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Adaptive inversion database for electromagnetic nondestructive evaluation

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Abstract

A novel method is proposed for generating an inversion database, by which the defect reconstruction problem of eddy-current testing can be solved. The database realizes a finite approximation of the forward operator that maps defect configurations to output signals. This approximation is achieved by interpolation on an n-dimensional simplex mesh, where n is the number of defect model parameters considered for the inversion. The inversion can be traced back to a nearest point search. The key element of the method is that the mesh supporting the database is optimized to fit the given testing experiment. On one hand, this feature allows the qualification of the inversion results. On the other hand, the mesh structure of the optimized database provides meta-information about the inverse problem, including the capabilities of the testing experiment and the suitability of the applied defect model among others. Some interpolation and meshing issues are discussed as well, and an application example is presented in the paper.

Keywords: Inverse problems; Database; Eddy current testing; Crack sizing

1. Introduction

Electromagnetic non-destructive evaluation (NDE) techniques enable us to explore material damage in manufactured components. In particular Eddy-current testing (ECT) methods are capable to detect flaws, voids or inclusions inside a conductive material or a deposit on its surface; the thickness of a coating, the extent of corrosion, or the gap between adjacent layers in a layered metallic structure can be aimed at as well. The range of applications is broad: machinery, aircraft, nuclear power plants, gas pipelines and many other complex systems. One can refer for a good overview of the field, and more technical issues, to [1], and to the 2002 special section of Inverse Problems dedicated to electromagnetic and ultrasonic NDE [2].

Beyond the mere detection of defects, whether and how long a damaged component can be kept in operation is a very important matter, and this means one needs to reliably assess such defects. However, the inverse problem of so-called defect quantification based on measurements—this is including localization, sizing and shape reconstruction—is ill-posed, among other reasons because the available data are usually aspect-limited, band-limited and noisy. Consequently, one single result of an inversion procedure cannot be accepted, say, in its own right: the inversion has to be qualified with its reliability (or uncertainty), which is depending upon several factors.

The ill-posedness of the inverse problem in NDE is often tackled by hypothesizing a defect model involving a finite number of variable parameters, with respect to which the inversion is carried out. This collection of parameters describes the geometry and electromagnetic properties of the defect. But such a model-based approach rises some further questions. What is the role and significance of each model parameter from the point of view of the inversion? Which parameters are connected and thereby redundant? What would be an optimal model for the class of defects to be examined? These questions cannot be answered without a proper understanding of the nature of the inverse problem. Since the pure mathematical description of both

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the forward problem and the inverse problem is often complex, a knowledge base containing the measurements achieved for some representative cases would be helpful in this understanding.

The defect reconstruction procedure should be fast enough to meet the requirements of manufacturing, service and maintenance. However, the rigorous numerical analysis of the defect-probe interaction in ECT arrangements is a time-consuming task. Consequently the computation time needed for optimization-based inversion might be also quite large, especially if stochastic optimization methods are applied. One possible mean to speed-up the inversion is the application of a pre-measured or pre-calculated database that contains the probe responses of selected defect prototypes, as is reported in [3]. Applying this, at every step of the optimization loop one simply retrieves the appropriate signal stored in the database instead of carrying out the whole time-consuming numerical analysis. It is obvious however, that the quality of the reconstruction might critically depend upon the database actually used in the procedure.

Investigating the main items noted above—such as an optimal defect model, a reliable database for the inversion, and the qualification of the results—has led us to consider a rather pragmatic solution for the inverse problem of non-destructive testing, which is founded on a specific inversion database, which is dealt with hereafter. The paper is organized as follows. In the next section the proposed method is introduced in more detail. Although the method is meant to be general, it will be analysed herein through a specific crack reconstruction problem. The forward solution of the selected problem is discussed in Section 3. Important issues of the database generation procedure are described in Section 4. Means of inversion together with a number of illustrative numerical results are presented in Section 5. Finally, in Section 6, one further utilization of the inversion database is proposed: in addition to its defect reconstruction capability, it can indeed provide substantial information on the test experiment and on the related inverse problem, respectively. Notice that some preliminary results have been published earlier in [4–6], but most of the concepts and results in the present paper are new.

2. Summary of the method

First of all, we adopt a sufficiently generalized defect model, which can be characterized by n parameters, for example the length, depth, position, and orientation of a potential in-material crack. Furthermore, we assume that the output signal measured by the sensors can be described—ultimately in some discretized form—with a finite number (m) of values. For example, these values are the impedances of a pick-up coil measured at a number of predefined scan positions, or the samples of some measured time-function. The relationship between defect model parameters and measured data can be formulated as

$$q_j = f_j(p_1, p_2, \ldots, p_n), \quad j = 1, \ldots, m \tag{1}$$

or in short

$$\mathbf{q} = \mathscr{F}(\mathbf{p}), \tag{2}$$

where $\mathbf{p}$ represents the n-tuple of defect model parameters and $\mathbf{q}$ the m-tuple of measured data. The so-called forward operator $\mathscr{F}$ considered here maps the parametric space or configuration space P into the space Q of conceivable output signals, denoted as signal space.

2.1. Approximation of the forward operator by means of a simplex mesh

We attempt to approximate $\mathscr{F}$ with a piecewise constant (PC) or a piecewise linear (PL) operator $\mathscr{G}$, so that the maximum error of the approximation—measured in the Euclidean norm—is less than a predefined bound

$$\max_{\mathbf{p}\in \mathrm{P}} \|\mathscr{G}(\mathbf{p}) - \mathscr{F}(\mathbf{p})\|_2 \leqslant \delta. \tag{3}$$

The practical realization of operator $\mathscr{G}$ is a nearest neighbour or linear interpolation on an n-dimensional simplex mesh, so that at the nodes of the mesh $\mathscr{G}(\mathbf{p}) = \mathscr{F}(\mathbf{p})$ holds.

Now, let us look at the above in different fashion. Let us assume that one has performed measurements for some collection of defect prototypes. Each of these prototypes can be seen as a separate point in the configuration space. The points in this space can be connected with each other so as to form a simplicial mesh. The output signal measured for a given defect prototype will be associated with (loosely speaking "stored in") that node of the mesh, which one is assigned by the given defect parameters as coordinates.

This collection of mesh nodes constitutes another kind of forward-database, indexed by the defect parameters, denoted hereafter as the "mesh database". One good advantage of this database over the classical look-up tables is that the output signal for a defect that does not coincide with any of the database nodes can be estimated by means of nearest neighbour or linear interpolation on the simplex mesh.

We are well aware that the above described method, which is called "tessellation and interpolation of multivariate multicomponent scattered data", is a routine task in many areas of applied mathematics and engineering—even in dimensions higher than three—and has a rich literature. See for example [7] for the general approach, and [8] for a particular application. However, the method proposed in this paper differs from the common solutions in some essential features, which are detailed in the remaining subsections.

2.2. Taking the noise of the experiment into account

The quality of the measured data evidently limits the accuracy of defect reconstruction—within the theoretical