Enhancement of Particle Swarm Optimization Algorithms for the 3D Crack Reconstruction from ECT Signals

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Abstract- This paper presents some strategies to enhance the efficiency of Particle Swarm Optimization (PSO) algorithms applied for the three-dimensional reconstruction of cracks from eddy current testing (ECT) signals. A fast forward FEM-BEM solver using database was adopted to simulate the ECT signals due to cracks with parallelepiped shape for various lengths, widths and depths. The inverse problem is formulated as an optimization problem, aiming to minimize the distance between the signal due to of the real crack and the signal due to a potential solution (crack). A novel technique which combines the features of PSO and local search methods is used in the inversion of ECT signals. The local search methods are specific to such kind of inverse problems. The points used in the local search are chosen in order to avoid local minimum in PSO algorithms. Numerical results of the 3D reconstruction of cracks from simulated 2D signals are presented and discussed.

Keywords: eddy currents, crack reconstruction, inverse problems, stochastic methods

I. INTRODUCTION

Eddy current testing (ECT) is one of the most used electromagnetic non-destructive techniques for inspection of conductive materials, especially the detection and possible diagnosis of discontinuities in the specimens. The stress corrosion cracks (SCC), which are natural cracks with complex distribution of the conductivity, usually appear in steam generator (SG) tubes of pressurized water reactor (PWR) of nuclear power plants [1].

The width of the EDM notches (artificial cracks with zero conductivity) has no significantly influence on the ECT signal, and it is imposed constant in the cracks reconstructions. In contrast, the width of cracks with not zero conductivity affects the signal [2], [3]. Consequently, the width has to be unknown for a reliable reconstruction of the natural cracks.

In this paper, some local search strategies are proposed to enhance the efficiency of Particle Swarm Optimization (PSO) algorithms [4], as Intelligent PSO (IPSO) [5], applied for the three-dimensional reconstruction of cracks from ECT signals.

II. ECT PROBLEM DEFINITION AND CRACK PARAMETERS

Fig. 1 shows the configuration of the conductive cracks problem considered in this study, a modified version of the JSAEM (Japan Society of Applied Electromagnetics and Mechanics) benchmark problem #2 (flat plate with a crack). A standard self induction pancake coil scans the surface of a non-magnetic conductor plate (Ω₀), with the dimensions of 40x40x1.25mm³ and conductivity of σ=10⁶S/m, which contains a single crack (conductivity of crack can be not zero), dashed domain. The crack is located only in the domain Ω₁ (crack region) from the whole plate (Ω₀).

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 2D scans are performed over the crack region at the frequency of 150kHz and the lift-off of 0.5mm.

The crack region (10x1x1.25mm³) is uniformly divided by a grid into nₓnᵧnᵣ (13x5x10) cells, which form geometrically the possible cracks. Thus, the dimensions of a cell are 0.77x0.2x0.125mm³.

In this paper, the cracks have parallelepiped shape, the same orientation and uniform conductivity (zero or smaller than the conductivity of base material) (Fig. 2). The width of crack can have the values: 0.2, 0.4, 0.6, 0.8, 1mm.

The crack parameters vector c consists of 6 integers [6], c=[ix₁,ix₂,iy₁,iy₂,iz], where ix₁ and ix₂ are the indices of the first and last cells of the crack along the length of crack, iy₁ and iy₂ 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 σᵣ=σ% of σ (σ - the conductivity of crack, σ_r - the conductivity of base material).

In Fig. 2, for a uniform grid with 13x5x10 cells, the parameters vector is c=[6,13,1,3,4,20]. Thus, the crack...
consists of 8x3x4 cells. The crack conductivity is $\sigma = 20\%$ of $\sigma$, and $s$ can have the values from 0 to 10, with the step of 1.

III. ECT SIGNAL SIMULATION

A fast-forward FEM-BEM analysis solver which uses database [7] is adopted here for the ECT signals simulation due to a crack with a given conductivity.

Actually, an upgraded version of the solver is used in this paper. In previous works [8], the authors had modified the algorithm of database to compute the ECT signals due to multiple cracks. The database, which contains information of the field in the plate in the absence of the crack, is designed for a three-dimensional defect region, and not as usually for a two-dimensional region (the crack width is fixed).

In this paper, the ECT signals are simulated for cracks with different widths, using the same database generated in advance, as the width significantly affects the signal for defects of non-zero conductivity [2], [3].

For the computation of the ECT signal due to a crack by the FEM-BEM code with database, it is necessary to solve only a very small dimensional linear equations system, which corresponds to the finite elements that form the crack. That means a great reduction of the computational time.

