Modelling, Simulation and Visualization for Eddy Current Non-destructive Testing

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Abstract

This paper reviews the state-of-the art and the recent development of modelling, simulation and visualization for eddy current Non-Destructive Testing (NDT) technique. Simulation and visualization has aid in the design and development of electromagnetic sensors and imaging techniques and systems for Electromagnetic Non-destructive Testing (ENDT); feature extraction and inverse problems for Quantitative Non-destructive Testing (QNDT). After reviewing the state-of-the art of electromagnetic modelling and simulation, case studies of R&D in eddy current NDT technique via magnetic field mapping and thermography for eddy current distribution are discussed.

Keywords: Modelling, simulation, visualization ,eddy current , non-destructive testing

I. INTRODUCTION

Modelling and simulation is a discipline for developing a level of understanding of the interaction of the parts of a system and of the system as a whole. As the development and application of modelling and simulation for system understanding [1-4], visualization and interpretation of simulation data [5-6] become important, extracting usable and useful information from large and complex data sets is a difficult and challenging problem.

Modelling is often used in Electromagnetic Nondestructive Testing (ENDT) to simulate electromagnetic phenomena. The constructed models in ENDT are typically used to simulate an ENDT test procedure and predict the resulting signals associated with different defect and experimental conditions. Results provided by the modelling and simulations can provide useful information for sensor design, visualization of the interaction of electromagnetic phenomena with defects and for defect identification, which can be used to develop signal interpretation algorithms.

In this work, we present a review of the state-of-the-art for modelling, simulation and visualization in eddy current NDT. Visualization of eddy current distribution has gained considerable research attention in providing easier signal interpretation. Through the visualization and mapping of eddy current distribution, visual indication of defects can be provided and information about the condition of the sample obtained over a relatively large area. Characteristics of defect geometries can be identified and differentiated from simple defects through comparison of the mapping profiles and extracted features, providing quantitative information for defect characterization.

The advantages of the visualization technique with eddy current NDT is presented and discussed in two case studies. The results from these case studies help to build a link between the acquired information, i.e. magnetic field or thermal distribution from eddy current interaction with a defect and defect information (shape, size and location).

This paper presents: (a) the review of the state-of-the-art of modelling, simulation and visualization for eddy current NDT; (b) the case studies of eddy current NDT; (c) summary and outcome of the work and conclusions drawn from the study.

II. STATE-OF-THE-ART OF MODELLING, SIMULATION AND VISUALIZATION FOR EDDY CURRENT NDT

Simulation or modelling has been a part of NDT since its earliest applications. It has been used for several of the common NDT methods including radiography, ultrasonics, eddy current and a variety of others. In the field of eddy current NDT, modelling and simulation is useful in the design of new probes and optimizing of existing probes for required inspection scenarios. Parameters relating to the probe, sample and type of defect can be investigated without the requirement to perform repeated experiments. Simulations based on either analytical or numerical models allow the user to predict the response of a probe when it is scanned over a defect. Knowledge of this response is useful for the purposes of defect characterization through feature extraction and the reconstruction of defects.

The application of analytical modelling for eddy current NDT began with Dodd and Deeds modelling of eddy current inspection applied to a coil on a conductive half-space and a layered specimen including a rod specimen, using integral expressions [7-8]. The Dodd and Deeds analytical models have been proven to be very useful in predicting experimental data from eddy current measurements and have been widely used by the NDT community in the design of eddy current tests [9]. Until now, many of the analytical packages for eddy current NDT modelling and simulations have not been widely commercialized, apart from CIVA, which has had applications in aerospace [10], oil and gas [11] and the nuclear [12] industry. The limitations of analytical packages lies in an inability to solve complicated problems, i.e. complex defect components and geometries, which hinders the utilization of this analytical approach towards solving real industrial problems.

Numerical simulations in general are more powerful and flexible than analytical models. In contrast to analytical simulation, it has the capability to model complex defect geometries, material nonlinearity and other complexities associated with real test scenarios, with the required accuracy [9]. At the same time, the solution is obtained as a numerical result rather than a closed form solution. Along with the rapid development of computers, Finite Element Method (FEM) simulation has moved from 2D to 3D modelling which is more suitable in handling asymmetric problems which cannot be simplified to a 2D problem using azimuthal coordinates [13]. 3D FEM simulation is beneficial to the theoretical study of eddy current NDT, because the geometries of specimens and components modelled in simulations are usually asymmetric [14]. The commercial simulation packages, such as COMSOL or MAGNET, which are prevalent in electromagnetic modelling are capable of implementing simulations in 2D and 3D, as a result, better understanding of magnetic fields underlying the inspection systems can be obtained and can be used to verify the experimental results. In addition, some situations of test geometries that are difficult, expensive or impossible to simulate experimentally has made numerical modelling the only practical way to provide defect characterization parameters in eddy current testing [9]. These software packages use numerical models to simulate and visualize multiple physical phenomena and allow the modelling of complex geometries but can be very time consuming when compared to analytical models, especially when solving three-dimensional problems.

