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EXPLORING PARAMETRIC-MANIFOLDS FOR EDDY-CURRENT DEFECT CHARACTERISATION

Robert R. Hughes[1] and Bruce Drinkwater
University of Bristol
Bristol, UK

ABSTRACT

The service lifetime of industrial components relies on an understanding of the size, location and orientation of defects present in the materials. This is often over-estimated due to inadequate methods of identification and characterisation in NDE techniques. Multi-frequency eddy-current measurement methods offer a promising way of obtaining sufficient information to accurately characterise and size surface-breaking defects. In this study a parametric-manifold database search approach is employed to low-MHz range eddy-current impedance spectra measurements, to characterise such defects. An in-house, air-cored solenoid coil sensor was used to inspect for surface-breaking defects and a hybrid finite-element and equivalent-circuit model was developed to simulate the impedance over a range of frequencies around it's electrical resonance. The hybrid-model was optimised, calibrated and validated against experimental standoff/thickness measurements demonstrating accuracy over small standoff distances. The model was used to simulate a database of 2D scans of surface breaking notches over a range of frequencies and a principle component parametric-manifold approach was employed to evaluate the sensitivity of the sensor and frequency range. Finally, simulated and experimental defects were characterized in Titanium 6V-4Al and Aluminum.

Keywords: electromagnetism, eddy-current testing, ECT, defect characterization,

NOMENCLATURE

ECT	Eddy-Current Testing
FE	Finite element
PC	Principle Component
EDM	Electro-discharge machined

1. INTRODUCTION

Eddy-current inductive sensing is a widely used and highly sensitive non-destructive evaluation (NDE) technique for the detection of potentially dangerous surface damage in high-value industrial components. Unchecked this damage can cause the critical failure of important infrastructure (transport, aerospace, oil and power) [1].

Unlike other NDE techniques, eddy-current testing (ECT) inspections are highly sensitive to very small (<1 mm) surface defects and can be implemented in-situ, without requiring couplants (ultrasonic methods) or expensive safety precautions (radiography). However, one of the major limitations of commercially used ECT systems is their inability to size and characterise defects effectively. Instead they are primarily used for defect detection in rudimentary screening tests. Modern manufacturing processes of high-value components require ever greater knowledge of the size and extent of defects in parts to evaluate the structural integrity and safety of these parts. As a result, significant ECT research has focused the development of defect inversion models as well as characterisation and classification techniques [2-4].

In this paper, we present a method for characterizing surface-breaking defects from resonant eddy-current impedance spectra scan data [5], by generating and searching a defect database from a hybrid finite-element (FE) and equivalent-circuit model. The characterization approach follows Velichko et.al. [6], employing principle component analysis (PCA) to generate N-dimensional parametric manifolds in principle component space (PC-space) from the scan database and characterization is achieved via an assessment of a test measurements proximity to the manifold.

This paper outlines the development, calibration and validation of the hybrid FEM-circuit model for simulating the behavior of a coil, electrically-resonant in the low MHz (<10 MHz) frequency range, and demonstrates the use of this model

[1] Contact author: Robert.hughes@bristol.ac.uk

for characterizing slot and notch dimensions in non-ferromagnetic materials via the parametric-manifold method.

2. MATERIALS AND METHODS

2.1 Experimental Setup

A TE3001 Impedance analyser was used to measure the impedance frequency spectra of an absolute ECT coil during 2D raster scans of the surface of test defects in Aluminum and Titanium 6Al-4V (Ti6-4). For the purposes of this investigation, rectangular electro-discharge machined (EDM) notches and slots are considered, both in simulation and in experimental validation.

2.2 Model Optimisation & Calibration Procedure

An FE model of the coil was developed to simulate the electromagnetic behavior of the physical absolute coil sensor. This was integrated into a equivalent-circuit model representing unknown properties of the coil and cable connections.

Unknown physical and circuit parameters of the hybrid model were optimized against experimentally measured impedance spectra using linear interpolation and least squares minimization genetic algorithms. Similar optimization methods were employed to optimize and validate the simulated stand-off distance of the FEM model from the surface of test materials. This process demonstrates an effective calibration procedure for implementing defect characterization.

Once the model optimization, calibration and validation process is complete, a parametric database of 2D scans above notch and slot defects of varying dimensions is performed.

2.3 Parametric defect database

A parametric study of EDM defect dimensions was performed, simulating the coil impedance over a range of frequencies as a function of position relative to the center of each defect. Due to the defect axes of symmetry, only one quadrant of the scan was required. The full scans were then reconstructed from this quadrant.

2.4 Parametric-Manifolds & Defect Characterisation

The simulated 2D impedance scans were used to generate parametric-manifolds by applying PCA to the parametric database. In this way, each simulated defect scan is condensed into a handful of principle eigenvalues. A parametric manifold can then be created from the defect "vertices" in N-dimensional PC-space. The shape, extent and variance of the manifold provides information about the sensors ability to successfully characterize defect dimensions.

Test defect scans were performed, both experimentally and using the optimized hybrid-model, and placed in the same PC-space as the manifold. Euclidean distances can then be used to determine the closest defect dimension match and noise estimations used to determine the estimation error.

3. RESULTS AND DISCUSSION

3.1 Model Optimisation & Calibration

A hybrid FE-Circuit model was developed and calibrated in 3 calibration steps. The first step uses optimised unknown parameters of the FE component of the model to match the experimentally measured inductance of the coil in air (free space). The second calibration stage uses a least-square minimization via differential evolution to optimise unknown circuit parameters of the whole sensor (coil connected via a transmission-line cable) against experimentally measured impedance spectra in air. Finally, the third calibration stage optimised the coil standoff from a given material surface in the FE model to match experimental measurements of the inspection setup.

