データベースとグリーディ探索を用いた渦電流探傷法における欠陥同定*

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Identification of Crack Profiles using Database and Greedy Search Inverse Analysis Arising in Eddy Current Testing*

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This paper is concerned with an optimization method to recover crack profiles from measurement signals obtained by eddy current testing. This inversion technique uses Greedy search algorithm to find the optimum of least-square error between measurement signals and simulation data. In creating simulation data, a database called ECT database is used. This database is constructed as a set of parameters-to-output mapping data, by using hybrid FEM-BEM simulator derived from Maxwell's equations. Numerical experimental results show the effectiveness and feasibility of this method.

1. Introduction

Eddy Current Testing (ECT) is an Quantitative Nondestructive Evaluation (QNDE) technique, using to find material flaw by evaluating structure-sensitive electromagnetic properties from measurement data using electromagnetic sensors [1,2]. Eddy current testing technique has been widely used for QNDE because of its high detect ability and rapid scanning process.

An important application of ECT method in QNDE is to determine and characterize surface breaking cracks. The objective on crack detection and characterization using ECT is not only to find out flaws but also to determine the size, shape and orientation of each detective flaw. Furthermore, crack detection and sizing processes are needed to be optimized for reducing the consuming time, make it reliable to be applied in real-time inspection.

In recent decades, many efforts have been made in eddy current inversion QNDE in the material systems, aim to obtaining the best fit of the actual and estimated crack profiles found in conducting material, from measured ECT signals. The contributions of authors in this field can be classified in two main parts: Mathematical theoretical models to approximate ECT signal with certain measurement equip-

ments and conditions (forward analysis); and optimization techniques to recover crack profiles from ECT measurement signal (inverse analysis).

The forward problems of eddy current testing have been introduced by many authors. J. R. Bowler et al. [3-6] proposed general framework theories for the numerical model in predicting eddy-current coil impedance due to the present of flaw; or Z. Badics et al. [7] introduced a method to evaluate flaw ECT signal using the finite element technique, etc.

In the second approach, J. R. Bowler et al. [8] introduced inversion technique using gradient method; F. Kojima [9] introduced a parameter estimation technique for estimating the shape of surface crack, characterized by the finite number of unknown coefficients. The estimation scheme is a hybrid scheme of the finite element and boundary element method; and H. Fukutomi [10] introduced a method for the identification algorithm of the crack profiles using edge based finite elements and the parameter estimation by the trust region method. Furthermore, Z. Chen et al. and W. Chen et al. [11,12] introduced an inversion scheme reconstructs crack profiles from eddy current signals, using fast forward solver and a first-order optimization algorithm.

In different works, Y. Nagaya et al. [13] proposed an optimization technique for identification of cracks by template matching algorithm and inverse analysis with genetic algorithm. In this contribution, since eddy current signal is treated as a two-dimensional image and the location of cracks is determine by template matching algorithm, it requires an input im-

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age with a high density of measurement points and a large amount of templates, each template is also a two-dimensional image, for matching process. Furthermore, F. Kojima et al. [14,15] developed another methodology for shape recovery of natural crack using evolutionary programming. In both mentioned methods [13-15], crack profiles are determined by genetic algorithm. As a consequence, it leads to a compromise between the accuracy of inversion results and the time consuming in inversion process.

This paper introduces a new approach in optimization technique applied in inverse analysis for recovering surface breaking cracks. The proposed method is composed of two parts. Firstly, a Database is built, using ECT hybrid FEM-BEM simulator. This database is a set of parameters-to-output mapping data created by forward analysis. Secondly, Greedy search inverse analysis invokes simulation data from this knowledge base with different crack parameters to analyze and reconstruct combination of cracks from measured ECT signals.

This paper is organized as follows: Section 2 discusses problem description and inspection configurations. In section 3, strategy to build knowledge-base of parameters-to-output mapping data, called ECT database, is discussed. Section 4 introduces inverse analysis with Greedy search algorithm for cracks profile reconstruction from ECT signals. Section 5 presents some numerical experimental results of Greedy search inverse analysis on simulation data. Final part of the paper is dedicated to concluding remarks and sketching the plan of this work for the next stage.

