MŰEGYETEM 1782

Budapest University of Technology and Economics
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PhD Thesis book

RELATIONSHIP BETWEEN MECHANICAL STRESS AND MAGNETIC HYSTERESIS

by

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Budapest
2009

1 Introduction

The magnetic properties of material are sensitive to the external stress. The application of a mechanical stress to magnetic material changes its magnetic properties and results different magnetic induction at a given magnetic field for different value of the applied stresses. This phenomenon is known as the Villari effect or inverse magnetostriction. The change in magnetization due to the applied mechanical stress has been measured and modeled by many researchers as well as the effect of the magnetostriction. The magnetic behavior ofiron under applied mechanical stress is quite complicated phenomena. In general, the effect of unidirectional stress on magnetization depends on the magnetostriction of the material. Materials with positive magnetostriction expand under the effect of a magnetic field and their magnetization is increased with tensile mechanical stress. Materials with negative magnetostriction contract under the effect of a magnetic field and their magnetization decreases with tensile mechanical stress. Iron and iron alloys present both positive and negative magnetostriction, depending on the strength of the applied magnetic field. Under applied mechanical stress, their magnetization behaves in different ways with different magnetic fields. Inversely, the magnetostriction of these materials is not only field dependent but also stress dependent, respectively.

In soft magnetic materials, the magnetic microstructure can easily be changed in small fields either by magnetization rotation or wall motion. For example, easily displaceable domain walls yield steep magnetization curve providing high permeability in the core of inductive devices. The irreversible rearrangements of domains occurring during the magnetization are responsible for losses, noise in devices and pinning of domain walls by material imperfections. It results in hysteresis with coercivity and remanence.

Grain-oriented Fe-(3 wt%)Si laminations have major importance as a unique subject of basic research studies and industrial applications. This material has excellent crystallographic properties, it gives rise to the magnetic modeling and, it is an ideal material for many efficient electromagnetic devices.

Many authors have investigated the mechanical stress effects on the magnetic materials, the losses, the magnetization, the permeability and the magnetic induction. A significant amount of research has been made on the influence on the changes in hysteresis loops of low stressed Fe-Si electrical steels. Whereas, a little attention have been paid on highly stressed electrical steel specimens. In spite of the fact, that many researcher deals with the effects of the mechanical load on the magnetic properties of the ferromagnetic materials, the measurements and the results are not consistent and in most cases not unambiguous. The procedures of the measurements are considerably different, and the values of the results are quite various. Furthermore, there is no literature to describe in more details the behavior of the magnetic hysteresis loop under higher tensile stresses.

Over the years there have been developed several mathematical models of magnetic hysteresis, including Prandtl-Ishlinskii model, the Duhem model, the Preisach model, the Stoner-Wohlfarth model, Jiles-Atherton model, etc, to present the behavior of the magnetic materials. The Preisach model, originally introduced by Ferenc Preisach, and the Stoner-

Wohlfarth model have received much attention in recent years. The introduction of these and additional models, and they extension into the vector field are described in various monographs, however a few researcher deals with the effect of the induced and external mechanical forces, and stresses.

The numerical analysis of electromagnetic field problem results in an approximate solution of the partial differential equations derived from Maxwell's equations. Several methods are known to solve these partial differential equations based on the weighted residual method. The finite element method is a widely used technique to approximate the solution of the partial differential equations. Many researchers deal with the basic equations of the electromagnetic fields and their solutions based on different potential formulation. In the eddy current region two potential functions can be used, either a current vector potential $\boldsymbol{T}$ or a magnetic vector potential $\boldsymbol{A}$. The magnetic vector potential $\boldsymbol{A}$ can be coupled with the electric scalar potential V.

The different physical phenomena determining the behavior of the material can be modeled as uncoupled, or as coupled magnetoelastic problem at different levels. In the case of strong coupling, the effect of the elastic field on the magnetic field is also taken into account. This type of analysis is significant if the mechanical stress in the apparatus is high enough to change the magnetic properties of the material. The strong coupling method makes it possible to account for geometrical changes due to the magnetostriction and the applied external forces.

The aim of my research is to produce a measurement apparatus and a measurement procedure, to measure the magnetic characteristic under different scale of the mechanical stress and analyze the changing of the magnetic properties under mechanical load.

