PhD theses

Neural Network Based Vector Hysteresis Model and the Nondestructive Testing Method

by

Miklós Kuczmann
MSc in Electrical Engineering

supervisor

prof. Amália Iványi

Budapest
2004

1 The scope of my research

1.1 Literature overview

The simulation of the hysteresis characteristics of the magnetic materials is very important in a wide range of electrical engineering applications. The industrial sector has an increasing demand for magnetic materials, for example transformers in electric substations, various types of electrical equipments and so on. The improvement of the quality is also a very important requirement. Nowadays, computers are widely used to simulate the behavior of different arrangements, to design components or machines by applying Computer Aided Design (CAD) software. The design process of different arrangements by applying CAD is very favourable, becasue of the possibility of simulating the behavior of the machines under construction. From mathematical and engineering point of view, the hysteresis characteristic is a nonlinear and multivalued relationship between the magnetic field intensity and the magnetization of the magnetic materials, i.e. $\boldsymbol{M} = \mathscr{H}\{\boldsymbol{H}\}$. This phenomenon has been researched by many physicists and material scientists as well. The point of view of interests may be very different; the physicists are interested in the microscopic behavior and the microscopic description of the magnetic materials, mathematicians treat this as an interesting mathematical problem from the field of nonlinear systems. In electrical engineering applications, the researchers focus on the models of hysteresis characteristics of the ferromagnetic materials as a mathematical tool to simulate the hysteretic behavior of the magnetic materials, to work out a model with simple identification process (fitting the parameters of the model to measured data) which can be built into electromagnetic field calculation procedures, for example, into a finite element software.

The possible origin of magnetism is the motion of electrons at different energy levels in the atomic structures of the materials and this motion can be simulated by elementary current loops. The associated magnetic dipoles are characterized by the magnetic moments. The volume density of the vector sum of these moments results in the magnetization vector. The assumption of elementary current loops is the basis of a macroscopic description and of the theory of domain structure. Microscopic models consider energy contributions on very small dimensions, based on energy minimization of different energy terms (e.g. demagnetization, anisotropic, exchange and so on). The microscopic models have precise physical justification, but in some cases, it may be difficult to apply them on real engineering problems, because of the very large computation time.

The hysteresis phenomenon is encountered in many different areas of science, and it has been in the focus of research and investigation for a long time. Thanks to the fast computers available nowadays, it is possible to simulate hysteresis characteristics more and more precisely taking into account important physical phenomena. The developed models can be inserted into numerical field calculation procedures to examine an investigated material or an arrangement. There are many hysteresis models to simulate the behavior of magnetic materials, such as the Preisach model and its modifications, the Jiles–Atherton model, the Stoner–Wohlfarth model etc., and applying a new technique, the method of neural networks which has an increasing area of applications.

Applying neural networks in the field of function approximation has the advantage of easy identification, and the resulting model can approximate the measured object attractively as a continuous function. At the same time, neural networks are black box models, and there is no connection between the physical meaning of the phenomenon to be simulated and the parameters of the model. The main challenge of simulations is to predict the behavior of an arrangement, but the atomic level and the microscopic behavior are not in the focus of engineers. The basis of simulations is to work out a mathematical model of the given arrangement and a mathematical model of the material behavior. These models can be applied to calculate the physical quantities which we are interested in.

I have summarized the developed neural network based scalar hysteresis models which can be found in the literature. These models are based on the classical Preisach model, but the memory mechanism or the approximation of the distribution function or the Everett function has been solved via neural network approaches. In view of the advantageous and promising properties of the neural networks in this field, it is a great challenge for me to develop a new neural network based scalar hysteresis model. The development of precise two and three dimensional vector hysteresis models (especially in the anisotropic models) is also in the focus of research, therefore I have extended my investigations in this field.

In engineering practice, the simulation of different measuring arrangements and various electrical equipments is based on the numerical solution of Maxwell's equations coupled with the constitutive relations. It is very important to take into account the hysteretic behavior as well as the vector property of the magnetic field quantities. However, in some cases, it is adequate to use constant permeability (linear materials) or single valued nonlinearity (e.g. inverse tangent function). Hysteresis characteristics must be taken into consideration when, for example, hysteresis losses in electrical machines or effects related to the remanent magnetization are to be calculated.

