1. Cylia AMRANE[1], 2. Souri Mohamed MIMOUNE[2], 3. Mohamed Lotfi KHENE[2], 4. Yasmine GABI[3], 5. Hassane MOHELLEBI[1], 6. Lotfi ALLOUI[2], 7. Benjamin STRAß[3], 8.Bernd WOLTER[3]

Department of Electrotechnics, Mouloud Mammeri University of Tizi-Ouzou, Algeria (1)
Laboratory of energy systems modelling LMSE, University of Biskra, Algeria (2)
Fraunhofer Institute for Nondestructive Testing IZFP, Saarbrücken, Germany (3)
ORCID. 1. 0000-0002-5002-4145, 2. 0000-0001-9552-4699, 3. 0000-0003-2466-3274, 4. 0000-0002-6148-4008, 5. 0000-0003-1257-0986, 6. 0000-0001-7058-4759, 7. 0000-0002-1657-2164, 8. 0000-0003-0595-2847

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Impact of Lift-Off in 3MA-NDT Harmonic Analysis Signal-via Numerical Methods and Experiment

***Abstract**. In this paper, the impact of lift-off on the 3MA minaturized probe head via harmonic analysis method is discussed. The electromagnetic signals are examined using two numerical computational methods; the finite element method (FEM) and the finite volume method (FVM) by taking into account the hysteretic and eddy current behavior of ferromagnetic parts. The investigation is run on bilayer specimen and the result demonstrates the ability and accuracy of both FVM and FEM to reprocduce the experimental signals. Beside this, simulations are carried out for various lift-off in order to evaluate the skin depth and limit of the magnetic NDT technique.*

***Streszczenie.** W artykule omówiono wpływ oderwania na głowicę sondy zminaturyzowanej 3MA metodą analizy harmonicznej. Sygnały elektromagnetyczne są badane za pomocą dwóch numerycznych metod obliczeniowych; metoda elementów skończonych (MES) i metoda objętości skończonych (FVM) z uwzględnieniem histerezy i zachowania prądów wirowych elementów ferromagnetycznych. Badanie prowadzone jest na próbce dwuwarstwowej, a wynik wykazuje zdolność i dokładność zarówno FVM, jak i MES do odtworzenia sygnałów doświadczalnych. Oprócz tego przeprowadzane są symulacje dla różnych podniesień w celu oceny głębokości skóry i granic magnetycznej techniki NDT. (**Wpływ odbicia w sygnale analizy harmonicznych 3MA-NDT analizowany za pomocą metod numerycznych i eksperymentu**)*

Keywords: FEM and FVM methods, magnethistereza, ic nonlinear properties, hysteresis, eddy current, multilayer and multi-scale.
Słowa kluczowe: badania nieniszczące, rozkład pola magnetycznego, histereza

Introduction

The industry of steel production is growing steadily and is in constant competition, including production rate which becomes more important. The industrial main objective is to provide a flawless product to meet high reliability requirements and to claim a permanent process control.

In quality assurance, microstructure states and aimed material properties such as hardness (HV, HCR) and tensile parameters (Rm, Rp, A, etc.) are commonly determined by taking random samples, i.e. randomly selected parts and subject them to semi or full destructive techniques such as mechanical hardness testing or metallographic inspection of polished sections , etc.

These methods are too time consuming and expensive. Besides this, they request highly qualified testing operators. For these reasons there is strong demand for non-destructive testing (NDT) methods, which are less time consuming and expensive. Due to the ferromagnetic properties of many steel grades electromagnetic NDT methods are generally good candidates for determining microstructure dependent properties of these materials.

Fraunhofer IZFP has developed a robust micromagnetic testing technique called 3MA (Micromagnetic Multi-parametric Microstrucure and Stress Analysis) which is used in a wide range of applications, e.g. in automotive [1], aerospace and nuclear industry [2]. The 3MA system uses a combination of 4 micromagnetic methods, namely eddy current [3], Barkhausen noise [4], incremental permeability [5], and the harmonic analysis (HA) method. The latter uses lower magnetization and analyzation frequencies then the other, therefore it offers a larger analyzation depth, which is reflecting the frequency-dependent skin depth.