On the basis of the measured data I want to develop a model to simulate the stress dependent magnetic scalar hysteresis, and I intend to validate the model with the measured data. According to the stress dependent magnetic scalar hysteresis model I want to develop a stress dependent magnetic isotropic and anisotropic vector hysteresis models to represent the effects of the mechanical stress on the magnetic characteristic. I am going to introduce the installation method to parameter identification trough the measurements results, and I want to prove the accuracy of the scalar models compared with the measurement results.

I want to develop the implementation of the introduced mechanical stress dependent magnetic hysteresis model into the numerical field analysis to represent the interaction between the electromagnetic eddy current field and the mechanical load on the specimen. I intend to realize the numerical field analysis with COMSOL Multiphysics environment combined with the MATLAB environment. The COMSOL Multiphysics developed for designing, optimizing and simulating scientific phenomena, such as solutions in electromagnetic field computation, although it is not ready to use hysteretic characteristic in the calculations. I want to introduce the method of the implementation of the developed stress dependent magnetic hysteresis model trough a 2D model of the modified Epstein frame and I am going to present the results of the simulation emphasizing the mechanical aspect of the solution.

2 Stress dependent magnetic measurements

To realize a complete investigation on magnetic material under mechanical load, I have developed and implemented two magnetic measurement systems, which are able to consider the mechanical stress effects on the studied iron probe, an apparatus with a tensile screw system, and a system with a modified Epstein-frame. I have realized the measurements with a grain-oriented GO Fe-(3,1 wt%)Si alloy with positive magnetostriction. Most transformers cores are built today with GO Fe-Si laminations, where the crystallites have their easy axis close to the rolling direction and their plane nearly parallel to the lamination surface.

To the investigation the specimens are 250 mm long, and 12 mm wide in the case of measurements with the tensile screw system. The applied laminations have thickness 0.27 mm, and the maximum specific total core loss $W_{15/50}$=0.89 W/kg at 1.5 T and 50 Hz. The density of the material is 7.65 kg/dm^3, the yield point is 335 MPa, tensile strength 350 MPa, the maximum elongation 9.5 %. The apparatuses of the measurement contain two computers to measure the mechanical and the magnetic properties independently. The Computer 1 carried out the mechanical measurements. This platform is able to do the data acquisition and processing, the calculations and the storage. Computer 2 estimates and stores the result of the magnetic measurement.

Using the tensile screw system the force has been realized through two high strength steel sheets with known mechanical properties with stretching a screw. The iron sheets have strain gauge stamps in full bridge and the applied forces are calculated from the elongation of these plates. The mechanical properties of these plates have been measured, and exhibit linear elongation in the measuring range. The applied strain gauge stamps (HBM 1-LY11-6/120) were temperature optimized for steel. The change of resistance of the stamps has been measured through the Spider 8 with the Catman Express software. It was applied as a static force, adjusted by the assistance of the software. Two hinged clamps on the tip of the winded lamination fixed the probe.

The magnetic field strength has been calculated from the current of the primary winding, and Computer 2 has derived the magnetic field density from the voltage of the secondary coil. The excitation has been generated with a Virtual Instrument developed in LabVIEW code and fed through by the KIKUSHUI PBX 20-20 bipolar power supply with amplification 2. This KIKUSUI power amplifier is suitable to generate ±20 V and ±20 A bipolar signals with optional signal shapes. It is possible to be controlled by current (CC mode) or voltage (CV mode) depending on the problem to be solved. In the case of magnetic hysteresis loop measuring, CC mode is recommended, because the current is proportional to the magnetic field intensity [5]. The measured data gained with the multifunction DAQ sampling card NI PCI-6030E has been post processed to extract the needed H and B fields.

The advantage of the tensile screw system is that it is a strong construction, which is suitable applying high tensile stress for the measured specimen. The disadvantage of the system is that it is unable to apply compressive force to the laminations.

The apparatus of the measurement with the modified Epstein-frame contains the same two computers to measure the mechanical and the magnetic properties independently. The tensile force has been realized with a screw through a load cell. The load cell is an S9 type

Hottinger-Baldwin device, which is able to measure the tensile and the compressive forces. The maximum load of the instrument is 5kN. The signal of the load cell has also been measured through the Spider 8 with the Catman Express software on Computer 1.