An electromagnetic field calculation problem can be characterized by the field intensities and the flux densities described by the partial differential equations derived from Maxwell's equations and the boundary conditions. There are several potential formulations applicable to calculate the field quantities, fundamentally using scalar and vector potentials.

The finite element method is the most widely used and the most popular and flexible simulation technique in the solution of electromagnetic field problems. The weak form of the partial differential equations formulated by potentials, obtained from Maxwell's equations can be solved by using simple shape functions on a discrete mesh of the arrangement. When hysteresis characteristics must be taken into consideration, the solver and the model must be coupled by an adequate iteration scheme, because the resulting system of equations is nonlinear.

Nowadays, electromagnetic nondestructive evaluation methods have a dynamic and intense development applied to secure the structural integrity of complex mechanical systems. Nondestructive inspection techniques require continuously better and better detection sensitivity and field applicability. There are several benchmark problems can be found in the literature aiming to compare different measuring systems, computer software and solvers. There are some common areas of nondestructive testing, for example the optimization of probes, fast electromagnetic field analysis to reconstruct natural cracks, etc.

1.2 The aims of my research activity

The scope of my PhD dissertation is to develop a new neural network based vector hysteresis operator and the insertion of this model into a three dimensional finite element procedure to simulate an installed nondestructive testing equipment.

In view of the advantageous properties of neural networks in function approximation, it is a challenge for me to develop a new neural network based scalar hysteresis operator. I intend to build a measurement system to show the applicability of the predictions of the model by comparing scalar measurements and simulation results. I will measure the hysteresis characteristic of a toroidal shape core, since the magnetic field intensity and the magnetizaion vectors are parallel inside the core, and the assumption of scalar hysteresis characteristic gives very accurate results. I will generalize the scalar model to describe the vector hysteresis properties in two dimensions and in three dimensions, and I will take into account the anisotropic behavior as well. My aim is to develop an original identification procedure to fit the isotropic and the anisotropic models to measured hysteresis curves. Unfortunately, the vector hysteresis measurement is a large project in itself, especially no three dimensional vector hysteresis measurements are known to me. This is beyond my research's scope, that is why I will generate two dimensional and three dimensional measurements via the Preisach model as theoretical measurements.

I intend to build a nondestructive testing measurement system, and to realize simple test measurements by applying the FluxSet sensor and the Hall–type sensor as well. I will examine manufactured specimens with well defined artificial slots and holes. My aim is not to work out a new measurement system, but to allow the checking of the simulation results obtained from nonlinear simulations introduced in the next paragraph.

To simulate the above measurement system, I will apply the finite element method with the combination of the nodal and the edge shape functions. It is known from the literature, that the interface conditions along the crack surface can be prescribed easily by applying the edge shape functions. I intend to develop a three dimensional finite element model of the arrangement and to take into account the effect of the hysteresis characteristic by comparing measured and simulated results. I will use the $\boldsymbol{T}, \Psi - \Psi$ potential formulation, because this directly gives the magnetic field intensity vector and I can apply the direct isotropic neural network based vector hysteresis model. I intend to identify the isotropic vector hysteresis model from measurements, using a specimen of toroidal shape made of the same material as the nondestructive testing arrangement. I will handle the hysteresis characteristic by using the polarization method. I will develop and implement in the finite element procedure a fixed–point iteration scheme to solve the linearized system of equations.

1.3 Methods and algorithms

When using neural networks for function approximation, it is difficult to take into account the multivalued property of the hysteresis characteristics. To overcome this problem, I have introduced a new variable ξ associated with the systematically generated first order reversal curves, i.e. the multivalued characteristic can be represented by a single valued two dimensional surface with two independent variables H and ξ. This surface can be approximated by a feedforward type neural network. The memory mechanism of magnetic materials must be realized by an additional algorithm based on heuristics. It is the so called knowledge–base which contains if–then type rules about the hysteresis characteristics, e.g. the minor loops are closed, the concentric hysteresis curves are symmetrical [2, 5, 6, 12, 15]. I have built a measurement system in the frame of the software package LabVIEW to measure scalar hysteresis characteristics on a toroidal shape C19 structural steel [1, 4]. Comparisons between simulations and measurements have shown a very good agreement.