In order to optimize and disign new methodical and instrumental of 3MA approaches, Gabi et al. have developed a full automated 2D and 3D FEM simulation tool based on Flux software for electromagnetic modelling of the micromagnetic techniques combined in 3MA [6]. The suitability and robustness of this FEM code was verified in various inspection situations, such as for dual phase steel [7], residual stress determination [8-9], hardening depth determination and the determination of iron losses in electrical steel [10-11]. It was establish link between HA measuring quantities to microstructure and hardness [12] via FEM simulation and experiment.

Gabi et al. have stated the limit of the models due to the time calculation using multi-layered micro-structures. The use of the finite volume method FVM seems to be an alternative way in order to reduce the computation time drastically by simultaneously keeping the accuracy of the calculation.

In this work, the harmonic analysis (HA) method is simulated using two numerical computational methods (FEM and FVM) on Matlab environment. The lift- off sensitivity is evaluated for measurements with a miniaturized probe head on a multilayer material. A simulation campaign is applied using the two computation methods and the results are compared to experimental data. Furthermore, the sensitivity of 3MA miniaturized probe head is highlighted.

3MA-NDT Harmonic analysis technic

The micromagnetic test procedure for this application is the analysis of the upper harmonic in the time signal of the measured tangential magnetic field. It requires the dynamic magnetization of the specimen along a period via simultaneous measurement of tangential magnetic field via Hall sensor. As it is illustrated in the (Fig.1), a 3MA miniaturized probe head is directly applied on the sample.

In addition to the fundamental component, the non linear character of the ferromagnetic hysteresis induces upper harmonics in the measured tangential magnetic field signal. The harmonics occurs during alternative excitation signals and are dependent on the ferromagnetic properties of both yoke and specimen to be investigated. The upper harmonics are defined via Fourier analysis and occur as odd order harmonics owing to the hysteresis symmetry.

By combining three signals : magnetic tangential fields, sum of odd harmonics and fundamental, measuring quantities can be derived such as:

- $A3$, $A5$ and $A7$ are amplitudes of Fourier harmonic 3 to 7

- *Phi*3, *Phi*5 and *Phi*7 are phase of harmonic 3 to 7
- *K*, is the total harmonic distortion, it is usually linked to the material operating point.
- *UHS* is the sum of all upper harmonics.

Fig.1. 3MA-NDT system

Adding to this, a special feature of harmonic analysis has been developed at IZFP [3]. An approximate value of the coercive magnetic field and remanence can be defined. For this purpose, the raw signal and the fundamental signal are observed as a function of time. The intersection of the raw signal value with the fundamental signal gives the value of the coercive field, 'Hco'. Furthermore, the 'Hro' is given by the zero crossing of the harmonic content.
Several studies have confirmed that coercive field and remanence defined via harmonic method have strong link to those values determined via standard conventional hysteresis frame.

Sample magnetic properties

Recent generation of carbon steel are subjected to different thermo-mechanical process such as: hot stamping, quenching, skin pass, rolling,..ect. Usually, these process treatments are adjusted in order to reach their final target specifications and to meet the request of the end user.

In this study, the analysis will be realized on a multi layered material. From meso-macrospic point of view, the specimen can be described by two layers (soft and hard layer). The specimens were carefully cut in toroidal shape in order to run Fluxmetric hysteresis measurement. The Fig.2 shows the hysteresis behavior of both layer soft and hard at B_{max}= 1.6T, f= 10 Hz.

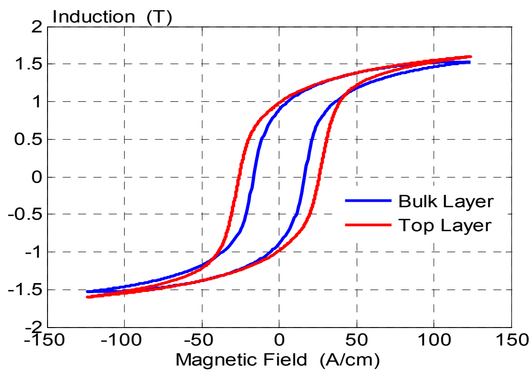

Fig. 2. Hysteresis curves of specimen layers

The quasi static behavior of ferromagnetic parts are described via Jiles-Atherton (JA) hysteresis model [14]. The (JA) parameters are extracted via Artificial Bee Colony method [15].