The material of the probe sheets is the same, but the size of the specimen has been changed. The sheets are 340 mm long, and 30 mm wide, the thickness is 0.27 mm. The middle magnetic length of the frame is 250x250 mm. The force has been realized through a screw system. An axial bearing was fastened to the framework. It allows applying the tensile and compressive force as well.

At both set-ups the other parts are the same and the magnetic measurements have been solved similarly, the magnetic and the mechanical properties have been measured independently with the two computers. The measurements have been performed with field control, namely the waveform of the excitation is controlled [6].

The advantages of this system compared to the former set-up are that, it is able to apply tensile and compressive force too, the load cell is very sensitive, it is able to measure the magnetostrictive forces, and the system allows to use plates with larger thickness. The disadvantage is the load cell has a maximum load of 5 kN. In this case the thickness was small, so the maximum force was enough to yield a high mechanical stress in the sheet. On the other hand the small thickness does not permit the compressive investigation of the probe.

On the basis of the measurements the magnetic behavior of the material has been analyzed. The measurements have shown that the magnetic behavior of iron under applied stress is a quite complex phenomenon, and the magnetic properties are very sensitive to mechanical stress.

The measurements with the screw system and the modified Epstein frame produced sufficiently similar results. At each apparatus the flux lines are closed, however at the screw system the yoke is the structure from different material with slightly different magnetic properties, meanwhile the modified Epstein frame has a yoke from the same material with a known size in the middle. Consequently, the results of the measurement with the modified Epstein frame are more accurate, although, the differences between the measured values are not considerable.

The measurement proved, that the increase of the measurement frequency increases the energy loss per cycle, increases the coercive field H_c, so the width of the hysteresis loop is growing. The reason of this behavior is that the eddy currents at higher frequency cause higher classical loss and the turning of the domains results in higher hysteresis loss.

Carrying out the measurements with triangular waves results in higher magnetization than with sinusoidal waves. The triangular waves lead to lower energy loss per cycle and lower coercive field. The main reason of these effects is that a sine wave is steeper in the region of changing sign than the triangular one. Thus the rate of flux density changes in the vicinity of the coercive point is higher for sinusoidal excitation. The difference increased by increasing the measurement frequency [14].

The tensile stress has significant effect to the shape of the hysteresis loop and to the energy losses of the curve. The increase of the tension yields increased magnetization, and magnetic flux density for the same applied field strength. The coercive field H_c is decreased and the energy loss is decreased by increasing the tension. The measurements proved, that the effect of the applied stress is observable at any measurement frequency. The changing rates of the energy losses are approximately 25-48% at the maximum applied stress of σ =136.66 MPa. The ΔH_c values are very small at all frequencies and it is getting higher by applying mechanical tension. The effect of the stress is independent of the shape of the excitation curve. The shape of the loop and the energy loss at the triangular excitation changed in the same way like at the sinusoidal excitation. The effect of the applied stress can be influenced as well with increasing the number of the iron sheets in the coil core [9].

I have performed measurement in transverse direction using laminations with the same material cut perpendicular to the rolling direction. The experimental results in the transverse direction with the screw system and the modified Epstein frame are very similar. The measurements gave the similar results as in the rolling direction by using tensile stress, namely the growth of the measurement frequency increases the area of the hysteresis loop, increase the energy loss, and the growth of the tensile stress changes the shape of the curve and decreases the energy loss, however not to a so great extent.

To summarize, the applied mechanical stress has a significant effect on the magnetic behavior of the magnetostrictive materials. In general, this effect of unidirectional stress on magnetization depends on the magnetostriction of the material. However the magnetic behavior of iron under applied mechanical stress is quite complicated phenomenon, it does not allowed to neglect this influence. It yields changes on the shape of the characteristic and on the energy losses of the magnetic material [16].

3 Stress dependent magnetic hysteresis model

I have developed an experimentally identified stress and rate dependent hysteresis model for magnetic materials with respect to the mechanical interaction. I have realized the installation process in three steps as it is described below. The results of the measurements versus the stress and the measurement frequency were the base of the model identification [13].

The first step the determination of the Everett-functions from the measured results. To develop the model I have applied 25 hysteresis loops in this process at 1 Hz, 2 Hz, 5 Hz, 10 Hz and 20 Hz. At each frequency I have measured the magnetic curves under the tensile stress value of 0 MPa, 34.16 MPa, 68.33 MPa, 102.49 MPa, 136.66 MPa. It resulted in 5x5 Everett-surfaces. I have stored the values of the Everett function as discrete points in a two dimensional array.