The two dimensional and the three dimensional vector NN based models of the magnetic hysteresis are constructed as a superposition of scalar neural network based models [3, 8, 9, 14]. In the case of isotropic vector hysteresis property, the scalar models are the same in the given directions, otherwise they are depending on the phase. I have developed an original identification procedure based on the Everett function to predict measured vector hysteresis characteristics. I have realized that, a recursive algorithm can be worked out to identify the unknown Everett function by discretizing the Everett functions and I have recommended a procedure for the identification of the vector hysteresis model. I have recommended a preprocessing task based on the Fourier expansion to take into account the phase dependence of the measured anisotropic Everett function. I have generalized the Fourier expansion in three dimensions. I have shown the behavior of the developed vector hysteresis models in linear and in rotational magnetic fields and I have compared the behavior of the isotropic and the anisotropic models. I used the Everett function, because there is a very close connection between the first order reversal curves and the Everett function, and the reversal curves are the basis of the developed neural network based hysteresis model.

As a computer aided design tool in electrical engineering, I have used the nodal and the edge finite elements to approximate the scalar and the vector potentials in the frame of the finite element method. The partial differential equations obtained from Maxwell's equations have been solved in the time domain by the method of the weighted residuals, because the effect of hysteresis characteristic of the simulated material has been taken into consideration. The $\boldsymbol{T}, \Psi - \Psi$ potential formulation directly obtains the magnetic field intensity vector $\boldsymbol{H}$, so the direct vector hysteresis operator can be applied, i.e. $\boldsymbol{B} = \mathscr{H}\{\boldsymbol{H}\}$. I have solved a time varying magnetic field problem, then an eddy current field problem in linear media. Finally, I have inserted an identified isotropic neural network based vector hysteresis operator into the finite element procedure. I have analyzed the effect of the eddy currents by comparing simulation results obtained from the time varying magnetic field problem and from the eddy current field problem. In the case of magnetic hysteresis, the hysteresis characteristic can be handled by the polarization method and the obtained linearized system of equations has been solved by using the fixed–point iteration scheme [10, 13]. I have implemented the finite element software myself.

I have manufactured a nondestructive testing equipment in our Magnetic Laboratory [7,11]. My aim was not to work out a new measurement system, but to allow the checking of the developed finite element based procedure. A U–shaped yoke has been magnetized by the currents flowing in the excitation coils and a specimen with well defined artificial surface cracks has been inserted among the legs of the yoke. In my experiments, I have applied the FluxSet sensor and the Hall–type sensor to measure the leakage magnetic field above the tested specimen. The applied sensor has measured the three orthogonal components of the magnetic field. The yoke and the specimen are made of the same magnetic material. I have worked out calibration methods to predict the output voltage of the sensors by using simple arrangements.

The size of a manufactured crack is very small comparing with the size of the whole arrangement: e.g. the diameter of a surface hole is maximum 2.5 mm and its depth is maximum 5 mm, the size of the U–shaped yoke is 320×240×5 mm, i.e. the order is two. The generated mesh of the whole arrangement is not accurate to simulate the effect of a crack. If a very dense mesh is used, then the number of unknowns is increasing very much. On the other hand, if a coarse mesh is applied, then the system of equations is not very large, but the result around the crack is inaccurate, since the number of elements around the crack is very few. Therefore, a global to local model (domain–decomposition) has been applied in two steps [13]. I have generalized the domain–decomposition method in the time domain. First, a large–scale (global) model without any crack is used to determine the boundary conditions of the local model, then the local domain including the crack is investigated. The global model has been applied on a coarse, but appropriate mesh to calculate the boundary conditions of the local model. The local model on a dense mesh around the crack has been applied to calculate the field quantities more accurately. If the local model is used, then the artificial boundary conditions can be calculated from the global model as described above, but the terms from the surface integrals in the weak form obtained from the partial differential equations must be included into the assembled system of equations. Finally, I have simulated the scanning process by calculating the signal of the Hall sensor at the same scanning points which I have measured. I have found that, the simulated signals are a bit narrower than the measured ones, but the pick values show very good agreement.