In (HA) mode, the specimen is magnetized at H_t = 65A/cm and f = 50Hz. In order to take into account the skin depth, the electrical resistivity is associated to the material which value is ρ = 19 10^{-6} Ω.m.

The magnetic properties of the ferromagnetic parts are summarized in table1.

Table 1. Jiles Atherton model parameters

Parameters	Bulk layer	Top layer	Yoke
Ms	1.52 10^{6}	10^{6}	1.41 10^{6}
a	4000	7700	85.73
α	73 10^{-4}	14 10^{-3}	10^{-6}
k	2600	6600	65.53
c	0.4	0.5	0.316 10^{-2}

Numerical model

Fig.3 shows the geometry of the studied 3MA–NDT system, composed of a U-shaped ferrite magnetic yoke, magnetization coil, and a Hall sensor which is placed in the middle of the detection zone between the pole arms of the magnetic yoke. The U-shape ferrite of order of 53 cm (medium length) dimensions is used to canalize and to ensure a homogeneous magnetic field in the specimen.

The Hall sensor is used to record the entire tangential magnetic field developed during the hysteresis cycle. The specimen is represented by two layers: hard top layer with a thickness of 300 μm, and a bulk soft layer in bottom part of the sample.

Beside this the tangential magnetic field is measured near the surface sample, in the middle of the yoke arms [10].

The electromagnetic time domain formula in terms of magnetic vector potential A that governs the 3MA–NDT system is given as follows:

$$\nu_0 \vec{\nabla} \times \vec{\nabla} \times \vec{A} + \sigma \frac{\partial \vec{A}}{\partial t} = \vec{J}_s + \vec{\nabla} \times \vec{M} \tag{1}$$

where: ν_0 is the reluctivity of the vacuum, $\vec{A}$ is the magnetic vector potential, $\vec{J}_s$ is the source current density, $\vec{M}$ is the magnetization function which depends on magnetic vector potential and σ is the electrical conductivity.
The backward Euler method is used for the time domain resolution. The increased nonlinearity of the hysteresis behavior and the presence of skin depth due to magnetic-conductive materials impose in general a very small time step to reproduce exactly the dynamic hysteresis behavior.

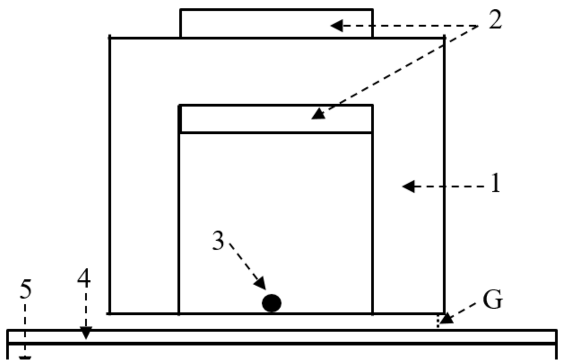

Fig.3. Geometry of 3MA system, 1-Yoke, 2-Magnetization coil, 3-Hall sensor, 4-Top layer, 5-Bulk layer

Calculations are conducted for several tests 80 and 100 and 200 time steps per period with the iterative process. The obtained results are similar with a reduced computation time for the first test. The results presented below are all for the first calculation (250 μs time step). This has greatly decreased the computational time.

At each time step, by using the magnetic vector potential A and the calculated flux density $\nabla \times A = B$. The inverse Jiles-Atherton model is used to evaluate the magnetic field in the ferromagnetic zones [19]:

(2) $$\frac{dM}{dB} = \frac{\eta}{\mu_0 (k\delta + (1-\alpha)\eta)}$$

(3) $$\eta = M_{an} - M + kc\delta \frac{dM_{an}}{dH_e}$$

(4) $$M_{an}(H_e) = M_s\left(coth\left(\frac{H_e}{a}\right) - \left(\frac{a}{H_e}\right)\right)$$

(5) $$H_e = H + \alpha M$$

(6) $$\frac{dM_{an}}{dH_e} = \frac{M_e}{a}\left(1 - coth^2 \frac{H_e}{a} - \left(\frac{a}{H_e}\right)^2\right)$$

where: H_e , M_{an} and M_s – are the effective field, the anhysteretic magnetization and the saturation magnetization respectively.

