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Numerical scalar hysteresis model and its precision

***Abstract**. The calculation of magnetic fields in the electromagnetic devices is an important part of the design process. The numerical approach in consideration to the measured material hysteresis is discussed in the paper. Some precision problems of the model are pointed out. The results of the calculation are compared with the measurement results made on the magnetization set up for the characterization of semi and hard magnetic materials.*

***Streszczenie.** Obliczanie pola magnetycznego w urządzeniach elektrycznych jest istotną części procesu projektowania. W artykule dyskutowane jest numeryczne podejście do zmierzonej histerezy. Pewne precyzyjne problemy zostały wypunktowane. Wyniki obliczeń porównane są z wynikami pomiarów wykonanych na zestawach magnetycznych charakterystycznych dla materiałów magnetycznych twardych i półtwardych. (**Numeryczny model skalarny histerezy i jego dokładność**)*

Keywords: Finite element methods, Magnetic fields, Measurement.
Słowa kluczowe: metoda elementów skończonych, pole magnetyczne, pomiary

Introduction

The program for the 3D finite element magnetic field calculations includes the numerical scalar hysteresis model. The description of the magnetic material is based on the measured major hysteresis loop and as many as possible measured first order reversal curves (FORCs) for the increase and for the decrease of the excitation current.

In each of the finite elements, the new magnetic induction ***B*** is calculated on the basis of the nonlinear finite element method calculation made with different magnetization curves in each finite element. The magnetic induction in each of the finite elements, calculated from the previous time step, the history of the magnetic density and the excitation current, are the basis for the evaluation of the new magnetization curve, which will be used for nonlinear calculation in the current time step. Some calculations must be repeated, if the result is on the wrong magnetization curve.

Some problems with shapes of the new magnetization curves have been pointed out in [1].

Some precision problems of the model will be explained.

Evaluation of the new magnetization curves

Usually, we do not know the history of the magnetization process. Because of that the calculation starts with the virgin magnetization curve. Each magnetization curve is used for the calculation as long as excitation current continual increases or continual decreases. At the moment when the excitation current changes its direction (it starts to decrease after the increasing or it starts to increase after the decreasing), we have to evaluate the new magnetization curve.

If the calculated ***B*** is on the major hysteresis loop, the FORCs are used for the evaluation of the new magnetization curve. If the calculated ***B*** is inside the major hysteresis loop, the new magnetization curve is evaluated with mirroring. The mirroring is made over the line connecting two points in the hysteresis loop where the change in the direction of the excitation current takes place.

Simple algorithm of the calculation procedure is shown in Fig. 1.

The more exact algorithm for the definition of the new magnetization curve is shown in Fig. 2. The definition of the new magnetization curve, made with mirroring can be particularly questionable.

Some parts of the algorithm, shown in Fig. 2, are more precisely explained in [1].

