



Simulation of Electromagnetic Inspection Techniques Using FEM Analysis

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Abstract. Currently, the development of new production integrated applications of micromagnetic NDT methods require a detailed expert knowledge in order to proof the feasibility and to optimize the application of specific devices, sensors, mechanics and set-up parameters. Often, a huge amount of experiments is necessary to establish the formulas, describing the correlations between Micromagnetic behaviour and mechanical material characteristics. These developments are often very costly in terms of time and money, which is why the use of such NDT techniques often remains limited. Analytical and numerical simulations can be used in order to predict the a priori electromagnetic behaviour of the material in different inspection situations and to reduce the experimental efforts in order to accelerate new developments. Therefore, Fraunhofer IZFP has developed an FEM simulation platform using Flux software (developed by Cedrat) which is able to simulate the electromagnetic field distributions and reproduce the 3MA Micromagnetic signatures in different inspection situations.

Introduction

The 3MA electromagnetic NDT system, developed at IZFP is based on the determination of various electromagnetic properties of the material, which are detected by measurement at several frequencies and modulations. It combines 4 different magnetic NDT methods (harmonic analysis, eddy current, Barkhausen noise, and incremental permeability) [1]. For better interpretation of measuring results and equipment optimization it is necessary to simulate the signals of these NDT methods. The numerical modelling of the inspection situation by 3MA device is very challenging due to the multi-scale and complex geometry of the system, the multi-scale time signal and the management of nonlinear and hysteretic behaviour of the material. Then, an intelligent strategy calculation method is developed in order to manage the convergence and time calculation problem. The robustness of the tool is assessed by comparison between simulation and measurement.



2. 3MA system

2.1 Physical principal

3MA is abbreviation of Micro-magnetic Multi-parameter Microstructure and stress Analysis. This device enables a nondestructive evaluation of steel sheets using four electromagnetic techniques: Barkhausen noise, eddy current computation, harmonic analysis of the magnetic field and incremental permeability. In this last mode, low frequency (f_{LF}), and high frequency (f_{HF}), excitation sources are combined [2], [3]. The incremental permeability (IP) method consists in applying a low frequency (LF) excitation to the sample, with sufficient amplitude to reach induction levels ranging from 1 to 1.6 T in the specimen. Simultaneously, the sample is submitted to high frequency (HF) excitation of very low amplitude (eddy current). The HF exciting coil investigates the central area of the sample along hysteresis loop created by the f_{LF} signal, generated locally in the material.

The measured signal of the search coil after specific signal processing is proportional to the incremental permeability (IP). In practice, the variation of the voltage of this signal versus tangential magnetic field (H_t) is recorded. Besides others, it allows accessing to the value of the magnetic coercive field.

3. FEM Modelling

3.1 Simulation challenges

Fig. 1 shows the total domain of the proposed inspection model for evaluating the signature of 3MA system. The model is composed of a magnetic yoke (ferrite) and the exciting and search coils. The distance between the magnetic yoke and the surface of the sample, also called lift off (G), is equal to 0.5 mm.

