Unlocking the Potential of Eddy Current Arrays (UPECA)

Prof Steve Dixon - Royal Society Industrial Fellowship
Additional Supporting Information for the Proposed Research

Background to this proposal

Eddy Current (EC) inspection has been used in Non-Destructive Evaluation (NDE) of metallic components for several decades. It is a non-contact method, but is often applied in such a way that the eddy current sensors are in close proximity to the sample under test as this improves sensitivity and sensor stand-off consistency. EC inspection is generally applied to detecting surface defects in a sample, but by lowering the frequency or using a range of frequencies such as is employed in pulsed EC testing, one can probe deeper into the sample approximately down to a depth no deeper than the coil diameter. EC inspection is used extensively in both industry and research, and the technological and commercial benefits of using this technology have been clearly demonstrated across a broad range of applications. Successful deployment of Eddy Current Array (ECA) technology would produce significant cost and safety benefits. ECAs have the potential to decrease scan times and simultaneously increase reliability and probability of detection (PoD) of defects. There are significant benefits to be obtained from improving the scientific understanding of the operation and optimisation of ECAs, developing better methods for using all of the available data and using new methods for low cost, rapid design and construction of customised arrays.

Prof. Steve Dixon holds a joint research appointment between the Department of Physics and School of Engineering at the University of Warwick. His main area of expertise is in non-contact ultrasonic techniques and applications, from a fundamental research level through to the implementation of equipment into industrial environments[T1,T2]. His research group at Warwick is recognised as a world leader in the field of non-contact ultrasound with unique equipment, facilities and expertise, particularly in the use of electromagnetic acoustic transducers (EMATs)[T3-T5]. Dixon holds several research grants and has over 90 publications in peer reviewed scientific journals. Dixon was until 2015 the Academic Chair and Board Member of the EPSRC Research Centre in NDE (RCNDE), former Chair and member of the Technical Committee of the British Institute of NDT and Editor-in-Chief of the journal Nondestructive Testing and Evaluation. He is also a Director of the spin-out company, Sonemat Ltd, supplying industry with NDT equipment and consultancy. Dixon has recently led a project, using Micro-Stereo-Lithography (MSL) to construct novel eddy current arrays with complex geometries, in parallel to an EngD project with Cummins, where a prototype, conformable, eddy current array was designed and constructed for use in diesel engine turbines [T6-T8]. The research in this area naturally led from the EMAT research, where the first stage of EMAT operation is concerned with the generation of an eddy current in a sample. Indeed, many of the models that were developed originally for eddy current measurements such as the seminal work of Dodd and Deeds [T9], have been implemented in our work on EMATs [T10,T11], or on our recently reported work on Near Electrical Resonance Signal Enhancement

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Technical Background

Technical Summary

Methods will be demonstrated for the rapid design and construction of high density eddy current arrays on rigid, conformable and flexible formers. New designs of eddy current arrays (ECAs) will be tested and the results validated using finite element (FE) packages such as Comsol, quantifying the performance of various ECAs designs and inspection techniques. Eddy current coils in arrays tend to be driven at a particular frequency, but as will be explained, it is advantageous to have the ability to change or sweep the drive current frequency during a measurement. ECAs currently tend to be used in such a way that one measures either the absolute electrical properties of each coil in turn or by actively driving current through one coil (the transmit) and measuring the voltage induced in one or more neighbouring coils (the detector/s). We shall design closely packed arrays, sweeping the drive current frequency, measuring the electrical properties of each coil in turn and simultaneously measuring the signal induced on neighbouring coils temporarily set to act as detectors, achieved by multiplexing the coils.

Background to Eddy Current Testing

The principle of eddy current testing is well established [1,2]: when a coil carrying AC current is placed close to an electrically conducting surface, an eddy current whose amplitude and phase varies with depth is generated in the sample surface and produces a magnetic field outside the sample that effectively opposes the field from the coil [3]. This results in a drop in the effective coil inductance, as there is mutual inductance between the coil and the sample surface. If the surface of the sample contains a surface breaking defect then the total eddy current generated is reduced and the apparent inductance of the coil is higher than it would be if the sample was defect free[1].