FEM method modelling

In the FEM method, the computational time is prohibitive and hence the modeling is faced with a problem of large mesh. The thickness of the sample is about 750 μm with two layers of 350μm and 400μm, which are very small compared to the yoke dimensions. This difference in scale requires a very thin mesh in order to guarantee good elements quality. For this purpose, it was necessary to create sub-domains in the specimen layer in order to refine the mesh (Fig.4).

For simplification of the numerical problem and to reduce the computation time, it was preferred to describe the yoke behavior via a nonlinear and non-hysteretic behavior, via McGregor formula (EQ: 8):

Saturation: B_s = 2 T.

- Initial relative permeability μ_{ri} = 2000.
- α Parameter (α = 0.4).

The input parameters B_s, μ_r and α are used to determinate the relation between applied magnetic field H and magnetic flux density B.

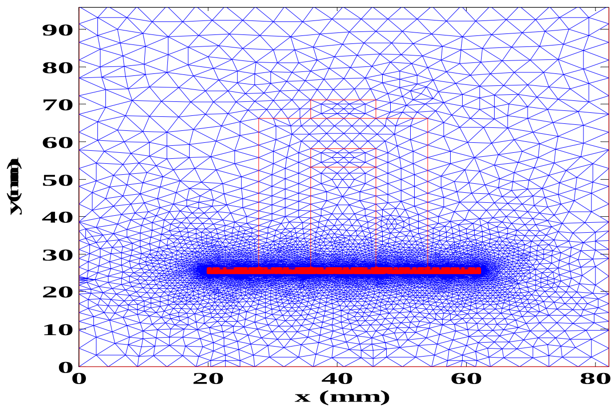

Fig.4. FEM mesh generation

(7) $$H_a = \frac{H\ \mu_0\ (\mu_{ri} - 1)}{B_s}$$

(8) $$B = \mu_0\ H_a + B_s \frac{H_a + 1 - \sqrt{(H_a + 1)^2 - 4\ H_a (1-\alpha)}}{2(1-\alpha)}$$

So, the number of variables is important in terms of storage memory (21685 nodes and 43272 elements). The computational time takes less than 30 min for three periods. In improve time calculation, finite volume method FVM seems to be good candidate to overcome this problem. The strategy of this method is introduced in the following.

FVM method modelling

The FVM can be adopted to overcome problems of large mesh via non-conformal meshing (Fig.5). A team of Biskra university have developed ‘non conformal mesh’. It offers the opportunity to mesh separately different area of the geometry, with different manner. The first time where the computation method where introduced was for the solving of 3D coupled electromagnetic-heat-transfer equations, using non conformal mesh [16]. Later, Mimoune and Boudib [17] have driven simulation on 2D coupled electromagnetic-Shrodinger equations in quantum dot transistors structures for problems "with" complex geometry.

The FVM can be considered as a special form of the weighted residuals method. It consists of dividing the whole domain into defined number of non-overlapping subdomains or control volumes, with the condition that each node is surrounded by one control volume (Fig.6). The weighting function is set to be fixed at unity in the control volume and zero elsewhere.

The number of nodes is extremely reduced by a factor of 7 using only 2912 nodes with "appropriate" interpolation to obtain stable and accurate convergence.

The basic formula for dynamic non linear electromagnetic problem is defined by equation (1). By integration of the electromagnetic formula on the finite control volume and taking into account the 2D configuration problem, the algebraic system is obtained (Equ. 9).

The FVM is known to be powerful by using "appropriate" interpolations of the variables (linear, parabolic, power and exponential and so one) which preserve the physical balance of energy exchange, conductive and difusive electromagnetic problems. These approximations allow to reduce the huge amount of nodes.

After arrangement of the numerical integration of all terms, the relation (1) leads to the following algebraic system (the developement of the 2D algebraic system are detailed in Alloui [17]).