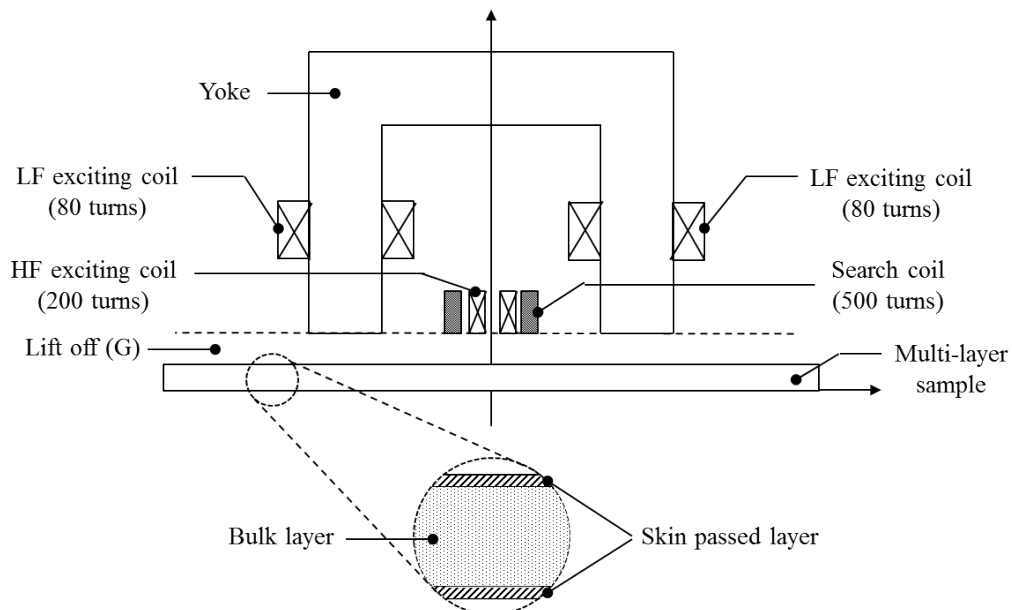


Fig. 1. 2D sketch of 3MA system

The combined sample-sensor system has a multi-scale geometry. The sample itself is a multilayer system, which is made up of a surface layer (skin passed layer, hard layer, tensile layer), which thickness varies from 10 to 30 μm and the bulk material layer of

around 1 mm thickness. The width of the yoke of the 3MA sensor is 100 mm. This geometrical scale difference requires adapted meshes depending on the area of sample-sensor system.

Moreover, the f_{LF} frequency varies between 50 and 1000 Hz, whereas f_{HF} component ranges between 10 kHz and 100 kHz. Thus, the time scale ranges from 10^3 to 10^4 . Therefore an adapted temporal discretization is required to identify the high-frequency phenomena.

The magnetic material behavior must be locally described by a nonlinear hysteresis model. From the static hysteretic behavior, the local dynamic behavior was derived with a move-back method based algorithm. This approach will be detailed in section 3.2.

A conventional computation, carried out in magnetic transient domain, of the whole system has been performed using Flux® software [4], and constitutes a reference simulation. However, for a half low frequency period with sampling rate of 400 kHz, the simulation lasted more than three hours. To overcome these problems of resolution and memory space, a new computation strategy was developed.

3.2 computation strategy

The strategy consists in dividing the computation in two phases [5], [6]. The LF and HF simulations are performed separately, but remained linked by the magnetic state of the different layers induced by the LF computation. Thus, two models are created with the same geometries and meshes and are run consecutively at each time step of the LF computation. Only the boundary conditions, the current excitations and the magnetic properties of the sample change. Moreover, this separation enables to restrict the simulations on the half of the geometry using symmetries and boundary conditions. The strategy computation is illustrated on fig.2.

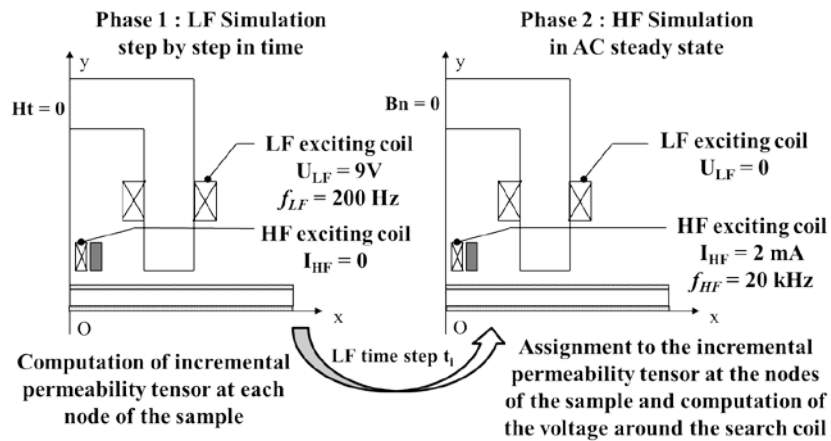


Fig. 2. Diagram of computation strategy

First, the LF simulation is run in transient domain. At each time step t_i , the value of incremental permeability tensor is computed and stored at each node of the sample model. Then, the tensor is exported to the HF model and applied to the physical properties of the sample region. The HF simulation is performed in harmonic domain due to the low excitation level, and enables to compute the voltage around the search coil. The process is repeated at each time step of the LF period.

A macro control in Python language compatible with Flux software is developed in order to implement automatically this process. In order to validate this strategy, the separated

computation is compared to the conventional transient simulation (Fig. 3).

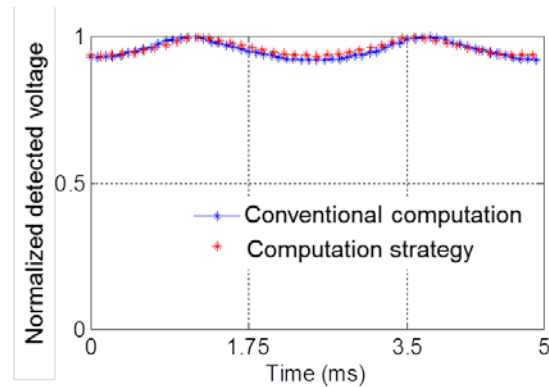


Fig. 3. Validation of the computation strategy

The computation strategy produced results in good agreement with the conventional computation. A maximum deviation of the detected voltage is estimated at 3%.