There are various schemes for measuring the inductance of an individual coil, often referred to as an "absolute" measurement[4]. If current is driven through a "transmit" coil, one or more secondary coils can also be used as "detectors", and the response of the detector coil/s depends on how the transmit coil is electrically driven and how both coils electromagnetically couple to the sample and each other[5]. Coils can also be used in differential modes, with the reference coil residing in the array itself or in the instrumentation. Such multiple coil systems can be used in a variety of different ways, including using differential electrical measurement type approaches [6] to compensate for lift-off, or multiplexing the coils to perform absolute measurements on each coil or a transmit-receive type arrangement. The two coils shown schematically in figure 1 are 3 layer, 75 turn coils, integrated into a customised plastic former (figure 2) as part of a proof of concept project, using Micro-Stereo-Lithography[7,8] (MSL) for rapid prototyping of customised coil formers.

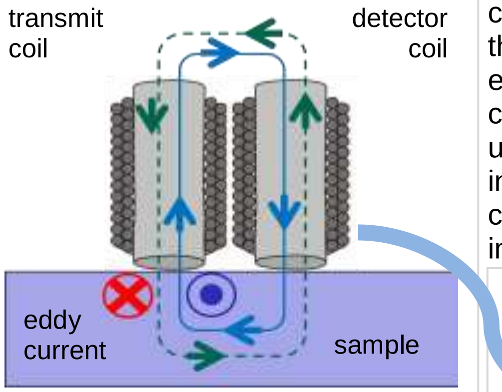


Figure 1 - Schematic diagram of coils, eddy current and resulting magnetic fields when on an electrically conducting sample. The magnetic field from the transmit coil and eddy current are shown as the dotted and solid lines respectively, and both are detected by the detector coil. The current induced in the detector coil will also induce another, smaller eddy current (not shown here).

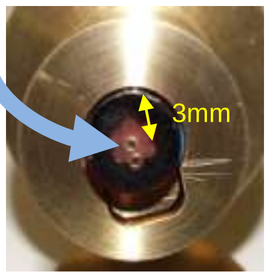


Figure 2 - Two 1mm diameter coils in one of our custom-made, rapid prototyped formers designed to provide a hexagonal array.

Most recent eddy current modelling research can be traced back to the seminal work of Dodd and Deeds[1], who developed an axi-symmetric analytical model for an air cored coil held over an electrically conducting half-space coated with a layer of different electromagentic properties. However, in ECAs, the use of multiple coils and ferrites in close proximity to each other, on curved surfaces, means that the most viable way to model the ECA is using Finite Element (FE) methods[9,10] , and we shall use Comsol or a similar FE package to do this.

Comparison With Existing Technologies

Whilst eddy current approaches can be used for sub-surface defect detection, the bulk of eddy current applications are for surface crack detection. Magnetic Particle Inspection (MPI), Liquid Penetrant Inspection (LPI), Visual Inspection and Automated Optical Inspection are valuable tools in surface crack detection[11-13], but are not suited to many applications as explained in more detail in the Pathways to Impact. Ultrasonic testing is more typically used in subsurface defect detection[14], but its use is well established in surface defect detection[15,16,17]. Viable ultrasonic wavelengths for industrial applications (> 0.1mm), afford lower sensitivity when compared with eddy current methods. Eddy current arrays (ECA) have been in the literature for 20 years[18 or more, as these are essentially the combination of multiple eddy current (EC) probes.There are many commercial suppliers of both ECA and EC equipment, and the following section will focus on ECAs, as the advatages that they offer include speed of inspection, ease of use and applicability to automated inspection, higher degrees of coverage and increased PoD [19-22].