2. Description of Problem

The objective of ECT inversion system considered in this paper is to detect and identify surface breaking cracks profiles on structural material from measurement data obtained by ECT scanning processes. This measurement data is a collection of measurement points arranged in parallel scan lines as illustrated in Fig. 1. Each measurement point is a detecting voltage in receiver coil caused by eddy current in conducting sample (inspection object) with respect to alternative current source applied in transmitter coil.

Fig. 1 ECT inspection configuration: Measurement data is a collection of T-R measurement points arranged in parallel scan lines.

This measurement technique, namely TR ECT probes, has an improvement in detect ability compared with single pancake coil probe. However, the design of coils and control parameters, such as position of receiver coil with respect to transmitter coil, lift off, applied frequency, etc have certain impact on measurement signal. Detail discussion on coil design and measurement parameters are not in the scope of this paper. Based on the ECT measurement method proposed by Nishimizu et al. [18], coil and measurement parameters used in this research are described in Table 1.

Table 1 Coil and measurement parameters

Coil inner diameter	1.0 mm
Coil outer diameter	2.5 mm
Coil height	2.5 mm
Coils distance in x-direction	4.8 mm
Coils distance in y-direction	1.7 mm
Measurement point distance (x pitch)	0.1 mm
Scan lines distance (y pitch)	1.7 mm
Lift off	0.5 mm
Applied frequency	20 kHz

With the measurement parameters described in Table 1, the inversion system proposed in this paper can be applied with measurement data obtained by multi-coil ECT sensors introduced by Nishimizu et al. Apparently, using this multi-coil ECT sensors, two different measurement data can be taken into account: Xscan (coils arrangement is perpendicular to scanning direction) and Yscan (as described in Table 1). According to experimental results in [18], using Xscan mode, the detectability of crack depth is limited to 5.0 mm with SUS316L material but using Yscan mode, the detectability of crack depth is extended to 10.0 mm on the same material. The most effective way in using multi-coil ECT sensors is to use measurement data from both Xscan and Yscan mode. For simplified implementation without losing the accuracy of inversion results, only measurement data of Yscan mode is used in the proposed inversion system of this paper.

On the other hand, the selection of applied frequency is also an important issue. It is proved that current density of eddy current, produced by electromagnetic wave, beneath the surface of a conductor is declined versus depth from the surface. The electromagnetic skin depth is defined by

$$\delta = \frac{1}{\sqrt{\pi f \mu \sigma}}$$

where f , μ , σ denote frequency of electromagnetic wave, magnetic permeability of material and material electrical conductivity. With high applied frequency, skin depth is relatively small, that makes measurement data obtained by ECT sensors with high frequency smaller in amplitude, compared with that of

lower frequency. Experimental results in [18] show that using the same sensors on the same EDM slits, output voltage of measurement signal with applied frequency of 20 kHz are relatively higher than that of 100 kHz.

Naturally, surface breaking cracks are characterized with: (i) Position and size (depth, length, width); (ii) Boundary profiles (surface and bottom shape); (iii) Slanting profile; (iv) Depth branches profiles; and (v) Electrical conductivity profile. Although, some achievements has been made in addressing slanting profile [19] or electrical conductivity profile [18,20] of cracks, the identification of natural cracks or Stress Corrosion Crack (SCC) profiles is still open problems in the area of nondestructive testing. In the scope of this research, boundary, slanting, depth branch and electrical conductivity profiles of cracks are not taken into account. In other words, cracks are treated with rectangular shape, homogenous electrical conductivity and perpendicular to the surface of inspection object.

In other to identify crack parameters from ECT measurement signal, ECT database and greedy search algorithm are applied in inverse analysis as discussed in sequel.

3. ECT Database

A conventional inversion model is depicted in Fig. 2. First, a set of crack parameters is initialized; then this parameter set is used by forward analysis for producing corresponding simulation data.

