Development of a Very Fast Simulator for Pulsed Eddy Current Testing Signals

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Abstract — In this paper, a very fast numerical solver for simulation of the pulsed eddy current testing (PECT) signals was developed based on the database approach and the frequency domain summation strategy. At first, the frequency domain summation method with interpolation strategy was described for the simulation of PECT signals. Second, the fast numerical solver of database approach was upgraded in order to apply it to the ECT problem of local wall thinning. Finally, based on the frequency domain summation method and the fast simulation scheme for single frequency excitation, a very fast numerical solver was developed and validated for the simulation of PECT signals due to a local wall thinning.

I. Introduction

Pulsed eddy current testing (PECT) method shows many advantages comparing with the conventional eddy current testing due to its features of applicability of large excitation current and rich frequency components [1]. The simulation tool for the transient PECT problem, however, is still not satisfactory for the inspection of specimens in complicated geometry [2]. Most of the past researches on the PECT simulations focused on the analytical solution which is only valid for regular shaped specimen and is very difficult for specimen and probes of relative complicated shape [3]. In addition, for probe optimization and especially for the inverse analysis of PECT problem, fast numerical solver is very necessary and crucial [4]. A fast and efficient simulator for PECT signals is the base for the further development of PECT technology.

In nuclear power plants (NPPs), to guarantee the safety, periodical Non-destructive Testing (NDT) to the pipes is regulated. Local wall thinning is a kind of defect in pipes due to flow accelerated corrosion and/or liquid droplet impingement of the coolant inside the pipe. PECT is considered as a powerful candidate for the NDT of the local wall thinning defect in NPPs.

According to this background, a very fast numerical solver for simulation of PECT signals is developed in this work based on the frequency domain summation strategy and the database approach for PECT of the local wall thinning. Through comparing the numerical results using the present fast solver and a conventional method, it was verified that the fast solver is over 100 times faster than the conventional one but with similar accuracy.

II. Frequency Domain Summation Strategy

In PECT, the excitation signal is usually introduced as repetitive square wave pulse which can be considered as summation of serial harmonic sinusoidal waves shown in formula (1) according to theory of Fourier transformation,

$$\mathrm{I}(t)=\sum_{n=1}^{N}\widetilde{F}_n e^{j\omega_n t} \qquad n=1, 2, 3, \ldots\ldots \qquad (1)$$

where ω_n is the angular frequency of sinusoidal excitation and $\widetilde{F}_n$ is the amplitude coefficient. As PECT problem can be considered as a low frequency one, its governing equations after Galerkin FEM discretization strategy can be written as,

$$[\mathrm{K}]\{\mathbf{A}\}+[\mathrm{C}]\left\{\frac{\partial \mathbf{A}}{\partial t}\right\}=\{\mathrm{M}\}\,\mathrm{I}(t), \qquad (2)$$

where A is the vector potential, [K], [C] and {M} are coefficient matrices of FEM equations. Because of the linear property of Eq.(2), the response signal due to pulsed excitation in form of Eq.(1) can also be composed by the sinusoidal waves of the frequencies appeared in the driving current. After formulae deduction, the response of the magnetic flux density $\boldsymbol{B}$ can be obtained by summarizing up the response signals of each frequency $\boldsymbol{B}_{n0}$ as shown in Eq.(3). When each $\boldsymbol{B}_{n0}$ has been calculated, field signal B(t) can be obtained easily by using [5]

$$\{\mathrm{B}(t)\}=\sum_{n=1}^{N}\widetilde{F}_n\left(\nabla\times\left\{\widetilde{A_{n0}}\right\}\right)e^{j\omega_n t}=\sum_{n=1}^{N}\widetilde{F}_n\left\{\widetilde{B_{n0}}\right\}e^{j\omega_n t} \qquad (3)$$

To simulate PECT signal based on Eq.(3), it is necessary to know the response signals of selected single frequency sinusoidal excitation, which can be calculated by using a conventional FEM numerical code. The response signal of the pulsed excitation can be obtained through a summation of response signals of harmonic components of different frequencies and with use of coefficients shown in Eq.(3). Hereafter, this strategy will be called as the Frequency Domain Summation Method (FDSM).

As the frequency response curve of single frequency ECT is smooth, the amplitude of the response signal of a given harmonic frequency can be calculated from the signals of selected frequencies through interpolation. The number of total frequencies for signal summation and the number of selected frequencies for interpolation are important to guarantee the precision of simulation. Figure 1 shows a comparison of simulated and the measured signals due to an OD local wall thinning defect (length × width × depth: 100mm × 10mm × 5mm), where the square specimen is 100mm in length and width and 10mm in thickness of austenitic stainless steel 316. Good agreement shows the validity of the FDSM.