2 New scientific results

1. Thesis I have developed a new scalar hysteresis operator based on the function approximation capability of the neural networks to simulate the behavior of ferromagnetic materials. I have represented the first order reversal curves with a surface by introducing the variable ξ and I have approximated this surface by neural network technique. I have built a knowledge–base which contains if–then type rules about the behavior of the hysteresis characteristics. I have shown the applicability of the model by comparing simulated and measured results. I have taken into account the vectorial behavior of the magnetic field intensity and the magnetic flux density by applying the neural network based vector hysteresis model, and I have recommended a new identification procedure to build up the vector model. I have worked out the three dimensional anisotropic vector hysteresis model, and I have analyzed the behavior of the developed vector models.

1.a I have developed a new neural network based mathematical representation of the scalar hysteresis operator. I have handled the multivalued property of the hysteresis characteristics by introducing the new variable ξ associated with the measured first order reversal curves. This preprocessing can be applied on any kind of hysteresis characteristics. I have built a knowledge–base which contains if–then type rules about the behavior of the hysteresis characteristics. This is the memory mechanism of the model. I have realized the identification procedure by the training of the neural networks. I have built a measurement system to measure hysteresis curves on a toroidal shape C19 structural steel, and I have used these measurements to show the applicability of the neural network based scalar hysteresis model by comparing measurements and simulation results.

1.b I have developed the two dimensional and the three dimensional isotropic vector hysteresis models based on the neural network based scalar model. I have worked out an original and new identification procedure based on the measurable Everett function both to predict two dimensional and three dimensional isotropic hysteresis characteristics. I have compared the measured and the predicted curves and I have shown the behavior of the vector model in linear and in rotational magnetic fields.

1.c I have developed the two dimensional and the three dimensional neural network based anisotropic vector hysteresis models by the means of Fourier expansion of the measured Everett function of the anisotropic material. I have generalized the two dimensional model in three dimensions as a theoretical expansion of the two dimensional model, and I have recommended an identification procedure to fit to measured curves. I have compared the measured and the predicted curves and I have shown the behavior of the vector model in linear and in rotational magnetic fields, finally I have compared the isotropic and the anisotropic models.

2. Thesis I have implemented the developed neural network based vector hysteresis model to the finite element method. I have applied the Ψ and the $\boldsymbol{T}, \Psi - \Psi$ potential formulations, because these directly give the magnetic field intensity vector which is the input variable of the direct vector hysteresis model. I have used the nodal and the edge shape functions for the approximation of the potentials. I have handled the neural network based vector hysteresis model by applying the B–scheme of the polarization method, and I have solved the linearized system of equations by the fixed–point iteration technique. I have used an under–relaxation scheme to speed up the convergence of the method. This results in a convergent and a well applicable method to solve both time varying magnetic field problem and eddy current field problem.

3. Thesis I have confirmed the three dimensional nonlinear simulation technique by comparing simulated and measured results. I have worked out a measurement system which is able to detect the surface cracks of a specimen and I have developed the numerical simulation of this arrangement. I have worked out the global to local model (domain–decomposition) of the arrangement in the time domain. The boundary conditions of the local model have been calculated by using the global model. I have compared the simulated and the measured output signal of the Hall sensor, and these comparisons show very good agreement.

3.a I have built a measurement system to analyze the FluxSet sensor and the Hall–type sensor in the field of measuring the crack signals. I have examined the signals corresponding to cracks with different size and shape. I have worked out calibration methods to predict the output voltage of the sensors by using simple arrangements. The measurements are performed by using the software environment LabVIEW.

3.b I have developed the three dimensional nonlinear numerical analysis of the built nondestructive testing measurement system and I have used the finite element method and the $\boldsymbol{T}, \Psi - \Psi$ potential formulation. I have developed a global to local model of the built arrangement in the time domain. I have used the global model without any crack to predict the artificial boundary conditions of the local model where the crack has been taken into account. I have developed the surface integrals obtained from the weak form of the partial differential equations necessary to use in the local model. I have implemented the identified three dimensional neural network based isotropic vector hysteresis model to the eddy current field problem by applying the fixed–point iteration technique and the B–scheme of the polarization method. The comparisons between the measured crack signals performed by the Hall sensor and the simulation results show the good applicability of the developed model.

