

PHD THESES

**JILES-ATHERTON MODEL
IMPLEMENTATION TO EDGE FINITE
ELEMENT METHOD**

by

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Budapest
2006

Introduction and scope of research

Several hysteresis models have arisen due to the evolution of the digital computers. The validity of the models is not restricted to the description of the ferromagnetic hysteresis phenomena. The hysteresis models are widely accepted in other areas of science (e.g. biology, economics, mechanics etc.), as these phenomena also play very significant role in several domains of scientific practice.

There are several classifications of the hysteresis models. One of them is according to the description level. Three classes can be distinguished: the microscopic, the macroscopic and the mezosopic models. The microscopic models deal with the description of the hysteresis phenomena, they often use a sub-atomic range approach (e.g. Ising-model, Landau-Lifshitz equation). This type of models is not suitable for simulating the hysteresis effect in complicated situations, as modeling a real scale material would be a very time consuming task. The macroscopic models seek to eliminate these shortcomings of the microscopic model. In fact they can not be compared with the microscopic ones, since the macroscopic models can provide no information about the physical background of the phenomena, though they can be employed in real scale problems. The macroscopic models are usually function approximations of the hysteresis curves, where several types of analytical functions can be applied (e.g. transcendent functions, polynomial functions, ratio of two polynomial functions etc.).

We can realize that neither the micro- nor the macroscopic models meet engineering needs, as the microscopic models are too slow in computations and the macroscopic models do not take into account the physical background of the phenomena. As a result, the mezosopic models are very popular in engineering. The mezosopic models are ranked between the micro- and macroscopic models, because they are less accurate than the microscopic ones, but are more flexible than the macroscopic models. They include the Jiles-Atherton model, the Preisach model, the Chua model and the neural network based models and so on.

The Jiles-Atherton model is discussed in detail in this work. The Jiles-Atherton model was established in the last decades of the twentieth century. Despite being a mezosopic model, its equations can be derived from the energy balance equation, which is very close to the physical representation of the hysteresis. It can easily be extended to describe the frequency dependence (rate dependence) and the influence of mechanical stress, due to the energy formulation. Though the model has some outstanding features, some drawbacks must be highlighted. Namely the energy based model equations have non-physical solutions, which triggers the negative slope part of the hysteresis curve at the loop tips. Furthermore, the solution of the model differential equation is very sensitive to the step size. Totally different hysteresis curves can be generated by applying different step sizes.

The investigation of the magnetic field in the presence of ferromagnetic materials constitutes the focus of my research work. The Jiles-Atherton model is applied for describing ferromagnetic materials in the simulations. The partial differential equations are discretized by the finite element method (FEM). Two types of FEM is distinguished, the nodal and the edge elements. The magnetic field computations including the eddy-current investigations cannot be carried out by using the nodal FEM, because of the spurious modes.

The edge element formulations with respect to the electromagnetic field computations are summarized and combined with nonlinearity caused by the hysteresis effect.

Nonlinear system of equations are usually solved by applying the classical Newton method. However the Newton method does not converge at inflection points, which is usual in the case of magnetization curves. Another drawback is that the derivative must be determined analytically, otherwise numerical differentiation should be used. The analytical derivative is not available in most of the cases e.g. measured curves. The method is usually applied for magnetostatic problems by modifying the magnetization curve by removing inflection points. Of course in this case not the original problem is solved. Instead of the Newton method, the fixed-point method (polarization method) is applied in this work for solving nonlinear magnetic field equations, since it is convergent for any trial value and it is not sensitive to inflection points and the derivatives must not be known. Furthermore a piecewise linear approximation of measured points is also acceptable. A drawback of the fixed-point method is the slow convergence, which can be improved in several ways. These are discussed in the second thesis.

A test problem is going to be solved to prove the validity of the above mentioned computational procedure. The numerical solution of the test problem is compared with the given measured data.

1 Proposed research activity

The scope of my PhD dissertation is to develop a new computational procedure to analyse magnetic field based on the Jiles-Atherton model of hysteresis and combined with the higher order edge finite element method.

I intend to find a fast and accurate hysteresis model, which is required in electromagnetic field computations, since, in combination with the finite element method, a very huge number (several tens of thousand) of hysteresis models must be run simultaneously. The Jiles-Atherton model is based on a simple first order ordinary differential equation. Despite having a simple structure, the Jiles-Atherton model is based on physical considerations. I will reformulate the Jiles-Atherton model by means of the energy balance. As a result, the mathematical background will become clear. I intend to extend the original rate independent Jiles-Atherton model to a rate dependent one by considering the eddy currents and the excess losses. This is easily done by

the energy balance equation introduced. I intend to build a scalar hysteresis measurement system in LabVIEW environment to prove the validity of both the rate independent and the rate dependent models.

I want to introduce the edge finite element method as a numerical technique for determining electromagnetic fields. I intend to use higher order elements for obtaining better accuracy. I intend to fine tune the combination of hysteresis modeling and finite element method with the help of a simple one dimensional example of the well known half-space problem. I intend to investigate this problem by progressing from the simplest case to complicated ones. This means that I want to start the investigations with the linear case, I want continue with the Langevin characteristics and finally the Jiles-Atherton model will be used as material characteristics. I intend to introduce the fixed-point method to handle nonlinearity. I want to describe some speed up techniques for the fixed point method, which will be illustrated on the half-space problem.

Methods and algorithms

The purpose of this work is to find an efficient way to compute magnetic fields in the presence of highly nonlinear even hysteretic materials. Both magneto-static and eddy current fields are investigated.

