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Coupled electrical circuit method calculation with 3MA eddy current application for metal investigation

***Abstract**. This paper highlights the robustness of the semi analytical computation so-called 'coupled circuit' method for the simulation of the eddy current method integrated in the commercial non-destructive testing, 3MA equipment. For this purpose, semi-analytical development are carried out for calculation of voltage around eddy current- receiver coil, taking into account the skin depth of the sample. The challenge in the following is to reproduce the eddy current 3MA measuring quantities on conductive and ferromagnetic materials under several inspection situation. Furthermore, eddy current parameters will be underlined in impedance diagram varying the frequency and lift-off.*

Streszczenie. W artykule podkreślono niezawodność półanalitycznych obliczeń, tak zwanej metody „obwodów sprzężonych", do symulacji metody prądów wirowych zintegrowanej z komercyjnymi badaniami nieniszczącymi, sprzęt 3MA. W tym celu przeprowadza się półanalityczne opracowanie obliczania napięcia wokół cewki odbiorczej prądu wirowego z uwzględnieniem głębokości naskórka próbki. Wyzwaniem w dalszej części jest odtworzenie wielkości pomiarowych prądów wirowych 3MA na materiałach przewodzących i ferromagnetycznych w kilku sytuacjach kontrolnych. Ponadto parametry prądów wirowych zostaną podkreślone na wykresie impedancji, zmieniając częstotliwość i oderwanie. (***Obliczanie metody sprzężonego obwodu elektrycznego z zastosowaniem prądów wirowych 3MA do badania metali***)

Keywords: semi analytical calculation, skin depth, 3MA NDT system, eddy current material, characterization.
Słowa kluczowe: metoda prądów wirowych, system 3MA,

Introduction

Nowadays, the production in steel and other metal industry is subjected to restrictive quality requirements and high economic challenges. The general aim is to increase the production rate by implementing robust and fast NDT testing devices, which allow to use optimized process routes without affecting the requested quality requirements in regards to the mechanical material properties.

New digitized process monitoring and control solutions as important components in the industry 4.0 concept are needed in order to meet the future demands of production companies in regards to quality, productivity and especially in regards to reduction of emissions, resources and costs. Such concepts are based on distributed multi-sensors, collecting data at several production stages, which are combined and evaluated with robust machine learning algorithms in order to realize optimized and self-controlled value chains.

A key feature is the application of non-destructive testing (NDT) sensors, allowing the continuous monitoring of products and processes. In the past, NDT systems have been developed and implemented in-line in flat steel production for material characterization and process monitoring such as ultrasound [1], Barkhausen noise [2], tangential magnetic field analysis [3], multi frequency eddy current [4]. Furthermore, it is also stated that eddy current technique was predominately used in defect [5] and crack detection [6].

For many years researchers have been engaged to develop comprehensive and physical based computation algorithms for such electromagnetic NDT methods in order to better understand and optimize their applications. These are ranging from analytical [7], semi analytical [8] to numerical calculations [9]. Most challenging is to reproduce the NDT sensor signals, if they are used for material characterization. The aim is to develop robust simulation tools, which can offer high accuracy for traceability via inverse problems procedure [10]. Besides this, in some FEM (Finite Element Method) calculations, the mesh remains the major problems in convergence, space memory and calculation time. Therefore, the use of semi analytical method, based on coupled electrical circuit method (CECM) seems to be an advantageous alternative to FEM in order to overcome the drawbacks from above [11].

The coupled electrical circuit method was tested for the first time, for the simulation of the electromagnetic NDT device by Maouche and all [12].

The authors outline the interaction between inductor and the load of the axisymmetric eddy current device. The skin depth impact was discussed and taken into account in the impedance computation. After that, a full model was developed in Matlab® environment using the coupled electromagnetic circuit method for defect characterization.

The semi analytical formula of the impedance calculation was detailed and validated via finite element computation. This analysis provides a good agreement between these two simulation methods [13].

There are many additional reports from full parametric studies in ferromagnetic or conductive materials [14] [15]. The impact of frequency, conductivity in eddy current output signals were explored and carried out via finite element code and coupled electrical circuit method. Many others have proposed a multi-layer approach in order to simulate complex heterogeneous material, where the properties vary from the surface to the depth.