(9) $$[K][A]_t = [S]_{t,t-\Delta t}$$

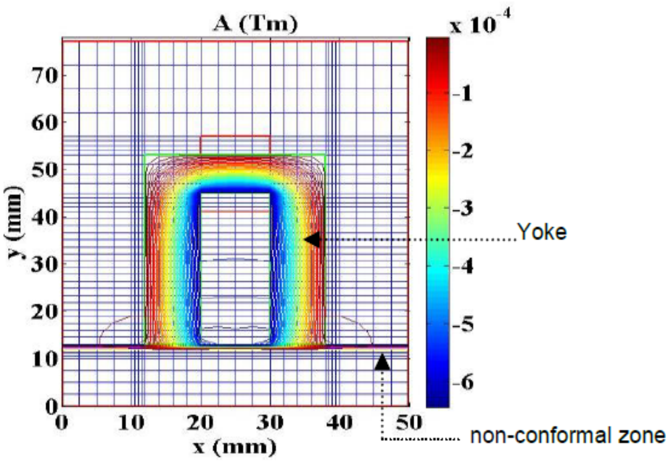

Fig.5. FVM Non-conforming control-volume mesh generation with the distribution of magnetic vector potential A

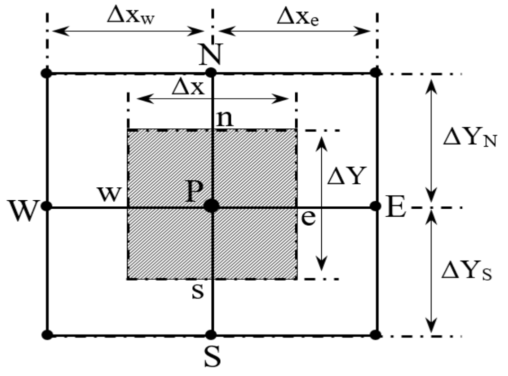

Fig.6. FVM Non-conformal Control-volume

where : P is the principal node associated to the volume element Dp, with four neighboring facets: s (South) and n (North) along the y direction, w (West) and e (East) along the x direction.

N and S along the y-axis, E and W along the x-axis are principal nodes of the neighboring elementary volume of the element Dp.

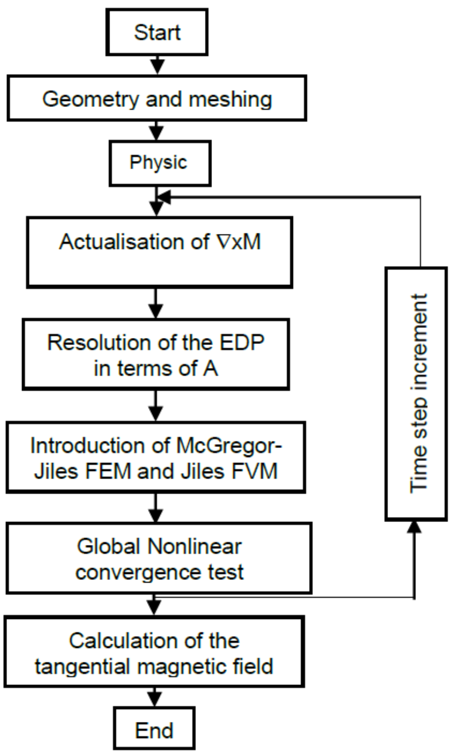

Fig. 7 Flowchart of FVM and FEM modelling

FEM and FVM modelling procedure

The modelling procedure of the FEM and FVM of the developed algorithm is illustrated in figure 7. It is very important to test the convergence at each time calculation step, especially when nonlinear time dependence of Jiles-Atherton model of hysteresis is taken into account.
A time-space non-conformal control volume criterion is used to firstly ensure the convergence stability.

The source term $\nabla \times M$ is crucial at the interface nodes between magnetic and nonmagnetic domains. Furthermore, it is also necessary to accurately evaluate the magnetic source term since it represents the second derivative of the vector potential A. This term represents the source current linear density. It is very small into magnetic materials and null elsewhere. A wrong evaluation of this term would lead to divergence and instability of the iterative solving procedure.