Research Hypothesis and Objectives

Customised ECA formers for optimised inspection

Other than for high value inspection challenges, ECAs are provided with a limited choice of array designs and coil types. We have demonstrated the potential for the low cost, rapid design and manufacture of customised ECAs, using rapid proto-typing. Without such approaches, the time and cost requirements of developing bespoke ECA solutions is prohibitive: users will employ an off-the-shelf ECA that will not be optimal or even capable of detecting critical defects. Figure 3 shows a photograph of a polymer ECA former made at Warwick using a CAD model of the turbine and MSL, designed to fit between turbine blades.

Figure 3 - Photograph of MSL manufactured ECA former profiled to fit between the curved blades of a diesel engine turbine. Note that the former has not been populated with coils at this point.

Commercially available ECAs utilise solenoid coils[23] (similar to figure 1), annular coils or flat pancake type coils[24] that can be manufactured into highly flexible arrays (on surfaces with 1D curvature) using kapton/polyimide printed circuit board (PCB) technology[25]. These ECAs are applicable to a range of samples, but are not optimised for any one particular inspection requirement. Our research will enable researchers and engineers to design and produce customised ECAs quickly and inexpensively that in turn will dramatically increase PoD, improve component reliability and safety and reduce operating and inspection costs.

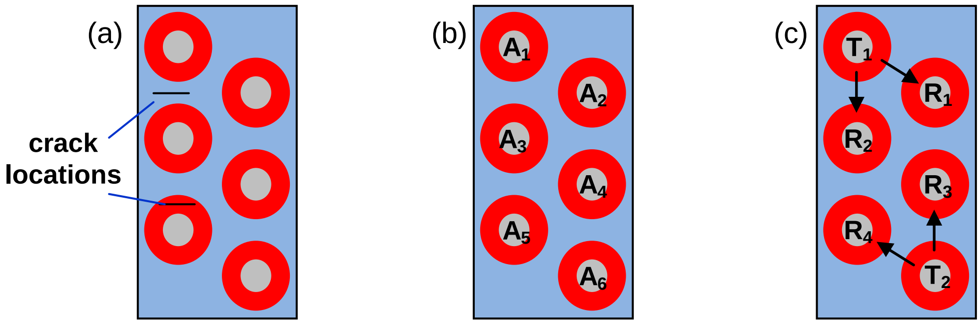
We will produce conformable, solid ECA formers, from robust but flexible polymer materials. These formers have the advantage of being near net shape, and are able to adapt to the surface of a complex profile part, that may have slight variations. The mould for these flexible formers is produced from the "negative" CAD drawing of the component. Conformable design ECAs are commercially available, but tend to be produced as a flat pad with limited conformability, especially where there are some constraints on access. Most ECAs are designed to be scanned, which to some degree, compensates for the fact that they are not tailored to specific components and this also increases the PoD.

For some existing ECA designs where there is significant spacing between the coils, this is essential if reliable coverage is to be obtained. In this project we shall use the same methods to design and manufacture ECAs with rigid, semi-rigid but conformable and with flexible formers, that will be designed to be scanned where required, access permitting. The use of flat PCB coil ECAs on kapton/polyimide is established, and we shall produce / source arrays of coils with less than 1mm diameter to demonstrate the ideas described in sections 5.2 and 5.3.

***Objective 1**:* Quantitatively investigate, design and demonstrate optimal ECAs with rigid (for flat samples), solid-conformable formers(for curved and complex shape samples) and flat PCB ECAs.

The multiplexing issue: absolute coil measurement or transmit-receive measurements?

For an ECA with widely spaced coils, scanning is essential in order to ensure that cracks that lie between a line of coils will at some point pass directly under at least one other coil in the array as shown in figure 4(a).



(a) The crack locations shown may have no significant (top) or a very small effect (bottom) on the eddy current – until the array is scanned when the other bank of coils should pick them up.

(b) The absolute electrical properties of each coil can be measured, but each will be affected slightly by the properties of their neighbours, depending on coil type, proximity or if ferrite is used.

(c) By switching between coils a transmit-receive and/ or differential scan can be employed and the absolute electrical properties of each transmit coil can be measured during the transmit period.