3.2 Implementation of non-linear hysteretic property

Various models which take into account the dynamic ferromagnetic response under sinusoidal excitation have been proposed [7], [8]. The five Jiles Atherton (JA) hysteresis parameters are identified in the quasi-static states. Different algorithms are developed in order to extract the JA parameters: deterministic and stochastic methods [9]. The Fig.4 shows two examples of material family. Minor symmetric hysteresis curves by model and measurement at different operating level described by one set of JA parameter. The difference between measurement and model results is estimated at less than 6% for the main hysteresis parameters such as coercive field (H_c), remanent induction (B_r), maximum induction (B_{max}) and magnetic field (H_{max}) and absolute permeability (μ_r).

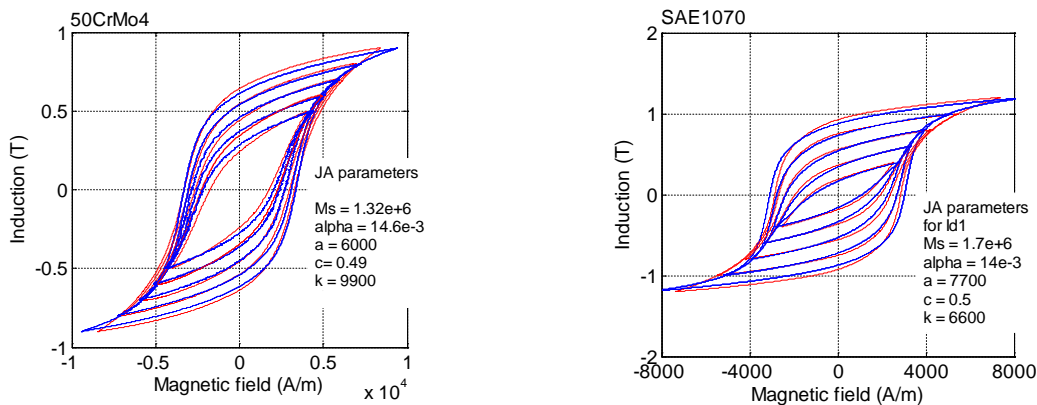


Fig. 4. Hysteresis by Jiles Atherton model (blue) and by Epstein measurement (red)

In order to reproduce the answer of the material at $f = 50$ Hz, the contribution of classical eddy current is added to the quasi-static. Good accuracy is observed between measurements and models. In order to reproduce the behavior of the material in dynamic, the contribution of classical eddy current is added to the quasi-static. The basic equation of the eddy current analysis using the A- Φ method described in details in [10], is given by (1)

$$\begin{aligned} \text{rot}(v \text{ rot} A) &= J_0 - \sigma \left(\frac{\partial A}{\partial t} + \text{grad } \Phi \right) \\ \text{div} \left\{ -\sigma \left(\frac{\partial A}{\partial t} + \text{grad } \Phi \right) \right\} &= 0 \end{aligned} \quad (1)$$

Where A is the magnetic vector potential, Φ is the electric scalar potential; v is the reluctivity, J_0 is the current density and σ is the conductivity. The flux and eddy current are analyzed by the step by step method taking into account the non-linearity of the material, especially the magnetic material history. The hysteresis behavior is taken into account just for the first phase of low frequency excitation. In order to attain the steady state results, the calculation is carried out during 3 periods (300 steps). For example, the time interval Δt of the step by step method is chosen as $5 \cdot 10^{-5}$ s, when the exciting low frequency is 200 Hz. The Newton-Raphson method (N-R) is used for the nonlinear iteration. The convergence is achieved after 7 iterations.

4. Assessment of FEM simulation platform

In order to assess the robustness of the FEM platform, two kind of validation are shown: Indirect and direct validation.

4.1 Indirect validation

The inspection case deals about the effect of cutting in the edge of FeSi 3% ring. There are different methods to study the cutting edge: temperature, losses analyses and macroscopic hysteresis characterization. Those methods are sometime insufficient and should be combined by other methods. In case of small deteriorated area, the macroscopic characterization gives an overview about the total surface of the sample and this degradation could be masked.

Fraunhofer IZFP has developed a new adapted probe for local characterization in motion. To facilitate the motion, the probe is inclined about 30° and moves from the outside area to the inner side of the sample. The path distance is about $5000 \mu\text{m}$. The fig.5 shows the 3MA Hcu coercive field quantity from IP mode.