IV. INVERSE PROBLEM

In this paper, a stochastic method, such as PSO, is applied for the three-dimensional reconstruction of a crack with uniform conductivity and parallelepiped shape.

The objective function $\varepsilon$ to be minimized in the inversion process is defined as:

$$\varepsilon(\mathbf{c}) = \sqrt{\sum_{i=1}^{N_c} (\Delta Z_i(\mathbf{c}) - \Delta Z_i^{true})^2},$$

where $\mathbf{c}$ is the parameters vector of the crack, $\Delta Z(\mathbf{c})$ and $\Delta Z^{true}$ are the simulated (reconstructed) and true (real) impedance changes of the coil at the $i$-th scanning point, respectively, and $N_c$ is the number of scanning points.

The classic PSO [4] algorithm has the roots in biology and is inspired from the social behavior inside a bird flock or a fish school. Each particle in the swarm is described by the current position and velocity. The position encapsulates the potential solution of the optimization problem while the velocity describes the way the position is modified during time.

PSO is an iterative algorithm that at each step the particles change their position and velocity. At the step $k$ the position and the velocity of a particle are computed as following:

$$v[k] = w_v v[k-1] + w_{PB} r_1 (x_{PB}[k-1] - x[k-1]) +$$
$$+ w_{GB} r_2 (x_{GB}[k-1] - x[k-1]),$$

$$x[k] = x[k-1] + v[k],$$

where $x_{PB}$, $x_{GB}$ are the best personal position and the best position in the group (swarm), $w_v$, $w_{PB}$, $w_{GB}$ are the weights for velocity, “cognitive” term and “social” term, and $r_1$, $r_2$ two random generated numbers uniformly distributed in the interval [0, 1].

To improve the performance of standard PSO algorithms different methods have been proposed: PSO with varying weights, PSO with sub-swarms, and Intelligent PSO (IPSO).

In IPSO [5] each particle has position, polarization ($p$, a sort of velocity), a creativity coefficient called temperament ($U$), and a learning coefficient ($a$) which affects how the temperament of each particle is changed with respect to the swarm:

$$dx^{IPSO}[k] = 2 r_1 U[k-1] dx[k] +$$
$$+ 2 r_2 (1 - U[k-1]) (x_{true}[k-1] - x[k-1]),$$

$$x[k] = x[k-1] + p[k-1] + dx^{IPSO}[k],$$

where $dx[k]$ is a random generated vector so that $x[k-1] + p[k-1] + dx[k]$ is in the searching space. The temperament and the polarization are also changed during the algorithm according to the performance obtained at the current step.

The standard PSO and the IPSO generate solutions containing real numbers. In order to obtain discrete (binary) results, the values at each step have to be rounded.

V. LOCAL SEARCH STRATEGIES

The inverse problem is ill posed which makes the inversion methods to be often trapped into local minima.

This paper proposes the simultaneous use of the optimization algorithm, IPSO, and local search methods, such as: local search with mild tuning, local search with greedy tuning and local search with aggressive tuning.

The proposed local search methods are problem specific, and they aim to avoid local minima and increase the speed of convergence of the inversion algorithm.

At each iteration of the optimization algorithm, the local search methods are applied on the best particle from the population, that generates a set of testing points (potential solutions) using operations as expansion, contraction and displacement.

The search with mild tuning (MT) uses expansion and contraction. Starting from one point the MT generates 12 testing points. One test point is obtained by changing only one coordinate of the initial point using expansion or contraction. The contraction (expansion) on $OX$ axis (along the length of crack) or $OY$ axis (along the width of crack) can be obtained in two ways: increasing (decreasing) the index of the first cell of the crack ($ix_1$ or $iy_1$) or decreasing (increasing) the index of the last cell of the crack ($ix_2$ or $iy_2$).
contraction (expansion) on OZ axis (along the depth of crack) can only be obtained in one way: decreasing (increasing) the number of cells of the crack along the depth of crack ($i_z$). The contraction and expansion are also used for conductivity and they generate 2 testing points. Fig. 3 shows the result obtained for the crack with parameters [6, 13, 1, 3, 4, 5] when an expansion is applied on the OZ axis.

