International Journal of Applied Electromagnetics and Mechanics 33 (2010) 1225–1229
DOI 10.3233/JAE-2010-1242
IOS Press

Pulse eddy currents using an integral-FEM formulation for cracks detection

Gabriel Preda*, Mihai Rebican and Florea Ioan Hantila
Department of Electrical Engineering, "POLITEHNICA" University of Bucharest, Splaiul Independentei 313, Bucharest 060042, Romania

Abstract. Pulse eddy currents are proposed for detection of cracks in structural conductive, non-magnetic parts. The rectangular pulse accounts for a multi-frequency analysis with the lower harmonics pentrating deeper in the material. An integral-FEM method for simulation of transient eddy-currents and model of defects as zero-thickness, two-dimensional flaws are used. Difference signals peak value depends on crack depth and the peak value moment is delayed for smaller outer defects. The method is effective for defects buried deep under the surface.

Keywords: Nondestructive testing, pulse eddy-currents, zero-thickness flaws

1. Introduction

For thin structural elements, Eddy Currents Testing (ECT) using sinusoidal mode was used as a standard in the past for detection of defects in steam generator (SG) tubing of pressurized water reactors (PWR) of nuclear power plants. The effectiveness of this method is limited by skin effect to only thin, nonmagnetic structural parts. Advantages of pulse eddy currents as a detection method are well documented in literature [1,2]. The rectangular pulse shape accounts for a multi-frequency analysis, the lower harmonics penetrating deeper in the material; in the same time the heating exposure of the coil-probe system is limited to only the short duration of a signal, allowing thus an increase in the signal power. Multiple industrial applications were reported, such as detection of cracks in multiple layered plates around fasteners for aeronautics industry [3], crack detection and thickness evaluation in structural steels [4]. Current study investigates the possibility to detect defects in conductive plates using simulated pulse eddy currents signals.

2. Formulation

The proposed method is based on application of **T**-electric potential to the integral equation of eddy currents, like in [5]. Starting from Maxwell equations in quasi-stationary form and the constitutive relationship:

$$\mathbf{E} = \rho \cdot \mathbf{J}, \tag{1}$$

*Corresponding author: Gabriel Preda, "POLITEHNICA" University of Bucharest, Splaiul Independentei 313, Bucharest 060042, Romania. Tel.: +40 744 523 359; Fax: +40 21 402 91 44; E-mail: preda@elth.pub.ro.

where **J** is the current density, **E** is the electrical field and ρ is the resistivity in the conductive domain Ω_c. The electrical field is:

$$\mathbf{E} = -\frac{\partial \mathbf{A}}{\partial t} - \nabla\varphi, \tag{2}$$

where ϕ is the electric scalar potential and **A** is the magnetic vector potential. **A** can be calculated using Biot-Savart formula:

$$\mathbf{A} = \frac{\mu_0}{4\pi}\int\limits_{\Omega_c}\frac{\mathbf{J}}{r}dv_c + \mathbf{A}_0, \tag{3}$$

$\mathbf{A}_0$ being the magnetic vector potential due to the impressed current sources, placed in the air domain Ω_0. Only conductive media Ω_c are meshed. The current density is expressed in terms of shape functions associated to the edges in the inner co-tree [5,6], with the unknown the circulations of **T** on those edges. Applying Galerkin approach:

$$\mathbf{J} = \sum_{k=1}^{n}\alpha_k\nabla\times\mathbf{T}_k, \tag{4}$$

the following equation system is obtained:

$$[R]\{I\} + [L]\frac{d\{I\}}{dt} = \{U\}\,, \tag{5}$$

where the terms of matrices [R] and [L] and the right-hand term {U} are:

$$L_{ij} = \frac{\mu_0}{4\pi}\int\limits_{\Omega_c}\int\limits_{\Omega_c}\frac{\nabla\times\mathbf{T}_i\cdot\nabla\times\mathbf{T}_j}{r}dv_c dv_c, \tag{6}$$

$$R_{ij} = \int\limits_{\Omega_c}\nabla\times\mathbf{T}_i\cdot\rho\nabla\times\mathbf{T}_j dv_c, \tag{7}$$

$$U_i = -\frac{\partial}{\partial t}\left(\frac{\mu_0}{4\pi}\int\limits_{\Omega_c}\int\limits_{\Omega_0}\frac{\nabla\times\mathbf{T}_i\cdot\mathbf{J}_0}{r}dv_c dv_0\right) \tag{8}$$

and the unknowns term is:

$$[\mathbf{I}] = \begin{bmatrix}\alpha_1\\ \alpha_2\\ \vdots\\ \alpha_N\end{bmatrix} \tag{9}$$