One of the recent trends in eddy current NDT is the advancement from qualitative evaluation of a defect towards quantitative evaluation (estimate defect shape, type, size, and position) [15]. Many methods have been proposed by researchers working in this field for the Quantitative NDT (QNDT) of materials and defects using the eddy current technique [16-20]. To date, the Pulsed Eddy Current (PEC) technique has been shown to exceed the capabilities of other eddy current techniques in the provision of quantitative information in the evaluation of defects. Apart from containing a large spectrum of frequency components in its excitation, for better eddy current penetration compared to other eddy current techniques, information about a defect such as the location, depth and defect size can be obtained through the features present in the transient signal. Generally, the time-to-peak and the peak height of the PEC differential signals are the main features used to obtain the depth information and the size of the defect [21]. However, despite significant advancements, characterization of deep sub-surface flaws still poses a major challenge.

Various techniques have been developed to put PEC inspection data in the form of images for visualization. This has been made possible by the use of magnetic sensors for imaging of eddy current distribution through the mapping of magnetic field distribution using scanners or sensor arrays. In the scanning method for PEC imaging, the PEC system is linked to a scanning application. Positional information is acquired using one of many different types of scanner controlled by the scanning application software. The images are then recorded based on the amplitude of the magnetic field distribution. Typical PEC imaging commercially available system e.g. Trecscan (UK) and Tecscan (Canada) uses a sensor array and scanning to visualize large areas (typically aircraft fuselages).

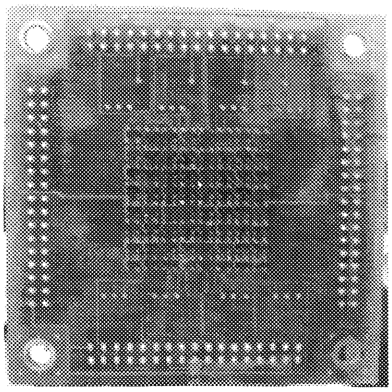


Figure 1. Magnetic camera having a 8x8 sensor array

Sensor arrays and sensor networks have become the focus of attention in the sensor world recently. NDT methods, which are highly dependant on sensing and imaging, are no exception. Sensor arrays offer many advantages, such as the acquisition of more information simultaneously, improved detection accuracy [22], and maintaining the probe in close contact with the inspected sample during the inspection. An example of a sensor array containing 64 (8×8 array) magnetic sensors (Hall sensors) for magnetic field visualization is shown in Fig. 1.

This sensor array arrangement provides an image of a relatively large area (when compared with a single sensor) simultaneously, without the need to scan the probe over the area of the defect. The potential of using sensor arrays with the PEC technique provides a method to obtain more information about defect location and geometry, in addition to rich depth information. With the construction of more sophisticated array arrangements, the imaging technique can provide more reliable and faster inspection results for defect characterization, assessment and reconstruction of 3D defects [23].

Even though the PEC imaging through scanning or the use of sensor arrays has advantages in providing the solution towards defect characterization for QNDT, the feasibility for real-time imaging still poses problems. PEC imaging through scanning leads to low inspection efficiency due to the time taken to complete the scan and the dependency on a scanning system. Sensor arrays on the other hand, depend on the spatial resolution of the array arrangement in providing detection sensitivity and the resolution needed for defect characterization from the mapped distribution. For these reasons, the suitability and limitations of scanning and sensor arrays for should be taken into consideration when the PEC imaging technique is employed for defect characterization and QNDT.

To overcome the limitations of the PEC technique for the characterization of defects, an integrative technique which combines PEC and thermography is proposed. PEC thermography inspection with eddy current excitation allows the imaging of eddy current distribution with the ability to inspect for defects over relatively large areas with high spatial resolution, rather than using magnetic sensor arrays or scanning. In the heating process using the PEC thermography technique, the inspected sample is heated rapidly by an inductively generated current flow (20-200 ms pulses). The presence of defects will disturb the flow of the induced eddy currents and affect the temperature distribution on the sample surface which results in the defect to be visualized using suitable thermographic camera.

