Reconstruction of Conductivity Distribution of Stress Corrosion Crack from DC Potential Drop Signals

Wenlu CAI, Shejuan XIE, Xiaojuan WANG, Cuixiang PEI, Yong LI, Zhenmao CHEN*

State Key Laboratory for Strength and Vibration of Mechanical Structures, Xi’an Jiaotong University, Xi’an, 710049, China
* Corresponding author, Tel/Fax: 86-29-82668736, chenzm@mail.xjtu.edu.cn

Concerning the safety influence of Stress Corrosion Crack (SCC), its Quantitative Nondestructive Evaluation (QNDE) is significant to guarantee the structural integrity of nuclear power plants (NPPs). However, the QNDE accuracy of SCC is still not satisfactory especially for the electromagnetic NDE methods such as Eddy Current Testing (ECT). The unknown conductivity distribution in crack region is one of the key factors restricting the precision enhancement for SCC sizing with ECT. As an effort to solve this problem, the conductivity distribution is investigated in this work through inversion of measured direct current potential drop (DCPD) signals. The inversion strategy, consisting of an efficient forward DCPD signal simulator using multi-medium element and the conjugate gradient optimization method, is proposed and implemented for the reconstruction of the conductivity distribution around SCC region. The reasonable reconstruction results from measured DCPD signals of a SCC specimen validate the proposed scheme.

Index Terms — **Finite element analysis, Inverse problem, Nondestructive testing, Numerical analysis, Gradient method**

I. INTRODUCTION

Quantitative nondestructive evaluation (QNDE) of stress corrosion crack (SCC) is a necessary and critical issue for ensuring the integrity of nuclear power plants (NPPs). Eddy current testing (ECT), as an effective supplement of ultrasonic testing (UT) method for QNDE of NPPs, has advantages over UT for treating surface SCC [1]. A lot of studies have been conducted on the quantitative ECT of SCC and it was found that the conductivity around the SCC may significantly worsen the ill-posedness of inverse problem for crack reconstruction [2-4]. Up to now, few investigations have been reported related to the detailed conductivity distribution in SCC region. On the other hand, direct current potential drop (DCPD) method is a conventional way for global conductivity measurement [5-6]. However, whether it is applicable to evaluate local conductivity of SCC is not clear yet.

Based on the backgrounds, an inversion numerical scheme for evaluating the conductivity distribution around SCC from DCPD signals is proposed and implemented in this work. An efficient DCPD forward simulator with multi-medium element (MME) and the conjugate gradient (CG) optimization method are adopted for the conductivity reconstruction. From measured DCPD signals of the sliced SCC segments, 3D distribution of conductivity is obtained for a practical SCC.

II. INVERSION SCHEME FOR CONDUCTIVITY EVALUATION

To simulate the DCPD signals due to a SCC, the finite element method (FEM) using MME is applied as the forward solver. The CG inversion method is adopted to reconstruct the conductivity distribution in SCC area. During reconstruction, the geometric profile of the SCC is supposed as known parameters and was observed with a microscope from the sliced SCC planar segments.

A. Forward simulation of DCPD signals with MME

A forward numerical simulator is necessary to calculate the DCPD signals due to a SCC for reconstruction of crack conductivity. Concerning the complicated geometric profile of SCC, a 3D FEM code using MME developed by authors is updated at first for the efficient simulation of DCPD signals due to a SCC [7]. Covered by both air and base material (conductor) regions, MME is very efficient to treat crack with complicated boundary, such as the SCC [4].

