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Model-assisted NDT for sub-mm surface-breaking crack detection in alloys

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Abstract

A model has been developed to quickly and accurately simulate the response of eddy current probe to sub-mm crack in alloy. Electromagnetic (EM) modeling technique employed a fast and yet stable integral equation (IE) method. Enhanced detection can be achieved via an EM circuit co-simulation approach, which significantly boosted the response signals above the background noise threshold. With this, surface breaking cracks is detected by the resonant frequency-shifting of eddy current response. The developed model was validated by comparing simulated results to the experimental response obtained using an eddy current data collection system.

1. Introduction

Eddy current (EC) inspection is used extensively in the Non-destructive Testing (NDT) industry to detect surface-breaking defects in electrically conductive engineering components. However, in the last few years the sensitivity of eddy current inspection has plateaued. For example, currently the smallest size of fatigue crack that can be reliably detected is approximately 0.8 mm in length and 0.4 mm in depth [1]. Besides making use of advanced signal/image processing techniques [2] to improve the signal-to-noise ratio (SNR), there are testing methods developed to overcome the limitation in detection capability of the conventional eddy current inspections such as pulsed eddy current (PEC), and near electrical resonance signal enhancement (NERSE) [3, 4].

In fact, the ability to detect smaller defects would allow engineering components to remain in-service safely for longer [5]. This requires optimization process of EC testing has to be performed; but it is usually time-consuming and costly to conduct such process through practical trials. Hence, there is an opportunity to use high-fidelity computer models to simulate eddy current inspections for optimizing equipment design, testing parameters and signal processing to further enhance the detection sensitivity.

Many eddy current models that employed electromagnetic modeling techniques such as Finite Element Method (FEM) or Integral Equation (IE), have been developed over the years for emulating NDT inspections. The FEM-based model is accurate in handling three-dimension (3D) complex shapes with inhomogeneous (bulk) materials; but still time-consuming, especially, for solving multi-scale problems, where large number of elements needed for meshing small features. The IE-based model, on the other hand, requires much less number of meshes for addressing such multi-scale problems resulting in very fast solution; however, this is not very efficient to handle complex geometries and nonhomogeneity [6, 7]. In addition, there is growing interest in adopting model-based inversion technique for quantifying the depth information of cracks, making fast and efficient eddy current models more and more attractive [8, 9]. With this, the FEM-based model, due to its computation complexity for achieving sufficiently real-time operation requirement in NDT, would not be a promising choice.

In this paper, attempt has been made to develop a fast model to simulate the response of eddy current probes to small cracks (especially closed fatigue crack with bridge connection) in multi-layered conducting structure; with the ultimate aim for its application in inversion-based NDT. The contribution of this work is in the development of a more stable IE-based model to evaluate the impedance variation due to cracks within the layered structure, and to provide a flexible interface for coupling with circuit analysis to perform the NERSE simulation, whereby the response signals can be significantly boosted above the electrical noise. The developed simulation model was validated using practical experiments on commercially available probes.

2. Modeling Methodology

2.1 Electromagnetic modeling

The electromagnetic (EM) model of ferrite-core current coil above a layered electrically conducting structure has been developed to simulate the response of eddy current due to the existence of cracks within the structure. The impedance variation due to crack within such conductive media can be calculated via by the reciprocal theorem, as:

$$\Delta Z = -\frac{1}{I}\int_{\text{coil}} \Delta\bar{E}(\bar{r}) \cdot \bar{J}(\bar{r}) d\bar{r} = -\frac{1}{I}\int_{\text{crack}} \bar{E}^{\text{inc}}(\bar{r}) \cdot \bar{J}^{\text{ind}}(\bar{r}) d\bar{r}\,, \quad (1)$$

where $\bar{E}$ is the total electric field, and $\bar{J}$ is the current density of the coil with I the current carrying on each turn of the coil; $\bar{E}^{\text{inc}}$ is the incident electric fields on the crack from the coil and the ferrite, and $\bar{J}^{\text{ind}}$ is the induced electric current on the crack due to the change of the material within the conductive media [6].