III. A Fast Solver for Conventional ECT Simulation

A fast simulator for ECT of crack has been developed by authors [6], [7]. As the wall thinning is of 3D geometry, the fast solver has to be upgraded in order to be applied to the quantitative wall thinning inspection. The major difference between crack and wall thinning problem is the dimension of the databases of the unflawed potentials and the way to establish the inverse matrix [H]. The theory of the fast scheme is as follows:

Through subtracting the governing equations with and without defect and conducting Galerkin FEM discretization, the following system of linear equations can be obtained,

$$\begin{bmatrix} \bar{K}_{11} & \bar{K}_{12} \\ \bar{K}_{21} & \bar{K}_{22} \end{bmatrix} \begin{Bmatrix} A_1^f \\ A_2^f \end{Bmatrix} = \begin{bmatrix} \hat{K}_{11} & 0 \\ 0 & 0 \end{bmatrix} \begin{Bmatrix} A_1^f + A_1^0 \\ A_2^f + A_2^0 \end{Bmatrix}, \quad (4)$$

where subscripts 1 and 2 denote the areas at the defect and at the other area, while superscripts f and 0 denote the potentials perturbation by flaw and that of the unflawed material. $[\bar{K}]$ is the unflawed global coefficient matrix of FEM equations.

From Eq.(4), one can obtain a smaller system of linear equations for solving the potential perturbation $\{A_1^f\}$ and $\{A_2^f\}$,

$$\begin{Bmatrix} A_1^f \\ A_2^f \end{Bmatrix} = \begin{bmatrix} H_{11} & H_{12} \\ H_{21} & H_{22} \end{bmatrix} \begin{bmatrix} \hat{K}_{11} & 0 \\ 0 & 0 \end{bmatrix} \begin{Bmatrix} A_1^f + A_1^0 \\ A_2^f + A_2^0 \end{Bmatrix}, \quad (5)$$

where [H] is the inverse matrix of [K]. The equations related to $\{A_1^f\}$ can be easily separated from Eq.(5) as,

$$\left[I - H_{11}\hat{K}_{11} \right]\{A_1^f\} = [H_{11}][\hat{K}_{11}]\{A_1^0\}, \quad (6)$$

As coefficient matrices [H] and [K] are independent of the flaw geometry, they can be calculated *a priori* and stored as databases [7]. In this way, calculation burden of $\{A_1^f\}$ can be greatly reduced because the number of the nodes related to defect is always much smaller than the node number of the whole system. In present work, the region for database and shifting scheme for extracting [H] from the database are modified for treating the wall thinning defect, and the corresponding numerical code is upgraded.

Figure 2 shows a comparison of ECT signals of 100 kHz by using the present fast solver and the conventional simulator for OD20% and OD60% local wall thinning defects. The very well accordant results verified the validity of the present fast scheme and the modified code. However, this fast solver only needs about 3 seconds to obtain the results while it takes more than 10 minutes for the conventional method by a PC using Dell OptiPlex 755: Intel Core 2 Duo E6850, 3 GHz, Memory 2 GB.

IV. Fast Solver for Simulatioin of Pulsed Excitation

The fast numerical solver for simulation of PECT signals due to local wall thinning is as follows. At first, the ECT signals of selected frequencies due to local wall thinning are calculated by using the fast solver described in section III. Then, the response signal due to pulsed excitation (PECT signal) can be calculated through the FDSM given in section II. In this way, the transient PECT signals can be obtained within very short time.

Figure 3 shows the comparison results of OD20% and OD60% local wall thinning defects under pulsed excitation by using the present fast solver and conventional simulator respectively. Though the results show very good agreement, the conventional method takes more than 100 times of computational time than the present fast solver. The development of this fast simulator gives a good basis for the further inversion problem study of PECT technology.

V. Acknowledgments

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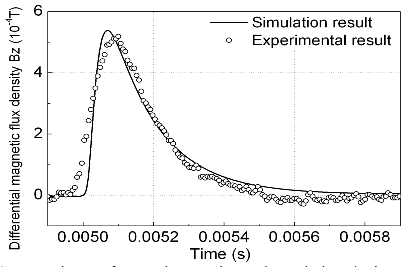

Fig. 1. Comparison of experimental result and simulation result

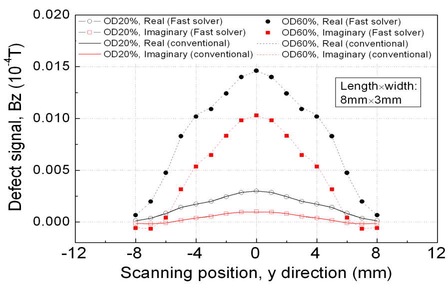

Fig. 2. Comparison of fast solver and conventional simulator due to OD 20% and OD60% local wall thinning under single frequency excitation

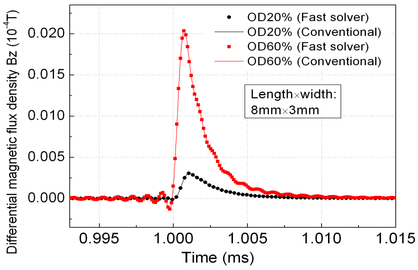

Fig. 3. Comparison of fast solver and conventional simulator due to OD 20% and OD60% local wall thinning under pulsed excitation

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