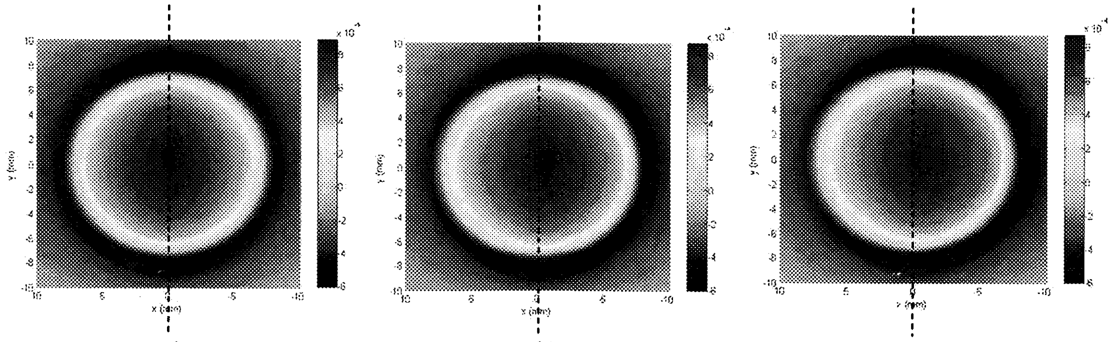
III. CASE STUDIES OF MODELLING AND SIMULATION APPROACHES IN EDDY CURRENT NDT

Two modelling and simulation case studies have been investigated and discussed; these are magnetic field distribution for complex geometric shape by PEC and thermal distribution for PEC thermography.

A. Visualization and mapping of magnetic field distribution for angular defect characterization

Industry requirements mean that quantification of defects such as size and length of the defect inside the investigated sample has to be addressed as accurately as possible for component lifetime prediction and the overall assessment of the structure. However, since the nature of defects is that they have complex geometries i.e. growing at an angle, the influence of defect angular characteristic on the inspection results posed a major problem for characterization and quantification. Much attention has been given to developing techniques and inspection systems which could give the best possible inspection sensitivity and efficiency for QNDT of defects, but little attention has been given to the study of how the defect shape and orientation affected the inspection results. The study of angular defects and its influence towards the gathered information would provide the knowledge and the much needed solution in achieving quantification of defects. This would benefit industry and the NDT research communities by providing the explanation of results and QNDT assessment of defects.

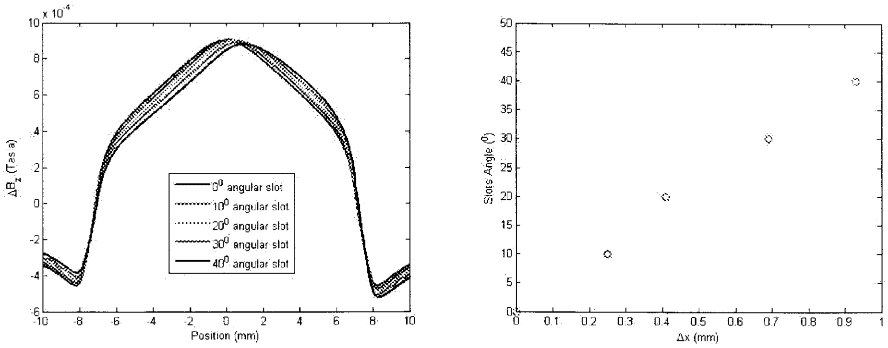
A forward approach of characterizing the angular defects has been taken based on the visualization and extracted features of the resultant magnetic field mapping from the interaction between the eddy current and the defects in the sample. FEM simulations for the 3D visualization of magnetic field are conducted in transient mode. The simulation is conducted to visualize the magnetic field distribution change with different angles of the angular defects. Through the simulated magnetic field visualization analysis, features from the mapping are extracted to be used for the angular defect discrimination and quantification. The extracted features can help in building the inverse model for defect identification from the acquired magnetic field mapping. The investigation is also intended to facilitate sensor selection and the requirement for experimental design and its practicality for eddy current imaging through magnetic field mapping and visualization for defect characterization using PEC.



a) b) c)

Figure 2: Simulated differential magnetic field visualization at 1ms for (a) 0° angular defect (b) 20° angular defect (c) 40° angular defect