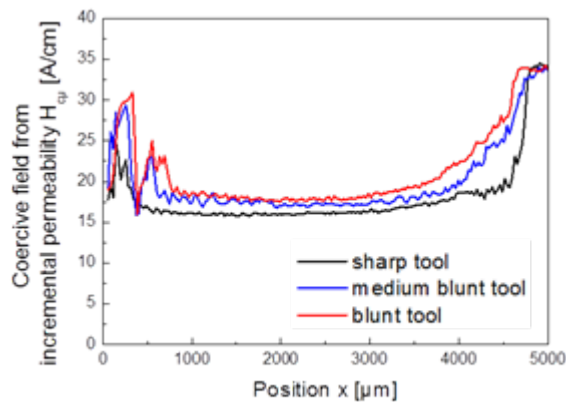


Fig.5. Coercive field Hcu from IP mode distribution from external side to inner side

Three zones are clearly distinguished: outer side, central area and inner side. The external and the inner area are not symmetric; it seems that inner area is more affected by the

cutting. The microscopic analysis shows no difference in external and inner area. In order to understand this dissymmetry, FEM simulation is run in same conditions as the measurement.

This Fig. 6 illustrates the simulated magnetic behaviour of 3MA probe in inclination to FeSi3% ring, three configurations: inner side, centre and external side of the ring.

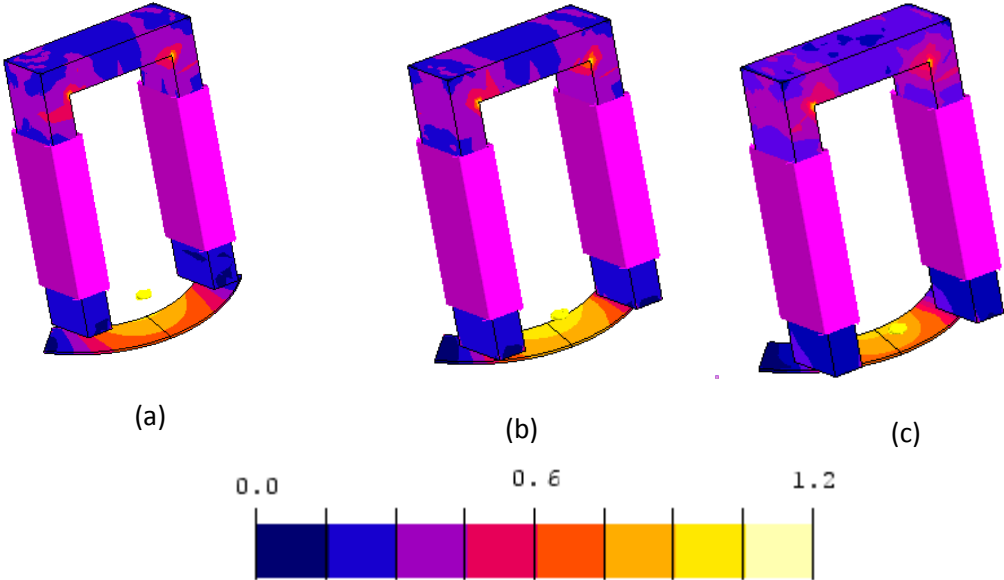


Fig. 6. Flux density distribution of the system yoke –sample (a: inner side of the ring, b: center area, c: external side of the ring)

It is clear that the induction distribution is different from one configuration to another due the stray field and 3MA position. In the 3 configurations, the magnetized surface area is different and then magnetic field is not homogeneous. The magnetic field is calculated along the ring path from external to inner side (Fig.7).

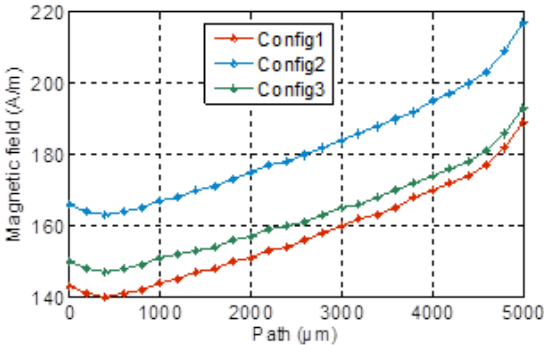


Fig. 7. Calculated magnetic field from the external side to inner side

The asymmetry of the magnetic field is not only due the cut edge effect but also to the ring shape of the material which induce non similar distribution of magnetic field in each situation.