Among these efforts in developments of semi analytical expressions and study of sensitivity analysis of the eddy current parameters (frequency, amplitude, etc.), there is no direct validation to experiment so far. Furthermore, simulations were performed in eddy current double function technology, where the excitation coil is also used for detection.

In the following study, the CECM formula is developed on Matlab® environment, for a specific eddy current technology. It is based on two separate function coils: transmitting and receiving. In order to assess the robustness of the developed code, a campaign of measurements is performed on different ferromagnetic samples and aluminium parts, varying frequencies and lift-off. The impact of electrical resistivity and permeability of the specimen are analysed. Beside this, the skin depth or the penetration depth is determined via experiment and simulation.

3MA NDT micromagnetic system

The electromagnetic non-destructive 3MA testing was designed during the 80 ties. The 3MA is abbreviation of Micro-magnetic Multi-parameter Microstructure and stress Analysis [16-17]. It is a methodical and operative combination of four electromagnetic testing methods, namely: (see Fig.1),

- Barkhausen Noise
- Harmonic analysis of the tangential magnetic field
- Multi-frequency eddy current analysis
- Incremental permeability.

3MA-Eddy current method (3MA-EC)

A sinusoidal current with low amplitude (typically of the order of mA) and high frequency (typically between 10 and 1 kHz) is send to the transmitter coil. This excitation is performed locally and perpendicularly to the sample surface. It results in a very low level of induction, which is limited to a few μT (Rayleigh domain).

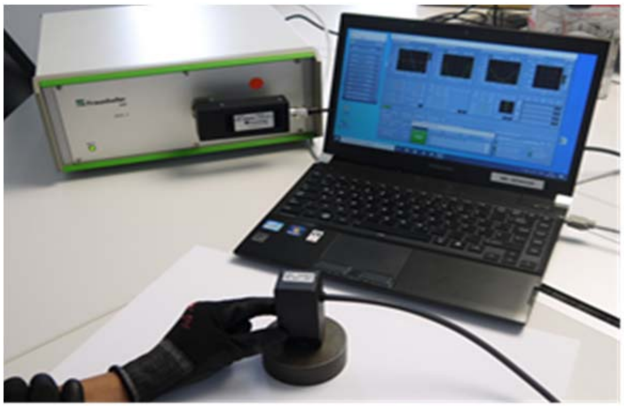

Fig.1. 3MA NDT system under inspection

Table 1. EC-coil characteristics

Sensor type	Dimensions [mm]	Winding numbers
Transmitter coil	Inner radious: 2 mm Outer radious: 4 mm	100
Receiver coil		300
Electrical Conductivity	59×10^6 S/m	-

The induced voltage is detected across the receiver coil. Based on a specific treatment of the signal, the real and imaginary part and the modulus and phase of the impedance are recorded.

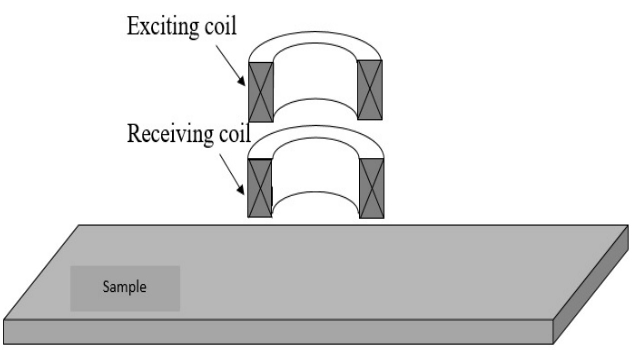

Fig.2. 3MA-EC and sample Sketch geometry

The 3MA system offers four different eddy-current frequencies in a single measuring cycle, resulting in 16 measuring parameters: Real and imaginary part of the detected voltage for multiple frequencies. In this mode, the skin depth varies reciprocal to the square root of the frequency. It depends on the initial permeability and electrical resistivity of the material.

Electromagnetic formulation

The Maxwell's equations stated that the variation of magnetic field in space and in time, in a defined point on space results from another field in space or from itself created by another field. These equations offer a local description and can be applied in any coordinate system. Thus, the study of non-destructive testing phenomena by eddy currents method requires the resolution of these equations.

It is assumed that the excitation frequencies are sufficiently low to consider harmonic steady state solving problem.

