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AN INVERSE METHOD FOR CRACKS CHARACTERIZATION FROM ULTRASONIC BSCAN IMAGES

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INTRODUCTION

Concern has been expressed about the capabilities of performing non destructive evaluation (NDE) of flaws located near to the outer surface in nuclear pressurized water reactor (PWR) vessels. The ultrasonic examination of PWR is accomplished from the inside with ultrasonic focused transducers working in the pulse echo mode. By recording the echoes as a function of time, the Ascan representation may be obtained. Many ultrasonic flaw detectors used for NDE are based on the simple Ascan concept involving measuring a time interval called "time of flight". By combining the Ascan concept with synchronized transducer scanning, one can produce Bscan images that are two dimensional descriptions of the flaw interaction with the ultrasonic field.

In the following, the flaw is assumed to be an axially oriented crack (the most serious flaw to be found in a pressurized component). In the case of the outer surface cracks (OSC's), analyzing and interpreting ultrasonic Bscan images become difficult because of the various reflections of the ultrasonic beam on the crack and on the outer surface (the so-called corner effect). Methods for automatic interpretation of ultrasonic experimental data are currently under investigation. In this paper, we present an inverse method for determining the geometrical characteristics of OSC's from ultrasonic Bscan images. The direct model used for the inversion procedure predicts synthetic Bscan images of ultrasonic examination of blocks containing planar defects interrogated by focused probes [1,2].

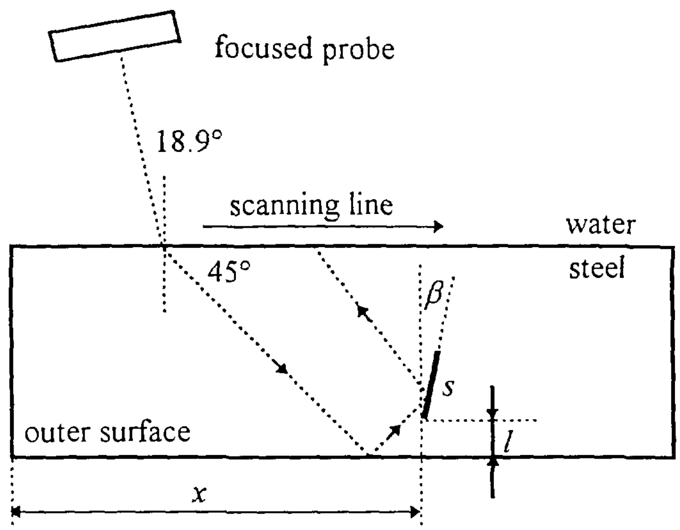

Figure 1. Inclined outer surface crack in a stainless steel plate.

Experimental Configuration

Let us consider a steel block containing an inclined crack located near to the outer surface (see Figure 1). The control is performed with an immersion focused probe functioning in the pulse echo mode. This probe is placed at an angle (18.9°) such that the crack is insonified by a mode converted 45° shear wave. We assume that the crack is completely characterized by a parameter vector $\boldsymbol{p} = (x, l, s, \beta)^T$, where x is the position, l the ligament, s the size and β the crack orientation ($-10° \leq \beta \leq 10°$). We call ligament the distance between the bottom of the crack and the outer surface.

Pre-processing of Experimental Data

In many cases, the approaches used to solve inverse problems are based on an iterative minimization of some performance criterion measuring the dissimilarity between the experimental and synthetic data (generated by the current estimate of the direct model).

In order to "measure" their dissimilarity and to reduce operational requirements, the experimental and synthetic Bscan images have to be described in a computer-understandable and compressed way. Direct comparison of Bscan images (a non-parametric approach) would lead to a tremendous amount of computational burden. Moreover, such a non-parametric approach suffers from instability to small perturbations of the data (ill-posed problem). Considering previous works [3,4] a parametric approach was chosen. In this approach, a Bscan image is treated as a set of echoes. The basic idea is to map the Bscan image into a parameter space such that an echo, which much support in the original image, i.e., with many pixels on, corresponds to a point of this parameter space. Its coordinates must be sensitive to the variations of crack parameters if the parametric description of the Bscan image has been correctly achieved [3]. To obtain a substantial reduction in representation of the useful information contained into a Bscan image, line segments may be associated to echoes through a segmentation operation.

