Recent Trends in Electromagnetic NDE Techniques and Future Directions

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Abstract
Electromagnetic NDE area is continuously growing upon incorporating the contemporary advances in sensors, material science, numerical modelling, signal processing and image processing and automation. Use of array sensors, image fusion, inversion approach, and model based investigations has significantly enhanced the scope and application of the electromagnetic NDE techniques for materials evaluation. This paper gives an overview of recent developments in electromagnetic NDE techniques for reliable detection of defects and for quantitative characterization of defects and microstructure variations in metallic materials. The paper specifically highlights how the recent technologies have enabled detection of very shallow surface defects and deeply buried defects in engineering components. It is shown how numerical modeling enhanced the capability of flux leakage, eddy current and potential drop techniques.

Keywords: Eddy current, flux leakage, Barkhausen noise, stainless steel, sensors, numerical modelling

1. Introduction

Detection of defects, characterization of microstructures and evaluation of mechanical properties and residual stresses by non-destructive evaluation (NDE) techniques is vital for any engineering industry. NDE techniques enable safe and reliable operation of components and structures. NDE Techniques that use some form of electromagnetic excitation for nondestructive testing are called electromagnetic NDE techniques. These include primarily eddy current (EC), magnetic flux leakage (MFL), magnetic Barkhausen emission (MBE), potential drop and microwave techniques [1]. In these techniques, material under investigation is excited electromagnetically and the manifestations of electromagnetic fields due to material anomalies that affect the electrical conductivity, magnetic permeability or dielectric permittivity, are measured using a sensor. The detection sensitivity, capability, applicability, and versatility of various electromagnetic techniques differ. Analysis of the electromagnetic interaction in a material can be effectively utilized for detection and evaluation of defects and other forms of damage. The general approach in electromagnetic NDE techniques encompasses identification of suitable NDE signal or image parameter, subsequent to optimization of the test conditions and establishing appropriate calibration for quantitative evaluation or decision making.

2. Electromagnetic NDE Techniques

Electromagnetic NDE area is steadily growing upon incorporating the contemporary advances in sensors, material science, numerical modelling, signal processing and image processing and automation (Figure 1) [2]. Use of array and integrated sensors, image fusion, inversion approaches, and model based investigations has significantly enhanced the scope and application of the electromagnetic NDE techniques for materials evaluation and component inspection. A clear result of this is the detection and sizing of defects and material degradations that could not be detected, say, three decades ago. These advances have clearly enhanced the capabilities of the electromagnetic NDE techniques enabling detection and
sizing of very shallow defects as well as buried defects, degradation in microstructures, corrosion and accumulated plastic deformation prior to crack formation. In order to reduce noise from extraneous sources and enhance the signals, digital signal processing, image processing and artificial intelligence are being increasingly applied, thus, enabling increased the probability of detection of defects. Computer based smart NDE instruments and dedicated industrial systems are becoming more popular for automated NDE and enhanced manufacturing quality and productivity. Further, the size of electromagnetic NDE sensors is coming down drastically in the recent past, enabling high-resolution imaging and reliable sizing of defects [3]. Wireless sensors, embedded sensors, sensor networks and remote data transmission means are slowly gaining ground and acceptability.

Figure 1 Recent advances in electromagnetic NDE techniques.

This paper discusses some recent advances in electromagnetic NDE techniques for detection of defects and characterization of microstructure variations in metallic materials through example applications from the authors’ laboratory. In these examples, discussed are the advances such as finite element model based technique optimisation, automated detection using array sensors, wavelet transform based processing of signals, inversion of image data, image fusion and evaluation of coatings as well as microstructures.

3. Recent Advances

In this section, some of the recent advances in eddy current, flux leakage, Barkhausen noise, potential drop, and microwave electromagnetic NDE techniques are discussed based on the research work carried out at the authors’ laboratory. In these advances, case studies discussed include finite element model based determination of array sensors’ location, wavelet transform based processing of remote field EC signals from bend regions, inversion of eddy current image data for defects sizing, pixel based image fusion for detection of sub-surface defects, assessment of thin SiC coatings and characterisation of microstructures.

