FVM model and virtual instrument based system for electromagnetic characterization of steel material

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Abstract: This paper deals with a finite volume model and virtual instrument based system for electromagnetic characterization of steel material. Both magnetic permeability and electrical conductivity are electromagnetic properties must be defined. These two parameters are strongly required for electromagnetic problems analysis such as in eddy current nondestructive testing problem. The magnetic permeability is measured by using the B(H) loop of the steel material which is illustrated by experimental measurement through a virtual instrument based system. However, the electrical conductivity is obtained by the solution of an inverse problem. For that reason a direct electromagnetic model is analyzed using the finite volume method.

1. Introduction

Steel is a metal that has several and very important applications. Indeed, this metal is very crucial in several fields of technical applications such as in mechanical components. The diversity of use gives importance to researchers to study its mechanical proprieties and its state against defects and fatigue. Therefore, nondestructive testing methods are required. Such tests include radiographic, ultrasonic, eddy current,…etc. The eddy current nondestructive testing method is widely used with regards to some features including speed of inspection, high sensitivity, and the ability of executing on complex structures (Aguiam et al. 2014; Hamia et al. 2014). However, both magnetic permeability and electrical conductivity are electromagnetic quantities must be provided to handle with the analysis of such method (Palanisamy and Lord 1979). There are a numerous measurements method approved for both magnetic permeability and electrical conductivity. For example the Van-der-Pauw or double probe configuration mode, and other improved modes such as four-point scanning tunneling microscopy probe are well known methods used for electrical conductivity measurement (Baglio et al. 2001; Li et al. 2012; Mironov et al. 2007).

In this paper, experimental measurement and numerical modeling are carried out to give the magnetic permeability and the electrical conductivity of steel material. The magnetic permeability is measured for different frequencies by using the B(H) loop of the material which is illustrated by experimental measurement using a virtual instrument based system (Kis et al.2004; Motoasca and Helerea 2008; Polik and Kuczmann 2008). On the other hand, the electrical conductivity is obtained by the solution of an inverse problem (Nelder and Mead 1965) in which the Finite Volume Method (FVM) is used.

2. FVM formulation

The FVM method is demonstrated as a promising and competitive method in solving electromagnetic problems (Cheriet et al. 2007; Zou et al. 2004). Compared to the popular Finite Element Method (FEM), the FVM is particularly attractive because a number of features such as a small storage memory is required and reduced CPU time (Mabrouk et al. 2013). Thus, starting from Maxwell's equations in harmonic representation, the implemented formulation is:

$$rot\frac{1}{\mu}rot\vec{A}+jw\sigma\vec{A}=J_s in\Omega \quad (1)$$

In equation (1), A is the magnetic vector potential, σ is the electrical conductivity, μ is the magnetic permeability and J_S is the source current density. Ω denotes the entire problem domain. The Dirichlet condition is imposed as:

$$\vec{A} = 0\, in\, \Gamma \quad (2)$$

Γ denotes the boundary of the entire problem domain. The Green-Ostrogradsky formula, give:

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$$-div\frac{1}{\mu}grad\vec{A}+jw\sigma\vec{A}=J_s \tag{3}$$

The basic purpose in the FVM method is to subdivide the geometrical model, which is deducted from the entire problem domain, into a finite number of control volumes. In the case of triangular mesh scheme (Figure 1), each control volume Dp is limited by three surrounding edges de1, de2 and de3, and has three neighborhood control volumes D1, D2 and D3 of nodes P1, P2 and P3. At that time, equation (3) must be integrated over the principal control volume Dp as:

$$-\iint_{Dp}div\left(\frac{1}{\mu}grad\vec{A}\right)+\iint_{Dp}jw\sigma\vec{A}=\iint_{Dp}J_s \tag{4}$$

The integration of all terms resulting from equation (4) leads to the following algebraic equation:

$$A_p=\frac{1}{c_p}\left(c_1A_1+c_2A_2+c_3A_3+c_s\right) \tag{5}$$

The coefficients c_1, c_2, c_3, c_s and c_p describe the physical and geometrical properties of the control volume D_p :

$$c_i=\frac{d_{ei}}{d_{li}\mu\sin\sin\left(\mathrm{d_{ei}},\mathrm{d_{li}}\right)},i=1,2,3. \tag{6}$$

$$c_s=J_s.S \tag{7}$$

$$c_p=jw\sigma S+c_1+c_2+c_3 \tag{8}$$

Equation (5) must be set for all control volumes, thus leads to an algebraic system of equations which can be solved by an iterative method.