Eq. (1) can be solved using integral equation, where the computational complexity and the stability of the algorithm are mainly addressed in the computation of the incident fields that involves the solution of the integral equation (2) describing the field behavior within ferrite structure:

$$\bar{H}(\bar{r}) = \bar{H}^{inc}(\bar{r}) + (-i\omega\epsilon_0)\int_D \bar{\bar{G}}(\bar{r},\bar{r}')\,\bar{M}(\bar{r}')d\bar{r}' , \quad (2)$$

where $\bar{\bar{G}}(\bar{r},\bar{r}^{'})$ is the dyadic Green's function for the background layered media [10]; D is the ferrite domain; $\bar{r}$ and $\bar{r}^{'}$ are the computation points within D; $\bar{H}$ is the magnetic field, and $\bar{H}^{inc}$ is the incident magnetic fields from direct incidence from the coil and reflected incidences from the layered media; $\bar{M}$ is the induced magnetic sources within the ferrite structure; ϵ_0 and μ_0 are the permittivity and the permeability, respectively. The relation between the magnetization and the magnetic field $\bar{M}(\bar{r}) = i\omega\mu_0[\mu_r(\bar{r}) - 1]\bar{H}(\bar{r})$ can be employed for solving (2) using the method of moments (MoM) with Galerkin's scheme to find out $\bar{M}$, with which the total incident electric fields from the coil and the ferrite structure within the conductive layered media can be obtained.

The calculation can be further accelerated to address the issue of a fully dense matrix due to the interactions between the induced secondary magnetic sources within the ferrite structure based on the fast multipole method, which could drastically reduce the costs from O (N^2) to O ($N\log N$) where N is the matrix size.

In the proposed model, the reflected waves from the layered media were constructed by using the phase matching scheme in the boundary conditions, accomplished by an iterative solver such as conjugate gradient method result in a stable solution [10].

2.2 EM circuit co-simulation

Enhanced response of eddy current signal via resonance can be achieved by incorporating the EM model into an equivalent lumped electric circuit, which can be solved in SPICE-like circuit simulators [11] to perform the system-level simulation of the eddy current NDT system. Here, the equivalent circuit of the 3D EM structure is a 1-port network with its parameter can be represented by the impedance found by solving the EM problem in the previous part. This can be imported to the circuit simulator via an ASCII text file. The effect of the co-axial cable, which connects the current source to the eddy current probe, was taken into account by its characteristic capacitance C. The equivalent circuit model is shown in Fig. 1, where the Touchstone (TS) file accounts for the response of EM model; and the resistance R is the internal resistance value of the coil.

The electromagnetic coupling occurs between the eddy current coil and the component surface when the coil is in close proximity to a conducting structure. The defect-decoupling phenomenon can be observed with the presence of defects on the inspection surface, which is caused by the reduction in the coupling coefficient from that of the eddy current system coupled to an undamaged surface. This will result in a shift in the resonant frequency of the response signal [4].

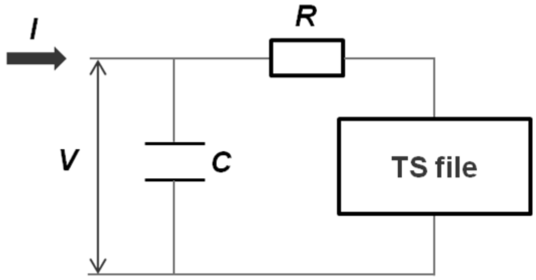

Figure 1. Coupled eddy-current probe equivalence circuit; Touchstone file contains the coupling interaction from the 3D EM simulation.

