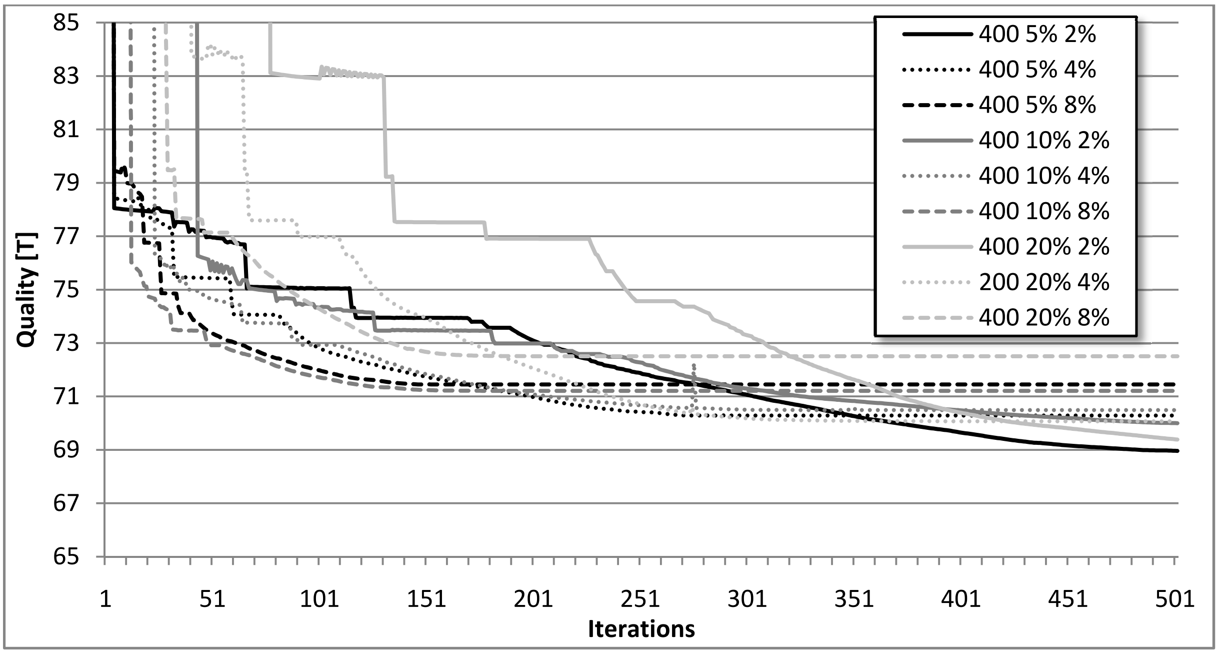

Figure 7. Influence of the adapted algorithm parameters

Simplex Algorithm:

The well known simplex method is very useful for multi parameter optimisation tasks as needed for the J-A model parameters. A simplex is a polygon made of different parameter sets representing each edge. In order to optimise five parameters, six edges are needed.

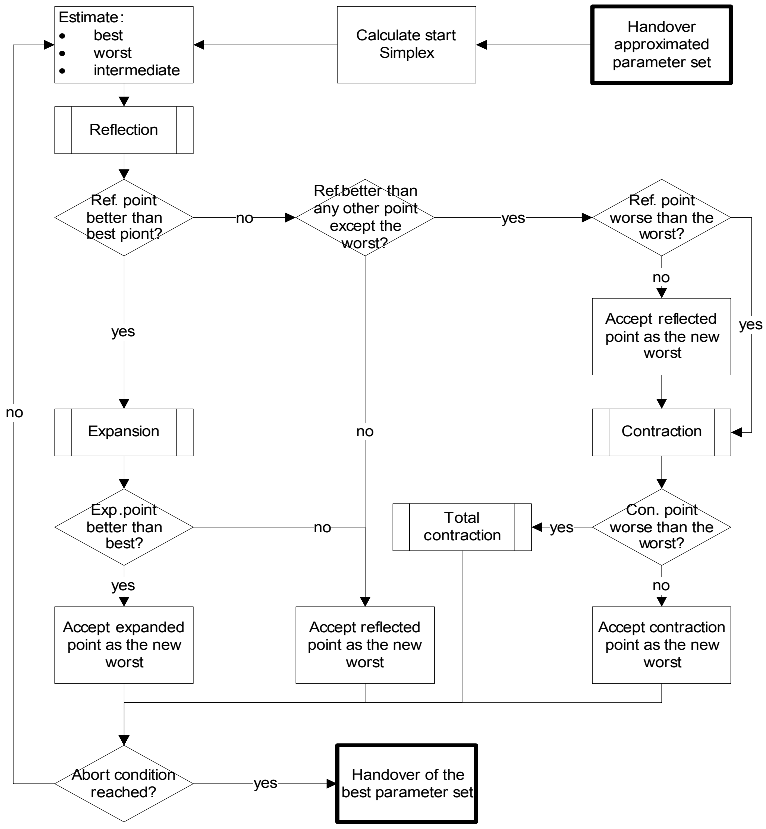

Figure 8. Overview for the simplex algorithm

The simplex is moving through the solution space by replacing his worst edge with a better one. Therefore three operations are applied: expansion towards an optimum, reflection of the worst at the meridian and contraction around the middle point of the simplex (Fig. 8).

