A New Approach for Optimal Design of Eddy Current Testing Probes

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The optimal design of ECT probes for advanced nondestructive inspection of steam generator tubing in nuclear power plants is studied in this paper. A new approach for probe design is proposed, on basis of both a simplified detectability analysis method and a ring current model newly developed by the authors. The new approach is incorporated in the optimization of pick-up arrangements as well as the corresponding excitation coils. Two designs of a potential ECT probe which may show high performance in practical applications are proposed finally. In addition, the ring current model and the simplified detectability analysis method are validated further for a conducting tube by comparing the magnetic field perturbation due to a crack and the S/N ratios evaluated by the present method and an FEM-BEM hybrid code respectively. Consequently, the validity of the new design approach and the high performance of the new probe designs are assured.

KEY WORDS: ECT; probe optimization; simplified approach; steam generator tubing.

1. INTRODUCTION

The Eddy Current Testing (ECT) technique is indispensable in the In-Service Inspection (ISI) of Steam Generator (SG) tubing of nuclear power plants. The reliability and detectability of the ECT technique are strongly required to be enhanced because of the increasing importance to ensure the safety of SG tubing of the Pressurized Water nuclear Reactor (PWR). Considerable effort is being made in two major directions for the purpose. One is an improvement of detection sensitivity and the other the development of efficient and suitable data processing and inversion techniques. The development of new probes of higher performance plays a dominant role in the acquisition of ECT data with high signal to noise (S/N) ratio with use of the probes. The present work will contribute to this subject by proposing a new design approach and the new ECT probes designed by using the method.

Conventionally, the ECT probes have been designed on the basis of empirical experiences. The recent development of the electromagnetic field computation techniques⁴⁻⁶,²¹ enables us to apply the finite element, boundary element or volume integral methods to the detectability analysis of ECT probes. The problem with the numerical approach, however, is the high computational cost. At the same time, systematic design methodology is still not available yet for guiding the development procedure of new ECT probes. As well known, the basic difficulty of the optimized design of ECT probes is caused by the many parameters to be determined—not only the parameters of a given probe configuration but also the parameters of its shape and arrangement such as the number of the excitation and pick-up coils which also need be modified. Therefore, it is difficult to choose the best probe parameters by a normal optimization scheme unless the basic structure of a probe with potential high performance can be known a priori. To determine this basic structure, some qualitative methods are

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necessary for predicting the crack-probe interaction and the probe detectability.

Several simple models have been developed for the qualitative description of the eddy current perturbation due to a crack.\(^{(3-5)}\) One of them is the current loops model proposed by Atherton.\(^{(5)}\) However, this model does not consider the effect of the crack opening which may significantly affect the pick-up signal in case of a shallow artificial crack (EDM notch) problem. The present authors have modified the current loops model by introducing an additional set of ring currents to take into account this effect.\(^{(6)}\) In the same paper, we also proposed a simplified relationship to describe the connection between \(B_0\), the source magnetic flux density of the driver coil (hereafter, we call it excitation magnetic field), and \(J_e\), the eddy current density induced in an unflawed conducting plate. Using this \(J_e-B_0\) relation and the ring current model, a simplified approach to the detectability analysis has also been developed. It is likely that the ring current model and the simplified detectability analysis method satisfy the requirements of a qualitative analysis during the probe design. In this work, we first extend the theory to a conductor of tube geometry, and then, propose a systematic approach for the probe design based on this theory, i.e., optimizing the pick-up arrangement with use of the ring current model and determining the corresponding excitation using the simplified detectability analysis method.

In the present paper, the simplified \(J_e-B_0\) relation and the corresponding approximate detectability analysis method are described for a tube geometry in Sect. 2. A further validation of the proposed ring current model is also presented. In Sect. 3, some possible excitation coils are proposed and the corresponding optimal arrangements of pick-up coils are analyzed based on the ring current model. The optimal probe designs are developed in view of the combinations of these excitation and pick-up coils by comparing their detectabilities evaluated with the simplified analysis method. The new approach for probe design is then summarized concerning this typical example of new ECT probe development. Finally, two probe designs which may have higher S/N ratio in practical applications are proposed based on this procedure.

To validate the new approach, detectability analyses of over ten probe structures are carried out by using an FEM-BEM hybrid code. The results of the accurate numerical code verified the high signal-to-noise ratio of the proposed new probe structures. Based on these basic structures, the optimization of the detailed profiles and the experimental validations can be performed later.

2. THE SIMPLIFIED METHOD FOR PROBE EVALUATION

2.1. Relation Between the Source Magnetic Field and the Induced Eddy Current

There are many ways to evaluate the eddy current induced by the excitation magnetic field. However, an analytical solution has a complicated infinite integral form\(^{(7,8)}\) even for very simple conductor geometry such as a tube. It is difficult to get a clear image about the eddy current distribution in terms of density and pattern from these conventional methods without complicated numerical computations. Because of this, we have proposed a phenomenological relationship to describe the connection between the the source magnetic flux density and the induced eddy current distribution for a non-magnetic conducting plate in Ref. 6. A validation of this relation has been given in the paper by an analytical derivation as well as comparisons with the results of an accurate numerical code. Through numerical calculations of the eddy current distribution for different frequencies and different arrangements of excitation coil, we found the relation is also approximately true for a tube geometry when a crack or abrupt deformation is absent and the probe is placed free of the conductor edge effect. This simple relation in a cylindrical coordinate system (see Fig. 1) is expressed as:

\[
J_e (r, \theta, z, t) = \alpha (r, \omega) n \times B_0 \left[ n_0 (\omega), \theta, z \right] \cos [\omega t + \phi (r, \theta, z)]
\]