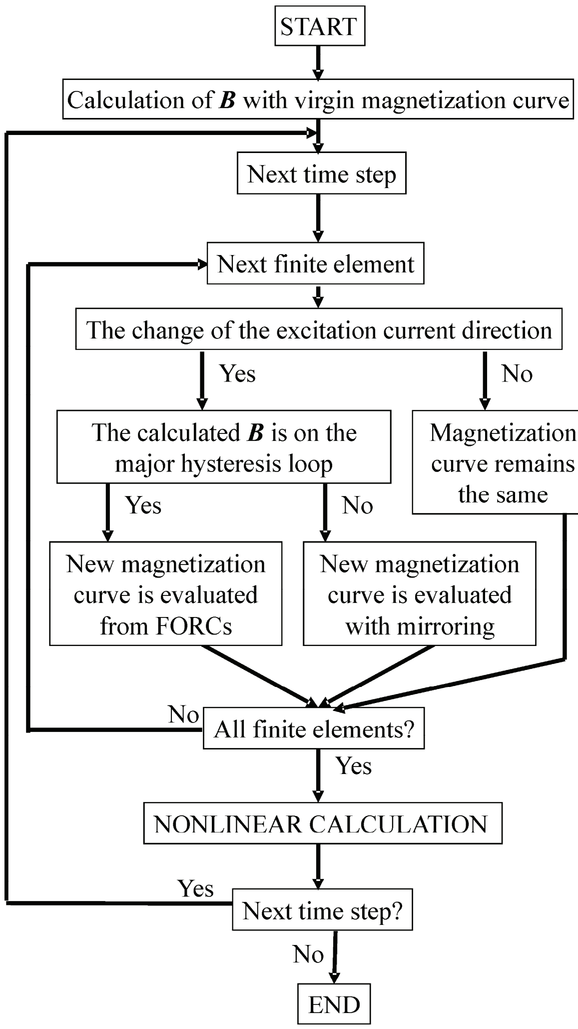

Fig.1. Algorithm of the calculation procedure

Measured FORCs for the increase of the excitation current are shown in Fig. 3.

Mirroring of the FORCs part together with two mirroring points is shown in Fig. 4.

The shapes must be smooth and there should not be any brakes on the curves. More about avoiding the curves with the brakes is explained in [1].

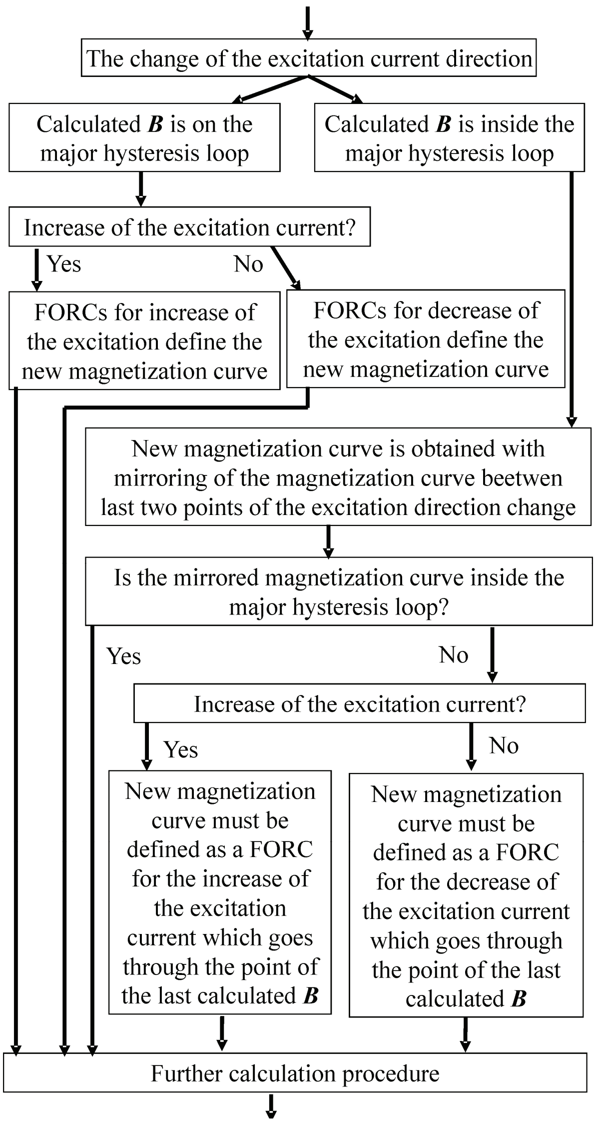

Fig.2. More exact algorithm for the definition of the new magnetization curve

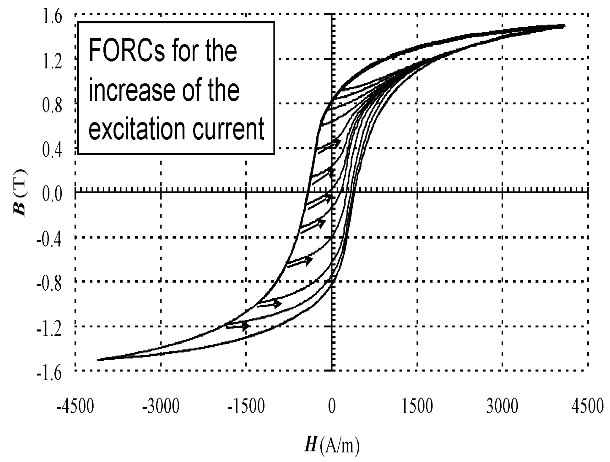

Fig.3. FORCs - the first order reversal curves

Also, the mirroring can cause problems. The mirrored part of the FORCs can appear out the major hysteresis loop.