3. Model-assisted NDT

The developed model is employed to simulate the eddy current inspection system at resonance in order to show its ability to optimize the equipment design of such NDT system for sub-mm crack detection in alloys. This is demonstrated through the experiment conducted using a built eddy current testing system, an available commercial eddy current probe, and a Ti 6AL4V calibration block with an artificial defect on its surface.

3.1 Eddy current data collection system

An eddy current data collection system was developed to obtain the necessary data for analysis and comparison. An automated scanning system was also incorporated to allow for accurate and repeatable measurements to be taken. The schematic diagram of the data collection components are presented in Fig. 2. The data collection system is connected to the EC single coil probe which is mounted on a spring-loaded probe holder. The test specimen is placed on the X-Y linear actuation stage which is manipulated via the laptop connected to the stage controller using LabView. The probe holder secures the EC single coil probe in position while the test specimen moves under it in a raster scan motion.

X-ray Computed Tomography (CT) image of a commercially available probe were taken to extract the actual parameters of the eddy current coil. The Titanium 6AL4V test piece (part number SRS-0824T supplied by Olympus IMS) was characterized to obtain its bulk material properties and the actual dimensions of the artificial defect – electrical discharge machining (EDM) notch along the width of the test piece – it contains. In fact, the notch defect, which is in the sub-mm range, is deliberately chosen in order for it to be detected using our testing system following the NERSE approach [4]. All specification information of the EC system was given in Table 1.

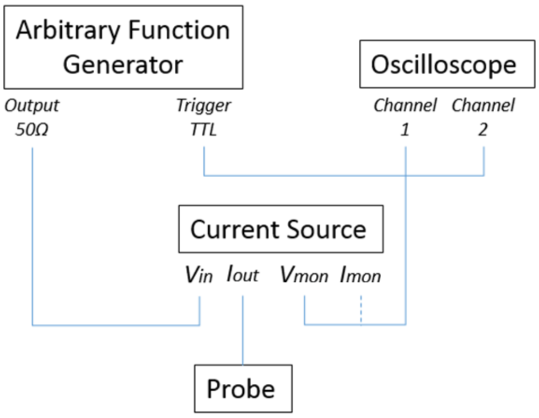

Figure 2. Schematic diagram of eddy current data collection system set-up: an arbitrary function generator to provide single-frequency, chirp and pulse excitation; a Howland Current source to convert the excitation voltage into an equivalent current input; a digital oscilloscope collects the eddy current response data received from the probe.

Table 3. Probe, test piece, and system specifications

Parameters (unit)	Value
Frequency range (MHz)	1 to 6
Driven current source (A)	0.05
Coil: inner radius (mm) outer radius (mm) height (mm) liftoff (mm) number of turns	 0.45 0.77 1.00 0.08 44
Ferrite: core radius (mm) cap size (mm) core-length (mm)	 0.45 0.55 1.94
Total capacitance of the co-axial cable (pF)	184.8
Ti 6AL4V: dimension (mm) conductivity (S/m)	 (L) 110 x (W) 26 x (H) 7 5.8×10^5
Notch defect: width (mm) depth (mm) profile	 0.18 0.52 round

3.2 Simulation results

Fig. 4 shows the results of the calibration with the probe operating in air and on the Ti 6/4 test specimen on an area away from the notches. The simulated result is in good agreement with the experiment one, where the error percentage is less than 2% (i.e. position of resonance frequency). It can be seen that the response signal near resonant peak is enhanced up to 300%. The result of the notch testing (with defect) from the experimental data collection system was shown in Fig. 5. As expected, we can observe a resonant frequency-shifting of 0.0196 MHz in case of defect from that without defect when the EC probe passes over the notch. Comparing to the experimental result, a good agreement can be observed from that of the simulation as in Fig. 6, where there is a frequency shift of 0.02 MHz due to the damaged component surface. In fact, the discrepancy between measurement and simulation is relatively small that the shifted frequency between the undamaged and defect response can be observed clearly for defect detection. This shows the developed model could be used to design an optimized system for enhancing the detectability of given crack sizes in alloys (e.g. fatigue crack).