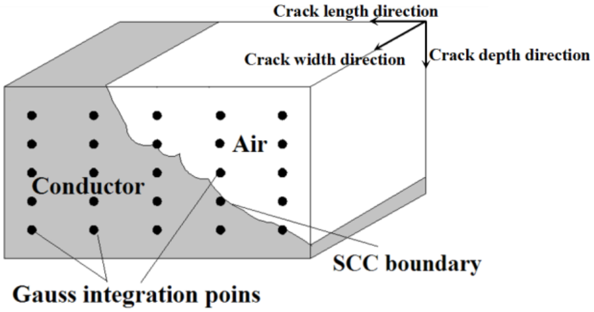

Fig. 1. The multi-medium element filled with different materials

To calculate the element coefficient matrix of MME for a SCC, the algorithm described in [7] can be simplified, as the width of SCC region is known and the conductivity is constant in the crack width direction. In such a case, the SCC region can be discretized by the MME as shown in Fig. 1, i.e., no material change in the crack width direction. By separating the Gauss integration points into crack and conductor groups based on the crack bottom boundary curve, the element coefficient matrix of a MME can be calculated by summing up the values at all the Gauss points with

$$\left[K\right]_e = h\sum_i \sigma_{\mathrm{i}} \nabla\{N\}^T \cdot \nabla\{N\}, \tag{1}$$

where $\{N\}$ is the shape function vector and h the crack width. Thus the computational efficiency can be greatly improved.

B. Inversion strategy

In this work, the CG inverse strategy is updated for the reconstruction of the conductivity distribution in SCC region together with the efficient forward solver just stated [8].

In practice, reconstruction of SCC from DCPD signals also can be expressed as an optimization problem, i.e., to search the optimal parameter vector {**b**} of SCC to minimize the error function between the measured DCPD signals $\{u^{exp}\}$ and the simulated ones $\{u^{sim}\}$ due to the SCC of profile {**b**}, and the optimization problem can be defined by objective function

$$\varepsilon(\mathbf{b}) = \sum_{m=1}^{M} (u_i^{sim}(\mathbf{b}) - u_i^{\exp})^2. \tag{2}$$

In general, crack profile vector {**b**} of a SCC consists of the crack shape and conductivity information. Aiming to get the 3D conductivity distribution in a relatively simple way, only conductivity distribution along the crack depth direction is taken as the crack parameters in this work, i.e., to slice the SCC test-piece into planar segments perpendicular to the crack length of given thickness and to reconstruct the crack conductivity slice by slice. The crack depth is supposed as a known value during the inversion as it can be observed with a microscope for the sliced planar SCC segments. By using the DCPD signals measured for each sliced segment, the 3D conductivity distribution of SCC can be reconstructed. In practice, the conductivity distribution along the crack depth is approximated with a polynomial function and its coefficients are taken as the reconstruction targets.

III. VALIDATIONS

A. *Experiments for DCPD signal collection*

To validate the DCPD method for conductivity evaluation of SCC, 4-probe DCPD experiments are conducted to collect DCPD signals of the sliced SCC planar segments. At first, a SCC specimen of 304 stainless steel plate is cut into 5 thin planar segments of 1.5 mm thickness perpendicular to the crack length direction. By applying DC current of 1 A from the two edges of the small planar segment (Fig. 2), DCPD measurements are conducted and the potential distributions at the segment surface are measured by scanning one of the pickup electrodes with an automatic stage in a pitch of 0.02 mm. The potential drops between the neighboring scanning points are extracted and applied to evaluate the SCC. As an example, a measurement result along the top edge of the planar segment is shown in Fig.2 as the solid line.

B. *Numerical example*

As a numerical example, the measured DCPD signal shown in Fig. 2 is adopted to reconstruct the crack conductivity with the crack depth at the selected SCC segment set as 2 mm. Due to the geometric complicity of SCC, the crack width is set as a small equivalent value 0.02 mm, which contains the whole crack region inside. In addition, the crack depth and width are supposed no change in the thickness direction of the sliced segment. As a preliminary simulation, the conductivity is set at first as a constant in the full crack region, i.e., only zero order polynomial is considered as the function of conductivity distribution. Fig. 2 shows the DCPD signals simulated with the updated DCPD code (dash lines) for relative crack conductivity of 1%, 2%, 3%, 4%, 5%, and 6% respectively. Comparing with the measured signals, one can find that the average conductivity at the SCC region is about 4%. To find the conductivity distribution in the crack depth direction, 2D signals measured at the whole cross-section surface of the planar segment are necessary. In addition, for a crack with branch structure, a more complicated numerical model is needed. By reconstructing conductivity distribution along crack depth segment by segment, the 3D conductivity of the whole SCC can be finally obtained. The detailed results will be presented in the full paper.