THE SOFTWARE ENVIRONMENT

All of the previous presented algorithms have been implemented into a stand-alone tool. This tool enables the user to simulate various hysteresis loops based on the J-A model. It also can combine every optimisation method with each other and adapt its optimisation values. The optimisation process has been preselected with the best and flexible optimisation algorithm combination (evolutional and simplex) and their in [4] determined optimal settings. Fig. 9 shows the main display of the program with a hysteresis loop plotted. In Fig. 10 the parameter optimisation dialogue can be seen.

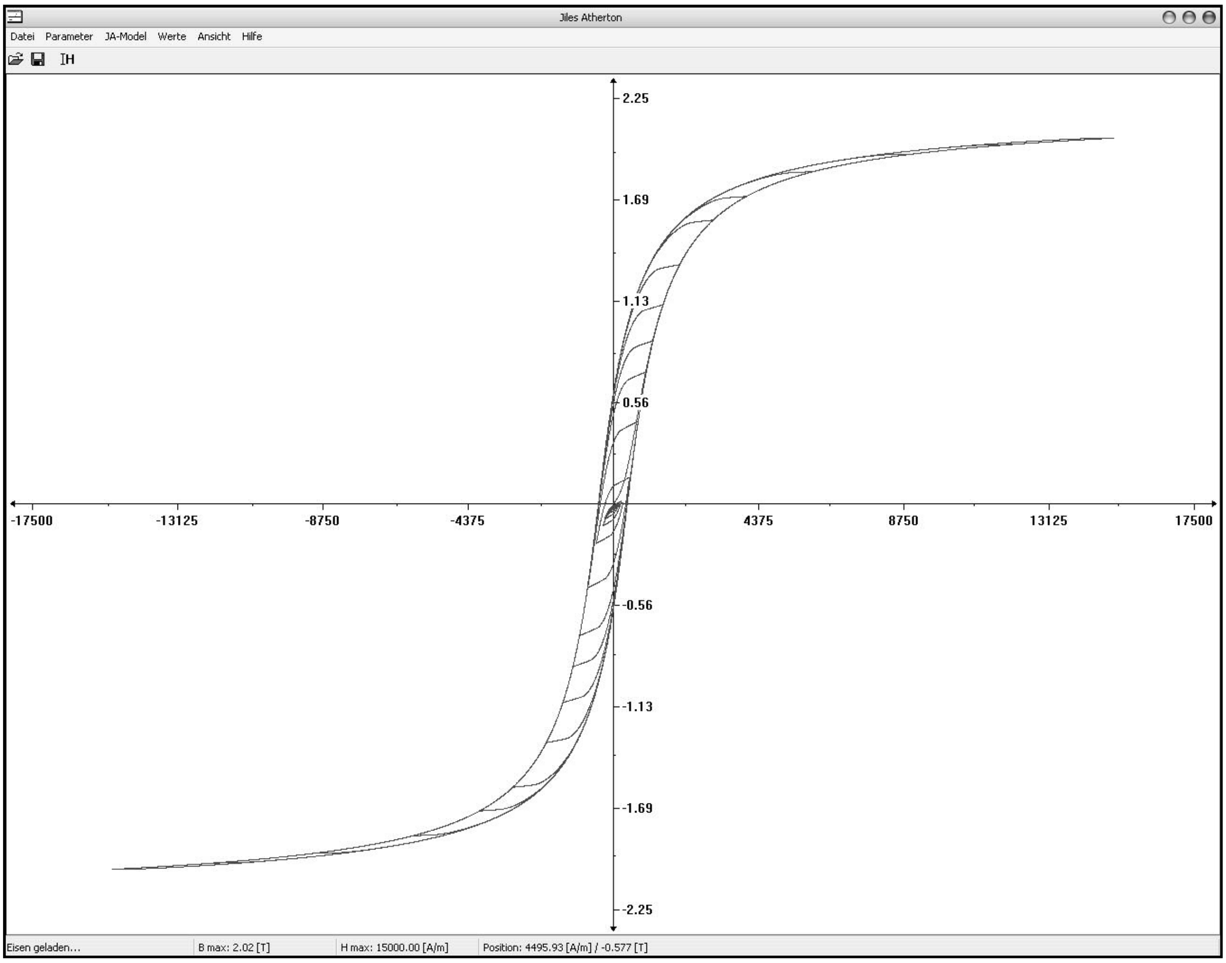

Figure 9. Main window of the Jiles-Atherton hysteresis tool

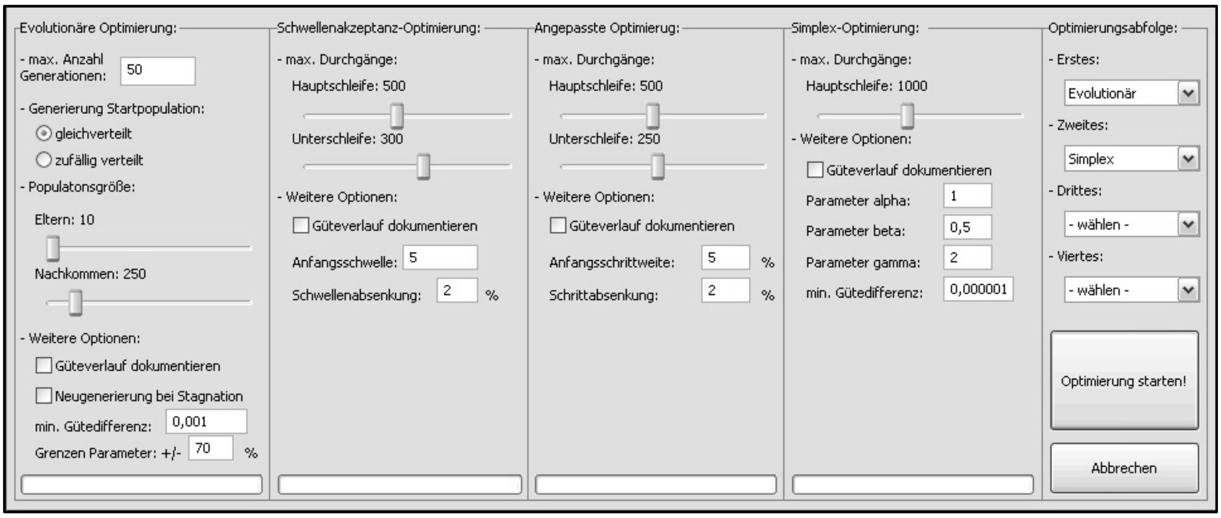

Figure 10. Optimisation dialogue

CONCLUSION

The procedure of curve fitting results in a set of parameters that leads to significantly reduced differences between measured and calculated data. Fig. 11 shows the result of a combination of the threshold accepting and