A fast and accurate hysteresis model is required for describing magnetic materials. The Jiles-Atherton model has been chosen for modeling hysteresis since it is based on physical considerations and it is not only a mathematical extraction of measured data. Another advantage of the model is that it is easy to extract to take into account dynamic effects, which might be sufficient in eddy current problems.

The finite element method is widely accepted and used in electromagnetism. A method has been worked out for combining the Jiles-Atherton model and FEM to be able to compute nonlinear magnetic fields. High order edge elements are considered in the computations for ensuring the desired accuracy.

The fixed-point (polarization) method has been applied for handling the material nonlinearity existing in the arrangement. The original fixed-point algorithm has been speeded up both by introducing a relaxation method and by using an update procedure, where the permeabilities (or reluctivities) are updated in each time iteration step.

Multigrid method with Vanka pre-/postsmoother has been applied for solving the large linear system resulted from the 3D problem. This approach allows to create a multigrid hierarchy based on the order of the finite element shape function.

Theses

Theses 1

I have extended the JAM of hysteresis to avoid the non-physical solutions and to represent the rate-dependent variation of the response with the input for the direct H - B and for the inverse B - H characteristics as well.

- a) I have developed an engineering approach based on an energy balance equation for obtaining the differential equation of the rate-independent Jiles-Atherton model. I have introduced a parameter δ_M to avoid the non-physical solution (negative slope) of the model differential equation. I have validated the developed rate-independent model by experiments.
- b) I have extended the energy balance equation of the rate-independent Jiles-Atherton model by two additional energy (eddy current and anomalous loss) terms to take into account the time variation of excitation magnetic field. I have validated the developed rate-dependent model by experiments.
- c) I have built a magnetic measurement system for measuring magnetic hysteresis in LabVIEW environment. I have proposed measurement method for measuring hysteresis loops, minor loops, first order reversal curves and I have worked out an under-relaxation method to obtain sinusoidal waveform in B .
- d) I have worked out a procedure for parameter identification of both the rate-dependent and rate independent Jiles-Atherton model of hysteresis based on the nonlinear least square method.

Theses 2

I have implemented the hysteresis simulation to the higher order vector shape functions of FEM for solving magnetostatic and eddy current problems and to handle the nonlinear iteration and I have worked out an efficient speed up technique of the fixed point method by combining the relaxation method and the local permeability update.

- a) I have extended the field equations for nonlinear magnetostatic and eddy current problems considering the gauge fixing with the Lagrange multiplier method. I have proposed formulations by assuming general hysteretic relationship between the \mathbf{H} and \mathbf{B} to offer for researchers the ability to use any type of hysteresis model and numerical method.
- b) To handle the nonlinear iteration I have worked out the relaxation method with the permeability updates to speed up the fixed-point iteration process.
- c) I have combined the solution of the field equations with higher order *Schöberl* type edge elements for nonlinear case. The introduced element type allows to choose finite elements with arbitrary polynomial degree utilizing the local complete sequence property.

Theses 3

I have confirmed the nonlinear field computational method with higher order finite elements by examples regarding magnetostatics, eddy current problems and diffusion equation. I have worked out three examples; one for the solution of one dimensional diffusion equation for ferromagnetic half-space, another one for the solution of a two dimensional (axisymmetric) eddy current problem for hysteresis measurement simulation and the third one for the solution of a three dimensional magnetostatic problem for the benchmark problem of COMPUMAG.

- a) I have illustrated the nonlinear simulation method on the one dimensional half-space problem. I have applied the nonlinear iteration method developed in the previous chapter for solving the half-space problem with the Langevin characteristics and with the Jiles-Atherton model, as well. The problem has been solved by the original fixed-point method and the fixed-point method with relaxation (R), which is different from the Hantila's over-relaxation method since $0 < \omega < 1$ is allowed and finally this FP+R method is improved by the local update of the permeability obtaining significant speed up.
- b) The simulation of the ferromagnetic hysteresis measurement has been worked out by using a two dimensional axisymmetric model. The simulations have been carried out at different frequencies using both the rate-independent and the rate-dependent JAM.
- c) I have developed the three dimensional nonlinear simulation technique for the T.E.A.M 13 test problem of COMPUMAG. I have used edge finite element method and \mathbf{A} vector potential formalism in combination with Lagrange multipliers λ . I have validated the simulation of the three dimensional nonlinear test problem by the available measurements. I have combined the higher order edge finite element method with the fixed-point method for solving this three dimensional magnetostatic problem. I have used geometric multigrid method for preconditioning the system by utilizing the hierarchical property of the introduced higher order edge elements. The coarse grid is represented by the DOFs of first order elements though the finer grid is defined by the DOFs of second order elements.

Further utilization of the inventions

The purpose of this work is to find an efficient way to compute magnetic fields in the presence of highly nonlinear even hysteretic materials. Both magnetostatic and eddy current fields were investigated.

Further investigations could be done by choosing hysteresis models other than the Jiles-Atherton. It would be very interesting to apply the Preisach model of hysteresis.

A different approach can be developed to take into account the ferromagnetic hysteresis, because these hysteresis models (Preisach, Jiles-Atherton etc.) were developed not for finite element computations. We have a finite element mesh for discretizing the electromagnetic field equations but same mesh can be applied for solving the equation(s) of the hysteresis model. The currently used hysteresis models do not utilize that the region is discretized by the finite element method. Both the electromagnetic field equations and the differential equations of the material could be solved simultaneously on the same finite element mesh as a coupled problem. In this way a more sophisticated approach could be achieved. The geometrical shape, the temperature of the material, the interaction between the magnetic domains and the effect of the mechanical stress could be considered by this coupled problem approach.

An interactive user friendly CAD software package can be developed for solving electromagnetic field equations in the presence of nonlinear magnetic material, which would be useful in designing electrical machines or power transformers.

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