For the description of the electromagnetic phenomenon, it's preferred to reduce Maxwell's equations to a system of two integral differential equations: Biot-Savart and Maxwell-Faraday laws. In the configuration of a sinusoidal electromagnetic field and an axisymmetric geometry, the formula yields to establish coupling between the current density and the magnetic vector potential A, as following:

(1)
$$div\left(\overrightarrow{grad}A(p,q)\right) = -\mu_0 J(q)$$

(2)
$$\frac{J(p)}{\sigma(p)} + j\omega A(p,q) = -\overrightarrow{grad}V(p).\overrightarrow{e_\theta}$$

(3)
$$\vec{A}(p,q) = \frac{\mu_0}{4\pi}\iiint_\Omega \frac{\vec{J}(q)d\Omega}{\overrightarrow{op}-\overrightarrow{oq}}$$

where: $A(p,q)$ –is the magnetic vector potential created by the transmitter point *q* at the receiver point *p*. $J(q)$ –is defined as azimuthal component of the current density point of transmitter ; $V(p)$ – is set to be the electric scalar potential at the point p, σ – the electric conductivity; μ_0 – The magnetic permeability of the vacuum.

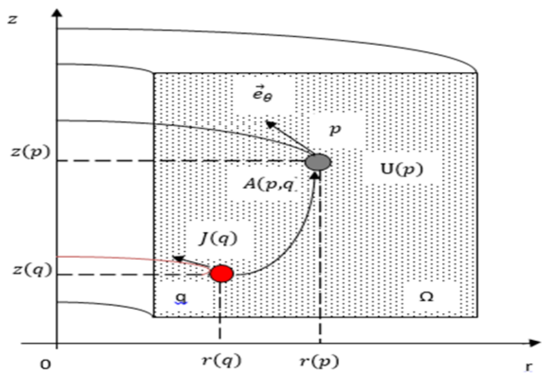

Fig.3. Symmetrical axis representation of the two turns

A(*p*, *q*) ,is then the local magnetic vector potential created on the point *p*, by the elementary turn *q* in coordinates *r*(*q*) and *z*(*q*) of the domain (*Ω*) .

Generalized integral equation

By combining the three previous equations, we get the problem equations [12], [13].

(4) $J(p) + \frac{j\pi}{\delta}\iint_\Omega G(p,q)J(q)d\Omega = -\sigma gradV(p)$

Where:

$\delta = \frac{2}{\sqrt{\mu_0 \sigma \omega}}$: Skin depth.

(5)

$$G(p,q) = \sqrt{\frac{r(q)}{r(p)}}\, E[k(p,q)]$$

(6)

$$E[k(p,q)] = \frac{(2-k^2)E_1(k) - 2E_2(k)}{k}$$

(7)

$$k(p,q) = \sqrt{\frac{4r(p)r(q)}{[r(p)r(q)]^2 + [z(p)z(q)]^2}}$$

$E_1(k)$, $E_2(k)$ – are elliptic Legendre functions of the first and second kind . *r(p), r(q)* – are the respective radial co-ordinates of the receiver and transmitter points; *z(p), z(q)* – are the respective axial co-ordinates of the receiver and transmitter points

The spatial variation of the electric scalar potential is expressed in terms of the applied or induced voltage u(p) at the terminals of the turn as follows:

(8)

$$\overrightarrow{grad}V(p) = -\frac{u(p)}{2\pi r(p)}\overrightarrow{e_\theta}$$

where: $u(p)$ – the turn voltage, $r(p)$ – radius of the point p

By inserting relation (8) into equation (9), the latter becomes:

(9) $$\frac{2\pi r(p)}{\sigma(p)} J(p) + \frac{2j}{\delta^2}\left[\iint_\Omega G(p,q)\, J(q) d\Omega\right] = u(p)$$

The modelling of the equivalent electrical diagram can be described as closed circuit. The detection coil is represented similarly to transmitter coil. There is no excitation, only induced current which is developed inside.

(10) $$\frac{\pi r(p)}{\sigma(p)} J(p) + \frac{j}{\delta^2}\left[\iint_\Omega G(p,q) J(q) d\Omega\right] = 0$$

Discretization of the integral form

The skin depth is taken into account since the material to be investigated can have conductor or magnetic conductor properties. Adding to this, the skin depth should have comparable characteristic dimension. This explains why the sample and the coils are subdivided. The exciting and receiving coil are defined respectively by N_e and N_r turn numbers, which are coupled in series. The aluminum part is subdivided in N_a turn numbers, which are coupled in parallel.