In order to model 2D, zero-thickness defects, from the set of inner co-tree edges are eliminated the edges placed in the defect surface, procedure equivalent to zeroing the circulation of **T** on those edges [6].

Table 1
Simulation setup: test specimen, excitation coil (coil geometry and excitation signal), flaw geometry

	Parameter	Value
Pancake coil	Inner radius (R_{min})	2 mm
	Outer radius (R_{max})	5 mm
	Length (l_z)	4 mm
	Liftoff (z)	0.4 mm
Coil signal	I_{max}	2000 AT
	Pulse shape	trapezoidal
	Pulse duration	70 μs, 10 μs rise and fall
Test specimen	Conductivity	10^6 S/m
	Thickness	10 mm
	Dimensions	16 cm $\times$ 16 cm
Flaw	Depth	40%-80% (OD)
	Length	5–15 mm
	Thickness	0 mm (2D)

3. Simulation setup and numerical results

The simulation setup for the test problem consists in a conductive plate, a pancake coil used for the specimen excitation and a Hall sensor to pick-up the signal. The simulation setup is described in Table 1. A pancake-shaped coil with trapezoidal pulse signal is used for excitation of the stainless steel specimen. The pulse has 70 μs duration, with rise and fall of 10 μs. The recurence is 50 times/second. In the simulation, 55 time steps are used for simulation of each pulse. For pick-up is used a Hall sensor to measure the vertical component of magnetic flux density (orthogonal over the specimen surface) in a point at $z = 0.4$ mm, centered under the excitation coil. The excitation coil – Hall pick-up sensor is less sensitive to frequency variation than the classic auto-induction coil used in AC detection [2]. In the case of AC, the pancake coil is optimized for a certain frequency. In the case of pulse excitation, due to the rich harmonic component of the signal, such a frequency optimisation technique is hampered [4]. The scan path is 20 cm long, in y-direction, centered over the plate; 9 scan points, with scan pitch 2.5 mm are analized. Simulation of scans are performed for flawed and un-flawed specimen, finally the difference signal of z-component of magnetic flux density between the case of flawed and the case of unflawed specimen being calculated. Defects from 40% to 80%, placed opposite to the exciting coil are analized. Length of defects ranges from 5 cm to 15 cm; defects are centered on the plate and longitudinal on y-direction.

In Fig. 1 we show the difference between signal with crack and signal without crack (difference signal), at central position over the crack ($y = 0$), for a 15 mm long, zero-thickness, longitudinal outer crack, with depths of 40%, 60% and 80%. The peak of the difference signal is shifted in time, appearing earlier for larger defects and later for smaller ones. This observation can be used for fine tunning of the detection setup, by selecting the pick-up moment, to a specific class of defects.

In Fig. 2 we compare the difference signal at center of scan path ($y = 0$) for the same crack depth (OD 80%) but for cracks with length of 5 mm, 10 mm and 15 mm. We can observe that the peak value of difference signal is obtained at $t = 22$ μs for all three cases.

Figure 3 shows the comparison of difference signals maximum for outer defects 40%, 60% and 80% depth; sample moment is selected for each crack depth in order to use the maximum difference signal. The peak of difference signal is obtained at $t = 22$ μs in the case of 80% crack, at $t = 32$ μs in the case of 60% crack and at $t = 38$ μs in the case of 40% crack.