3.1 Model based optimisation and realisation of GMR sensor arrays

Detection of damage in 64 mm diameter steel track rope is envisaged as part of the condition monitoring and life management programs. Non-destructive detection of damage in the track rope is challenging due to heterogeneous structure of the rope, multiplicity and uncertainty of
As a solution, a flexible giant magneto-resistive (GMR) array sensor has been developed for fast MFL testing. In order to identify the number of GMR sensors required to cover the top surface of the track rope and to determine the sensors locations, 3-D finite element modeling has been performed using COMSOL 3.4 Multiphysics software package. Figure 2a shows the mesh generated for the geometry which consists of track rope and two saddle coils (length 120 mm, width 35 mm) each consisting of 90 turns with a cross sectional area of 20x10 mm². Magnetizing current of 5A in the saddle coils is set in opposite directions to ensure axial magnetization of the rope region between the saddle coils. For simplicity, in the model the track rope is assumed as a solid rod and GMR sensor as well as velocity effects are not modelled. The magnetic vector potential is computed in the solution region and the axial component of the magnetic flux density ($B_z$) between the two saddle coils is predicted. As can be seen from Figure 2b, the magnetic flux density is nearly uniform for an optimum circumferential inter-coil distance of 80 mm (dotted region in Figure 2b). This region can accommodate 12 GMR sensor chips.

A flexible GMR sensor array shown in Figure 3 has been fabricated. Each sensor element in the array has a common power input of 5V and the array has 12 differential outputs. The overall size of the sensor array is 100x12 mm² and the sensor pitch is 6.6 mm. The sensor array is kept at the middle of the magnetizing coils. The sensors’ outputs are acquired and analysed using a LabVIEW based data acquisition system incorporating averaging and low-pass filter to minimize noise. The performance of the sensor array has been evaluated by measuring the axial component of leakage flux from localized flaw (LF) and loss of metallic cross-sectional area (LMA) type defects machined on the track rope. Studies confirmed that the GMR sensor array could reliably detect both LF and LMA type defects in the track rope. The sensor array has a fast detection speed along the length of the track rope and does not require circumferential scanning. It is also possible to image defects using the array sensor for obtaining their spatial information.
Typical MFL images of circumferential LF of size 5.5x2.0x2.0 mm$^3$ is shown in Figure 4a and that of axial LMA (42x9x3 mm$^3$) is shown in Figure 4b.

The images of circumferential notches are found to be sharp and localized as compared to that of the axial notches. The flexible GMR array sensor is useful for rapid non-destructive inspection of track ropes. Future direction includes enhancing the detection capability for defects located between the sensor elements as well as enhancing the resolution of the sensor array.

### 3.2 Reliable detection of defects in expansion bend regions of steam generator tubes

Steam generators (SG) are the most critical systems of prototype fast breeder reactor. For the in-service inspection of ferromagnetic SG tubes (outer diameter 17.2 mm, wall thickness 2.3 mm) made of modified 9Cr–1Mo steel remote field eddy current (RFEC) technique is chosen. The SG tubes have expansion bends to accommodate differential thermal expansion. During RFEC inspection, exciter–receiver coil misalignment, bending stresses, probe wobble, and magnetic permeability variations would produce disturbing noise hindering the detection of defects. As a solution, wavelet transform based signal processing method has been developed for detection of defects in the bend regions [5].

The wavelet transform method using Bior2.8 wavelet has shown both noise reduction and signal enhancement. Further, it unambiguously detected 0.23 mm deep grooves present in the bend regions with a SNR better than 7 dB, besides unambiguous detection of 2 mm diameter hole and 1.15 mm deep circumferential notch in the bend region. Further, the wavelet transform method has retained the double-peak behavior of the RFEC signals, as typically shown in Figure 5. Presence of oxide scales or fouling layer on tube inner side may cause a small shift in the base line of the RFEC signals. However, presence of corrosion wall loss or cracks on the inner and outer surface of tubes will produce RFEC signals with characteristic double-peak response with amplitudes proportional to the crack depths. Using the wavelet transform method, it is possible to detect defects present anywhere in the SG tubes.
3.3 Multi Label Ranking for sizing sub-surface defects