the adapted algorithm. It can be seen that the optimisation process drastically improves the fitting in comparison to the first approximation. Such an optimisation only takes less than a minute. This time mainly depends on the number of measured points given and the processing power of the computer system used.

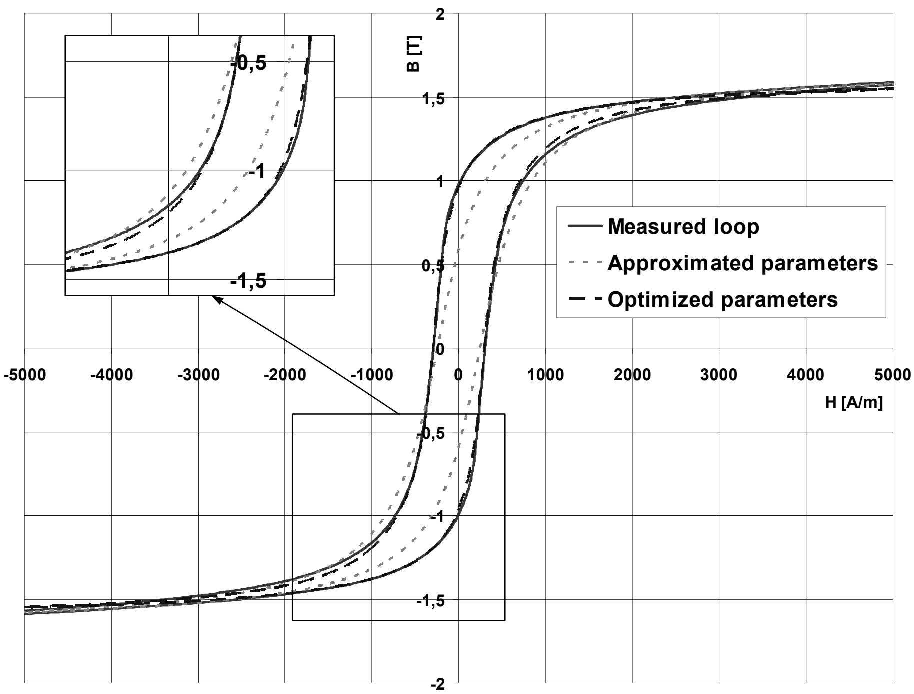

Figure 11. Results of the curve fitting process

Due to the combination of different fitting processes and the determination of the optimal settings for each algorithm in [6], a reliable material independent automation is achieved. The presented program is yet a stand-alone tool for the parameter identification but its optimisation routines are to be implemented into next generation solenoid design environments such as SESAM. Due to the universal applicability of the optimisation procedure the Jiles-Atherton model of hysteresis can be applied to fields where no hysteresis consideration was possible until now.

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