Integral-FEM Simulation and Independent Component Analysis for Multiple Defect Separation from Pulse Eddy Currents Signals

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Abstract. Pulse eddy currents simulated using an integral formulation and Independent Component Analysis (ICA) for signal separation are used for detection of multiple defects in thick conductive plates. Numerical results for the eddy-currents signals, and signal separation using ICA, are shown.

1. Introduction

Pulse eddy currents technique is proposed as a method to detect multiple cracks in conductive materials with large thickness. For thin structures, Eddy Currents Testing (ECT) using harmonic mode was used extensively in the past for detection of cracks in steam generator (SG) tubing of pressurized water reactors (PWR) of nuclear power plants. Although its advantages, as high speed and reliability for the routine inspections, skin effect limits this method only to thin and nonmagnetic structures. Pulse eddy currents has multiple advantages: its rectangular pulse profile accounts for a multi-frequency analysis, the lower harmonics penetrating deeper in the material, while limiting the heating exposure of the coil-probe system to only the short duration of a signal allows an increase in the power [1], [2]. Multiple industrial applications were reported, such as detection of cracks in multiple layered plates around fasteners for aeronautics industry, crack detection and thickness and conductivity evaluation in structural steels [3]. In the case of multiple cracks, the problem of composed signals is tackled by using Independent Component Analysis to decompose the original crack difference signals for each crack.

2. Integral Formulation

The proposed method is based on application of **T**- electric vector potential to the integral equation of eddy currents, like in [4]. Starting from Maxwell equations in quasi-stationary form and the constitutive relationship:

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

where $\boldsymbol{J}$ is the current density, $\boldsymbol{E}$ is the electrical field and ρ is the resistivity in the conductive domain Ω_c. We suppose that the field sources motion relative to the conductive domain is slow and therefore the component of the induced field through motion is very small and negligible. In the laboratory frame, the electrical field is:

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

where V is the electric scalar potential and $\boldsymbol{A}$ is magnetic vector potential. The magnetic vector potential can be calculated using Biot-Savart formula:

$$\mathbf{A} = \frac{\mu_0}{4\pi}\int_{\Omega} \frac{\mathbf{J}}{r}\,\mathrm{d}\,v + \mathbf{A}_0 \,, \tag{3}$$

with $\boldsymbol{A}_0$ being the magnetic vector potential due to the impressed current sources placed in the air. Only conductive media are meshed. The current density is expressed in terms of shape functions associated to the edges in the inner co-tree [5]. In order to model 2D, zero-thickness defects, from the set of inner co-tree edges are eliminated those edges placed in the defect surface. The procedure is equivalent to zeroing the circulation of scalar electric potential **T** on those co-tree edges [5]. All the coefficients in the system matrix are unchanged through time integration and, therefore, the resulting matrix system is formed and inverted only once. The rich harmonic components of a pulse impose adaptation of mesh size to the smallest skin depth, corresponding to the largest harmonic component to be taken into account [3].

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3. Independent Component Analysis

Independent Component Analysis (ICA) is a particular case of blind signal separation, being a computational method to separate multivariate signals into additive subcomponents supposing mutual statistical independence of the non-Gaussian signals [6]. If N source signals are assumed, at least N observation signals are required. In our case, we will subject the same plate with defect to a series of excitation signals; our assumption is that the result signals have multiple components, i.e. sources: the excitation signal, the plate and the different defects. We will investigate the effectiveness of the ICA algorithm for blind separation of the composed signals of adjacent defects.

4. Numerical Results and Conclusions

The simulation setup for the test problem consists in a conductive plate, a pancake coil used to energize the specimen and a Hall sensor to pick-up the signal. The pancake coil – Hall sensor system is less sensitive to frequency variation than the classical auto-induction pancake used in AC testing, which in turn can be optimized for a single frequency; for pulse excitation, such an optimization is not possible [1][2][3]. The plate is 16 cm × 16 cm, with 10 mm thickness and having conductivity $\sigma = 10^6$ S/m. Coil dimensions are inner radius $R_{min} = 2$ mm, outer radius $R_{max} = 5$ mm, axial length $l_z = 4$ mm, liftoff $z = 0.4$ mm. The pickup sensor measures the magnetic flux density and is placed in the coil axis, at $z = 0.4$ mm. The coil signal used is a 70 µs, trapezoidal shaped pulse, and with additional rise and fall intervals of 10 µs each, with amplitude I_{max} = 2000 AT, and with a repetition frequency of 50 Hz. 55 time steps are simulated for a single pulse. In Fig. 1 we show the difference between signal with crack and signal without crack (difference signal) of z-component of magnetic flux density, measured at y = 0, z = 0.4 mm and three different x positions, for two 12 mm length, 60% and 80% outer, 0-thickness defect, parallel and at 5mm distance each other. The composite signal will be subjected to ICA in order to separate the individual defect signals contributions.

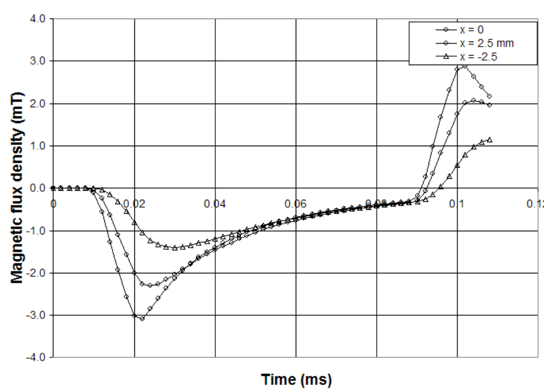

Fig. 1 Difference signals plotted against time. Defects are with zero-thickness, 12 mm long, open on outer side, 60% and 80%, parallel, and displaced by x = 5 mm. The scan is done at x=0, x=-2.5 mm (centred over the 80% defect) and at x=2.5 mm (centred over the 60% defect). The signal is the z-component of magnetic flux density, at z=0.4 mm over the plate.

References

[1] J. Bowler and M. Johnson, "Pulsed eddy-current response to a conducting half space", *IEEE Trans. on Magn*, Vol. 33, 1997, pp. 2258-2264.

[2] 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.*, Vol. 30, No. 3, 1997, pp. 163-170.

[3] 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.*, Vol. 38, No. 2, 2002, pp. 1241-1244.

[4] R. Albanese, F.I. Hantila, G. Preda and G. Rubinacci, "A nonlinear eddy current integral formulation for moving bodies", *IEEE Trans. on Magn.*, Vol 34, Issue 45, 1998, pp. 2529-2535.

[5] G. Preda, F.I. Hantila, 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, pp 98.

[6] A. Hyvärinen, "Fast and Robust Fixed-Point Algorithms for Independent Component Analysis", *IEEE Transactions on Neural Networks*, Vol. 10, No. 3, pp. :626-634, 1999.