For simultaneous determination of depth and height of sub-surface defects in stainless steel plates, a novel framework that uses multilabel ranking without prior believes and considers class dependency has been developed. In this framework, input multidimensional data are represented in the form of multilabel data and multilabel ranking is applied. Later, class for each dimension are predicted with a claim that a successfully learned system is able to produce maximum rank for a true class when compared to rank of other classes present in a given dimension. For multidimensional learning (MDLearn), two sets of EC signals are modelled using CIVA software; one set is used for training while other is used for testing. Evaluation of MDLearn wrapper framework is carried out in two stages. In first stage, ten-fold cross validation is applied on the training data and in second stage, separately modelled test data is used. For cross validation, the results are interpreted as mean ± std. deviation of ten independent runs.

Defects of three different lengths (3, 6, 9 mm) have been modelled (Figure 6). As width is less critical defect parameters as compared to depth and length, width is fixed as 0.5 mm. A total of 192 defects have been modelled with different heights (0.5 to 2.0 mm) and depth locations (1.0 to 3.0 mm). The task of multidimensional learning is to predict both depth and height of a defect. For convenience of learning, the defects have been categorized into three classes for depth and three classes for height (refer Figure 6). Signals from 27 defects varying in depth and height are shown in Figure 7. As can be observed, the signals from different classes of both height and depth are overlapping and it is very difficult to determine the height and depth.

<table>
<thead>
<tr>
<th>Depth, mm</th>
<th>Class</th>
<th>Height, mm</th>
<th>Class</th>
</tr>
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<tbody>
<tr>
<td>&lt;1.5</td>
<td>D1</td>
<td>&lt;0.7</td>
<td>H1</td>
</tr>
<tr>
<td>1.5-2.5</td>
<td>D2</td>
<td>0.7-1.6</td>
<td>H2</td>
</tr>
<tr>
<td>&gt;2.5</td>
<td>D3</td>
<td>&gt;1.6</td>
<td>H3</td>
</tr>
</tbody>
</table>

Figure 6 Modeled geometry and classes for defects height and depth.
For testing purpose, separate 26 dataset has been generated by changing the length (2 to 10 mm) and width (0.25, 0.75 and 1.0 mm) of the defects. Table 1 gives the performance of MDLearn for both the stages i.e. ten-fold cross validation and test case; in terms of the metrics i.e. mean accuracy, global accuracy and entropy of accuracy.

Table 1. Performance of MDLearn<sub>ML-RBF</sub> for EC data.

<table>
<thead>
<tr>
<th>Algorithms</th>
<th>Performance evaluation</th>
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<tr>
<td></td>
<td>Mean accuracy</td>
</tr>
<tr>
<td><strong>10 fold cross validation (mean ± std. deviation):</strong></td>
<td></td>
</tr>
<tr>
<td>MDLearn&lt;sub&gt;ML-RBF&lt;/sub&gt;</td>
<td>0.9599 ± 0.0046</td>
</tr>
<tr>
<td><strong>Test dataset:</strong></td>
<td></td>
</tr>
<tr>
<td>MDLearn&lt;sub&gt;ML-RBF&lt;/sub&gt;</td>
<td>0.9615</td>
</tr>
</tbody>
</table>

It can be observed from Table 1 that the MDLearn using ML-RBF has given good results for ten-fold cross validation. An optimal number of first five ranked features have been chosen as input to the MD-Learn<sub>ML-RBF</sub>. The MD-Learn<sub>ML-RBF</sub> has been trained using 192 datasets (length of 3, 6 and 9 mm, width 0.5 mm) and validated with the following three unique cases:

- Case 1: Evaluation of lengths 4, 5, 7 and 8 mm (interpolation of length).
- Case 2: Evaluation of lengths 4, 5, 7 and 8 mm and widths 0.75 and 1 mm (interpolation of length, extrapolation of width).
- Case 3: Evaluation of lengths 2 and 10 mm and widths 0.75 and 1 mm (extrapolation of length and width).

