MODELING PITTING AND CORROSION PHENOMENA BY EDDY-CURRENT VOLUME-INTEGRAL EQUATIONS

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Abstract: We apply **VIC-3D©**, a proprietary volume-integral code for eddy-current non-destructive evaluation (NDE), to the problem of simulating the response of a probe to pitting. We utilize the solid-model library in **VIC-3D©** to simulate pitting found in heat-exchanger tubes and aerospace structures by means of three-dimensional ellipsoids. We demonstrate the forward problem of determining the response of the probe to a known pit, and then the inverse problem, in which a pit has been machined into a stainless-steel substrate, and multifrequency data are obtained by means of a Hewlett-Packard network analyzer. The resulting impedance data are inverted by using a nonlinear least-squares estimator that is a part of the post-processing capability of **VIC-3D©**. The result of the inversion is an estimate of the size of the pit, given by the lengths of the three semi-axes of the approximating ellipsoid, and the location of the pit.

Introduction: In this note we describe our initial results in modeling pits as three-dimensional semi-ellipsoids that originate in the inner-radius of tube walls. The defining parameters of the ellipsoid are the semi-axes, A, B, and C, with A and B along the wall, and C normal to it. By modeling the pit in this manner, we hope to simplify the inverse problem, which is to determine the size of the pit (especially its depth) from measured data. In this case we hope to determine the three semi-axes, thereby solving the inverse problem. Clearly, C determines the depth of the pit.

The idea of representing the pits as semi-ellipsoids was motivated partly by photomicrographs of actual pits that appear in certain heat-exchanger tubes in nuclear power plants. Furthermore, these photomicrographs gave us insight into the sizes of typical pits, which was then translated into values of A, B, and C for such pits. Indeed, from these photomicrographs we see that the pits appear to be circular, when looking into the inner surface of the tube, with a nominal radius of 0.0625 inch. Hence, we model these pits by setting A and B equal to 0.0625 inch. We then choose C to be equal to the difference between 0.049 inch (the nominal wall thickness of the heat-exchanger tube) and the minimum measured wall thickness, as given in the photomicrographs.

In carrying out the model calculations of this report, we assume that the tube is made of 90-10 Copper-Nickel, whose electrical conductivity is 5.277×10^6 S/m (9.1% IACS), and is nonmagnetic. The outer diameter of the tube is 0.75 inch, and the nominal wall thickness is 0.049 inch.

Results: The major modeling effort deals with the inversion problem, first for individual semi-ellipsoidal pits, which we call simple pits, and then for complex pits, which consist of three intersecting simple pits. The simple pits are models of actual pits found in a heat-exchanger tube, whereas the complex pits model conditions that could exist in a heat-exchanger tube or in a wing station of an F-15 aircraft. Finally, we performed a multifrequency benchmark inversion test using an actual pit that was machined into a block of stainless steel.

In approaching the inversion problem, we generated model data using **VIC-D©**, and used these data to simulate measured impedance data, which were then submitted to the nonlinear least-squares estimator, NLSE, that is a part of the postprocessing capability of **VIC-3D©**. The output of NLSE is an estimate of the semi-axes, A, B, and C of the ellipsoidal pit.

The results of the numerical and benchmark experiments indicate that the algorithm for nonlinear estimation is reliable and robust. The important point to be made from this study is the reliability in reconstructing C, the semi-axis that determines the depth of the pit. Indeed, the results of the algorithm indicate that the computation is more sensitive to depth than to the lateral dimensions, which is exactly what we're looking for.

Discussion: **VIC-3D©** is used in two distinct manners in this study. First, it is a volume-integral electromagnetics code that efficiently solves the forward problem of determining the probe-flaw interaction that is the basis of the inverse problem. Secondly, its post-processing filter, NLSE, is an efficient nonlinear least-squares estimator that quickly solves inverse problems that contain a modest number of unknown parameters. In this case the unknowns are the semi-axes of a semi-ellipsoidal pit.

We have introduced in this study a method of systematically modeling complex pits that are generated by the intersection of simple pits. We used 0.0625 inch as a typical value of the lateral resolution of complex pits. The z-directed semi-axis of each simple pit, therefore, becomes the unknown that determines the shape of the complex pit, and it is these values that are determined by the inversion process. The solution of the inverse problem is quite robust, given input data in the form of either a spatial or frequency scan. The reader is referred to our website, **http://www.kiva.net/~sabbagh**, for a complete analysis of this study.