3 Further utilization of the inventions

A neural network based hysteresis operator has been presented in this work. The identification of the scalar model is a simple training method on measured and preprocessed first order reversal curves. The vector hysteresis model in two dimensions and in three dimensions have also been implemented for isotropic and for anisotropic case as well. However, the scalar hysteresis measurement is an easy task, the measurement of the two dimensional vector hysteresis characteristics is a great challenge, and it is a large project [16]. It is a future work to build a vector hysteresis measurement system in our laboratory. The three dimensional vector hysteresis measurement is an open question, I have not found any paper about this topic. I have developed a theoretical representation of the three dimensional anisotropic model, but I think there may be several generalizations of this model.

The finite element method and the presented neural network based vector hysteresis models can be connected via the polarization method and the fixed–point iteration scheme to simulate any kind of arrangement containing hysteretic nonlinearity.

Another and very important observation is that, a stand alone software should be used to simulate any arrangement, when applying the finite element method. The software package MATLAB is very powerful, but this is very slow in this case, i.e. a C–code (especially a parallel code running on a parallel computer) may be a better alternative. Higher order shape functions may also give better approximation as well. In the case of higher order shape functions, some case study have to be done (e.g. solving TEAM problems).

References

[1] P. Kis, M. Kuczmann, and A. Iványi. Hysteresis measurement in LabVIEW. *Physica B*, 343:357–363, 2004.

[2] M. Kuczmann and A. Iványi. Neural network based scalar hysteresis model. *International Journal of Applied Electromagnetics and Mechanics*, pages 225–230, 2001/2002.

[3] M. Kuczmann and A. Iványi. Isotropic and anisotropic vector hysteresis model based on neural networks. *Journal of Electrical Engineering 9/s*, pages 73–76, 2002.

[4] M. Kuczmann and A. Iványi. Measuring and identification of scalar hysteresis characteristics applying neural network based hysteresis (in Hungarian). *Híradástechnika*, LVII:4–9, 2002.

[5] M. Kuczmann and A. Iványi. Neural network model of magnetic hysteresis. *COMPEL*, pages 367–376, 2002.

[6] M. Kuczmann and A. Iványi. A new neural-network-based scalar hysteresis model. *IEEE Trans. on Magn.*, pages 857–860, 2002.

[7] M. Kuczmann and A. Iványi. Calibration and measurement with 3D FluxSet sensor (in Hungarian). *Híradástechnika*, pages 34–37, 2003.

[8] M. Kuczmann and A. Iványi. Neural network model for scalar and vector hysteresis. *Journal of Electrical Engineering 1-2*, pages 12–21, 2003.

[9] M. Kuczmann and A. Iványi. Vector hysteresis model based on neural network. *COMPEL*, pages 730–743, 2003.

[10] M. Kuczmann and A. Iványi. Nonlinear 2D edge element based FEM in $\boldsymbol{T}, \psi - \psi$ formulation. *Proceedings of the 9th OPTIM Conference, Brasov, Romania*, pages 41–48, 2004.

[11] M. Kuczmann and A. Iványi. Calibration of FluxSet sensor. *Proceedings of the 12th International Symposium on Theoretical and Electrical Engineering, Warsaw, Poland*, pages 389–392, July 16-19, 2003.

[12] M. Kuczmann and A. Iványi. Neural network based scalar hysteresis model. *Proceedings of the 10th International Symposium on Applied Electromagnetics and Mechanics, Tokyo, Japan*, pages 493–494, May 13-16, 2001.

[13] M. Kuczmann and A. Iványi. Simulation of a nondestructive testing measurement system. *Proceedings of the 11th IGTE Symposium, Seggau Castle, Austria*, pages 376–381, September 13-15, 2004.

[14] M. Kuczmann and A. Iványi. Vector hysteresis model based on neural network. *Proceedings of the 10th International IGTE Symposium, Graz, Austria*, pages 453–458, September 16-18, 2002.

[15] M. Kuczmann and A. Iványi. Neural network based simulation of scalar hysteresis. *Proceedings of the 10th International Symposium on Electromagnetic Fields in Electrical Engineering, Cracow, Poland*, pages 413–416, September 20-22, 2001.

[16] M. Kuczmann, P. Kis, A. Iványi, and J. Füzi. Vector hysteresis measurement. *Physica B*, 343:390–394, 2004.