Reconstruction of Deep Stress Corrosion Cracks Using Signals of the Pulsed Eddy Current Testing

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***Abstract*—In this paper, signals of Pulsed Eddy Current Testing (PECT) are applied to sizing of deep Stress Corrosion Cracks (SCCs) based on the multilayer reconstruction strategy in order to improve the sizing accuracy of SCCs. The shape profiles and conductivity of a SCC at different depth are reconstructed step by step by using different harmonic components of the PECT signals. The profiles of cracks are reconstructed from simulated signals of conductive notches and measured signals of an artificial SCC. It is demonstrated that the PECT signals are applicable for the reconstruction of SCCs.**

I. Introduction

In regular Nondestructive Testing (NDT) for key structural components of nuclear power plants, it is necessary to quantitatively evaluate the crack profile especially regarding the depth information in order to select a proper maintenance strategy. Recently, Eddy Current Testing (ECT) shows capability in crack sizing [1-2]. Traditional ECT technique is the single frequency excitation and only provides limited data. Sizing of natural cracks using traditional ECT often underestimates the crack depth especially for Stress Corrosion Cracks (SCCs) because of their complicated microstructures. To improve the sizing precision, a multilayer inversion strategy has been proposed to reconstruct a deep SCC by using multiple frequency ECT signals [3]. To obtain ECT signals of multiple frequencies, however, many inspections have to be performed and sometime the probe needs to be changed because of the frequency range. As it is difficult to keep testing conditions constant for different ECT testing, it is hard to achieve high-accuracy reconstruction results.

Pulsed Eddy Current Testing (PECT) technique [4] is a relative new NDT method. As its excitation current is in form of a pulse, PECT signals have rich frequency information and can catch information from relative deep position of targets under inspection. Recently, it has been proved that the PECT signal from a local defect is the superposition of multiple frequency ECT signals corresponding to the defect [5]. In other words, multiple frequency signals can be obtained from the PECT signal by using spectrum analysis. As the signals of different frequencies can be obtained at the same time, the testing conditions problem mentioned above can be avoided.

In this paper, a inversion scheme is proposed for sizing deep SCCs based on the multilayer reconstruction strategy by using the spectrum analysis of the PECT signals. Numerical simulation and validations are also presented.

II. Simulation Method for PECT Signals

To calculate PECT signal, a code of the time domain integration method based on the Ar formulation is developed. The constant time step Crank-Nicholson method is adopted to solve this transient eddy current problem.

Through Galerkin FEM discretization, the governing equations of electromagnetic field of the Ar formulation can be expressed as,

$$[K]\{A\} + [C]\{\frac{\partial A}{\partial t}\} = \{M\}I(t) \tag{1}$$

where $I(t)$ is the time function depended on excitation current, $[K], [C]$ are the global coefficient matrices. For transient problem, the derivative term $\partial A/\partial t$ can be replaced by using the time difference $(A^k - A^{k-1})/\Delta t$ with k being the $k-th$ time step, Δt being the time step and $A^k = A(k\Delta t)$. In order to improve the integration stability, the Crank-Nicholson direct integration method replace the vector A by

$$A = \theta A^{k-1} + (1-\theta)A^k, \tag{2}$$

where θ $(0 \leq \theta \leq 1)$ is a coefficient parameter to control the stability of the integration. By substituting equation (2) into equation (1), the vector potential A at present time step can be calculated through

$$\begin{aligned} &[[K](1-\theta)\Delta t + [C]]\{A^k\} \\ &= \Delta t\{M\}I(t_o + k\Delta t) + [[C] - [K]\theta\Delta t]\{A^{k-1}\} \end{aligned} \tag{3}$$

Based on the formulae described above, a numerical code to calculate PECT signals is developed based on an edge element code of Ar formulation. The validity of the PECT code has been verified by calculating conventional ECT signals whose excitation current was set as sinusoidal wave. Both the amplitude and phase of the signals can be properly calculated, which demonstrated the validity of the proposed method and the corresponding numerical code.

III. Correlation of ECT and PECT Signals

As well known, a square-wave can be represented by a summation of sinusoidal waves. Therefore, PECT signal under a square-wave excitation can be considered as a summation

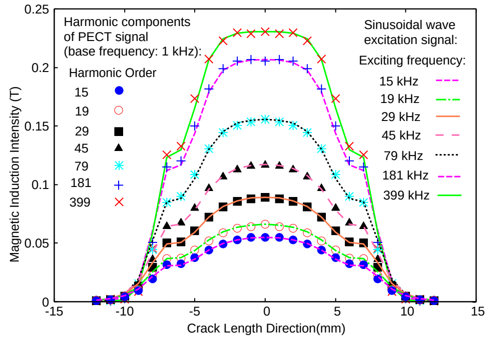

Fig. 1. Comparison of harmonic components of PECT signals and ECT signals of corresponding frequency under a sinusoidal wave excitation