Each element of the excitation coil is subjected to an elementary voltage u_e(p) and crossed by an elementary current density I_e(p), such as :

(11)

$$\sum_{p=1}^{N_e} \frac{2\pi r_e(p)}{\sigma_e S_e} I_e(p) + 2j \sum_{p=1}^{N_e} \frac{r_e(p)}{\sigma_e \delta_e^2}\left[\sum_{p=1}^{N_e} G_{ee}(p,q)\, I_e(q) + \sum_{q=1}^{N_a} G_{ea}(p,q) I_a(q)\right] = Ue$$

(12)

$$\frac{\pi}{S_a} I_a(p) + \frac{j}{\delta_a^2}\left[\sum_{q=1}^{N_a} G_{aa}(p,q)\, I_a(q) + \sum_{q=1}^{N_e} G_{ae}(p,q) I_e(q)\right] = 0$$

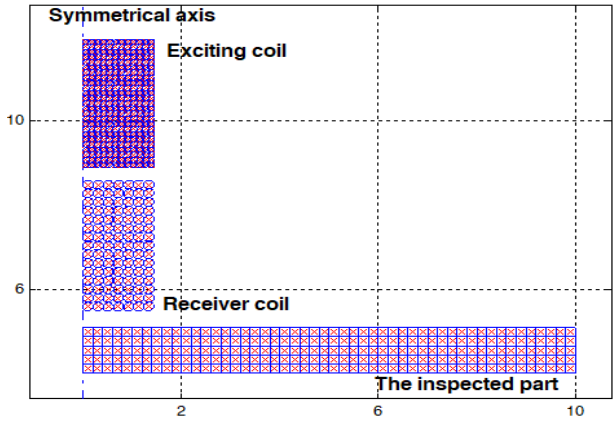

Fig.4. Discretization of the study domain

The voltage is calculated around the receiver coil via equation 13. It is linked to the geometrical and electrical characteristics of the aluminum part and the source excitation. For the calculation, it is necessary to determine the induced current in the sample. For this purpose, the equation 11 and 12 have to be solved.

(13)

$$U_r = 2j \sum_{m=1}^{Nr}\left(\frac{r_r(m)}{\sigma_r \delta_r^2}\left[\sum_{q=1}^{N_e} G_{re}(m,q)\, I_e(q) + \sum_{q=1}^{N_a} G_{ra}(m,q) I_a(q)\right]\right)$$

Validation

In order to assess the robustness of the developed code for eddy current within two coils: transmitter and receiver functions, measurements are carried out on steel and aluminum under different inspection situations.

Ferromagnetic sample:

The signal is collected on three different samples which have different magnetic properties as it is presented in table 2 The electromagnetic characteristics were determined via fluxmetric standard measurement.

Table 2. Electromagnetic properties of the specimen

Data	μ_r	ρ (Ω.m)
Sample 1	230	3.2×10^{-7}
Sample 2	197	2.9×10^{-7}
Sample 3	32	2.74×10^{-7}

The fig.5 denotes measured and simulated real and imaginary parts of detected voltage, collected at three frequencies f =40 kHz, 60 kHz and 80 kHz. The calculation results fit quite good to the experiments, especially at lower frequency f = 40 kHz. It is known that thermo-mechanical process affects the intrinsic properties and lead to heterogeneous magnetic characteristics from surface to bulk.

The measured permeability (table 2) is an apparent permeability representing the entire sample thickness. The simulation results are much better at f = 40 kHz, because skin depth is greater. In other words the system investigates deeper area, which is more representative of the standard magnetic characterization (full sample thickness).

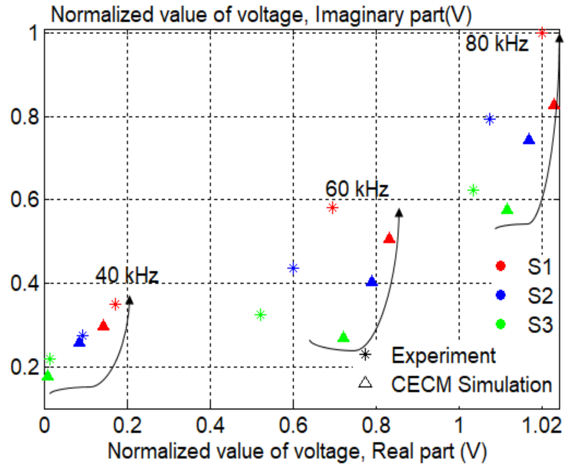

Fig.5. Normalized values of voltage in impedance plan, measured on three different samples at various frequencies: 40 kHz, 60 kHz and 80 kHz

The tendency of imaginary part progress in agreement with theory, it is linked to permeability. The imaginary part of sample 1 is greater than sample 2 and 3. The real part for different samples, under different frequencies indicate light changes, which is explained by the small variation in electrical resistivity.