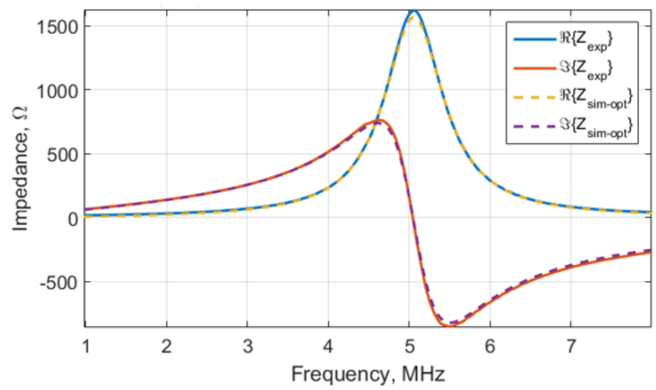

FIGURE 1: Optimised and calibrated hybrid-model complex impedance profile of a coil sensor about Ti6-4 compared to experimentally measured impedance spectra.

The optimised impedance spectra of the model is shown in Figure 1 at the final calibration stage compared to the experimental impedance spectra, demonstrating strong correlation.

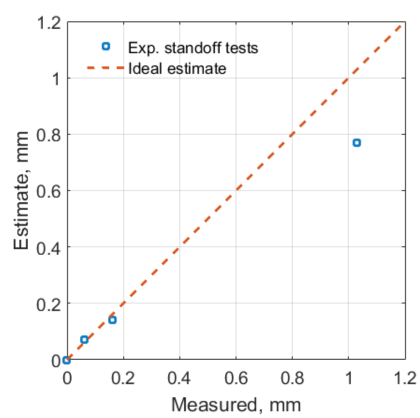

FIGURE 2: Model validation estimating material standoff distances above Ti6-4.

The model was then validated by estimating standoff distances of the coil from the surface of a given material. The results demonstrate that the model is valid only for small standoff distances (<0.5mm) but deviates from and underestimates the true value as the distance increases (see Figure 2). The implications of the standoff validation is that the model is ineffective at modelling certain proximity perturbation phenomena.

3.2 Generating a Defect Database

The validated hybrid FE-Circuit model was deployed to parametrically simulate different defect dimensions. Defect surface length and depth were varied in the FE model, and 2D scans of the material surface over the defect were simulated producing a 2D defect parameter database of 2D complex impedance spectra scans, $\tilde{Z}(x, y, f)$, shown for a single frequency in Figure 3.

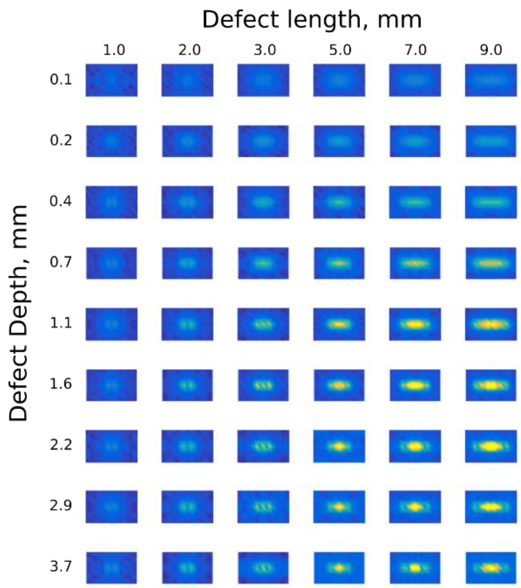

FIGURE 3: Defect parametric database showing simulated 2D impedance scans of surface breaking EDM notches at a single frequency.

From this dataset, specific frequencies can be selected and PCA used to identify new axes of significant coherent variation between defects of different dimensions. Plotting these PC eigenvalues for each defect generates a surface manifold, as shown in 3D PC-space in Figure 4.

The shape and distribution between vertices of these parametric defect manifolds provide valuable information about the sensitivity and suitability of a given sensor, and the frequency selection, to target defects. These manifold properties are quantified and explored as a function of frequency of excitation for both magnitude and phase components of the complex impedance.

3.3 Defect Characterization

Experimental and simulated defect scans were performed and used as test measurements for defect characterisation by transposing them into the same PC-space as the manifold.

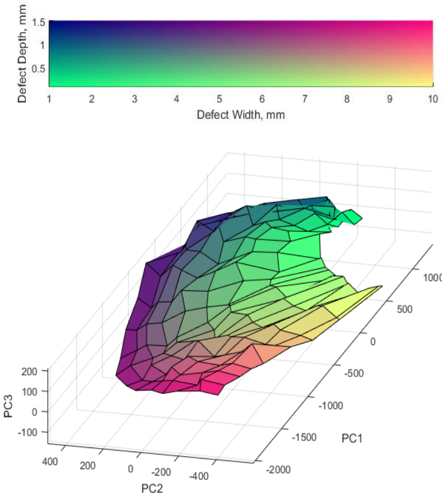

FIGURE 4: Example defect parametric manifold in 3D PC-space for EDM notches in aluminium.

4. CONCLUSION

In this paper we demonstrate a methodology for developing and validating a MHz range, resonant frequency spectra hybrid FE-circuit model of an eddy-current absolute testing coil sensor. This model was used to generate large databases of 2D defect scans which can be used for defect sizing and characterization following a principle component, parametric-manifold technique.

The results of this work represent the starting point for developing sophisticated multifrequency ECT inversion processes and could provide a more robust understanding of resonant behavior and it’s influence of defect detectability, sizing a characterizability. The approach outlined can also be used for a range of applications including sensor design and frequency selection optimization for different target defect types in different materials.

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