THREE-DIMENSIONAL RECONSTRUCTION OF CONDUCTIVE CRACKS FROM EDDY CURRENT TESTING SIGNALS

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Key words: Eddy current testing, Conductive crack, Numerical simulation, Crack reconstruction, Tabu search.

This paper presents an approach to reconstruct a conductive crack from simulated eddy current testing (ECT) signals by means of a stochastic method, such as tabu search. The ECT signals due to conductive cracks have been simulated by a fast forward FEM-BEM solver using database. As the width of a conductive crack significantly affects the signal, the database contain information about cracks for various widths. The length, depth, width and conductivity of the crack are unknown in the inversion process. Two crack models are proposed: cracks with parallelepiped shape and cracks with more complex shape; the cracks have uniform conductivity. Numerical results of the 3D reconstruction of conductive cracks from simulated 2D signals are presented and discussed.

1. **INTRODUCTION**

Eddy current testing (ECT) is one of the most common electromagnetic methods employed in non-destructive evaluation of conductive materials. The principle of ECT is based on the phenomena of electromagnetic induction. The interaction between of a time varying magnetic field and an inspected piece induces eddy currents in the material [1]. The presence of a crack in the examined body can be detected by means of the perturbation of the eddy currents path.

ECT is widely applied in various fields accounting for measurements of material thickness, proximity measurements, corrosion evaluation, sorting of materials based on the electromagnetic properties. However, the most widespread area of its application in present is the detection and possible diagnosis of discontinuities [2, 3].

Natural cracks, such as: stress corrosion cracks (SCC) and fatigue cracks (FC), usually appear in steam generator (SG) tubes of pressurized water reactor (PWR) of nuclear power plants. In the last years, several studies [4, 5] have revealed that the effect of crack conductivity on ECT signal is determinant in

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sizing of natural cracks. In the case of artificial electric discharge machine notches, the width is usually considered fixed in the inversion process of ECT signals. But for cracks with non-zero conductivity, the width affects the signal [6], and then the width has to be considered unknown in the crack reconstruction. Thus, for practical cases, reconstruction of conductive cracks, with crack models as closer as possible of natural cracks, is required [7].

In previous works [8–10], the authors developed an algorithm for the three-dimensional reconstruction of multiple cracks from ECT signals by means of some stochastic optimization methods, such as genetic algorithms, simulated annealing, tabu search. Therefore, the scheme is also appropriate for reconstruction of a conductive crack, when the width is not considered fixed.

In this paper, the multiple crack algorithm is modified to deal with conductive cracks with arbitrary widths. The length, depth, width and conductivity of the crack are unknown in the inversion process of the 2D ECT signals. Two crack models are proposed for cracks with uniform conductivity. In the first model, the crack has a parallelepiped shape (crack with constant depth), and in the second model, the crack has a more complex shape (crack with variable depth). The numerical results of the reconstruction of various conductive cracks from simulated signals for both two models are presented and discussed.

2. **PROBLEM DEFINITION AND CONDUCTIVE CRACK MODELS**

Fig. 1 shows the configuration of the conductive cracks problem considered in this study, a modified version of the JSAEM benchmark problem #2 (flat plate with a crack). A standard self induction pancake coil scans the surface of a non-magnetic conductor plate (Ω_0), with the dimensions of $40\times40\times1.25\text{mm}^3$ and conductivity of $\sigma = 10^6$S/m, which contains a single conductive crack (non-zero conductivity), dashed domain. The crack is located only in the domain Ω_1 (crack region) from the whole plate (Ω_0).

The inner and outer diameters of the coil are 1.2mm and 3.2mm, respectively, and the height is 0.8mm. The number of turns is 140. The C-scans are performed over the crack region at the frequency of 150kHz and the lift-off of 0.5mm.

The crack region ($10\times1\times1.25\text{mm}^3$) is uniformly divided by a grid into $n_x\times n_y\times n_z$ ($13\times5\times10$) cells, which form geometrically the possible cracks. Thus, the dimensions of a cell are $0.77\times0.2\times0.125\text{mm}^3$.

In this paper, the cracks have the same orientation and uniform conductivity smaller than the conductivity of base material. The width of crack can have the values: 0.2, 0.4, 0.6, 0.8, 1mm.