In all the validation cases, the MD-Learn<sub>ML-RBF</sub> has quantified the depth location and height with 100% accuracy. This reveals the fact that the MD-Learn<sub>ML-RBF</sub> methodology is robust for simultaneous quantification of defect depth location and height.

### 3.4 Enhanced detection of sub-surface defects using image fusion

Image fusion, in general, is defined as the process of combining complimentary and redundant information from several images obtained using different sensors or operating conditions. Combining information from several NDE techniques or variants of one technique is beneficial towards improving the reliability of inspection. Working in this direction, pixel level image fusion methodologies namely, Laplacian pyramid, Wavelet transform, Bayesian and principal components have been developed for combining the C-scan EC images of
subsurface defects. The input images at 125 kHz and 300 kHz have been obtained using the CIVA simulation software. Random noise of 30% of the maximum amplitude has been added to simulate the practical conditions. The performance of the three fusion methodologies has been compared using SNR and entropy. For better detectability, higher SNR and entropy are required. Figure 8 shows the raw EC images of the subsurface defect at 125 kHz and 200 kHz with noise. As can be seen, at 200 kHz the defect is not detected clearly. Figure 9 shows the fused images using different methodologies. As can be observed, good improvement in the quality of the images is observed after fusion. The Bayesian fusion and PCA methodologies have resulted in high SNR and Entropy (Figure 9). These methodologies have been successfully implemented for automated detection of sub-surface defects.

![Figure 8](image.png)

**Figure 8.** a) Raw EC images of subsurface defects with 30% random noise and performance.

![Figure 9](image.png)

**Figure 9.** Fused images using a) Laplacian pyramid b) Wavelet transform c) Bayesian and d) PCA methodologies.

### 3.5 Characterization of microstructures

During manufacture of components made of alloys, heat treatment is given to ensure required levels of mechanical and physical properties and desired microstructure. Likewise, during service life of components, it is essential to ensure that there is no undesirable degradation in microstructures. Electromagnetic NDE techniques are useful for assessing these two situations. These techniques exploit the measurement of changes in electrical conductivity and magnetic permeability either through continuous (EC, MFL) or pulsating excitations (Pulsed EC, MBE). Optimization of test parameters and selection of parameters is very important for the success of electromagnetic NDE techniques for quantitative characterization of microstructures. EC technique has been used for characterization of solution annealing behaviour of Ti alloys. In the case of VT-14 alloy, it has been found that both magnitude and phase angle of EC signals change with solutionizing temperature. Studies clearly established that EC based resistivity measurements can be used for quantitative characterization of
solution annealing behavior of VT-14 alloy as well as for identification of formation of different phases.

EC technique has been used to characterize ageing effects in heat treated M250 Maraging steels that are very attractive for aerospace industry by virtue of their high strength, fracture toughness and corrosion resistance. In order to study the microstructural changes occurring during heat treatment, specimens thermally aged at 755 K for 0.25, 1, 3, 10, 30, 40, 70 and 100h of duration have been examined. From the eddy current impedance measurements, the influence of various microstructural changes have been analysed. It has been established that after 0.25 h of ageing, there is a slight increase in magnetic permeability and reduction in electrical resistivity due to annihilation of dislocations. The impedance response from other specimens indicated that the permeability decreases with ageing duration due to formation of intermetallic precipitates namely, Ni₃Ti and Fe₂Mo and also due to reversion of magnetic martensite to non-magnetic austenite [6]. These measurements are in good agreement with magnetic Barkhausen emission (MBE) technique measurements. Studies established that the decrease in eddy current amplitude and phase angle can be reliably used for unambiguous classification of under-aged, correctly-aged and over-aged conditions. Recently, a multi-parametric method that combines EC, MBE and non-linear ultrasonic techniques has been developed for assessing the heat treatment adequacy [7].