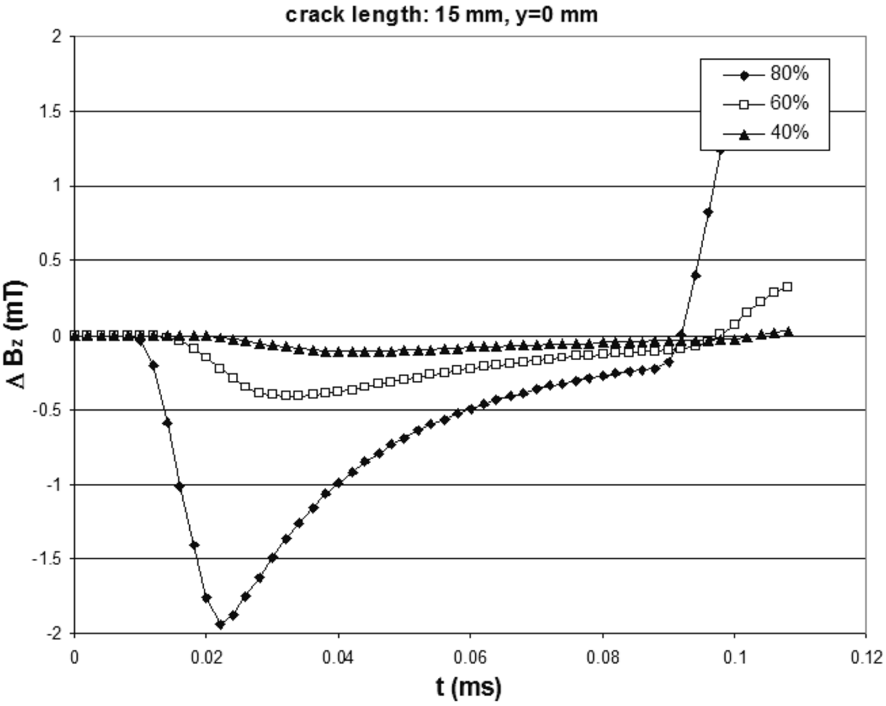

Fig. 1. Difference signal (magnetic flux density – z component) versus time; outer defects, 15 mm long, 40%, 60% and 80%; scan point is $y = 0.0$ mm.

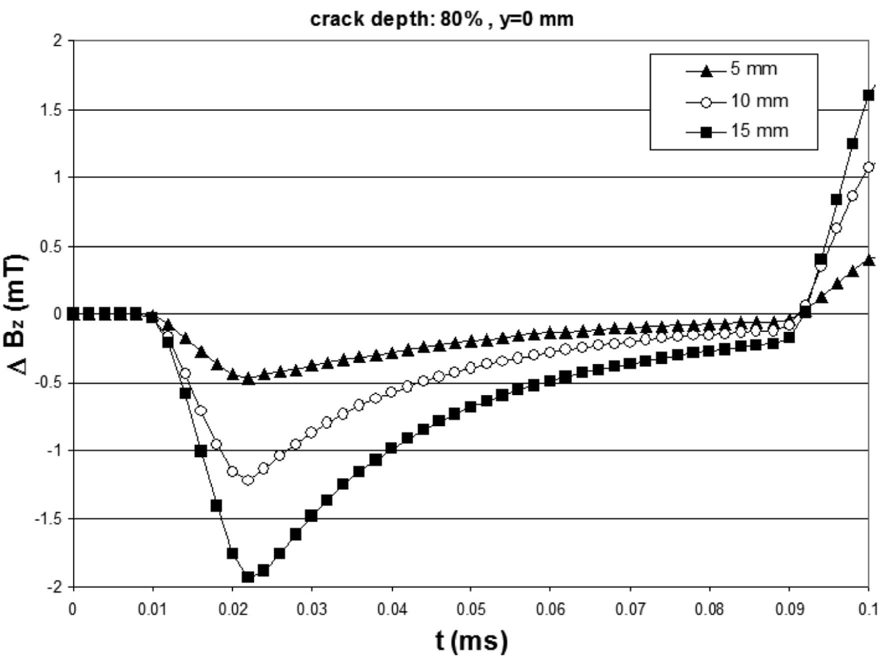

Fig. 2. Difference signal (magnetic flux density – z component) versus time; outer defects OD 80%, with 5, 10 and 15 mm length; scan point is $y = 0.0$ mm.