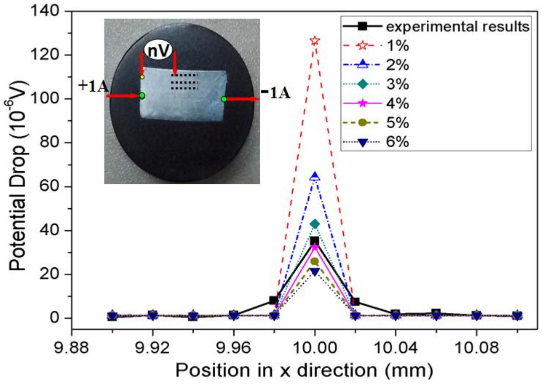

Fig. 2. Comparison of experimental signals and calibrated simulation results

IV. CONCLUSIONS

In this paper, an inversion strategy, consisting of an efficient forward DCPD signal simulator with MME and the CG inversion method, is developed to reconstruct the conductivity distribution around a SCC. The reasonable reconstruction results from the measured DCPD signals of a practical SCC demonstrate the validity of the proposed numerical scheme.

ACKNOWLEDGEMENTS

The authors would like to thank the National Magnetic Confinement Fusion Program of China (2013GB113005), National Science Foundation of China (No. 51277139, 11321062, 51407132) and National Basic Research Program of China (2011CB610303) for funding this study.

V. REFERENCES

[1] W. Cheng, S. Kanemoto, I. Komura and M. Shiwa, “Depth sizing of partial-contact stress corrosion cracks from ECT signals,” *NDT&E Int.*, vol. 39, pp. 374-383, 2006.

[2] Z. Badica, J. Pavo, H. Komatsu, S. Kojima, Y. Matsumoto, and K. Aoki, “Fast flaw reconstruction from 3D eddy current data,” *IEEE Trans. Magn.*, vol. 34, no. 5, pp. 2823–2828, 1998.

[3] N. Yusa, H. Huang and K. Miya, “Numerical evaluation of the ill-posedness of eddy current problems to size real cracks,” *NDT&E Int.*, vol. 40, pp. 185-191, 2007.

[4] Z. Chen, M. Rebican, N. Yusa and K. Miya, “Fast simulation of ECT signal due to a conductive crack of arbitrary width,” *IEEE Trans. Magn.*, vol.42, no. 4, pp. 683-686, 2006.

[5] N. Yusa and H. Hashizume, “Four-terminal measurement of the distribution of electrical resistance across stress corrosion cracking,” *NDT&E Int*., vol. 44, pp. 544-546, 2011.

[6] W. Cai, H. Chen, S. Xie, Y. Li, Z. Chen, T. Uchimoto, T. Takagi and Y. Kensuke, "A study on influence of plastic deformation on the global conductivity and permeability of carbon steel," *Int. J. Appl. Electromagn. Mech.*, vol. 45, no. 1-4, pp. 371-378, 2014.

[7] X. Wang, S. Xie and Z. Chen. “An efficient numerical scheme for sizing of cavity defect in metallic foam from signals of DC potential drop method,” *IEEE Trans. Magn.*, vol. 50, no. 2, pp. 125-128, 2014.

[8] J. Zhang, S. Xie, X. Wang, Z. Chen and Y. Li, “Quantitative NDT of metallic foam based on direct current potential drop method,” *IEEE Trans. Magn*., vol. 48, no. 2, pp. 375-378, 2011.