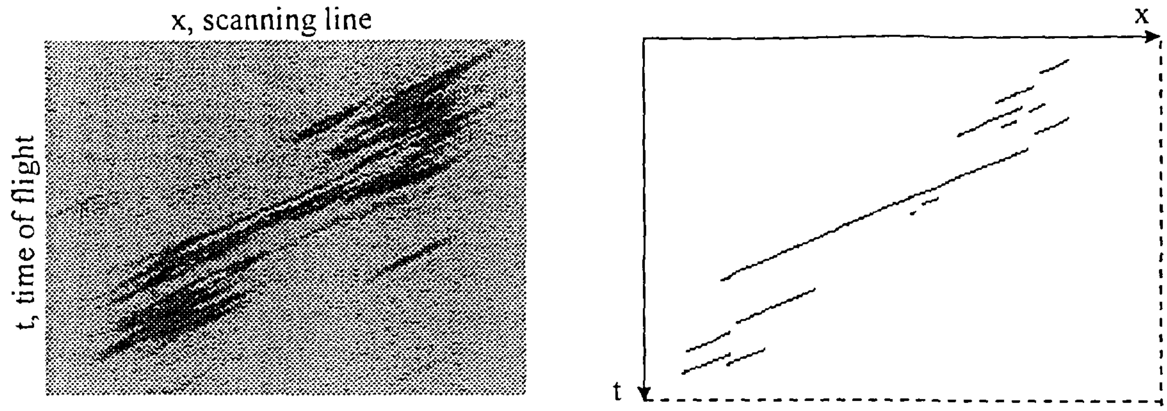

Figure 2. Experimental Bscan image before and after segmentation.

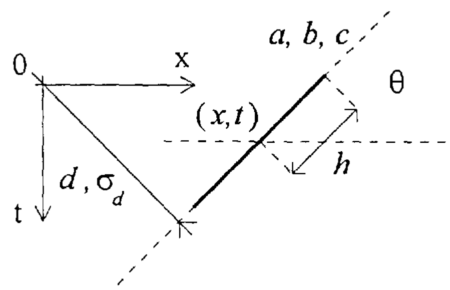

Figure 3. Parametric description of a line segment.

In our case, a segmented image can be directly obtained from the envelope of the original Bscan image by a thresholding operation and spatial interpolation of the resulting points according to certain parameters of the control configuration [8]. The segmented Bscan image can be viewed as a planar distribution of line segments having the same orientation θ (see Figure 2). A line segment is not considered to be a group of collinear pixels in the image but a separate geometric structure that is defined by a parameter vector $s = (x, t, h, \sigma_d, a, b, c)^T$ (see Figure 3) where (x, t) are the Cartesian coordinates of the mid-point, h the half-length of the line segment, σ_d the uncertainty in position d, perpendicular to line segment and a, b, c the parameters of the line support of the segment.

After the pre-processing step (see Figure 4) a Bscan image will be described as a set of parametric line segments

$$y = \left\{ s_i = (x_i, t_i, h_i, \sigma_{d_i}, a_i, b_i, c_i)^T \middle| i = 1,..,N \right\}, \tag{1}$$

where N is the number of line segments.

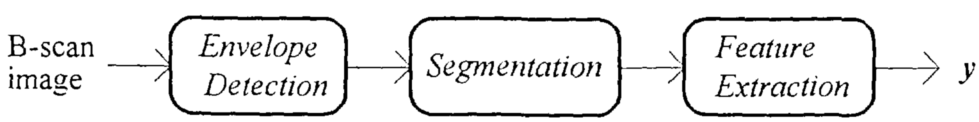

Figure 4. Bscan image pre-processing.

FORMULATION AND SOLUTION OF THE INVERSE PROBLEM

We want to get a good quantitative evaluation of the OSC parameters derived from the parametric description of the experimental Bscan image. In the following sections, the direct problem is first defined, the inverse problem is then formulated, and a solution methodology is finally developed for the inverse problem.

Direct Problem Statement

If the crack parameters are known, the problem lies in the calculation of reflected/scattered signal (the echo-response of the crack) at each position of the transducer. This constitutes the direct problem. The model developed at C.E.A. [1,2], can be called a "system" model since it is a combination of modeling the control configuration, the transducer, the incident ultrasonic field and its interaction with possible defects (see Figure 5). It predicts tip diffraction, corner effect and mode conversion echoes. The results of modeling for a given scanning line constitute the synthetic Bscan image.

