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Vibration and nonlinear hysteretic system analysis with modelling

PhD Theses

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1. Introduction

There are many research works and scientific investigations that deal with the phenomena *hysteresis*. Different developed hysteresis models (like Stoner-Wohlfarth, Preisach, Chua-type) occur in engineering as well as in physics, biology, economics, but the palette is not complete. In many complex methods like the Finite Element Method requires a *fast* and *identifiable* nonlinear hysteresis model because the heavy computation demand.

In the recent research the Finite Element Method becomes a common one but nowadays the attention is frequently on the keywords like *multiphysics* and *applied nonlinearity.*

An other rarely discussed and still open research direction is the investigation of the nonlinearity in the frequency domain.

The aims of my research work are the modelling and the measurement of the hysteresis phenomenon in time- and frequency domains and its application in coupled Finite Element models (electromagnetic, structural mechanics).

2. The aims of my research activity

I want to introduce a developed novel hysteresis model, to present its behaviour and efficiency through several examples. I show the electromagnetic, acoustic and vibration measurement results of sinusoidally excited thin plates. I also present the results of modelling of these phenomena using finite element method. Finally, I want to analyse the behaviour of the hysteretic non-linear system with different excitation signals in time- and frequency domains applying a novel decomposition method. I want to present two developed methods to produce the major loop from its prepared auxiliary function. I will show the results through several examples.

The implementations were realized primarily in MATLAB environment. The measurements were supported by the LabVIEW 2010 software from National Instruments. The more complex tasks such as the finite element modelling were realized in a strongly coupled COMSOL and MATLAB environment.

2.1. Novel hysteresis model

I want to present the improved Preisach model applying a new memory representation, that makes the Preisach model continuous and gives evolution in the calculating speed. I introduce the applied wavelet-interpolation technique to build up the continuous distribution function from discrete measurement data. I present examples, that show the model's efficiency and accuracy.

To solve finite-element computational problems the speed of the Preisach model was not satisfactory, that is why I have developed a novel, measurement based scalar and two dimensional vectorial model of hysteresis in a different point of view. It is based on a special modification vector field $\mathbf{\Psi}^*$ that is defined by the aim of the local differential permeability $\hat{\boldsymbol{\mu}}_{diff}$ vectors. The efficiency of the developed model is based on its simplicity, its easy identification property and the great progress in the calculation speed. In spite of its simplicity the model can prove the accommodation property.

According to the literature, I want to introduce the improved vector hysteresis model. I examine two important problems in the introduced vector model: the effect of the accommodation property of the scalar model and the definition of the initial value in the output vectors for every directions.

Thesis:

I have shown the improved faster and continuous Preisach model that is demonstrated and identified on discrete measurement data. I have also developed a measurement based novel scalar and two dimensional vector models that are based on a special field of the modification vector $\mathbf{\Psi}^*$. *Its simplicity and very efficient calculating property has been demonstrated through many examples.*

2.2. Measurement and modelling of excited transformer sheets

I want to present my the measurement and finite element modelling results of the electromagnetic and vibration properties of two excited transformer sheets. By the aim of the computer aided measurement method I have examined the electromagnetic, the vibration and the acoustic waves of sinusoidally excited thin plates applying different excitation frequencies and amplitudes. The magnetic field intensity H and magnetic flux density B variables can be determined and calculated in time- and frequency domains. The reference signal is amplified by a Kikusui PBX 20-20 programmable linear power amplifier and generated by NI PCI6024E DAQ card. The CTC AC102 low-noise accelerometer was used for vibration measurements. The high fidelity dynamic microphone allows to measure the acoustic resonance by the aid of NI PCI 4472 DAQ card.

The measurement results show various examples of the excitation frequency and amplitude effects of both the $H - B$ curve, both the vibration and acoustic properties both in the time and the frequency domains.

I present the finite element model of the previously described and measured excited transformer sheets applying the developed non-linear hysteresis model and coupled finite element models (electromagnetic, structural mechanics).

The goals of the developed model are:

- to derive the magnetic field intensity H, induced current density J_i, and with hysteresis non-linearity the magnetic flux density B properties inside the transformer sheets;
- to calculate the Lorentz force F distribution and plane stressed along the sheets;
- applying the ALE moving mesh, the deformation of plates is simulated.

From the simulation results I conclude the vibration frequency of the plates at a given excitation frequency.

Thesis:

I have analysed the time and the frequency domain behaviour of two non-linear magnetic sheets under harmonic excitation. I have determined and proved with measurement the variation of the magnetic force through the Lorentz relations and neglected the permeability inhomogeneity in the material and the magnetostriction. I have coupled multiphysical models together with non-linear hysteresis and deformed mesh models to calculate electromagnetic, structural mechanics and displacement results from the Finite Element Model.

2.3. Spectral properties and decomposition method of the hysteresis curve

Firstly, I want to show the novel decomposition method that splits the non-linear signal into *odd* and *even* components. I present the advantages of the decomposition investigating the spectral behaviour of the hysteretic non-linear system. I present the behaviour of the non-linear system applying three different excitation signals:

- ideal harmonic excitation;
- the excitation signal contains higher frequency harmonic components;
- the excitation signal contains Gaussian noise.

I want to show two different methods to produce the major loop from its prepared even auxiliary function. To produce the major loop I examine the necessary bandwidth of the non-linear system, in other words I examine the effect of the harmonic cutting of the major loop to show the relevance of the higher harmonics. I present two different methods to produce the major loop:

- a simple derivative method;
- linear approximation based method in the spectral domain.

Thesis:

I have presented the advantages of the developed novel decomposition method that splits the non-linear signal into odd and even parts. I have also worked out two different preparation methods to produce the major loop from previously prepared auxiliary even function.