If the mirrored curve is outside of the major hysteresis loop, we have to evaluate the new magnetization curve as FORC, which goes through the point of the last calculated ***B*** [1].

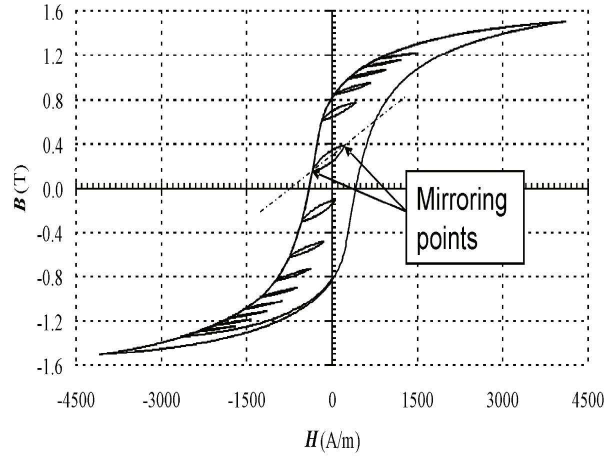

Fig.4. Mirrored part of the magnetization curve

Precision of the model

Different magnetization curves are used during the calculation. Some of them are evaluated from FORCs and some of them are evaluated with mirroring. Sometimes dependant on the magnetization process, there is a lot of changes of the excitation inside of the major hysteresis loop. If the calculation on each of the magnetization curves is made with small mistake, at the end after more excitation changes, the result can be far off from the real solution. This case is shown in Fig. 5.

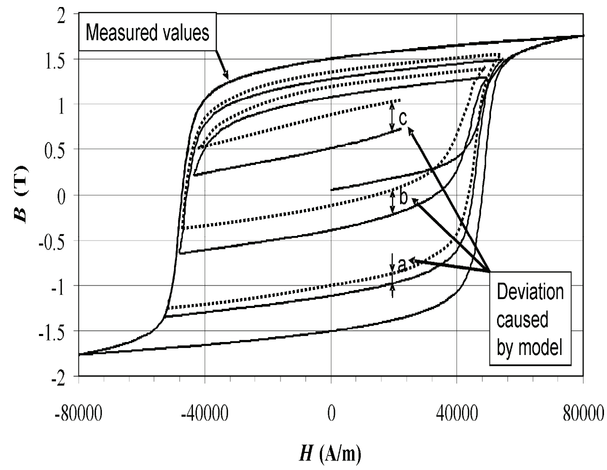

Fig.5. Going away from the real result

We can see from the Fig. 5 that the calculated value can be after the use of more magnetization curves, after each calculation more off from the result. It can be seen that the distance b is bigger than the distance a, and the distance c is bigger than the distance b. After each change of the excitation, we are more off from the real value. Sometimes, after calculations with more different curves, the result is far off from the real value and for some other input data (measured major hysteresis loop and FORCs) the result is quite correct.

The problem can appear through the calculation of the subhysteresis loops too. If the subhysteresis loop is calculated on the part of the hysteresis, where ***B*** is changed fast with the change of $\boldsymbol{H}$, the calculated subhysteresis loop can be easily away from the real position of the subhysteresis loop, as it is shown in Fig. 6.

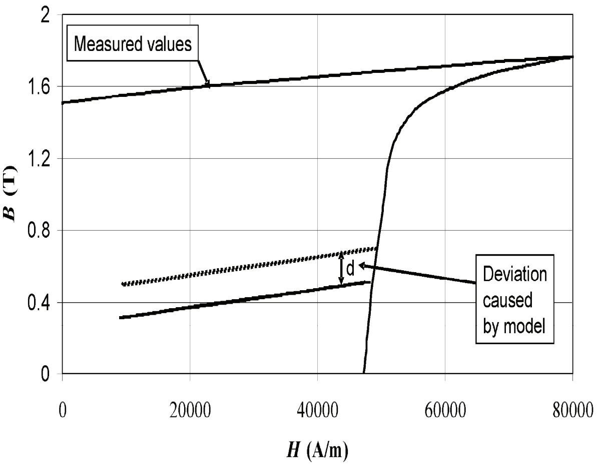

Fig.6. Calculated subhysteresis loop, which is far away from the real subhysteresis loop

The model is more precise at the calculation of the subhysteresis loop on the part of major hysteresis loop where $\boldsymbol{B}$ is changing slower with the change of $\boldsymbol{H}$, as it is shown in Fig. 7.