Two crack models are proposed for conductive cracks. In the first model (Fig. 2), the crack has a parallelepiped shape. The crack parameter vector **c** consists of 6 integers, **c** = [ix_1, ix_2, iy_1, iy_2, iz, s], where ix_1 and ix_2 are the indices of the first and last cells of the crack along the length of crack, iy_1 and iy_2 are the indices of the first and last cells of the crack along the width of crack, iz is the number of cells of the crack along the depth of crack, and $\sigma_c = s\%$ of σ (σ_c – the conductivity of crack, σ – the conductivity of base material).

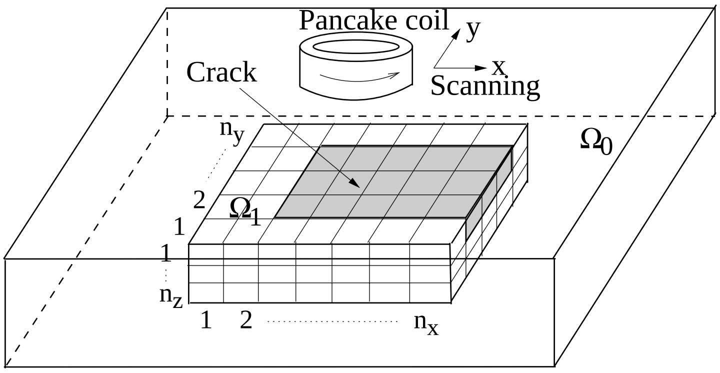

Fig. 1 – Non-magnetic conductor plate with a conductive crack scanned by a pancake coil.

In Fig. 2, for a uniform grid with 13×5×10 cells, the parameter vector is **c** = [6, 13, 1, 3, 4, 20]. Thus, 8×3×4 cells form the crack, and the crack conductivity is $\sigma_c = 20\%$ of σ.

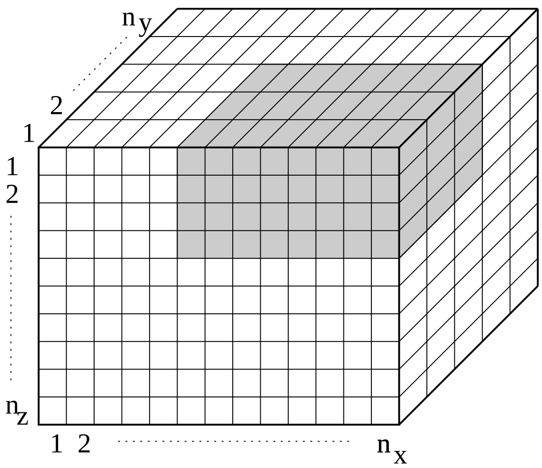

Fig. 2 – Crack region division – parallelepiped shape of the crack.

The second crack model (Fig. 3) adopts a more complex shape (crack with variable depth). The crack parameter vector **c** consists of n_x+3 integers, **c** = [iz_1, iz_2, ..., iz_{nx}, iy_1, iy_2, s], where iz_k, $k = 1, n_x$ is the number of cells of the crack along the depth of crack, iy_1 and iy_2 are the indices of the first and last cells of the crack along the width of crack, and $\sigma_c = s\%$ of σ (σ_c – the conductivity of crack, σ – the conductivity of base material).

In Fig. 3, for a uniform grid with 13×5×10 cells, the parameter vector contains 16 integers, as **c** = [0, 0, 0, 0, 0, 8, 4, 1, 2, 5, 3, 6, 4, 1, 3, 30]. Thus, (8+4+1+2+5+3+6+4) × 3 cells form the crack, and the crack conductivity is $\sigma_c = 30\%$ of σ.

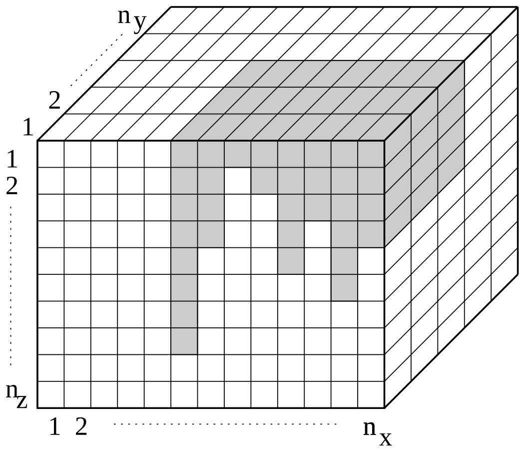

Fig. 3 – Crack region division – complex shape of the crack.