Let us consider that the output solution of the direct model, the synthetic Bscan, is essentially a function of the crack parameters. A model of the interaction between the incident ultrasonic field and the crack induces a mapping A associated with this model. The map $A: P \rightarrow Y$, where P is the OSC parameter space and Y the data parameter space, is defined in terms of the non-linear relationship between the OSC parameters and the Bscan image. Let us describe it in abstract form of an operator equation of the first kind

$$A(p^{\circ}) = y, \tag{2}$$

where $p^{\circ} \in P$ is the OSC parameter vector and $y \in Y$ is the data set. Notice that in practice map A also depends on the control configuration parameters, the ultrasonic field profile, etc., that are supposed to be known.

The inversion of the direct model is not feasible with conventional mathematical methods. The Equation (2) has not an explicit mathematical formulation and there is no possibility to get an algebraic solution of the inverse.

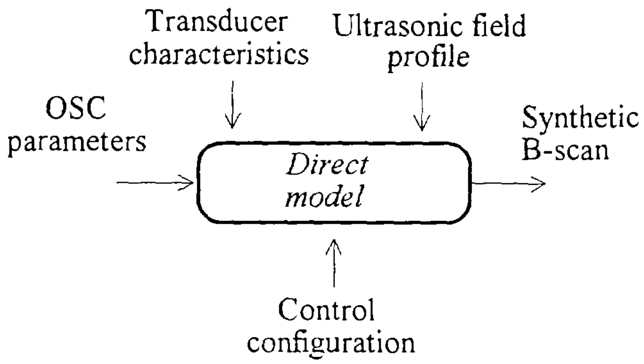

Figure 5. The direct model.

Inverse Problem Statement

Instead of the precise data (A, y) in Equation (2) we dispose of an approximate data (A_m, y^e), where A_m is our knowledge of modeling the physical reality and y^e are the available noisy data. The OSC's characterization problem can be posed as follows : find the so-called pseudo-solution of (2) from the perturbed data (A_m, y^e), i.e., a vector

$$p^* \overset{def}{=} \arg\min_{p \in P} \left\{ d(y^e, y^m) \right\}, \; y^m = A_m(p), \tag{3}$$

where $d(y^e, y^m)$ is a scalar function of the OSC parameters that measures the degree to which y^e and y^m differ one from the another. In other words, the pseudo-solution is defined as the OSC parameters at the input of the direct model for which the synthetic data best match experimental data and also represents a good approximation of the actual crack parameters. We use an iterative inversion procedure to obtain solution p^* by numerical way (see Figure 6).

The Dissimilarity Criterion

The experimental Bscan image contains the essential useful information, i.e., mirror tip diffraction echoes (arriving at the probe after reflections on the outer surface), direct tip diffraction echoes, corner echoes and it also contains some "parasitic" informations (not predicted by the direct model), e.g., echoes due to surface waves traveling along the crack faces or that might be caused by the crack surface (actual fatigue cracks have surface roughness whereas modeled crack is assumed to be perfectly plane and stress free). One can consider the experimental Bscan image as two sets of echoes, the useful echoes set and the parasitic echoes set, that are superimposed on one another. After the segmentation step, the experimental segmented Bscan contains additional parasitic segments and, sometimes, missing useful segments. On the other hand, the synthetic segmented Bscan contains only the line segments corresponding to the echoes of the approximate predicted crack signature. So, a perfect correspondence between experimental and synthetic data is not expected even for parameters at the input of the direct model corresponding to the actual ones.

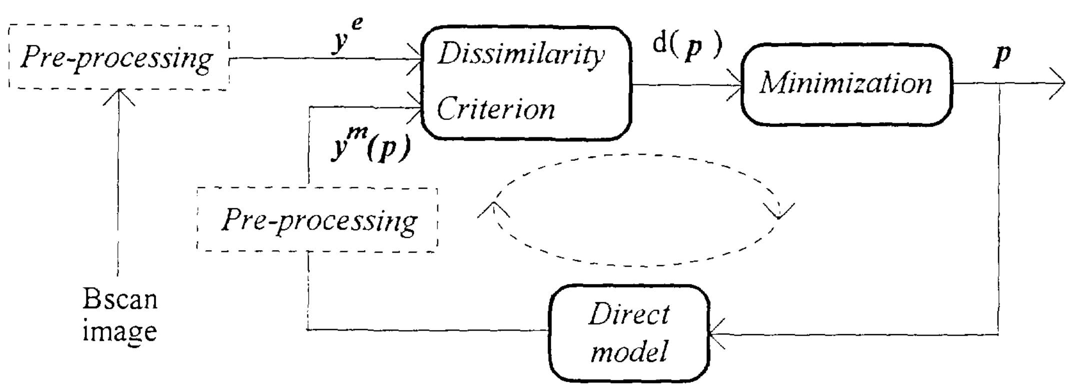

Figure 6. Schematic flow chart for the iterative inverse procedure.