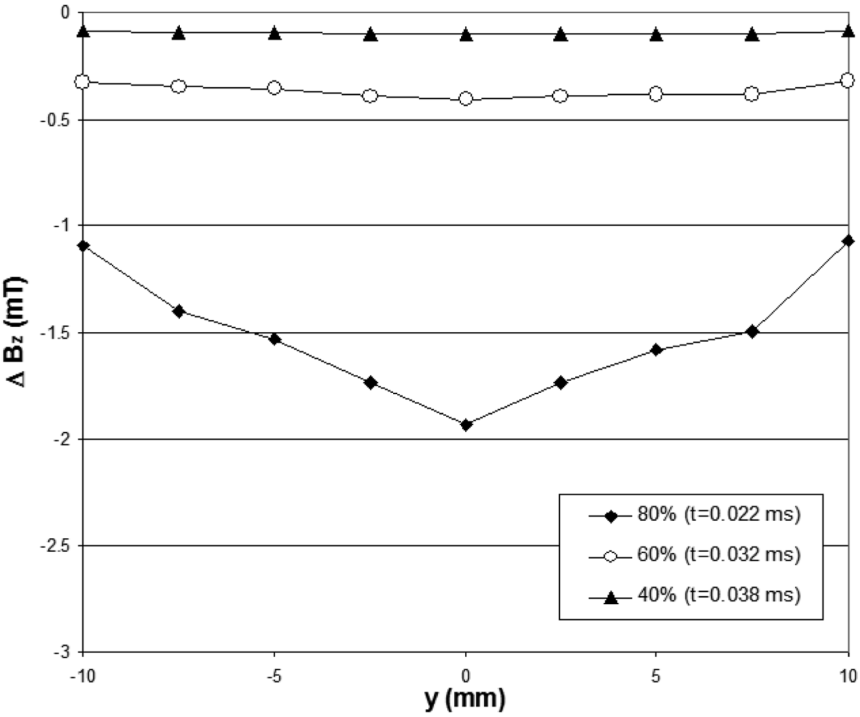

Fig. 3. Scan from – 10 mm to 10 mm over a 15 mm long OD crack, comparison of difference signals of magnetic flux density for crack depths 80%, 60% and 40%; sample moment is selected for each crack depth in order to use the maximum difference signal.

4. Conclusions

Using an integral-FEM formulation, zero-thickness cracks can be simulated without approximation, by zeroing the circulation of electric vector potential in the surfaces that define the crack. Difference signals maximum position is correlated with crack depth, cracks deeper burried under surface resulting in delayed peak of difference signal in comparison with closer to surface cracks. Pulse eddy currents were shown as an effective method for investigation of cracks in thick conductive plates.

References

[1] M. Gibbs and J. Campbell, Pulsed eddy current inspection of cracks under installed fasteners, *Materials Evaluation* **46** (1991), 51–59.

[2] J. Bowler and M. Johnson, Pulsed eddy-current response to a conducting half space, *IEEE Trans on Magn* **33** (1997), 2258–2264.

[3] B. Lebrun, Y. Jayet and J.-C. Baboux, Pulsed eddy-current signal analysis: Application to the experimental detection and characterization of deep flaw in highly conductive materials, *NDT&E Int* **30**(3) (1997), 163–170.

[4] G. Preda, B. Cranganu-Cretu, F.I. Hantila, O. Mihalache and K. Miya, Nonlinear FEM-BEM Formulation and Model-Free Inversion Procedure for Reconstruction of Cracks using Eddy Currents, *IEEE Trans on Magn* **38**(2) (2002), 1241–1244.

[5] R. Albanese, F.I. Hantila, G. Preda and G. Rubinacci, A nonlinear eddy current integral formulation for moving bodies, *IEEE Trans on Magn* **34**(Issue 45) 1998, 2529–2535.

[6] G. Preda, F.I. Hantila and M. Rebican, Eddy Current Solver for Nondestructive Testing using an Integral-FEM Approach and Zero-Thickness Flaw Model, *Proceedings of 13th Biennial IEEE Conference on Electromagnetic Field Computation-CEFC 2008*, Athens, Greece, 2008, p. 98.