Fig. 2 Conventional inversion system for crack profiles identification using direct forward analysis

This simulation data is compared with input measurement data, using a least square error function:

$$E(C) = \frac{1}{2} \left| \sum_{c \in C} V_S - V_M \right|^2 \quad (1)$$

where C , V_S , V_M are set of crack, simulation data and measurement data respectively. Based on the value of $E(C)$, inverse analysis adjusts crack parameters and then uses forward analysis to produce new simulation data corresponding to new crack parameters. This process is repeated until the system reaches an optimum of least square error:

$$E^* = \min E(C)$$

It is obvious that this system is not effective in terms of processing speed because of high computational cost needed to produce simulation data by forward analysis. An alternative of ECT inversion system used ECT database is illustrated in Fig 3. This system used an ECT database for creating simulation data in inversion process.

Fig. 3 ECT Inversion system using ECT database

ECT database stores parameter-to-output mapping data of simulation outputs on various crack parameters. In building ECT database, ECT simulator with hybrid FEM-BEM model (see Fig. 4) derived from Maxwell's equations is used [16].

Fig. 4 ECT simulation model

In this model, each simulation entry is detecting voltage at 161 measurement points (one scan line). Measurement points are always set at point 0.0 in y-direction and from -8.0 mm to 8.0 mm in x-direction where point $(0, 0)$ in (x, y) plane is located in the middle of the model. In order to build database with various crack parameters, crack depth, beginning point and end point of crack in y-direction are changed according to the descriptions depicted in Table 2 (crack position in x-direction is set fixed at $x = 0$). With this setting, crack length can be determined as [end point - beginning point]. For example, if beginning point of crack is set as -7.0 mm and end point is set as 7.0 mm, then crack length is 14.0 mm and scan line comes across the middle of crack in y-direction.

The forward problem considered in this simulation is to estimate the detecting voltage in receiver coil caused by eddy current in conducting sample with respect of alternative current source applied in transmitter coil and other parameters, such as crack profiles, coils position, material conductivity. Given a set of parameter, simulator will produce a value of simulation data as a mapping:

$$\{J_s, q, c, x, y\} \rightarrow V_S \quad (2)$$

where J_s , q , c , x , y and V_S are current source, crack

profiles (depth, length, width), material conductivity, x and y position of scan point and scan line with respect to crack position, and the detecting voltage in receiver coil respectively. Current source J_s is given by:

$$J_s = \bar{J}_s \cos(\omega t) \quad (3)$$

where $\omega = 2\pi f$ is the angular frequency corresponding to the applied frequency f . Each entry of ECT database is a set of parameters-to-output mapping value, given by:

$$\{J_s, q, c, y\}_{x \in X} \rightarrow \{V_S\}_{x \in X} \quad (4)$$

where X is a set of scan point comes along scanning direction. Fig. 5 illustrates crack parameters and a typical simulation data entry of ECT simulation. Simulation parameters used to build ECT database are described in Table 2.

In ECT database, each entry is equivalent to one scan line of measurement data. In inversion process, simulated data is constructed by calculation relative position of each scan line with respect to crack position and pick up corresponding data entry from database. In the cases that distance from one scan line to one crack end comes greater than 7.0 mm, the data entry that has 7.0 mm length from crack end to scan line position is picked up. Simulation produces no different output on cracks with end point position from scan line excess 7.0 mm.

Fig. 5 Crack parameters in building ECT database and an instance of ECT simulation output

This ECT simulation is targeting on non-magnetic materials and the parameter used in this simulation for building database can be flexibly set, according to the setting of real measurement system (coil setting, material conductivity, measurement parameters, etc). The setting of simulation parameters described in Table 2 was selected based on the objective of this research: Making a contribution to applications used in nondestructive evaluation using ECT technique, for damage detection and evaluation, applied in inspection for the structural integrity of the pressurized water reactor nuclear power plants, in which stainless steel (SUS304, SUS316L, etc) with 15.0 mm thickness is widely used.