4.1 direct validation

Two inspection cases are chosen: forged shaft steel and press hardened 22MnB5 steel. In both cases, the material shows heterogeneous magnetic properties from the surface to the depth. Microscopic and mechanical destructive analyses are realized (fig.8 and fig.9)

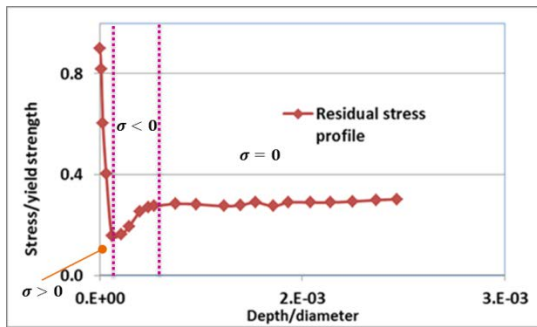


Fig.8. Residual stress distribution on forged shaft steel

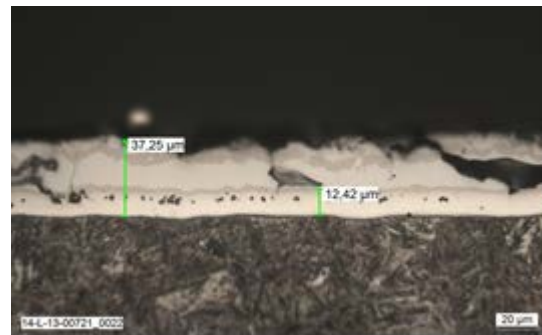


Fig.9. Cross section polish of 22MnB5 hot formed normal state

In this context, a multi-layer approach is considered in order to model the magnetic response of the sample. Each layer of the sample has been characterized in order to build its own hysteresis model.

Firstly, series of specimens have been cut so as to measure only the effect of the bulk layer. Indirect methods are used in order to access to the properties of the surface layer. For example submit the bulk sample to tensile and compressive force in order to get magnetic response of these upper layers. After definition of magnetic hysteresis behavior, the set of 5 JA parameters are identified and implemented in FEM hysteresis module. The simulations are run in the same condition as the measurement.

The Fig.10 shows simulated and measured magnetic signatures in case of forged shaft and press hardened 22Mn B5 steel.

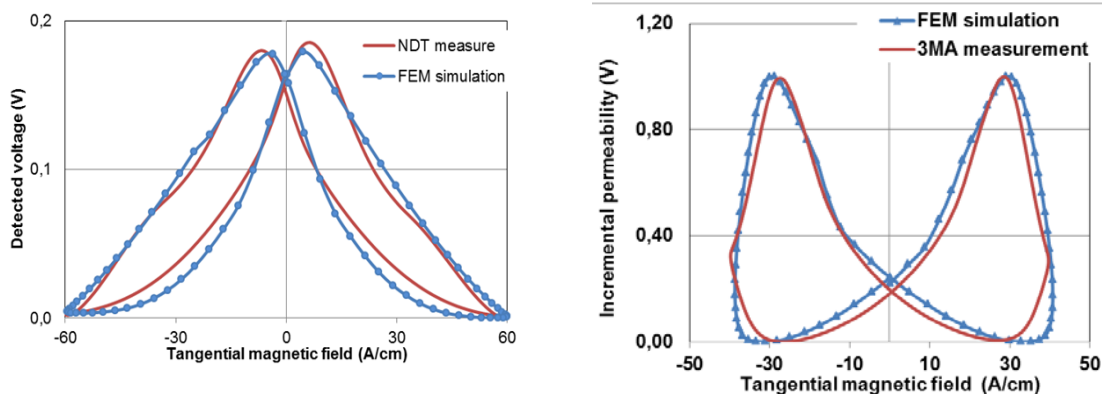


Fig.10. Comparison of simulated and measurement signal in both inspection case: a) Forged shaft- b) press hardened 22MnB5 steel

All the parameters from simulation show good accuracy with those from measurement with less than 10% relative error measurement in main important parameter such as coercive field, remanent points, larger at 25, 50, 75% of the incremental permeability amplitude.

Conclusion:

A 3MA finite element code has been developed in order to study the magnetic response of different material. A simulation methodology is built in order to make the computation easier and faster. This methodology is based on intelligent calculation which overcomes numerical problems such as: meshes, convergence, magnetic history management, space memory. The 3MA simulation results prove the applicability of 3MA on a large panel of material with different geometry. Good correlation between 3MA measuring results and simulated signals are established with high accurate precision.

Aknowledgement:

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