3. Electromagnetic characterization of steel

3. 1. Magnetic permeability

A fabricated ring of the steel material is used to give the magnetic permeability (Figure 2). As in electrical transformer, two coils are assembled around the fabricated steel ring; a primary coil of N1=516 and a secondary coil with N2=247. The magnetic field is deduced from the impressed primary current, while the magnetic flux density is calculated by numeric integration of the induced voltage in the secondary coil.

Accordingly, the measured signals are the current of the primary coil and the voltage of the secondary coil. The magnetic field and the magnetic flux density are given according to equations (9) and (10), respectively.

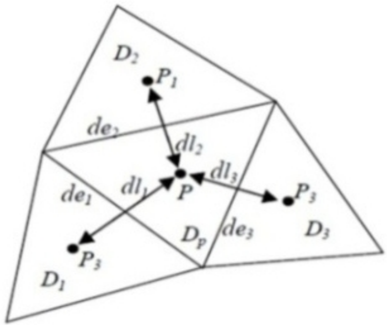

Fig. 1. Triangular mesh scheme for the FVM method.

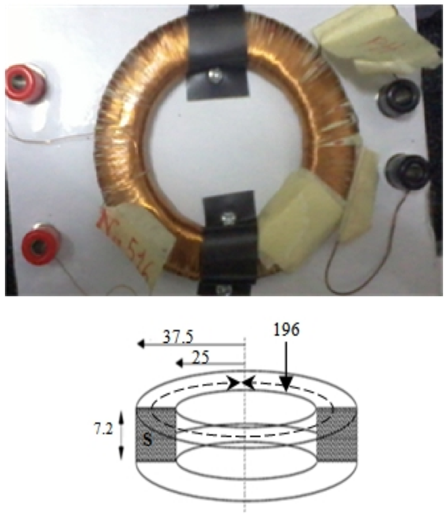

Fig. 2. Steel ring used for magnetic permeability characterization.

$$H(t)=\frac{N_1}{l_{eff}}i_1(t) \tag{9}$$

$$B(t)=\frac{1}{S_{eff}.N_2}\int u_2(t)dt \tag{10}$$

Figure 3 shows the measurement setup of the magnetic permeability. One can set signal channels and specimen parameters; the resistance R_s, the number of turns of the primary coil N1, the secondary coil N2, the cross-section of the magnetic circuit S_{eff} and its length l_{eff}. The computer, in which the Labview program is installed, communicates with the measuring environment through the data acquisition card DAQ NI-PCI-6036E. Only two input analog channels of the DAQ have been used for real time acquisition of both primary current and secondary voltage. The developed Labview application is so called to display the B(H) loop of the steel material and what's more to give the magnetic permeability. Since the magnetic permeability is function of the frequency (Bowler 2006). The B(H) curve has to be displayed for different frequencies.

3.2. Electrical conductivity

The inverse problem methodology is used to evaluate the electrical conductivity σ of the steel material. The problem deals with an eddy current based sensor placed above a steel plate with a lift-off equal to 0.5 mm (Figure 4).

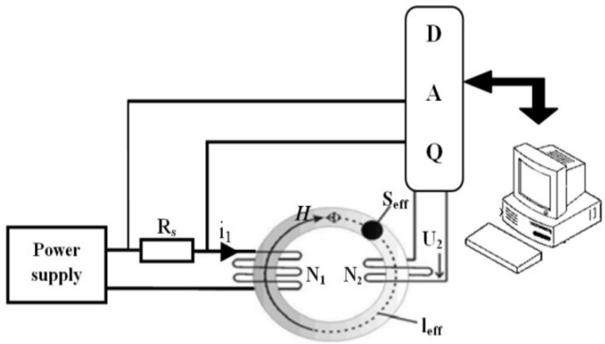

Fig. 3. Measurement setup for the magnetic permeability.

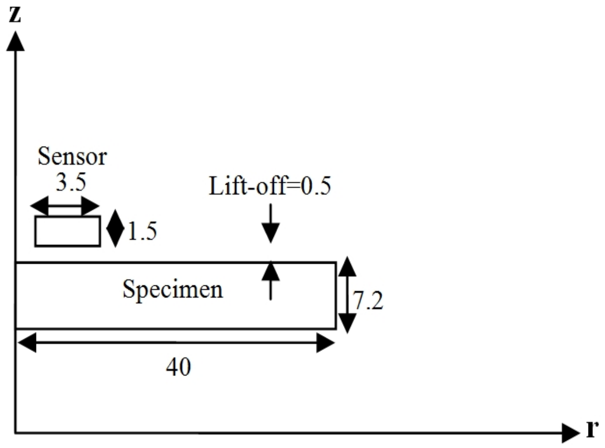

Fig. 4. Geometrical model of the problem, dimensions in mm.