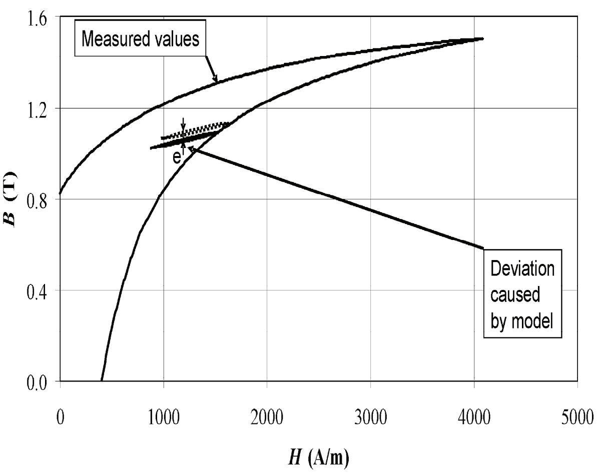

Fig.7. Calculated subhysteresis loop, which is not far away from the real subhysteresis loop

In the Fig. 6, the calculated subhysteresis loop is for the distance d away from the real position of the subhysteresis loop and in the Fig. 7, it is for the distance e away from the real position of the subhysteresis loop.

The use of the model is quite complicated for the devices with more excitation coils, with more excitation currents, which are changing different - some of them increasing and some of them decreasing. The problem appears, because the magnetization curve for higher magnetizations is different from the magnetization curve for the lower magnetizations. A simple algorithm is shown in the Fig. 8.

In this case we can just predict, for each finite element separately, the higher or lower excitation and after the calculation, we have to check if the excitation has been really the same as it was predicted. If real change of the magnetization differed as predicted, we have to repeat the calculation with different magnetization curves in the finite elements, where the predicted change of the magnetization has been different from the real change of the excitation.