3. ECT SIGNALS SIMULATION OF THE CONDUCTIVE CRACKS AND INVERSE APPROACH

The fast-forward FEM-BEM analysis solver using database [11, 12] is adopted here for the ECT signals simulation. Actually, a version of the algorithm of database, upgraded by the authors in previous works [8–10], for the computation of the ECT signals due to multiple cracks is used in this paper. The database is designed for a three-dimensional defect region, and not for a two-dimensional one, with a given crack width, as usually. Thus, the ECT signals can be simulated for conductive cracks with different widths, using the same database generated in advance.

The area of the simulated 2D ECT signals is 20×2mm^2. The number of scanning points on the two directions are 27 and 11, respectively.

Fig. 4 shows the dependence of the peak values of the crack signals on the crack widths for a crack (inner defect ID60, length of 10mm). The crack width is 0.2, 0.6, and 1mm, and the conductivity is 0%, 10%, 50%, and 80% of the plate conductivity.

The ECT signal for a conductive crack is more sensitive with the crack width than a non-zero conductive defect. When the crack width is increasing five times, the growth rate of the crack signal is twice higher for a crack with a conductivity of 80% of the plate conductivity than a non-conductive crack, for a standard self induction pancake coil.

By using this strategy, the fast-forward scheme is suitable for the reconstruction of not only the length and depth of a conductive crack, but also the width, as the width significantly affects the signal for cracks of non-zero conductivity [6].

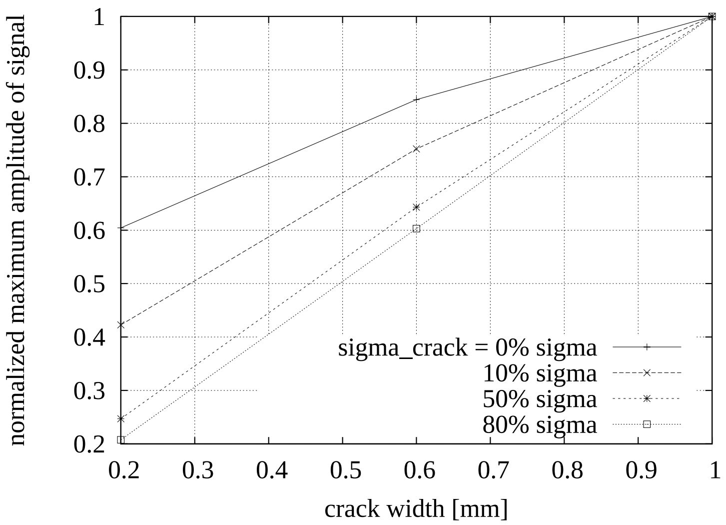

Fig. 4 – Dependence of normalized maximum amplitude of signal on the crack width for various conductivities.

In this paper, a stochastic method, as tabu search [4, 10] is applied for reconstruction of conductive cracks with uniform conductivity.

The error function ε to be minimized in the inversion process is defined as:

$$\varepsilon(\mathbf{c}) = \sum_{n=1}^{N_{sc}} |\,\Delta Z_n(\mathbf{c}) - \Delta Z_n^m\,|, \tag{1}$$

where **c** is the parameter vector of the crack, $\Delta Z_n(\mathbf{c})$ and ΔZ_n^m are the simulated (reconstructed) and true (real) impedance changes of the coil at the n-th scanning point, respectively, and N_{sc} is the number of scanning points.

It should be noted that the aim of paper is to confirm methodology of the proposed approach and thus any noise has not been added to the simulated signals at this stage.

4. NUMERICAL RESULTS AND DISCUSSION

The numerical simulations of the crack reconstructions were performed on an ordinary PC (Intel Core 2 Quad 2.4GHz, 3GB RAM).

In the table 1 are presented the numerical results of the conductive crack reconstructions, when the cracks are modeled as parallelepiped shapes (crack model 1).

Three inner defects (ID) are considered. In the Table 1, the column named "Real" gives the dimensions ($L\times W\times D$) and conductivity (σ_c) of the crack. The results are given in the column "Reconstr., 2", and in all cases (from ID-1 to ID-3) the real parameters are reached (zero error, $\varepsilon(\mathbf{c}) = 0$). The time required for one reconstruction is around 30–60 minutes.

More simulations were performed using the same model 1, but the width of crack was kept fixed, $W = 0.2$mm, the column "Reconstr., 1". The length of crack is precisely reconstructed, but the depth is slightly different (the error is not zero). Consequently, the width has to be not fixed for more accurate results of the reconstructions of the conductive cracks.