As can be seen from the maps shown in Fig. 2, the peak of the distribution for each angular defect is shifted towards the right which shows the defects angle direction inside the sample. Analyzing the visualization results obtained, it is found that the peak of the magnetic field distribution of the angular defects will be shifted corresponding to the angle of the defects as it increases from 0° to 40°. This shows that the shifting of the peak distribution can be used as a feature for quantitative estimation of angular defects. Through the analysis, a correlation between the peak distribution shift and the defects angle to predict the angle of the defects can be made as shown in Fig. 3. These can be developed as potential features for angular defect characterization.



a) b)

Figure 3: (a) Differential magnetic field distribution against angular defect (b) Correlation between peak distribution shift and defect angle

The results of angular defect characterization by numerical simulations through the visualization and mapping technique has shown that angular defects characterization can be made through extracted features from the magnetic field mapping. Through the mapping analysis of the features, geometrical information of the angular defects in relation to the distribution profiles has been obtained.

B. Simulation and visualization for PEC thermography

PEC thermography inspection with eddy current excitation is an integrative NDT method which allows the visualization of eddy current distribution with the ability to inspect for defects over relatively large areas with high spatial resolution, rather than using magnetic sensor arrays.

The resultant surface heat distribution from direct eddy current heating and diffused heat can be obtained easily with a thermal camera, but techniques for the determination of heating mechanisms around a particular defect for quantitative defect characterization are required. Consequently, modelling of PEC thermography is essential if the relationship between the applied field and the resultant temperature distribution is to be fully understood. The modelling can also provide guidance on the experimental specification and configuration for the PEC thermography technique.

In this case study, numerical (FEM) modelling is used to investigate the PEC thermography underlying phenomena on simple discontinuity defects, including eddy current distribution and heating propagation. Through the visualization provided by the numerical simulations, heating distribution by the presence of defects can be explained and provide the means for evaluating the proposed PEC thermography capabilities (through eddy current heating) for defect characterization by the visualization and mapping technique.

With the intention of understanding the fundamental behavior of eddy current heating and heating diffusion, two fundamental defect models are introduced:

i. The slot - finite in length but extending completely through the sample
ii. The notch - infinite in length, but finite in depth

These defect models will demonstrate the variation in the induced eddy current distribution which is dependant on the geometry of the defect within the inspected sample. Through the acquired knowledge of the heating mechanism around a particular defect, the resultant thermographic images can be explained in relation to the encountered defect and its geometrical parameters.

Fig. 4 shows the simulation results for the slot and notch after 200ms of heating. The eddy current flow for the two defects is visualized by the streamline plot in Fig. 4(a). In the presence of a defect, eddy currents will divert to complete their closed loop path which leaves a unique eddy current distribution based on the defect geometry that can provide useful information about a defect. Comparison of the streamline plots for the slot and the notch shows that the presence of the through slot causes an obvious diversion of the eddy currents around the tip of the slot. The diversion of the current flow for the notch is less obvious, but some disturbance in the eddy current distribution surrounding the notch can be identified. The streamline plots also illustrate the large influence that sample geometry has on eddy current distribution; where the eddy current loops encounter a material edge, an area of higher current density is formed e.g. at the sample edge, under the coil. Thus, defects with the same geometry and orientation, but different positions on the sample under inspection can interact with the induced eddy currents in different ways and cause very different heat distributions.