Contrary to the magnetic permeability, the electrical conductivity is constant and independent of the frequency. For that reason, the sensor made of 800 turns is supplied with one sinusoidal current of frequency 10 kHz.

The open source grid generator GMSH (Geuzaine and Remacle 2009) is used to generate the triangular mesh of the geometrical model of the problem (Figure 5). The computation is carried out by using a developed axisymmetric FVM solver associated to the GMSH gird generator.

Here, the solution requires the determination of the impedance variation of the sensor. For that reason two cases will be taken into account: sensor above the steel plate and sensor without plate. The impedance of the sensor is given by:

$$Z = \frac{-jw\oint A.dl}{\int_{\Omega} J_S d\Omega} \quad (11)$$

The inverse problem method searches the electrical conductivity σ by minimizing the objective function F_{obj} given by (12). Figure 6 shows the inversing algorithm used to determine σ.

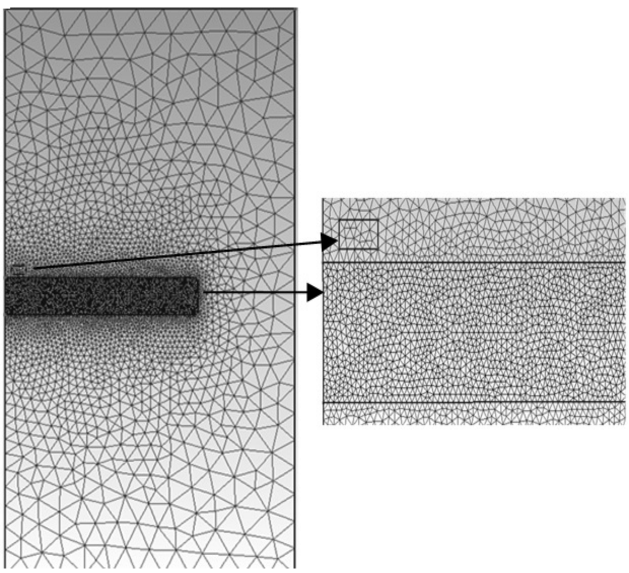

Fig. 5. GMSH mesh of the geometrical model.

$$f_{obj} = \sqrt{(1-\frac{R_{Ncal}}{R_{Nmes}})^2 + (1-\frac{X_{Ncal}}{X_{Nmes}})^2} \quad (12)$$

Where:

$$R_{Ncal} = \frac{R_{ccal} - R_{0cal}}{X_{0cal}} \quad (13)$$

$$R_{Nmes} = \frac{R_{cmes} - R_{0mes}}{X_{0mes}} \quad (14)$$

$$X_{Ncal} = \frac{X_{ccal}}{X_{0cal}} \quad (15)$$

$$X_{Nmes} = \frac{X_{cmes}}{X_{0mes}} \quad (16)$$

X_{0cal} and X_{ccal} are respectively the computed sensor reactance without and with the steel plate. R_{0cal} and R_{ccal} are respectively the computed sensor resistance, without and with the plate. X_{0mes} and X_{cmes} are respectively the measured sensor reactance without and with the plate. R_{0mes} and R_{cmes} are respectively the measured sensor resistance, without and with the plate.

In Figure 6, the Nelder and Mead Simplex algorithm is used to minimizing the objective function.

4. Results

4.1. Magnetic permeability

The B(H) loop of the steel is measured at 5Hz, 10Hz, 50Hz and 1kHz with primary current i1=5mA (Figure 7). Table.1 summarizes the relative magnetic permeability obtained for each frequency.