of signals due to the excitation of single sinusoidal wave in different frequencies if the electromagnetic material properties are linear. Similarly, to know the signal due to a single frequency excitation, one only needs to get the signal component of corresponding harmonics from the PECT signal. Supposing that the probe excitation current I(t) is a square wave with $1/f_0$ period, 50% duty, and A_0 amplitude, the excitation current can be represented by a series of sinusoidal waves as,

$$I(t) = A_0/2 + A_0/2 \sum_{n=1,3,5,...} \frac{1}{n} sin(2n\pi f_0 t) \quad (4)$$

where n is the order of harmonic component. If denoting the response PECT signal due to current I(t) as P(t), it can be expressed as the following series,

$$P(t) = \sum_{n=1,3,5,...} [P_{an} sin(2n\pi f_0 t) + P_{bn} cos(2n\pi f_0 t)] \quad (5)$$

where the coefficient P_{an}, P_{bn} can be obtained through Discrete Fourier Transformation (DFT). Therefore, the real and imaginary parts *Re* and *Im* due to unit current source can be obtained as:

$$Re = 2nP_{an}/A_0, \quad Im = 2nP_{bn}/A_0. \quad (6)$$

Using the procedure and the numerical code described above, the PECT signals with the base frequency of 1 kHz due to a surface crack of 14 mm length, 4 mm depth and 0.2 mm width in a $200 \times 100 \times 10$ mm^3 SUS304 plate (conductivity:$1.4MSm^{-1}$) are calculated and different harmonic components (from $15th$ to $399th$ order) are extracted. To show the validity of these signals, a Ar code for conventional ECT problem is applied to calculate signals of corresponding frequencies (from 15 kHz to 399 kHz). Figure 1 shows good agreement between the harmonic components of the PECT signals and the conventional ECT signals for corresponding frequencies.

IV. Multilayer Inversion Scheme for A Deep SCC

If we subdivide the inspection target plate into many layers of same thickness, the crack signal of high excitation frequency mainly depends on crack profile at the near surface layers due to the skin effect. Therefore, if the crack profile at the surface layers has been obtained properly by using signals of high frequencies, a signal of smaller frequency is more suitable for the reconstruction of the crack profile at

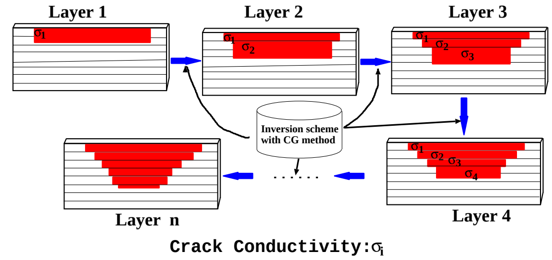

Fig. 2. Multilayer strategy for deep crack reconstruction

deeper layers. In this way, the sizing accuracy is possibly to be improved by using signals of multiple frequencies. Hereafter this method will be called as the layering analysis strategy.

In practice, the depth of each layer is set as a constant value referring to the skin depth of the selected highest excitation frequency, while the crack conductivity and length can be different in different layers. As the crack width and conductivity simultaneously affect the crack signal, the crack width can be taken as a constant for all crack segments if we consider the crack conductivity as an equivalent parameter [6].

In the layering analysis method, the crack profile of the top layer is predicted by adopting ECT signals of high frequencies and the conventional ECT inversion scheme [2]. By utilizing information reconstructed at top layers, the crack profiles of deeper layers can be evaluated by using signals of lower frequencies step by step. The layering analysis scheme based on multi-frequency signals is illustrated in Fig.2.

Based on the proposed inversion strategy, profiles of SCC models are reconstructed using the harmonics of PECT signals. The numerical results show that the proposed strategy is reasonable and can improve the sizing precision. The detailed reconstruction results will be given in the full paper.

V. Conclusions

In this paper, a spectrum analysis technology and layering scheme are proposed for the reconstruction of deep SCCs from PECT signals. The validity of the proposed scheme is demonstrated through reconstruction of several conductive notch cracks and an artificial SCC.

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References

[1] N.Yusa, Z.Chen and K.Miya, Sizing of stress corrosion cracks in piping of austenitic stainless steel from eddy current NDT signals, NDT&E Int., vol.20, pp.103-114, 2005.
[2] Z.Chen, M.Rebican, N.Yusa and K.Miya, Fast simulation of ECT signal due to a conductive crack of arbitrary width, IEEE Trans. Mag., vol.42, pp.683-686, 2006.
[3] L.Wang, Z.Chen, A multi-frequency strategy for reconstruction of deep stress corrosion cracks from ECT signals of multiple liftoffs, Int. J. Appl. Electromagn. Mech., vol.33, pp.1017-1023, 2010.
[4] J.Kim, G.Yang, L.Udpa, S.Udpa, Classification of pulsed eddy currentnext term GMR data on aircraft structures, NDT&E Int., vol.43, pp.141-144, 2010.
[5] S.Xie, Z.Chen, T.Takagi, T.Uchimoto, Development of Efficient Numerical Solver for Simulation of Pulsed Eddy Current Testing Signals, submitted to NDT&E Int., 2010.