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A 2D HYBRID APPROACH TO MODEL A COMPLEXED SHAPED DEFECT IN AN ULTRASONIC INSPECTION SITUATION

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ABSTRACT

Nondestructive testing methods (NDT) are used to evaluate in-service induced defects, such as fatigue and stress corrosion cracks. All NDT methods are indirect and based on the interpretation of received signal, which is always the basis for judgment of the quality of the component. Different degradation mechanisms produce very different kind of cracks or defects in a morphological perspective. Therefore, they interact and influence the received signal in an individual manner, and ultrasonic NDT methods are not always reliable in such applications.

But it is possible to do parametrical studies that address such interactions and dependencies by using hybrid methodology, which combines finite element (FE) and an integral representation and takes advantage of both semi-analytical and numerical approaches. Such hybrid model has, in the development into a corresponding 3D description, a great potential when it comes to the complexed shape defects (SCC) or defects surrounded by strongly anisotropic material.

Keywords: k-wave, simSUNDT, 2D Hybrid modelling

1. INTRODUCTION

In the nuclear industry advanced forms of nondestructive testing methods (NDT) is commonly used to evaluate the integrity of individual components, which might be exposed to different degradation mechanisms (e. g. fatigue, corrosion and stress corrosion cracking). In-service induced defects such as fatigue and stress corrosion cracks can, if they are detected, be sized and monitored in order to postpone repairs or replacements. Such defects become more and more essential to address as the power plants are exploited beyond their estimated lifetimes in combination with an increase of power outage in recent years.

The reliability of NDT method is highly dependent on how the equipment is adjusted to a specific object and to anticipate crack features. The crack feature and morphology vary widely between different crack mechanisms and between material types, in which crack appear. Since all these NDT methods are indirect and based on prior information on signal into the component, some kind of interpretation of received signal is always the basis for judgment of the quality of the component. The different degradation mechanisms produce very different kind of cracks or defects in a morphological perspective. As a consequence, they interact and influence the received signal in an individual manner.

2. Hybrid model

Stress corrosion cracks (SCC), defects which are frequently appeared in the nuclear industry, are often tends to have a heavily branched macroscopic shape with a large number of crack tips. The diffraction from the cracks tips is commonly used as the basis for the defect size analysis, and ultrasonic NDT methods are not always reliable in this kind of application. By exploiting mathematical modelling, it is possible to do parametrical studies that address such interactions and dependencies that never would be possible to achieve by experiments. A two-dimensional hybrid method [1], combining finite element (FE) and an integral representation, is used to study ultrasonic waves. Mathematical modelling of NDT techniques is also essential when it comes to quantifying the capacity of a specific procedure and technique (NDE) in a specific application.

The above-mentioned hybrid method takes advantage of both semi-analytical and numerical approaches. The basic idea is to surround the defect by a finite element scheme and deal with the propagation between the probe and the defect with a semi analytical method. In this way it is possible to model more complex crack geometries that involves a complicated scattering processes without getting to large numerical models. Where it is possible to implement, semi-analytical and fully numerical approaches are complementary.

2.1 The analytical model

The governing linearized equations for wave propagation in an elastic medium are the equation of motion, Hooke's law and the strain-displacement relation. If time harmonic conditions are assumed (time factor $e^{-i\omega t}$ is suppressed) these three relations

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can be combined into the elastodynamic equation of motion governing the displacement field $\mathbf{u}$

$$k_p^{-2}\nabla\nabla\cdot\mathbf{u} - k_s^{-2}\nabla\times\nabla\times\mathbf{u} + \mathbf{u} = \mathbf{0} \qquad (1)$$

where k_p and k_s are the compressional and shear wave numbers. The total displacement field is given by the sum of the incident field ($\mathbf{u}^i$) and the scattered field ($\mathbf{u}^s$). Let us expand the incident field in terms of regular spherical partial vector waves ($\mathrm{Re}\boldsymbol{\Psi}_n$) and the scattered field in corresponding outgoing spherical partial vector waves ($\boldsymbol{\Psi}_n$), i.e.

$$\begin{cases}\mathbf{u}^i = \sum_{\boldsymbol{n}} a_{\boldsymbol{n}} \mathrm{Re}\,\boldsymbol{\Psi}_n \\ \mathbf{u}^s = \sum_{\boldsymbol{n}} f_{\boldsymbol{n}}\, \boldsymbol{\Psi}_n\end{cases} \qquad (2)$$

Then it is possible to find a linear relationship between the expansion coefficients for the incident and scattered field and this entity is known as the transition matrix $\mathbf{T}$

$$f_{\boldsymbol{n}} = \sum_{\boldsymbol{n}'} T_{\boldsymbol{nn}'}\, a_{\boldsymbol{n}'} \qquad (3)$$

All information about the scattered field is contained in its transition matrix and the characterization of the probe acting as a transmitter is encapsulated in the expansion coefficients for the incident field (a_n). To evaluate its behaviour as a receiver we use an electromechanical reciprocity argument by Auld [2]. Then the change in the electrical response of probe b, due to the presence of a defect (enclosed by a control surface S), is found as

$$\delta\Gamma \sim \sum_{nn'} a_n^{\mathrm{b}}\, \mathrm{T}_{nn'} a_{n'}^{\mathrm{a}} \qquad (4)$$

.