In the FVM, the source term $\vec{\nabla} \times \vec{M}$ can be evaluated precisely at the interface nodes by using correct flux density and then correct magnetization. The calculation of this term is done by using the difference of magnetization at the faces (w, e and n, s, with little capitals in Fig.6) of the control volume and not at the neighboring nodes. The magnetization must be equal to zero at the faces outside the magnetic material.

Validation

After few calculation periods, steady state regime is reached. The time signal of the tangential magnetic field provides material characteristics. The results presented in Figure 8, illustrate the tangential fields obtained by both simulation methods (FEM and FVM) and by measurement.

The numerical tools reproduce the 3MA harmonic signals which are run via miniaturized probe head. The accuracy is quite good.

After signal processing of the numerical simulations (FEM and FVM) signals via Fourier analysis, the data are compared to measurement result. The 3MA Harmonic analysis output parameters: amplitudes ($A3$, $A5$, $A7$) and phase shifts ($Phi3$, $Phi5$, $Phi7$) and other derived parameters (K, UHS, H_{ro}, H_{co}) are determined.

The relative error between numerical and measurement data, for all output parameters are diplayed in figure 9.

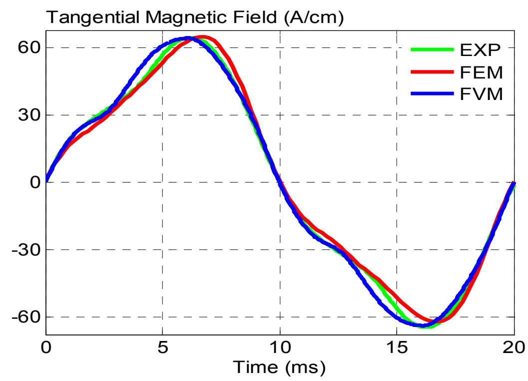

Fig.8. Measured and simulated tangential magnetic field H_t

The accuracy of both numerical method is quite good, where the error is less than 10 % for all parameters except for the phase of harmonic 5. This can be explained by the offset of the signals and can be improved by increasing the number of calculation periods.

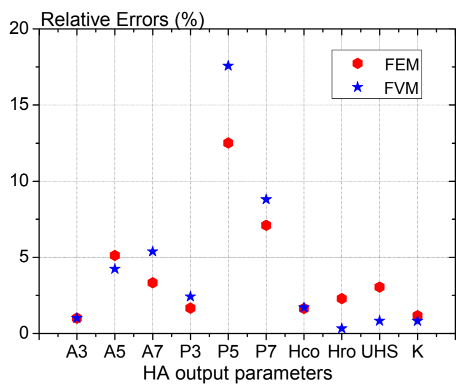

Fig.9. FEM and FVM parameters comparison

In order to evaluate the impact of lift-off, a campaign of measurement is performed for various lift-off, which varies from 0.5 up to 3 mm. The Fig.10-12 show the impact of lift off on $A3$, H_{co} and H_{ro} profiles via numerical methods and experiments.

The presented curves in Fig.10, 11 and 12 indicate that both numerical FEM and FVM are able to reproduce experimental signals with high accuracy. Both profile- H_{ro} and $A3$, show a drop of tendency with increasing lift-off values. This is explained by the alteration of magnetic apperent and effective properties of the area made of ferromagnetic sample and air.