Thus, the dissimilarity criterion used by our matching method must be able to work with two descriptions that are not likely to have strict one-to-one correspondence at the segment level. Given the experimental data set

$$y^e = \left\{ s_i^e = (x_i^e, t_i^e, h_i^e, \sigma_{d_i}^{\,e}, a_i^e, b_i^e, c_i^e)^T \,\middle|\, i = 1,..,N \right\} \quad (4)$$

and the synthetic data set

$$y^m = \left\{ s_j^m = (x_j^m, t_j^m, h_j^m, \sigma_{d_j}^{\,m}, a_j^m, b_j^m, c_j^m)^T \,\middle|\, j = 1,..,M \right\} \quad (5)$$

(corresponding to the experimental and synthetic Bscan images, respectively), we will define a specific dissimilarity criterion $\mathrm{d}(\boldsymbol{p}): P \rightarrow R_{\geq 0}$ as,

$$\mathrm{d}(y^e, y^m) = \mathrm{d}(\boldsymbol{p}) \overset{def}{=} \tfrac{1}{2}\left\{ \tfrac{1}{N} \sum_{i=1}^{N} \min_j \left\{ \mathrm{Sim}(s_i^e, s_j^m) \right\} + \tfrac{1}{M} \sum_{j=1}^{M} \min_i \left\{ \mathrm{Sim}(s_i^e, s_j^m) \right\} \right\} \quad (6)$$

where

$$\mathrm{Sim}(s_i^e, s_j^m) = \frac{\left(x_i^e - x_j^m\right)^2 + \left(t_i^e - t_j^m\right)^2}{(h_i^e + h_j^m)^2} + \frac{(a_j^m x_i^e + b_j^m t_i^e + c_j^m)^2}{(\sigma_{d_j}^{\,m})^2} + \frac{(a_i^e x_j^m + b_i^e t_j^m + c_i^e)^2}{(\sigma_{d_i}^{\,e})^2} \quad (7)$$

is a similarity measure between two segments s_i^e and s_j^m ($s_i^e \in y^e$ and $s_j^m \in y^m$). Two segments having the same orientation will match if they are roughly collinear and overlap. $\mathrm{Sim}(s_i^e, s_j^m)$ is a form of Mahalanobis distance [9], that is a distance normalized by variance. The measure of overlap is made using the difference between mid-points. The half-length of the segments provides the tolerance for overlap. The measure of colinearity is made using the distance from the mid-point of each segment to the line of other segment. The variances σ_{d_i} and σ_{d_j} provide the tolerance for similarity of colinearity.

The Choice of a Minimization Technique

For a given Bscan image, the OSC's characterization problem is subsequently similar to a nonlinear minimization problem. Its solution gives the OSC geometrical parameters at the input of the direct model for which synthetic data best match the experimental data. Mathematically, the closeness of the match is quantified by the presented dissimilarity criterion. This criterion has specific features that prohibit the selection of any classical optimization technique. It is non-linear and not differentiable with respect to the OSC parameters. It must also be emphasized that its "surface" may be multimodal, so that the deterministic optimization methods tend to get stuck in local minima. Global optimization methods are appropriate in such cases. These methods are designed to overcome the multi-modality of the dissimilarity criterion without incurring the enormous expense of exhaustive search. Their main idea is to generate at each iteration new parameter vectors $p^k \in P$, until an acceptance criterion (Metropolis criterion [6], for example) is satisfied. The advantage of such methods is that no special analytic property of the criterion has to be assumed.

We have tested the performances of three likely candidates: the Simulated Annealing (SA) [6], the Adaptive Random Search (ARS) [5] and the Genetic Algorithm's (GA's) [7]. Among these methods the Adaptive Random Search (ARS) strategy has been selected owing to its simplicity and efficiency. By incorporating SA into ARS one can improve performances considerably especially in terms of probability of escaping from local minima.

EXPERIMENTAL RESULTS

The optimization-based inversion procedure described in this paper has been tested with both synthetic and experimental data. We present here the estimation results for an artificial OSC with the following parameters: position x = 135 mm, size s = 15 mm, ligament l = 25 mm, orientation β = 0°. The ultrasonic inspection of the stainless plate containing the artificial crack was performed using the same procedures as used for *in-site* testing configuration. The inversion of the information contained into the experimental Bscan image allows accurate estimation of the crack parameters (see Figure 7) for a global calculation time lower than two minutes on a HP 9000 workstation.