Table 1

Results of the conductive cracks reconstruction – model 1

Defect	ID-1			ID-2			ID-3		
	Real	Reconstr.		Real	Reconstr.		Real	Reconstr.	
		1	2		1	2		1	2
L[mm]	5.39	5.39	5.39	3.85	3.85	3.85	6.93	6.93	6.93
W[mm]	0.6	0.6	0.6	1.0	0.2	1.0	1.0	0.2	1.0
D[%]	50	60	50	30	40	30	20	40	20
σ_c[%]	10	1	10	30	1	30	5	0	5
$\varepsilon(\mathbf{c})$	–	1.31	0	–	0.84	0	–	1.90	0

Fig. 5 shows the result of the reconstruction of a conductive crack (ID-1 in Table 1) when the crack model 2 is used (crack with variable depth). The length and width are precisely reconstructed, with a small difference of the crack position. The depth is not very close to the true one, but quite acceptable, as the searching space is high. The time required for one reconstruction is around 90–120 minutes.

In order to reduce the searching space, the crack model 2 is modified, the crack parameter vector consists of $n_x/2+3$ integers (simplified shape along the length direction of the crack). Along the length of the crack, starting from the first cell, a pair of two consecutive cells have imposed the same depth at each iteration of the reconstruction process, $iz_1 = iz_2$, $iz_3 = iz_4$, and so on. For this crack model, Fig. 6 shows the result of the reconstruction of the conductive crack (ID1 in Table 1). The length and depth are precisely reconstructed, but the width is one cell larger (0.2mm) than the true crack. The time required for one reconstruction is around 60–90 minutes.

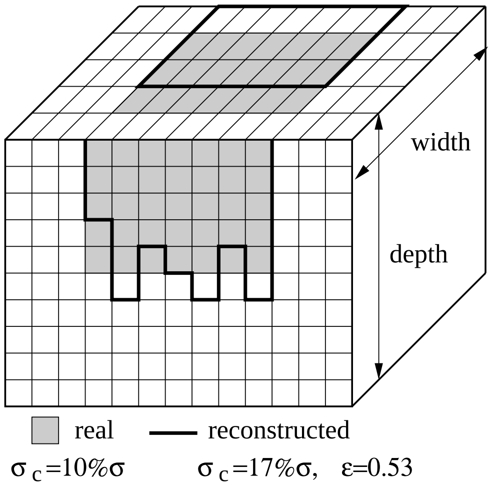

Fig. 5 – Reconstruction of a conductive crack – model 2.

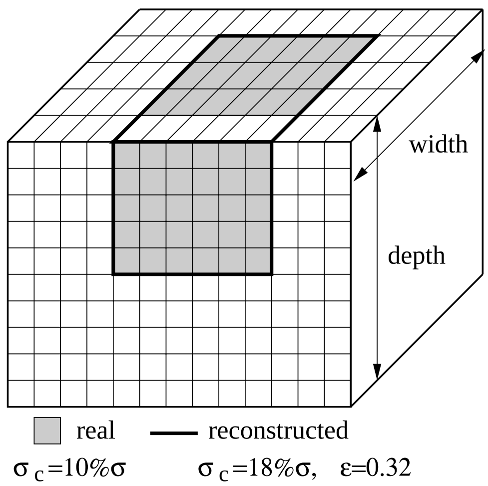

Fig. 6 – Reconstruction of a conductive crack – model 2 simplified.

In the reconstruction of the conductive cracks, the conductivity and width of crack have to be also considered unknown, besides length and depth, in order to obtain reliable results. In the adopted models, the crack conductivity is uniform, but in reality, such as SCC, the conductivity of the crack has a very complex distribution [13]. A model with variable conductivity inside the crack will improve numerical results of the reconstruction: small conductivity near to the surface of the crack and large conductivity in the deep part of the crack.

5. **CONCLUSIONS**

This study presented two crack models used to reconstruct conductive cracks from simulated eddy current testing signals by means of a stochastic method. The length, depth, width and conductivity of the crack were considered unknown in the inversion process. The reconstruction of a conductive crack was a 3D one, using 2D signals. Cracks with parallelepiped shape and more complex shape were modeled, respectively. The cracks had been imposed with a uniform conductivity. The numerical results of the reconstruction of various conductive cracks proved that the width of crack has to not be fixed.

In future works, a parallelization of the inversion algorithm will improve the results in the case of the second crack model or more complex crack model (with distributed conductivity). Also, measured data from natural cracks (SCC) will be considered for a reliable reconstruction.

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