However, there are uncertainties that need to be identified in order to obtain a precise calibration model that could provide compensation factors for different types of probe used. The resonant frequency of the coupled system is sensitive to a number of factors such as circuit components, lift-off, tilt, material properties, degree of surface roughness, and temperature. Indeed, operating at frequencies approaching electrical resonance will therefore lead to a greater sensitivity to this issue.

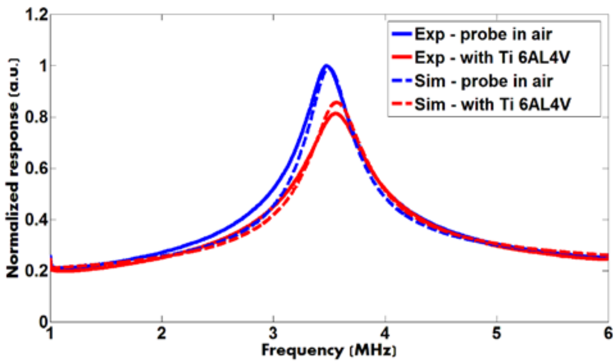

Figure 4. Comparison of measured and simulated results obtained from – probe in the air and with Ti test piece.

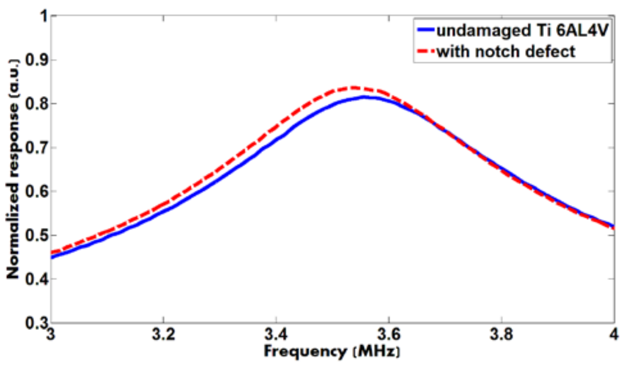

Figure 5. Inspection defect-decoupling resonance shift on eddy current defect signal measured by experimental data collection system.

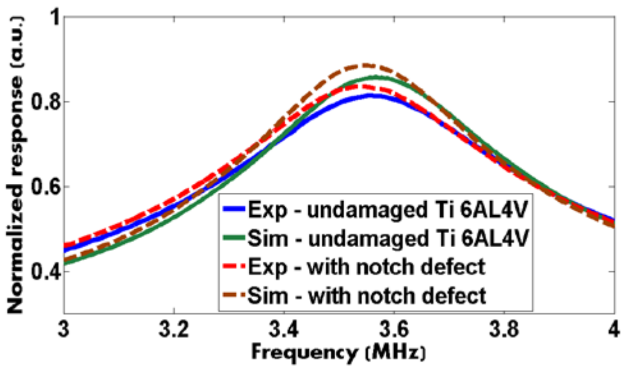

Figure 6. Comparison between measured result and simulated one of defect detection based on resonance-shift of eddy current response when the coil passes over a surface-breaking crack.

4. Conclusions

A fast and reliable model has been developed to simulate the response of eddy current probe to sub-millimeter surface-breaking cracks in a Titanium test piece (Ti 6AL4V). Enhanced detection sensitivity via resonant peak (up to ~300%) and frequency shifting (~0.02 MHz) for electrical discharge machining (EDM) notch can be captured in the simulation model via an EM circuit co-simulation. Good agreement between simulated and measured results from a developed eddy current data collection system can be seen. Extension of developed model is planned to incorporate the material inhomogeneity for the microstructure evaluation and evaluation of material noise as alloy is well-known for its microstructural background noise because of different crystallographic orientation of the grains. The model would help for optimized equipment design to improve defect sensitivity given cracks sizes in alloys. This could lead to improved inspection procedures in NDT.

5. References

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