Conductive sample

The 3MA eddy current data is also collected on Aluminium part for different frequencies, which ranges from 20 kHz to 80 kHz by step of 20 kHz. Four measurements were carried out: in the air, in contact to Aluminium, with 1 mm (G) and 2 mm lift-off (2×G). CECM simulations is performed in similar conditions as measurements. The model results are compared to experimental data.

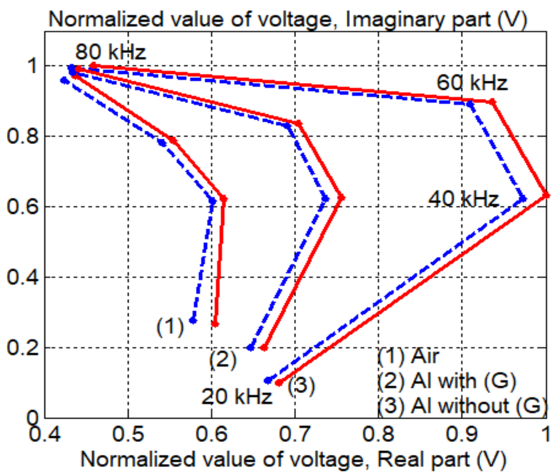

Fig.6. Normalised values of voltage in impedance plan, measured on vacuum, aluminium direct contact, and under lift-off G= 1 mm

The fig. 6. shows comparison between of real and imaginary parts of voltage in impedance diagram, detected in the air, in contact to aluminum and with lift-off G = 1 mm.
It is visible that measurement data matches very well the results from CECM simulation, with a total error less than 6%.

The detected data progress as snail behavior when excitation frequency is decreasing, which stays in agreement with theory.

The imaginary part for different configurations: in air, in contact to Aluminium and with 1 mm and 2 mm lift-off is quasi similar (fig.7). It is also known that the imaginary part of detected signal is predominately sensitive to permeability and in all these configurations, the apparent permeability equal 1, which explains the non-variation of the behavior.

The real part is almost linked to the dissipative part of the coupling system (NDT device-sample).

The fig.7. shows a significant increase in real part of detected voltage, from the profile of air zone to sample area, which explained by the strong coupling between NDT and sample.

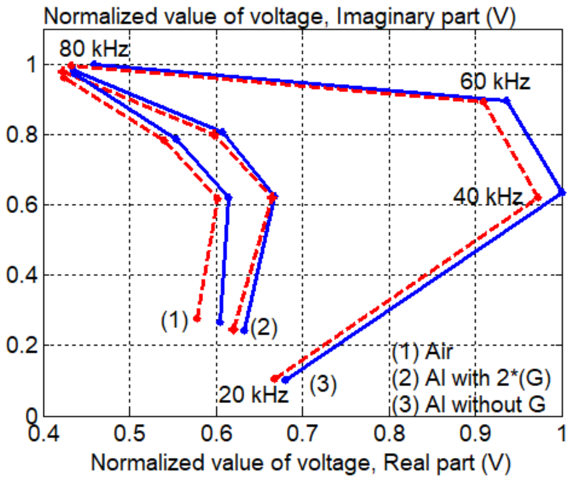

Fig.7. Normalized values of voltage in impedance plan, measured on vacuum, in contact to aluminium, and under lift-off G= 2 mm

Conclusion

A robust CECM simulation platform is developed in Matlab® environment, for specific eddy current transmitter-receiver coils. The simulated data is for the first time validated by experiments, processed by the eddy current module of the commercial 3MA NDT system. Measurements are performed on both conductive and ferromagnetic parts, under various frequencies and lift-off values. The comparison between modelling results and experiments shows good accuracy with a total error less than 7%. Furthermore, it is highlighted that 3MA eddy current device offer higher detection sensitivity, even with greater values of lift-off, up to 2 mm.

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