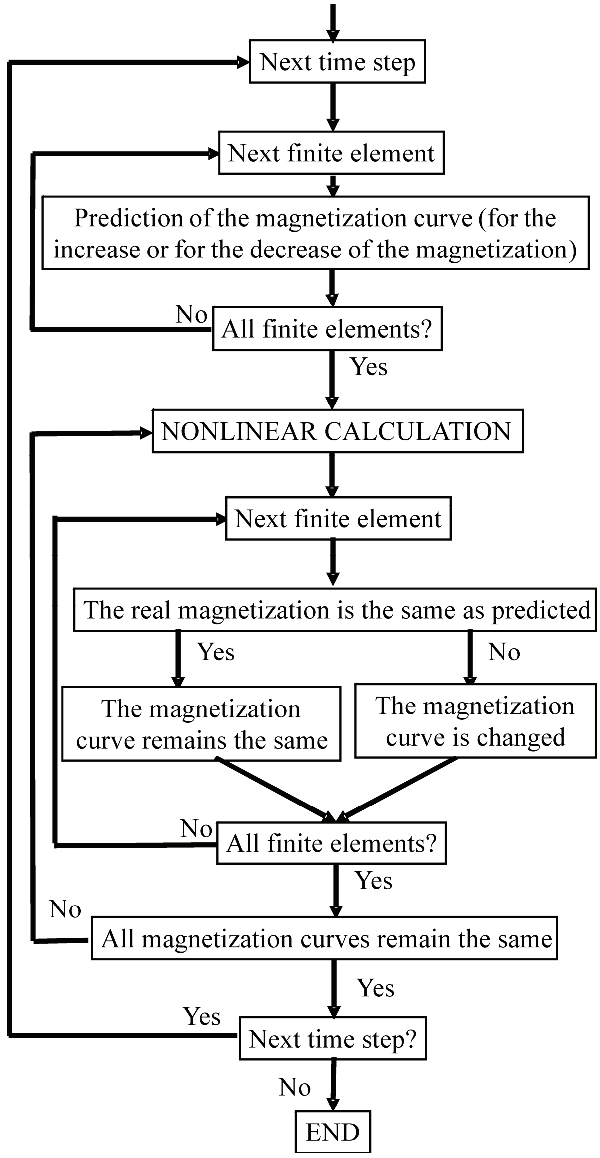

Fig.8. Algorithm of the calculation procedure for the different changing of the excitation currents in different excitation coils

Measurement

All measurements are made on the device for the characterization of semi and hard magnetic materials. The device is shown in Fig. 9.

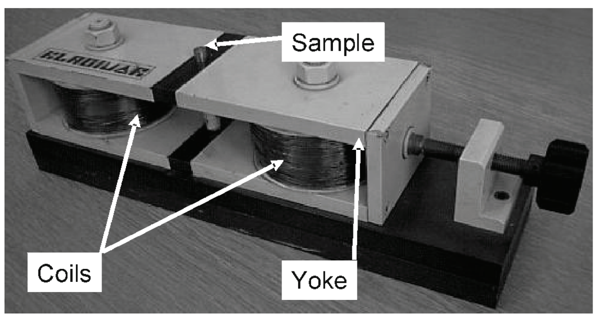

Fig.9. The magnetization set up for the characterization of the semi and hard magnetic materials

$\boldsymbol{H}$ is measured by Hall sensor, which is placed near the sample and $\boldsymbol{B}$ is measured by induction in the measuring coil, coiled around the centre of the sample. The frequency of the measurement was 10 mHz.

The same device has been modelled with 3D finite elements. The calculation has been made as a three-dimensional nonlinear transient calculation.

The calculation has been made to test the precision of the model, which has been previously explained.

The comparison between the calculation and the measurement of the minor loop, made on the mayor hysteresis loop, is shown in the Fig. 10.

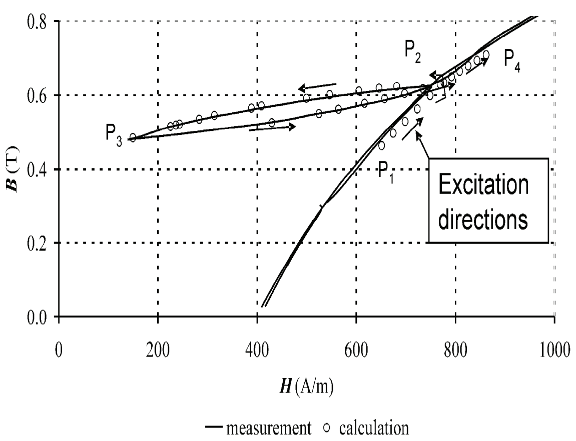

Fig.10. Comparison between the calculation and the measurement of the minor hysteresis loop made on the major hysteresis loop

The calculation is made with the magnetization curve, which covers the part of the major hysteresis curve. Points P_1 and P_4 are on that curve. Excitation current increases. At point P_2 excitation current starts to decrease and at that point new magnetization curve is defined on the basis of the FORCs for the decrease of excitation current. At point P_3 excitation current starts to increase again and the new magnetization curve is defined with mirroring of the previous magnetization curve between the points P_2 and P_3, which are the points of the last two excitation current directions changes. At point P_2 the magnetization curve, which covers the part of the major hysteresis curve, is used.

In the Fig. 10, we can see some difference between the calculated and measured values, however in spite of that the calculation and the measurement are in a good agreement.

Conclusions

After all problems appeared during the calculation, it is difficult to say that this model is better than other models, which can be found in the literature [2-19].

The model is easier for use in case, when we know the change of the excitation and we do not need to make the procedure, shown with algorithm in the Fig. 8.

If there are a lot of changes of the excitation, inside the major hysteresis loop, the model can lead us to the wrong solution, as it has been previously explained. However when the magnetization leads us back on the major hysteresis loop, the mistake in the fallowing iterations will not be so big any more.

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