Table 2 Simulation parameters of ECT database

Crack depth	1, 2, 3, 4, 5, 7, 10 mm
Crack width	0.3 mm
Measurement points in x-axis	161 points in 0.1 mm pitch
Crack position in y-axis (Beginning point of crack)	-7.0 mm to 6.0 mm in 0.1 mm pitch
End point of crack	[Beginning point + 1] to 14 mm in 1.0 mm step
Applied frequency	20 kHz
Applied current	1.0 A
Sample with (y-size)	22.0 mm
Sample length (x-size)	24.3 mm
Sample thickness (z-size)	15.0 mm
Material electrical conductivity	$1.39 \times 10^6 \text{ Sm}^{-1}$
Magnetic permeability	1.0 (non-magnetic)

4. Inverse Analysis

Inverse Analysis completes in two steps. In the first step, Pre-process examines measured ECT signals to estimate possible length and position of cracks (assuming that all cracks are perpendicular to scanning direction) and possible crack depth. Secondly, Greedy search algorithm invokes ECT database to create simulated data and estimate the size and exact position of cracks, from which simulated data has minimum error in comparison with observation data obtained by ECT sensors. The flow chart of Greedy search inverse analysis is illustrated in Fig. 6.

Fig. 6 Crack profile recovery flow chart of inversion system using ECT database and greedy search

4.1 Pre-process

The purpose of Pre-process is to determine number of possible crack existed in inspection area and its initial profiles.

Recently, some methods have been proposed in determining the initial state of crack profiles, such as Template matching [13] or Adaptive regularization [14]. Algorithm in [13] tries to match templates of known cracks with measurement signal, treated as a two-dimensional magnetic image. This method requires very large number of templates for matching process; and the increasing in number of templates lead to the increasing of consuming time. On the

other hands, adaptive regularization [14] can only estimate crack surface profile (crack position) from measurement signal.

In this study, Pre-process uses a direct method to estimate both crack surface and depth profiles by determining measurements signal. Depending on scanning method, on the other words, depending on the position of receiver coil with respect to position of transmitter coil, ECT scanning signal always reach a peak value when the coils come near crack position in scanning direction. Knowing scan method, pre-process can determine crack position in x-axis by searching the peak values of all scan line from measurement data and assemble the information from all scan lines to create a set of crack with initial size and position. With scan method described in Section 2, in which measurement point is determined as the middle point of transmitter and receiver coils, peak values in one scan line can be found at crack positions in scanning direction.

After determining peak values of all scan lines, a matrix $\{a_{ij}\}$, $a_{ij} \in \{0,1\}$ is created. If $a_{ij} > 0$, there is possible crack in scan line i at position j (in x-axis). The process to assemble information from matrix $\{a_{ij}\}$ to create initial set of crack is given in following algorithm.

Algorithm: (4.1)

```

for i = 1 to [Number of scan lines] {
  for j = 1 to [Number of scan points] {
    for k = 1 to [Number of scan points] {
      if  $a_{ij} > 0$  and  $a_{(i+1)k} > 0$  and  $|k - j| < \sigma$ 
        then  $a_{ij}$  and  $a_{(i+1)k}$  are in the same
          crack at position  $(k + j) / 2$ 
    }
  }
}

```

End. (Algorithm 4.1)

In practice, σ can be used as an input parameter for inverse analysis to recover natural crack as minimum distance between two parallel cracks. After determine initial crack surface profile, maximum peak value of measurement data corresponding to each crack is compared with typical peak value of simulation data from database with different crack depth to estimate initial depth profile of each crack. The set of initial crack profiles will be the input for the next step, greedy search.

4.2 Greedy-Search

Greedy algorithm [17] is an optimization technique which belongs to the family of local search, by making the locally optimum choice at each stage. This algorithm always takes the best immediate, or local, solution while finding an answer. Greedy algorithms find the overall, or globally, optimal solution for some optimization problems, but may find less-than-optimal solutions for some instances of other problems, especially when the problem has local maxima in the search space which are not solutions. To

over come this potential fail, a “steepest ascent hill climbing” technique is applied. Different from “simple hill climbing”, in which the first closer node is chosen, this Greedy-search compare all successors and the closest to the solution is chosen. As discussed in 4.1, by using certain information from measurement signal, Pre-process manages to initialize a set of crack with initial size and position. Then, Greedy algorithm is applied to search for each crack from this set in four dimensions: crack length, depth and position in x, y axis to find the most appropriate profiles that minimize the least square error: $E^* = \min E(C)$. Greedy-Search algorithm is proposed as follows:

Algorithm: (4.2)

Input:

- C_{init} : Initial set of crack produced by Pre-process.
Each crack $c_i \in C$ is determined by parameter

$$q^i = (x^i, y^i, l^i, d^i)$$

where x^i, y^i, l^i, d^i are position in x-axis, position in y-axis, crack length and crack depth, respectively. After Pre-process, each crack c_i has been determined with initial parameter

$$q_0^i = (x_0^i, y_0^i, l_0^i, d_0^i)$$

- Input measurement data.
- ECT Database (for producing simulated data)
- dx: Initial step search for crack position in x-axis
- dy: Initial step search for crack position in y-axis
- dl: Initial step search for the length of cracks
- dp: Step search for crack depth;
- $E(C_{init})$: Initialized least square error (Eqs. 1).

Output:

- C: Set of crack that has $E^* = \min E(C)$.

Begin

$E_{min} = E(C_{init})$

for each crack $c_i \in C$ {

n = 0

while $(dx, dy, dl > \delta)$ {

repeat {

n = n + 1

for sx in $[-dx, 0, dx]$ {

for sy in $[-dy, 0, dy]$ {

for sl in $[-dl, 0, dl]$ {

for sd in $[-1, 0, 1]$ (level) {

$x_n^i = x_{n-1}^i + sx$

$y_n^i = y_{n-1}^i + sy$

$l_n^i = l_{n-1}^i + sl$

$d_n^i = d_{n-1}^i + sd$

$E_n = E(C|c_i(x_n^i, y_n^i, l_n^i, d_n^i))$

if $(E_n < E_{min})$ {

$E_{min} = E_n$

$q^i = q_n^i$

}

}

}

}

}

```

    } until ( $E_n > E_{min}$ )
      reduce dx, dy, dl
    }
    reset dx, dy, dl to initial values.
  }
End. (Algorithm 4.2)

```

Fig. 7 Searching strategy for one crack profiles in four-dimensional search space

In this algorithm, each node (or local optimum) in four-dimensional search space is selected if the least square error of this node is the minimum value among the least square error values $E(C)$ of children nodes determined from selected node in previous step.

In algorithm 4.2, at each search step, 81 (3^4) different possible crack profiles are determined for finding local minimum of the least square error $E(C)$. This large number of searching point gives certain effect on calculation speed. To optimize this algorithm for improvement of speed, some techniques can be applied as follows:

1. Track back all calculated points $q_n^i = (x_n^i, y_n^i, l_n^i, d_n^i)$ to avoid recalculation.
2. Preserve search direction of each crack parameter $x_n^i, y_n^i, l_n^i, d_n^i$. For example, at step n , local minimum of $E(C)$ is found at $x_n^i = x_{n-1}^i + dx$, then in step $n+1$, dx should be searched in $[0, dx]$ instead of $[-dx, 0, dx]$.

The selection of δ depends on the resolution of ECT database. In the numerical experiments discussed in section 5, δ is set as 0.1 mm.

5. Numerical Experiments

In numerical experiments, a database is built with crack and simulation parameters given in Table 2.

Experiments have been made using simulation data with 3 types:

1. Single rectangular crack in inspection area.
2. Two rectangular cracks in inspection area.

The result of inverse analysis from these two cases confirms the capability of proposed method in recovering both single and multiple cracks.

3. Crack with complex boundary in both surface and depth profiles. In practice, depth and surface profiles of natural cracks are varying in different position along its length. This type is used in numerical experiment to verify the effectiveness of inverse analysis using ECT database in recovering natural crack profiles.