3. New scientific results

1. Thesis

I have shown the improved faster and continuous Preisach model that is demonstrated and identified on discrete measurement data. I have also developed a measurement based novel scalar and two dimensional vector models that are based on a special field of the modification vector $\boldsymbol{\Psi}^*$. Its simplicity and very efficient calculating property has been demonstrated through many examples [3],[8],[5],[13],[9],[6],[1],[2].

1.1 I have improved the classical Preisach model as built a new memory representational model that makes the Preisach model continuous and gives evolution in the calculating speed. I have worked out and applied a wavelet-interpolation technique to build up the continuous distribution function from discrete measurement data. I have demonstrated the modified model with calculated examples [3],[8].

1.2 To avoid all inconveniences of the Preisach model I have developed a novel, measurement based scalar and two dimensional vectorial model of hysteresis in a different point of view. In the novel scalar model the differential permeability $\hat{\boldsymbol{\mu}}_{diff}$ and the special field of the modification vector $\boldsymbol{\Psi}^*$ can be obtained from the positive and negative reversal loops. In spite of its simplicity the model can be prove the accommodation property [5],[13],[1],[2]. I have shown the simplicity and its easy identification property and the great progress in the calculation speed that allows it to include in the field calculation models. I have demonstrated its accuracy and simplicity through many examples.

1.3 I have also introduced the improved vector hysteresis model. The applied scalar hysteresis model has been derived and introduced from the scalar measurement that I have developed. In the improved isotropic vector model a scalar hysteresis model can be applied to every directions over the 2D plane. I have also solved two important problems in the introduced vector model the effect of the accommodation property of the scalar model and the definition of the initial value in the output vectors for every directions [9],[6].

2. Thesis

I have analysed the time and the frequency domain behaviour of two non-linear magnetic sheets under harmonic excitation. I have determined and proved with measurement the variation of the magnetic force through the Lorentz relations and neglected the permeability inhomogeneity in the material and the magnetostriction. I have coupled multiphysical models together with non-linear hysteresis and deformed mesh models to calculate electromagnetic, structural mechanics and displacement results from the Finite Element Model [20],[17],[7],[16],[14],[15],[18],[21],[19].

2.1 *I have measured* the electromagnetic, the vibration and the acoustic waves of the sinusoidal excited thin plates. *I have also measured* the previous signals applying different excitation frequencies and different excitation amplitudes on the surrounded coil. *I have examined* spectral harmonics of the measured vibration waves. I have also presented that when the amplitude of the excitation signal is increased higher order harmonics appear in the magnetic flux density curves as well as in the vibration curves. It causes minor loops in the hysteresis curve. The calculated spectrograms justify that the odd and even harmonics are different because the amplitude of the even harmonics are changing periodically, exactly by the twice of the excitation frequency.

2.2 As in the recent research the coupled multiphysics calculations are very important direction of the finite element modelling. *I have presented* a method that connects the electromagnetic and structural mechanics Finite Element calculations together for the vibration calculation of the transformer sheets. *I have applied* the developed scalar hysteresis model in the electromagnetic calculations where from *I have calculated* the Lorentz force distribution along the sheets. *I have also calculated* the displacement vectors for every nodal points where from I can calculate the new deformed mesh. From the postprocessing values *I have calculated* the vibration of the plates.

3. Thesis

I have presented the advantages of the developed novel decomposition method that splits the non-linear signal into *odd* and *even* parts. I have also worked out two different preparation methods to produce the major loop from previously prepared auxiliary even function [10],[13],[4],[11],[12].

3.1 I have investigated the behaviour of a non-linear hysteretic system in spectral domain and I introduced a new decomposition method. I have worked out a novel decomposition method in frequency domain that splits the non-linear signal into *odd* and *even* components. Applying that novel decomposition I have proved the advantages of the decomposition investigating the spectral behaviour of the hysteretic non-linear system. I have also shown the behaviour of the decomposed non-linear system in time and frequency domains applying different excitation signals (with one harmonic component, with higher harmonic components and with Gaussian noise)

3.2 I have introduced the effect of the harmonic cutting of the major loop to show how many relevant higher harmonics are needed or in other word I have calculated the necessary bandwidth of the non-linear system for the later major loop preparation method. I have worked out two different methods to produce the major loop from its prepared auxiliary even function: a simple derivative method and an other that uses a linear approximation method in the spectral domain.

4. Further research

A novel developed hysteresis model has been presented in this work. Its accuracy, fast calculation speed and easy identification procedure has been developed. I have presented the identification algorithm in many types of hysteresis curves, but I have not developed a frequency and material dependent model where the investigated modification field can be varied with an other parameter according to the excitation frequency or the material type.

An other task with the developed non-linear hysteresis model is to expand a phenomenological model from that where any functions are continuous as well as the modification field.

The extension of the scalar model for two dimensional vector representation has been worked out according to the literature, but for the identification my plan is to build a single-sheet-tester.

I have built a measurement system for the acoustic, electromagnetic and vibration measurements. I have connected the measurement results with my computations. I have found that in the acoustic measurement there are unwanted noise components that could be eliminated by a more precise and acoustically insulated measurement system.

As I have written the multiphisics computation is a very good keyword for the current research directions. From the feedback of my conference presentations I see the multiphysical calculations coupled to an included fast non-linear hysteresis model is sometimes a big problem for a lot of scientific groups. The next task is to apply the developed method to find many industrial problems where those calculations are needed.

Finally, I have investigated the behaviour of a non-linear hysteretic system in spectral domain applying a new decomposition method. It confirmed my idea that an auxiliary function can accurately determines the major loop and the first order reversal curves inside the hysteresis loop. Based on this approach the developed hysteresis model would be connected with my decomposition method where an auxiliary function defines the modification field.

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