Figure 4- All of the methods shown above are used in various commercial eddy current systems. What is uncertain is which approach is optimum for a particular coil and array design or for a particular inspection challenge.

We shall design and produce small and densely packed coil ECAs, increasing measurement reliability and resolution. An array may not need to be scanned to detect a target defect size. Analytical solutions for air cored coils or FE simulations show that for a coil in close proximity to the sample, the eddy current amplitude is only significant under the area covered by the coil (red areas in figure 4). Thus, defects that are not covered directly by the coil area will have a greatly reduced PoD, including defects that sit within the inner radius of a coil. Eddy current density also varies across the area covered by the coil: this will influence ECA design and when considering if scanning is required. ECAs tend to be used in either an absolute coil measurement (figure 4b) or in a multiplexed transmit-receive type mode (figure 4c), where each coil in turn will act as either a transmitter or detector. Often only amplitude measurements are displayed.

Objective 2 *:* Create hardware and algorithms for performing measurements of multiplexed and transmit-receive coil measurements simultaneously. Investigate the potential for locating multiplexing and other required electronics close to or on the rear of an array former.

Exploiting all data available from the ECA

The Total Focusing Method for imaging using ultrasonic arrays has revolutionised research and commercial developments in ultrasonic NDT, and will provide some insight for the potential methods of dealing with data from 2D ECAs. We will use both experimental approaches shown above in figures 4b&4c simultaneously, and use data fusion, combining a number of amplitude and relative phase measurements. Initial research will focus on constructing a matrix of data, whereby each element in a 3D matrix corresponds to the time data from a chirp signal, containing the time domain signal of the chirp data from the absolute coil measurement and the time domain information from each drive coil's nearest neighbour.

To illustrate the potential of combining frequency dependent data in this way, consider the data shown in figure 5, obtained when scanning the two element, prototype probe shown in figure 2, over a flat sample of inconel with a 1mm long, 1 mm deep, laser- micro-machined slot at just one frequency. The relative orientation of the transmit coil (red), driven at a constant current amplitude at 2MHz and the detector coil (white) is shown in the bottom left corner of figure 5a. The defect location is shown as the white line towards the centre of each scan, and each pixel location corresponds to the position of the centre of the transmit coil during the measurement. The colour on each scan represents the relative magnitude of the parameter being measured (voltage or phase).

When the defect sits almost within the generation coil's inner radius, sensitivity to the defect is low, leading to the minima between the two maxima in each image. Figure 5a shows the change in the generation coil's impedance - effectively the absolute coil measurement (figure 4b). High sensitivity is obtained when the generation coil is over the defect (red/green region), with lower sensitivity when the detector coil sits over the defect (deep purple/black region).

The detector coil measurement (figure 5b) is effectively the send-receive measurement of figure 4c. Similar sensitivity is obtained when either coil sits above the defect but the form of the image is different to that of figure 5a. Figure 5c is the ratio of the data in figure 5a to that in figure 5b and is effectively a composite of those two images with higher signal:noise than either figure 5a or 5b, but results in the loss of some information and resolution. In this particular case, the phase difference measured between the voltage over each coil appears only to be sensitive to the defect lying under the transmit coil. The images provide valuable information about how the eddy current is distributed on the sample surface, and how the proximity of one element of a coil can effect the response of another. Collecting all of this information simultaneously will provide more detail about the defect and increase detectability. A key aim of this project is to understand how we can exploit this information and invert the results from the frequency swept measurements to measure variation in the electromagnetic properties of the sample from the surface to the bulk[26,27].