Table 3 Experiment result - Type 1

Noise rate	Recovered profiles (x, y, l, d) mm	Relative error (%) (x, y, l, d)
• Crack profile (x, y, length, depth)	(32.0, 11.5, 32.5, 7.0) mm	
Free	(32.0, 11.5, 32.5, 7.0)	(0.0, 0.0, 0.0, 0.0)
10%	(32.0, 11.5, 32.5, 7.0)	(0.0, 0.0, 0.0, 0.0)
20%	(32.0, 11.5, 32.5, 7.0)	(0.0, 0.0, 0.0, 0.0)

Table 4 Experiment result - Type 2

Noise rate	Recovered profiles (x, y, l, d) mm	Relative error (%) (x, y, l, d)
• Crack profile (x, y, length, depth)		
	- C1 (33.5, 9.1, 33.9, 4.0) mm	
	- C2 (25.3, -0.9, 23.5, 3.0) mm	
Free	(33.8, 9.3, 33.4, 4.0) (25.0, -0.7, 22.7, 3.0)	(0.9, 2.2, 1.47, 0.0) (1.2, 22.2, 3.4, 0.0)
10%	(33.7, 8.9, 33.9, 4.0) (25.1, -1.7, 24.0, 3.0)	(0.6, 2.2, 0.0, 0.0) (0.4, 66.6, 2.1, 0.0)
20%	(33.7, 8.9, 33.9, 4.0) (25.1, -1.7, 24.0, 3.0)	(0.6, 2.2, 0.0, 0.0) (0.4, 66.6, 2.1, 0.0)

Table 5 Experiment result - Type 3

Noise rate	Recovered profiles (x, y, l, d) mm	Relative error (%) (x, y, l, d)
• Crack profile (mean x, y, length, max depth)	(37.7, -3.9, 53.9, 4.9) mm	
Free	(37.8, -3.3, 53.5, 5.0)	(0.3, 15.4, 0.7, 2.0)
10%	(37.8, -3.0, 53.0, 5.0)	(0.3, 23.0, 0.7, 2.0)
20%	(37.8, -2.8, 53.0, 5.0)	(0.3, 28.2, 0.7, 2.0)

Simulation data of these types are constructed using ECT simulation with crack parameters specified in Tables 3, 4 and 5. However, when using actual measurement data, sometimes random error presents in the measurement taken. To stimulate this random error, random noises are added to the simulation data to test our methodology in the present of noise. A noise generator using Gaussian algorithm is used to generate a distributed set of random numbers $\eta[i]$ with mean 0 and variance 1. Then, this set of random noise is added to simulation data V as following:

$$\bar{V}[i] = V[i] + \max\{V[i]\} \times (\epsilon \times \eta[i])$$

where ϵ is the noise rate, taken from $\{0\%, 10\%, 20\%\}$. The relative error in inverse analysis results is computed as:

$$Error = \left| \frac{Estimated\ value - True\ value}{True\ value} \right| \times 100\%$$

As shown in Tables 3, 4 and 5, crack profiles recovered by Greedy search algorithm have no significant differences, compare with crack profiles of input data.

Fig. 8 illustrates a simulation data entry with 0%, 10% and 20% random noise, compared with measurement data in a scan line. In practice, before being

Fig. 8 Random noise in numerical experiments. (a) Simulation data of one scan line; (b) Simulation data with 10% random noise; (c) Simulation data with 20% random noise; (d) Measurement data after smoothing process.

used in inversion process, measurement data is filtered by a certain signal processing technique.

In these numerical experiments, a triangular smooth algorithm is applied with input data in pre-process for signal peak detection, and then simulation data with random noise are used in greedy search inverse analysis without any signal process. Inverse analysis results confirm the accuracy of the proposed method on crack profiling with random noise (up to 20%). When random noise rate comes greater than 20%, signal processing should be applied on input data for keeping the accuracy of inversion results.

Inverse analysis results on Type 2 verify the capability of the proposed method in recovering multiple cracks within inspection area. However, in this experiment, the distance between two cracks is far enough for pre-process to detect the number of crack and their surface profile. In the cases that cracks come closer to each other, using measurement data from Xscan mode (see Nishimizu et al. [18]), pre-process is still able to detect cracks surface profiles, provided that distance between cracks is not smaller than 3.0 mm. When this distance comes closer to 3.0 mm, it is proved by Nishimizu's work [18] that the number of crack can not be determined automatically, since measurement data does not show distinctive peak of each crack.