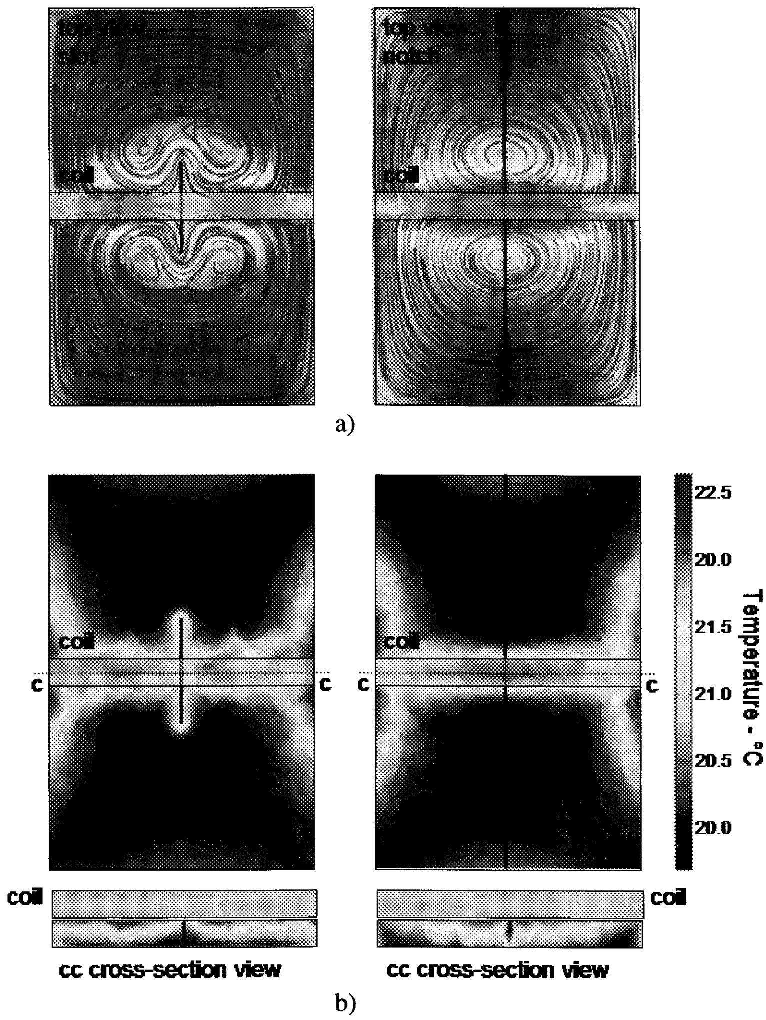


Figure 4: Simulation results of (a) eddy current and (b) heat distribution for ideal slot and notch

Fig. 4(b) shows the heat distribution for the slot and notch, viewed from the top of the sample for surface heating distribution and as a cross section directly under the induction coil. It can be seen from the top views that for both samples, there are hotter areas directly under the induction coil, plus a build up of heat at the edges of the samples. In addition to this, the slot exhibits a characteristic heat build up at the tips of the slot and cooler areas either side of the slot. The presence of the notch is not as obvious in the top view, but examination of the cross sectional view shows a clear build up of heat directly under the defect.

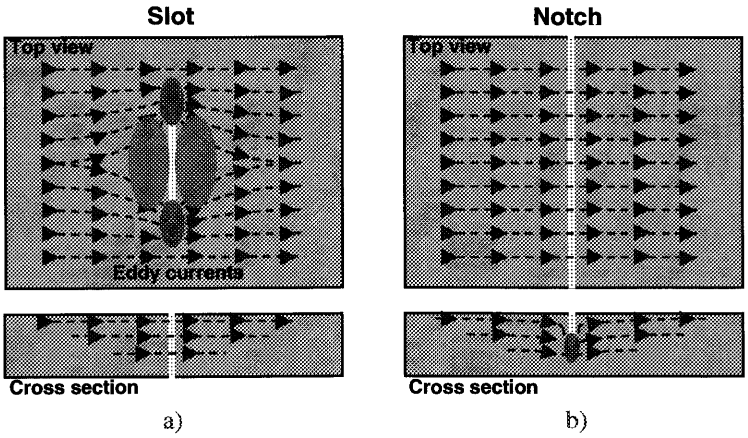


Figure 5: Theoretical (a) eddy current and b) heat distribution for ideal slot and notch

Based on the simulation results, the theoretical eddy current distributions and resultant heating for the two fundamental defects can be described and shown in Fig. 5. The introduction of a slot in the eddy current path results in a diversion of the eddy currents around the tips of the slot causing an increase in eddy current density and resultant hot spots at the slot tips coupled with a relatively cooler area at the centre of the slot where eddy current density is decreased. The introduction of a notch in the eddy current path results in a diversion of the eddy current flow underneath the notch, resulting in an increase in eddy current density and a resultant hot spot at the bottom of the notch. The heat distribution for real world defects can be understood by considering the contributions from the two modes; heating at the tips of defects due to lateral diversion of eddy currents and heating at the bottom of the defect due to medial diversion of eddy currents.

IV. DISCUSSION AND CONCLUSIONS

State-of-the-art of modelling, simulation and visualization for eddy current non-destructive evaluation has been reviewed. It has an important bearing to enable users to understand the physical phenomena and to design and optimize the sensing system. Two case studies on modeling and simulation of electromagnetic NDT and their investigation in visualizing data have been reported. Further research will concentrate on further visualization and signal processing techniques for defect characterization and reconstruction.

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