After that the second step is the interpolation between the 5x5 arrays to generate the new array of the Everett surface at the given measurement frequency and stress value. I have solved the assignment with 2D spline interpolation technique. To investigate the correctness of the simulation the mean squared error has been estimated between the calculated and the measured hysteresis curves. The maximum value of the error was 0.76%, and the MSE was 0.17% at 6 Hz measurement frequency and 115.66 MPa tensile stress value. The approximated error is rather small, consequently the method is appropriate to represent a stress and rate dependent scalar magnetic behavior in the measured interval [2]. The disadvantage of the model is, that the extension of the model to the vector field requires high computational demand. For this reason I want to develop a model, where the stress dependency of the magnetic hysteresis characteristic can be calculated commonly.

According to the results of the measurements, I have developed a magnetic Preisach-type scalar hysteresis model with analytical identification, including the mechanical stress effects as well. In the developed new model the Preisach distribution function, $P(\alpha,\beta,\sigma)$ contains the stress value.

I have developed an identification procedure for the model parameters according to the measured data. In this method the optimal parameter values are designated with coarse estimation, and in the area of the designated parameters the values have been refined. I have solved the optimization assignment with an algorithm that finds the values of the parameters at the minimal value of the mean squared error (MSE) between the measured and the simulated curves.

In the case of a Gaussian-type distribution function I have realized the identification in two steps. At first, the set of the four stress independent parameters have to be determined with the abovementioned identification procedure. I have solved it by using σ=0 MPa stress value. The four stress dependent parameters are the multiplier factor of the stress value, namely in the case of σ=0 MPa stress value it is not required to consider the values of these parameters. It is the optimization problem to fit the Preisach model with the parameters of the $P_G(\alpha,\beta)$ Gaussian distribution function to the measured hysteresis curve. I have tested the method with the data measured at 1 Hz excitation frequency.

The second step is to determine the four stress dependent parameters at $\sigma\neq0$ MPa stress value. I have accomplished the installation of the $P_G(\alpha,\beta,\sigma)$ for σ=136.66 MPa stress value with the adjusted four stress independent parameters. After adjusting the parameters of the $P_G(\alpha,\beta,\sigma)$ distribution function, an optional σ stress value can be chosen. The calculated mean squared error of the model are about 0.03%-0.06% at different σ stress values at 1 Hz measurement frequency [10].

By using Gauss-Lorentzian distribution function at σ=0 MPa stress value the model fits with better accuracy as it can be read in the literature. For this reason I have adapted the Gauss-Lorentzian distribution function at $\sigma\neq0$ MPa stress value. The reconstructed Gauss-Lorentzian distribution function $P_{GL}(\alpha,\beta,\sigma)$ can represent the stress dependent magnetic properties as well.
The Gauss-Lorentzian distribution function at σ=0 MPa stress value $P_{GL}(\alpha,\beta)$ is the base of the stress dependent $P_{GL}(\alpha,\beta,\sigma)$. I have realized the installation in two steps in the same way as in the case of the $P_G(\alpha,\beta,\sigma)$. The first step is to set the 7 stress independent parameters. After that I have accomplished the installation of $P_{GL}(\alpha,\beta,\sigma)$ for $\sigma\neq0$ MPa by adjusting the 7 stress dependent parameters.

As an example at 1 Hz excitation frequency and 115.66 MPa stress value the maximum error is 0.63% with the distribution function P_{GL} and 0.71% with using P_G. And the MSE is

0.035% and 0.029% respectively. The difference is very small, the accuracy of the model with P_{GL} is slightly better than with P_G, but the identification procedure is much more time-consuming. Consequently, I have preferred the model with applying P_G to extend the stress dependent magnetic scalar hysteresis model into the vector field [7, 8].

I have developed a stress dependent isotropic and anisotropic magnetic vector hysteresis model with using the developed stress dependent Preisach-type magnetic scalar hysteresis model with using the $P_G(\alpha, \beta, \sigma)$ distribution function. The stress dependent vector model has been constructed as a superposition of the scalar models. In 2D case the computation can be realized with finite number of directions, with finite number of scalar models. In my study I have applied 12 directions. In 2D case the projections of the magnetic field strength are determined in each direction. The magnetizations are computed in the specified directions by stress dependent scalar Preisach models with $P_G(\alpha, \beta, \sigma)$. The vector sum of the magnetizations represents the output of the vector model.