Fig. 9 shows surface and depth profiles of crack type 3 in the numerical experiments. Although surface profile of crack used as the input for inversion process has a complicated shape with x-position varying in different scan lines, because cracks in this re-

search are treated in rectangular shape, recovered surface profile is a straight line, which comes close to the mean value of x-position of all scan line (Fig. 9a).

Recovered crack length and position in y-axis strongly rely on the distance of scan lines. If scan lines come closer to each other, recovered crack length can be achieved with better accuracy. In other words, the error of recovered crack length is not greater than scan lines distances. When crack ends come out of one inspection area, for better results on crack lengths of inversion processes, different measurement data on overlap inspection areas should be obtained. Then, total length of the crack can be estimated based on the integration of cracks profiles recovered in each inspection area.

Fig. 9 Crack profiles (Type 3) of numerical experiments

Depth profile of input crack used in experiment Type 3 has a complex shape as shown in Fig. 9b and inversion system is able to recover maximum depth of the crack with the most appropriate profile predefined in the database. Because cracks are treated in rectangular shape, maximum depth of crack can be estimated with higher accuracy when crack shape is similarly to rectangle. In the cases that depth profile of crack has small segments with maximum depth come greater than the depth of rectangle container (as shown in Fig. 9c), recovered depth profile does not successfully cover the maximum depth of the crack. To overcome this limitation, recursive searching processes are applied in different segments of the crack to estimate the maximum depth in each segment. An illustration of recursive search result is shown in Fig. 9d, where crack depth is searched in 2 different segments and the inversion results successfully cover the maximum depth of input crack.

Another numerical experiment has been made with

crack Type 3, noise free, to compare between greedy search and steady-state genetic algorithm (SSGA) [14], running in the same computer system and both algorithms use the same database for construction simulation data. In SSGA, coding mechanism of a gene was given as follows: Given k cracks, each crack has a set of parameter $q_i = (q_i^1, q_i^2, q_i^3, q_i^4)$ where q^1, q^2, q^3, q^4 are position in x-axis, position in y-axis, crack length, crack depth, respectively. Then, one gene is constructed as:

$$\begin{bmatrix} q_1^1 & q_1^2 & q_1^3 & q_1^4 & \dots & q_k^1 & q_k^2 & q_k^3 & q_k^4 \end{bmatrix}$$

Result in Table 6 shows that Greedy-Search is much faster than SSGA whereas the least square error of crack parameters recovered by Greedy search is better than that of SSGA.

Table 6 Comparison between Greedy-Search and SSGA

Algorithm	Minimum least square error	Elapsed (seconds)
Greedy-Search	4.198e+02	18
SSGA - Gene: 50 - Generation: 2000 - Crossover rate: 0.5 - Mutation rate: 0.05	4.353e+02	203

6. Concluding remarks

An inversion system for crack profiling has been introduced with the purpose of making contribution to applications used in nondestructive evaluation, especially ECT technique, for damage detection and evaluation. This system can be applied in real-time, in-service inspection for the structural integrity of the pressurized water reactor nuclear power plants.

In this research, ECT database was built with as a set of parameters-to-output mapping data, by using hybrid FEM-BEM simulator derived from Maxwell's equations. With the use of a database that stores simulation data corresponding to different crack profiles and different system parameters, inversion process would be more effective in terms of speed and accuracy. In greedy search, since "steepest ascent hill climbing" method was used in searching for the successor with the best score (local optimum at each step), greedy search would likely come to the global optimum in the search space of each crack. Numerical experimental results confirm the probability and reliability of this inversion system.

Since inverse analysis results are relying on the construction of ECT database, with current state of the database structure, only crack parameters with discrete value are recovered. For recovering crack profiles with better resolution, another study on optimization of forward analysis for crack profiles identification using Proper Orthogonal Decomposition (POD) has been introduced in [21].

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