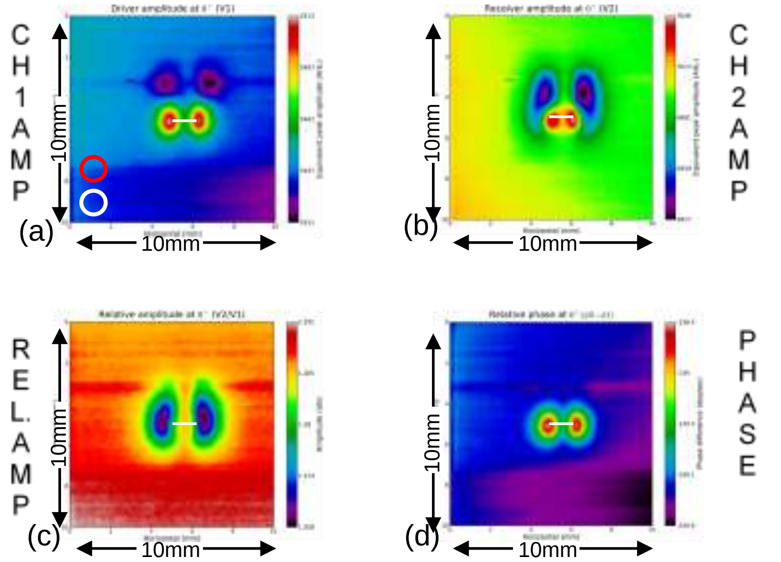


Figure 5- Data obtained from scanning the prototype probe shown in figure 2 over a 10mm×10mm area of an inconel sample with a 1mm long, 1mm deep, narrow slot. A constant amplitude current source was used to drive the transmit coil (CH1) whilst monitoring the voltage on this coil (a). On the detect coil (CH2) the induced voltage was measured (b). The relative amplitude and phase of these voltage signals are shown in (c) and (d) respectively. Note that the phase information is only really sensitive to the transmit coil being over the defect.

Having completed this preliminary work on a proof of concept ECA design using MSL, our findings are highly encouraging, but it would be premature to publish them without further work. In the field of ECAs, there is currently insufficient objectivity and scientific justification as to why particular ECAs are used in certain applications. This in turn has led to wider confusion amongst industrial users, who are highly supportive of the need to develop a scientific understanding of how ECAs operate and how they can be optimised.

Objective 3*:* Using FE and analytical modeling as a guide, design algorithms for combining the amplitude and phase data from absolute, transmit-receive and differential coil measurements, using swept and multiple frequency drive currents. Establish which approach, coil type and ECA design gives highest sensitivity, PoD and resolution to a particular defect type.

Methodology

Work Package 1 : Manufacture calibration samples.
Flat calibration samples will be specified, agreed and manufactured by the University using some representative alloys, using laser micromachining, EDM and fatiguing samples. This will include samples with cracks below defect free, conductive and non-conductive coatings.

Milestone 1 : (~Month 6) : A range of calibration and test samples specified and produced.

Work Package 2 : Construct coil driver and amplifier circuits.

The driver circuit will be based on our voltage driven, constant current amplitude AC current source (stability of 0.01%) which can be fed from a function generator. The amplifier is based on our low noise, high gain (up to 60dB) amplifiers that we developed for use with EMATs. Coil voltages will be measured directly and the use of signal averaging for these measurements may provide sufficient bit depth to negate the need for a balancing bridge (such as modified Maxwell-Wein bridges).

Milestone one 2.1 : (~Month 18) Complete construction and testing of constant current driver
Milestone 2.2 : (~Month 18) Complete construction and testing of wideband amplifier

Work Package 3 : Manufacture components to test research hypotheses using flexible, conformable and rigid ECAs.
In addition to the calibration samples manufactured in work package 1, we shall construct a series of control and nominally identical defective components using components with curved surfaces and complex geometries. At least 2 samples per ECA type will be required.

Milestone 3.1 (~Month 24) : Produce small library of more representative calibration / test samples.