2.2 K-wave MATLAB toolbox and SimSUNDT software

The open-source k-Wave MATLAB Toolbox is used for simulating elastic wave propagation for the two-dimensional model in the time domain [3, 4]. The problem is here discretized in 2D using a time-stepping pseudo spectral scheme. The perfectly matched layer is used to allow a free-field simulation at the borders of the computational grid. For the given geometry, a two layered structure with the upper layer consisting of a fluid and the lower of an elastic solid, is modelled with a defect in the solid layer. The ultrasonic source is placed between the layers and modelled as a pressure distribution with values for specific grid points. Several functions are included in the toolbox for the creation of both geometric shapes of the source and time dependent distributions, such as tone bursts. Special attention is given to the Courant-Friedrichs-Lewy (CFL) condition and the actual wavelength contra the discretization size.

3. RESULTS AND DISCUSSION

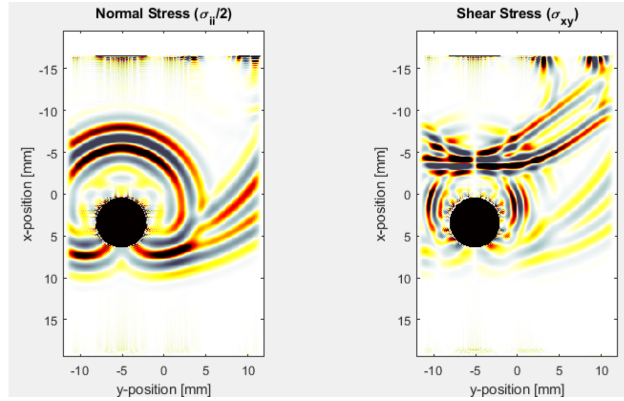

FIGURE 1: STRESS FIELD IN TIME DOMAIN FOR SIDE DRILLED HOLE IN k-Wave

A 6 mm line source is used to generate a toneburst signal with a source frequency of 2 MHz and 3 source cycles and the resulting stress field is shown in figure 2. Here the defect is a 6 mm side drilled hole at a dept of 20 mm.

The analytical model used as kernel in the simSUNDT software [5-9] is completely three dimensional though the component is two dimensional (infinite plate with finite or infinite thickness) bounded by the scanning surface where one or two probes are scanning the object within a rectangular mesh. The probe is modeled by an assumed effective area beneath the probe, used as boundary conditions in a half-space elastodynamic wave propagation problem. This enables an adaptation to a variety of realistic parameters related to the probe, e.g. wave type, angle, crystal (i.e. size and shape), focus depth and contact conditions. The receiver is modeled by applying a reciprocity argument by Auld [2].

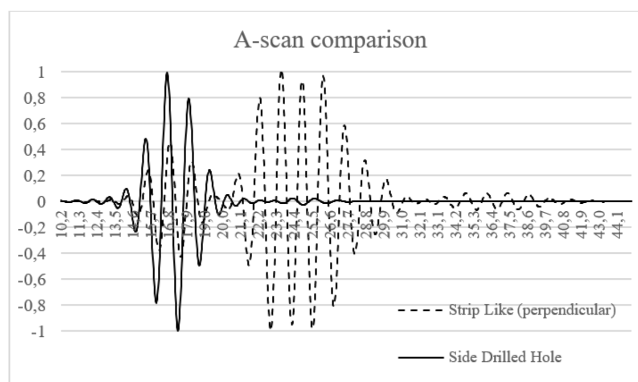

FIGURE 2: COMPARISON OF A-SCAN FOR STRIP LIKE DEFECT AND SIDE DRILLED HOLE IN SimSUNDT

The signal response in Figure 2 represents a longitudinal probe (0°) in pulse echo above two different defects at 20 mm in depth simulated with the simSUNDT software. The solid line representing a side drilled hole with 6 mm in diameter corresponds to above k-wave simulation, and the dotted - when the defect is a 6 mm strip like crack perpendicular to the scanning surface. The signal responses are normalized and the diffracted signal from the lowest tip at the strip like crack is -33dB below corresponding reflected from the side drilled hole. If a discretization method e.g. k-wave shall be able to model this kind of phenomena the elements must be kept very small. A hybrid approach can then reduce the discretized volume into a sphere that surrounds the defect (T-matrix representation).

A fundamental problem with modelling in-service induced cracks is that each defect is an individual with a unique morphology created by a unique stress and chemical environmental progress. Since these specific features of such cracks cannot be prescribed without a large amount of uncertainty, the conventional way to model these cracks is to generalize into a very simplified and idealized geometric shape.

In the future, it should be possible to combine hybrid method with specified numbers of material and environmental parameters together with historical stress state data of a specific object. It could be done after a parametric study aimed to clarify the influence of different degrees of branching in terms of defect detectability and complexity of the signal response which is the basis for a sizing procedure. And a reasonable realistic height and size can then be predicted by using existing growth laws. Based on these inputs, the simSUNDT software will randomly generate an individual stress corrosion crack (morphology), where the macro-structure is given by a model of grain size in the HAZ and the degree of branching is controlled by a limited number of material parameters [10].

4. CONCLUSIONS

The paper describes a developed methodology to combine a computational fast solution of the ultrasonic inspection situation (analytical) with a discretization approach to model only the actual defect (k-Wave). This hybrid model has, in the development into a corresponding 3D description, great potential when comes to investigations of how e.g. complexed shape defects (SCC) or defects surrounded by strongly anisotropic material have an impact on received signal. The major benefit will be in generating POD based on synthetic data and other parametric studies and the intention is to compare the signal response from branched cracks (SCC) with a model of a fatigue crack.

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