I have realized simulations at 0 MPa and 136.66 MPa stress values. With anisotropic model the same excitation causes different magnetization in different directions. The anisotropy changes the dynamic of the model, near the hard axis the time delay increases, and at the easy axis the time delay decreases [1, 11, 12]. At lower excitation the magnetic polarization cannot change due to the properties of the hard axis, where the polarization change requires higher energy investment, namely it needs higher magnetic field intensity in the given direction.

4 Magnetic field computation with FEM modeling

I have accomplished the implementation of the developed stress dependent Preisach-type anisotropic magnetic vector hysteresis model into the FEM. I have coupled the electromagnetic field calculation with the mechanical field computation, and it resulted in strong magnetoelastic coupling in the eddy current field assignment. The numerical field analysis has been realized with COMSOL Multiphysics environment combined with the MATLAB environment [4].

Maxwell's equations represent the magnetic behavior of the magnetic material. The Fe-Si laminations of the modified Epstein frame have been calculated both linear and hysteretic media. In this case I have tested the time-varying eddy currentfield with the developed stress dependent Preisach-type magnetic hysteresis model with consideration into the mechanical stress value of the yoke's laminations. The $\boldsymbol{A}, V - \boldsymbol{A}$ potential formulation have been applied for the calculation.

In nonlinear media the relationship between the magnetic flux density $\boldsymbol{B}$ and the magnetic field intensity $\boldsymbol{H}$ contains hysteretic behaviors. The investigation of the electromagnetic field problems in hysteretic material needs special methods of handling the nonlinearity. The fixed point technique is based on the decomposition of a hysteretic relationship $\mathsf{H}\{\cdot\}$ into a linear and a residual of nonlinearity. The residual has been iteratively computed in every time step [15].

I have introduced the results of the calculation with FEM of the modified Epstein frame's two-dimensional model in three local elements in different position at 1 Hz measurement frequency with sinusoidal excitation at 0 MPa and 136.66 MPa tensile stress value with respect to the mechanical properties o the material [3].

I have calculated the sum of the magnetic flux density ***B*** across the simulated specimen. I have computed hysteresis curves at 1 and 10 Hz measurement frequencies with sinusoidal excitation at 136.66 MPa tensile stress value. I have realized comparison between the measured and the computed hysteresis curves and I have calculated the mean squared error values. The values of the errors are acceptable to simulate the magnetic properties of the specimen under higher mechanical tensile stress.

5 Future research work

I introduced the developed measurement apparatuses and method in this research work for external static mechanical load to analyze the effects of the mechanical tensile stress on the magnetic properties of the investigated specimen, although both of the apparatuses are able to measure the magnetic characteristic under dynamic mechanical load. I intend to study the magnetic behavior of the investigated laminations under dynamically changing mechanical tensile stress, although it is need some modification to solve the automatism of the mechanical load.

The developed scalar magnetic model contains the static value of the mechanical stress. To simulate the influence of the dynamically changing mechanical load it is required to adapt the developed model. The adaptation of the theoretical model is a refinement of the developed model, however the realization of the model is a much more complicated assignment, due to the expansion of the required computational capacity.

In the research work there has been developed the implementation of the introduced stress dependent magnetic vector hysteresis model into the electromagnetic field computation. Although the presented example was a two-dimensional model of the modified Epstein frame loaded with external mechanical stress, it is possible to realize the three-dimensional implementation of the model as well, however it induces computational capacity problems. For more accurate simulation a computer grid system or the parallel computing technique can be applied, with its new scientific problems of managing the partitioning the programs and the managing the computers.

6 Summary of the new scientific results

Thesis I.

With the developed and realized two magnetic measurement systems, I could consider the mechanical stress effects on the studied iron probe. With the developed measurement process I could collect, handle and store the magnetic and the mechanical measured data independently. By the measurement of grain-oriented Fe-(3.1 wt%)Si electrical steel I have obtained a large number of data that characterizes systematically the mechanical stress dependent magnetic behavior of the investigated material, and the data are suitable to initialize the developed mechanical stress dependent magnetic hysteresis model. On the basis of the measurement data I can state that the application of the mechanical load with the 40% of the yield point of the investigated material can decrease the magnetic energy losses with 30% as well [5, 6, 9, 14, 16].