Work Package 4 : Analyse performance of chirp type drives for coils.
We will drive the coils with pseudo single frequency long pulses or chirp type pulses typically between 0.5 - 6MHz for the detection of small, shallow defects. Signal processing will automatically identify the most sensitive frequencies to use and discard any noisy data generated due to instabilities at electrical resonant frequencies. The data in figure 6 shows results from a scan of a titanium sample with a 2mm long crack, obtained using the coils shown in figure 2. It compares the maximum voltage signal amplitude over the defect to the noise in the amplitude measurements away from the defect. This S/N ratio (blue dots) shows a maximum, away from, but approaching the generation coil resonance, identified by the generation coil impedance magnitude (black line). Optimum frequency will vary between samples as the coil-sample electromagnetic coupling differs and from coil to coil. As we will combine amplitude and phase data, it is particularly important to obtain the most reliable data, and avoid the resonant peak where the phase will actually switch suddenly. This new approach will be automated through signal processing on the data collected. This will be done on flat samples initially, but will be extended for more complex shapes and close to sample edges.

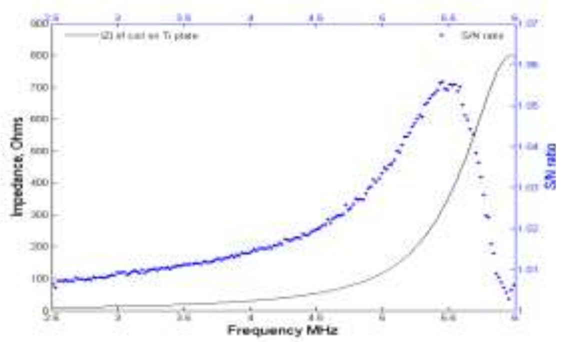


Figure 6- In this send-receive, two coil measurement, there is clearly an optimum signal:noise point for (blue dots) as the generation coil resonance (and impedance magnitude maximum)is approached.

Milestone 4.1 (~Month 36): Prepare quantitative evaluation of the relative performance of the different current driving methods.

Work Package 5 : Establish coil sensitivity matrix for small surface breaking cracks using absolute, send-receive and differential type measurements.
Using Comsol and experimental measurements, the coil-sample coupling and coil cross-coupling will be investigated for ECAs containing flat pancake coils, flat pancake annular coils and solenoid type coils. Surface breaking defects and cracks on components under conductive and non-conductive coatings (<1mm long defects) will be investigated.

Milestone 5.1 (~Month 46): Populate a matrix of defect type and coil / ECA type to establish quantified selection criteria to map optimal ECA and driving method for a particular defect and sample type. Reporting and preparing necessary documentation will take place from month 46-48.

Academic Impact of the Research

There is currently no clear scientific basis for the design of ECAs for particular measurement requirements. Capturing simultaneously absolute, differential and send-receive ECA measurements over a range of frequencies close to coil resonance is a step change in the field, and will introduce a new, scientifically based methodology for ECA design. We will design and construct modular instrumentation, where users can access the raw data and easily incorporate new designs making it suitable for research purposes or readily adaptable to bespoke applications.

Details of collaborative arrangements and project management

The project will be managed by the Fellow who will provide supervision of staff or students associated with the project. The Fellow and Industrial Research Team will hold monthly progress meetings. Key findings, questions and progress updates will be communicated electronically to the as they arise and the relevant project documentation will be stored on a University server with open access for the industrial partners. The Fellow will be responsible for tracking the progress of the project against the milestones and will post updates and/or modifications to the project timeline on-line, each month. Scientific results of a non-commercially sensitive nature will be disseminated on an open access webpage subject to the industrial partners' approval, acknowledging all of the supporting organisations, and will be updated on a 6 monthly basis. Presentations of project results and progress will be made, formally reported and reviewed annually a formal Review Meeting. The Fellow will also train Rolls Royce staff, and undertake direct research collaboration on test piece design/manufacture and will also introduce the technology to Rolls Royce and their external suppliers through lectures, meetings and hands-on training. The Fellow and 2 senior members of the Rolls Royce Research Team will form a steering group, ensuring that a strong scientific basis is maintained, whilst providing industrial impact. Practical research tasks will be undertaken by Rolls Royce staff, research students and the Fellow. Results will be disseminated in high profile research journals in the field of NDE and will also be presented at leading international research conferences including QNDE and IEEE meetings. These mechanisms will ensure efficient technology transfer and overcome the barriers to introducing new technology.

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