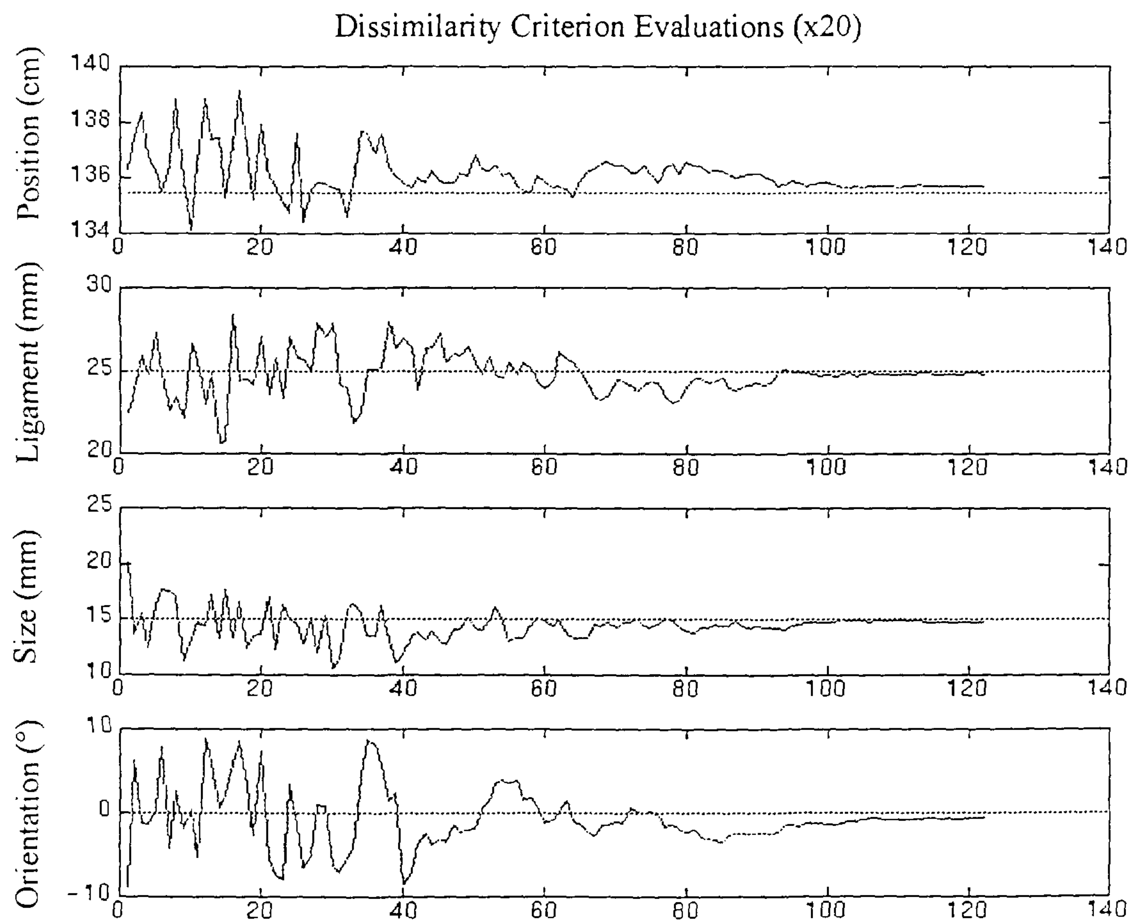

Figure 7. Convergence versus real parameters of the artificial crack.

SUMMARY

We have presented an inverse method for determining the geometrical parameters of OSC's from ultrasonic Bscan images. To avoid the ill-posed character of this inverse problem and reduce operational requirements, ultrasonic Bscan images are described in a parametric way. The relationship between Bscan images and OSC's parameters (the direct problem) cannot be mathematically formulated and there is no possibility to get an algebraic solution of the inverse. So, instead of searching its solution we will search the so-called pseudo-solution: the OSC parameters at the input of the direct model for which synthetic data best match experimental data. Mathematically, the closeness of the match is quantified by a specific dissimilarity criterion. The proposed dissimilarity criterion is non-linear and non differentiable with respect to the OSC parameters. Its "surface" is multimodal, so that the solution, defined as its minimizer, is obtained by using a global optimization method (a modestly-modified version of the ARS algorithm). The proposed iterative inversion procedure has been tested with both synthetic and experimental data, and satisfactory results have been obtained.

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