3.6 Assessment of thickness of silicon carbide coating on carbon-carbon composites

Carbon-Carbon (C/C) composites which are the materials for spacecraft and reentry vehicle components such as nose cap and wing leading edges, are coated with silicon carbide (SiC). It is essential to ensure that SiC coating on C/C composite structure is uniform and more than 20 μm thick. EC imaging based methodology has been developed for assessment of thickness of SiC coating. Despite scatter in the baseline data due to surface roughness on C/C specimens, EC methodology could successfully identify undercoating (thickness <20 μm) and heavy coating [8]. A calibration graph has been established between EC amplitude and coating thickness measured by other methods to evaluate the performance of the EC methodology. The error in coating thickness evaluation by EC methodology has been found to be less than ±5 μm as typically shown in Figure 10. Typical EC images for C0 (uncoated), C3 (SiC thickness, 17.30 μm) and C4 (SiC thickness, 29.54 μm) are shown in Fig. 11. As can be observed, in specimen C3 the coating is uniform at the center as compared to specimen C4. The EC image of C4 specimen clearly shows non-uniformity of coating that has resulted in large scatter and associated error in thickness assessment.

EC images are also useful to assess the suitability of a coating process as the images reveal variations within a coated specimen. It is possible to generate thickness images (using calibration graph of Fig. 10) of coated specimens to assess the variations in coating thickness, enabling easy identification of thinly coated regions on the coated surfaces. For rapid screening and automated identification of under coated as well as over coated regions, use of array sensors scanning the surface in a linear manner seems promising.
3.7 Microwave technique for imaging concrete structures

By virtue of the imaging capability and rapid inspection possibility, ground penetrating radar (GPR) is attractive for inspection of concrete structures. By scanning the antenna over the concrete surface, images are produced. In GPR images, brightness gives an idea about the objects in the concrete while depth of an anomaly is determined using the time delay between the transmitted and received pulses. GPR technique has been used on concrete structures of reactor containment and on waste immobilization facilities to identify rebar-free locations for undertaking drilling for structural modifications. For inspections, GPR antennae operating at 900 MHz and 1600 MHz have been used. Novel image processing and feature extraction methodologies have been implemented to determine the diameter of rebars located 300 below concrete structure. Investigations have been carried out to study the influence of moisture on GPR images and to identify metal pipes and leaks in them. Metallic and PVC pipes with drilled hole of 4 mm diameter have been tested separately by burying them in sand at a depth of 100 mm. Water has been then injected into the pipe from the surface through a plastic hose and the GPR images have been studied. The water leak from pipes locally increase the moisture content in the sand and as a result significant change in contrast has been observed in the B-scan GPR images, as typically shown in Figure 12. Microwave GPR technique is useful for rapid NDE of concrete structures.
3.8 Equivalent circuit model for accurate sizing by ACPD technique

The crack depth estimations in AC potential drop technique are prone to large deviations for very shallow and finite length cracks, especially in low conducting materials such as stainless steel. Upon considering the additional path available for current to flow around the surface length of the crack, a simple mathematical approach using the equivalent resistive circuit model has been developed [9]. Further, detailed 3-dimensional studies have been carried out using COMSOL finite element model to analyse the current path around the cracks. The use of modified equivalent resistive model that considers volume of interaction, instead of length, has significantly reduced the error in depth sizing to less than 10% in stainless steel, brass and aluminium. Studies clearly brought out the need to use a series of long notches in the calibration exercise, in place of a long notch with continuously increasing depth. Based on this, a scheme has been proposed to accurately measure the depth of cracks in stainless steel components.

4. Conclusions

Electromagnetic NDE techniques are useful for high sensitivity detection and characterization of defects and microstructure changes in metallic materials. This paper discussed a few recent advances such as GMR array sensors, digital signal and image processing techniques, model based optimisation and characterisation of microstructures and coatings. Clearly, the use of array sensors, image fusion, inversion approach, and model based investigations has significantly enhanced the application of the electromagnetic NDE techniques for materials evaluation. Miniaturisation of sensors, wireless sensor networks and multi-sensor fusion techniques extracting different data from on region by different sensors are expected to further enhance the capability of the electromagnetic NDE techniques in near future.

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