The search with aggressive tuning (AT) generates in addition to the test points from GT, points obtained using a complex operation. The complex operation is a combination between expansion (E) and contraction (C), with first being applied to one axis while the second is applied to the other axis. The combinations used are (in parenthesis, the number of test points generated by the combination): $Ex + Cy$ (4), $Cx + Ey$ (4), $Ex + Cz$ (2), $Cx + Ez$ (2), $Cy + Ez$ (2), $2Ex + Cz$ (2), $2Cz + Ez$ (2), $2Ez + Cy$ (2), $2Ez + Cz$ (2), $2Ez + Cy$ (2), $2Ez + Cz$ (2), $2Ez + Cy$ (2). The notation 2C/2E represents a double contraction/expansion. A 2C/2E for OX axis or OY axis is a contraction/expansion applied in the same time to the first cell of the crack and the last cell of the crack along the respective axis. The 2C/2E for the OZ axis is a contraction/expansion applied 2 consecutive times. The AT generates 40 (16 + 24) testing points. Fig. 5 shows the result obtained for the crack with parameters [6, 13, 1, 3, 4, 5] when a double contraction is applied on OX axis and a double expansion is applied on OZ.

VI. NUMERICAL RESULTS AND DISCUSSIONS

In this paper, the inversion of ECT signals is done by four different schemes, such as: standard IPSO, IPSO with mild tuning (MT), IPSO with greedy tuning (GT) and IPSO with aggressive tuning (AT).

Six inner defects (ID, the crack is on the same side with the coil) with zero conductivity (ID1-ID5) and with non-zero conductivity (ID6, crack conductivity is 3% of the plate conductivity) are considered to compare the efficiency of the employed schemes. In Table I the values of the crack parameters vector $c$ are given for the cracks. For example, ID2 has the length of 5.39mm (7 cells x 0.77mm), the width of 0.6mm (3 cells x 0.2mm), the depth of 50% from the plate thickness ($i_z=5$), and zero conductivity ($s=0$).

In order to make a relevant statistical study, ten numerical simulations (tests) were performed for each crack reconstruction, with different random initializations of the IPSO particles population, which contains 20 particles.

In Table II the numerical results of the reconstructions (ten tests) of the zero conductivity cracks are presented as: the rate of failure (F) or the average value of the necessary number of the objective function evaluations to find the true crack.

### Table I

<table>
<thead>
<tr>
<th>Crack</th>
<th>Crack parameters</th>
<th>$i_x$</th>
<th>$i_y$</th>
<th>$i_z$</th>
<th>$s$</th>
</tr>
</thead>
<tbody>
<tr>
<td>ID1</td>
<td>[4, 6, 3, 5, 4, 0]</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ID2</td>
<td>[4, 10, 2, 4, 5, 0]</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ID3</td>
<td>[5, 9, 1, 5, 3, 0]</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ID4</td>
<td>[3, 11, 2, 3, 2, 0]</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ID5</td>
<td>[4, 10, 3, 4, 4, 0]</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ID6</td>
<td>[4, 10, 2, 4, 5, 3]</td>
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</table>
The IPSO was stopped when: an imposed value of the objective function was reached for the best particle or the algorithm completed a maximum number of iterations.

The IPSO without tuning only manages to solve the inverse problem for the smallest crack, ID1. The results obtained for the IPSO with MT are better but the rate of failure for the cracks ID2 to ID5 is still too high. The best approaches are IPSO with GT and IPSO with AT. The numbers of the objective function evaluations to solve the inverse problem for the last two schemes are significantly improved comparing with the first two schemes.

The best two IPSO schemes, the IPSO with GT and the IPSO with AT were also tested for a crack with non-zero conductivity, ID6 (Table I).

Table III presents the necessary number of the objective function evaluations to find the true crack in the case of the two schemes for each of the ten tests.

Both of the schemes show promising results especially because they do not use yet an elaborate tuning for conductivity. For the IPSO with GT, the inverse problem was correctly solved for nine tests, but for the tests number 8 and 10, the number of evaluations is unacceptable high. In the case of the IPSO with AT, the inverse problem was solved for each test, but for test number 1, the true crack is reached after too many evaluations. The rate of failure can be considered at 30% for the IPSO with GT and at 10% for the IPSO with AT.

### VII. CONCLUSIONS

The paper presented some local search strategies to enhance the efficiency of Intelligent Particle Swarm Optimization (IPSO) algorithm applied for the three-dimensional reconstruction of cracks from ECT signals.

The inverse problem was formulated as an optimization problem, aiming to minimize the distance between the signal due to of the real crack and the signal due to a potential solution (crack).

The local search methods are specific to such kind of inverse problems. The points used in the local search are chosen in order to avoid local minimum in the IPSO algorithm, and they are obtained applying operations as contraction, expansion, and displacement on potential solutions (particles from IPSO’s population).

The proposed scheme of IPSO with local search proved to be much more efficient than a standard IPSO algorithm.

The schemes were also tested on cracks with non-zero conductivity showing promising results.

### REFERENCES