In detail:

- I have developed and realized two magnetic measurement systems with consideration to the mechanical stress effects. The tensile screw system is able to apply high tensile stress. It is a strong construction, where the mechanical force value can be set accurately. The modified Epstein-frame with the load cell is very sensitive for the stress effects. It is able to measure the magnetostrictive forces of the winded plates. The modified Epstein-frame is suitable applying tensile and compressive force as well.

- I have developed a measuring process to measure the magnetic and the mechanical properties on separated computers. Catman Express software collects the values of the mechanical stress, and my private programs developed in LabVIEW environment handle the excitation signal, the data acquisition, the data processing, filtering and storage.

- I accomplished measurements with grain-oriented Fe-Si electrical steel sheets. After analyzing results and comparing with observations can be found in literature I can state, that the mechanical tension promotes the magnetization, decreases the energy loss by the ferromagnetic material with positive magnetostriction.

<u>Thesis II.</u>

To simulate the stress dependent magnetic hysteresis characteristic I have developed two new models, an experimentally installed interpolation based and an analytical based model, identified using measured data. First, I have developed a model based on an interpolation technique to represent the stress and frequency dependence of the magnetic hysteresis, determined from the Everett surfaces by the measurement results. Second, I have completed the well-known Gaussian and the Gauss-Lorentzian distribution functions and their identifications with the tensile stress effect to realize an analytical based stress dependent magnetic hysteresis model. I have developed a stress dependent isotropic and anisotropic magnetic vector hysteresis model as an extension of the analytical based stress dependent scalar hysteresis model with the Gauss-type distribution function [1, 2, 7, 8, 10, 11, 12, 13].

<u>In detail:</u>

- I have developed an experimental stress and rate dependent magnetic scalar hysteresis model. It shows good accuracy in the identification process, however it needs measurement data in large quantities to calculate the Everett functions, and increased computational demand to realize the interpolations.

- I have developed an analytical stress dependent magnetic scalar hysteresis model. I have extended the Gauss-type and the Gauss-Lorentz-type distribution function for the simulation of the stress dependent magnetic behavior. I have accomplished the identification procedure for each model and I have performed comparison between the measured data and the results of the simulations. Both presented good accuracy, although the identification process of the model with the Gauss-Lorentz-type distribution function is much more time-consuming.

- I have developed a stress dependent isotropic and anisotropic magnetic vector hysteresis model based on the developed scalar model. According to the accuracy and the time-demand of the calculation I have prefered the analytical stress dependent scalar magnetic model with P_G distribution function to develop a stress dependent magnetic vector hysteresis model. I have tested and analyzed the vector model at different strength of the excitation and at the rotational magnetization procedure. The model can represent two and three dimensional isotropic and anisotropic stress dependent magnetic behavior, however it has been tested in two dimensions only.

<u>Thesis III.</u>

To represent the effects of the mechanical load on the electromagnetic properties of the ferromagnetic material of the specimen in the eddy current field I have implemented the developed stress dependent anisotropic magnetic vector hysteresis model to the numerical field analysis with the finite element method. I have accomplished strong magnetoelastic coupling for the stress dependent magnetic hysteresis, and implemented the developed model with the polarization method to handle the hysteretic relation between the magnetic flux density ***B*** *and the magnetic field intensity* ***H****, and I have solved the system of the equations by the fixed-point iteration technique. I have compared the measured and simulated magnetic hysteresis curves on the specimen, and I have found less the 5% differences between the measured and simulated data [3, 4, 15].*

<u>In detail:</u>

- I have formulated the required equations for the simulation from Maxwell's equations. I have defined the boundary conditions on the border of the assignment. I have determined the required mechanical equations for accomplish the strong magnetoelastic coupling for the stress dependent magnetic hysteresis.

- I have implemented the developed stress dependent anisotropic magnetic vector hysteresis model to the numerical field analysis with the finite element method in the eddy current field. I have applied the ***A***-*V*, ***A*** potential formulations for the approximation and I have applied the polarization method to handle the hysteretic relation between the magnetic flux density ***B*** and the magnetic field intensity ***H***. I have solved the equation system by the fixed-point iteration technique.

- I have realized comparison between the measured and the computed hysteresis curves. I have calculated the mean squared errors, and model is suitable to simulate the magnetic properties of the specimen under higher mechanical tensile stress with small values of the error.

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