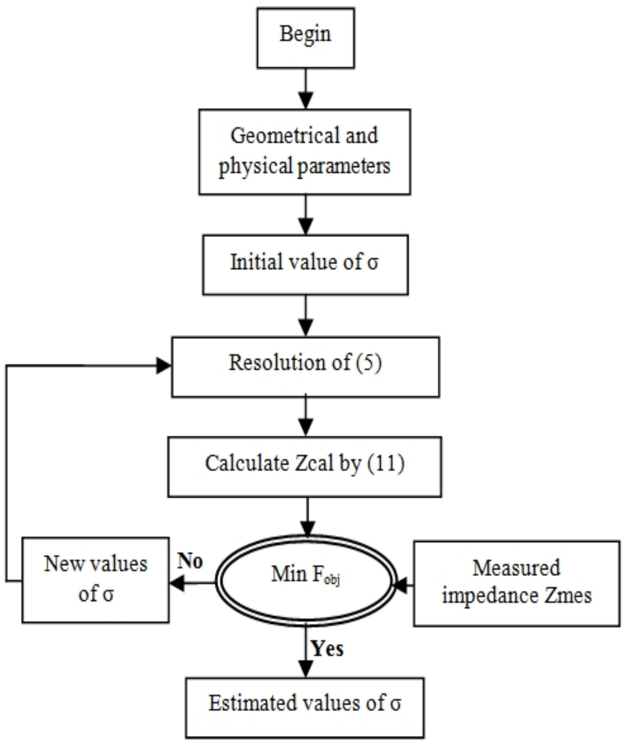

Fig. 6. Inversing algorithm.

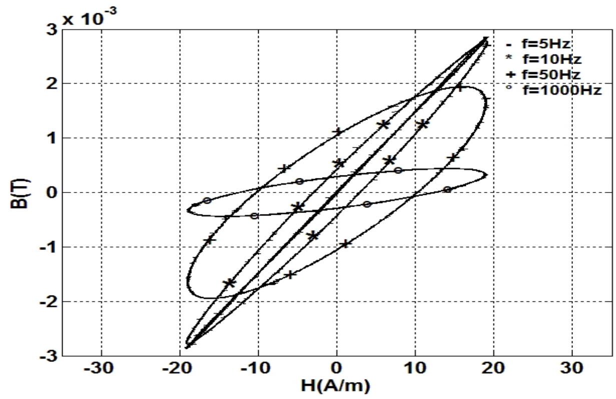

Fig. 7. B(H) loop of the steel for different frequencies, i_1 =5mA.

Table 1. Relative magnetic permeability for different frequencies, i1=5mA.

Frequency (Hz)	Relative magnetic permeability
5	126
10	123
50	87
1000	20

4.2. Electrical conductivity

The methodology of the inverse problem is carried out to find the electrical conductivity of the steel plate. Figure 8 and Figure 9 show respectively, the computed values of the electrical conductivity, for each inverse iteration, and the convergence characteristic of the inversing algorithm. For an initial value of the electrical conductivity equal to 1MS/m, its estimated value after 35 inverse iterations is 4.24MS/m.

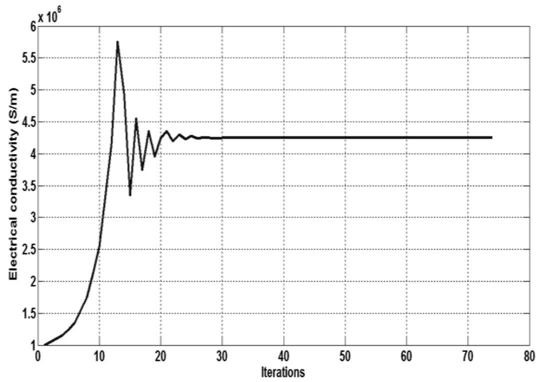

Fig. 8. Electrical conductivity of the steel vs. inverse iterations.

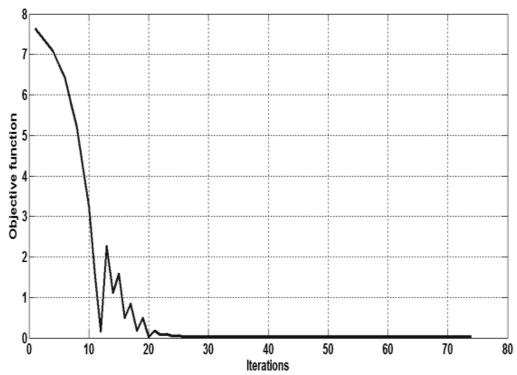

Fig. 9. Objective function vs. inverse iterations.

5. Conclusion

A finite volume model and virtual instrument based system are developed to give the magnetic permeability and the electrical conductivity of steel material. Basically, the magnetic permeability is measured by using the B(H) loop of the steel material while the electrical conductivity is obtained by the solution of an inverse problem. These two parameters are strongly required for electromagnetic modeling and analysis of eddy current nondestructive testing of such material.

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