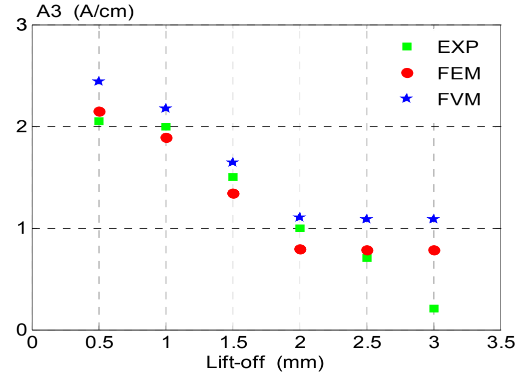

Fig.10. Variation of 3[rd] harmonic amplitude with lift-off

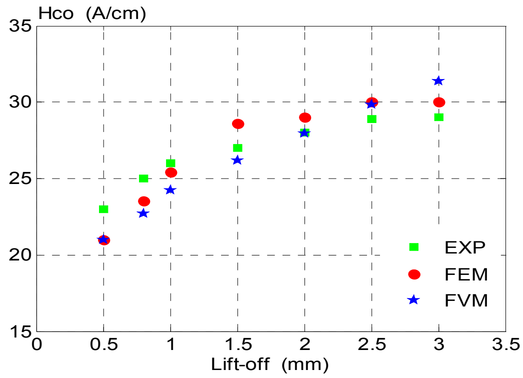

Fig.11. Variation of coercive magnetic field H_{co} with lift-off.

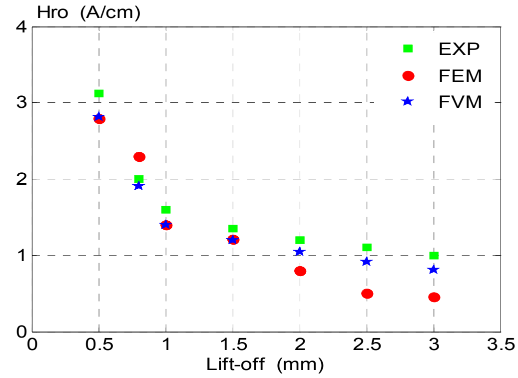

Fig.12 Variation of H_{ro} parameter with lift-off

The detected signals indicate that investigated area appears harder. This leads to the profile of H_{co}, where the coercivity increases steadily until it became fix. For the lift - off G = 3 mm, the 3MA harmonic method is not anymore sensitive to the specimen intrinsic properties.

Conclusion

The paper highlights the robustness of two computational methods (FEM and FVM) for simulation of harmonic analysis technique on 3MA "miniaturized" probe head. The hysteresis character and the dynamic behavior are taken into account in both computation methods. The solving of the complex algebraic matrix is successfully managed. The impact of lift off is studied via numerical methods and compared to experimental data. Furthere more, the sensitivity of 3MA miniaturized probe head to investigate multilayered specimen is underlined. The penetration depth is evaluated at 3 mm.

***Authors**: PhD student. Cylia Amrane,* Department of Electrotechnics*, Mouloud Mammeri University of Tizi-Ouzou, BP 17RP 15000, Algeria, E-mail: cylia.amrane@ummto.dz ; Prof. Dr. Souri Mohamed Mimoune, Laboratory of energy Systems modeling LMSE, Mohamed Khider University of Biskra BP 145RP 07000, Algeria, E-mail: s.mimoune@univ-biskra.dz ; Dr. Mohamed Lotfi Khene, Laboratory of energy Systems modeling LMSE, Mohamed Khider University of Biskra BP 145RP 07000, Algeria, E-mail: m.khene@univ-biskra.dz; dr. Yasmine Gabi, Senior scientist for electromagnetic simulation, Department of production integrated NDT, Fraunhofer Institute for Nondestructive Testing IZFP, Campus E3$_1$, 66123 Saarbrucken, Germany, E-mail: yasmine.gabi@izfp.fraunhofer.de ; Prof. Dr. Hassane Mohellebi,* Department of Electrotechnics*, Mouloud Mammeri University of Tizi-Ouzou, BP 17RP 15000, Algeria, E-mail: mohellebi@yahoo.fr ; Prof. Dr. Lotfi Alloui, Laboratory of energy Systems modeling LMSE, Mohamed Khider University of Biskra BP 145RP 07000, Algeria, E-mail: l.alloui@univ-biskra.dz ; Dr. Benjamin Straß, Department of production integrated NDT, Fraunhofer Institute for Nondestructive Testing IZFP, Campus E3$_1$, 66123 Saarbrucken, Germany, E-mail: benjamin.straß@izfp.fraunhofer.de; Dr. Bernd Wolter, Department of production integrated NDT, Fraunhofer Institute for Nondestructive Testing IZFP, Campus E3$_1$, 66123 Saarbrucken, Germany, E-mail: bernd.wolter@izfp.fraunhofer.de.*

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