Institution: University of Bristol

Unit of Assessment: 15 - General Engineering

Title of case study: Arrays - ultrasonic measurements enable reduced inspection costs in the naval, aerospace and nuclear sectors

1. Summary of the impact (indicative maximum 100 words)

Non-Destructive Testing (NDT) is essential for the safe and efficient operation of high-value engineering plant in many engineering sectors. Research into ultrasonic arrays at the University of Bristol has had a major impact on NDT. Exploitation of the techniques developed has directly led to combined sales of around *[text removed for publication]*. For major end-users of NDT such as Ontario Power Generation, BAE Systems and Rolls-Royce, the research is leading to reductions in inspection costs, *[text removed for publication]*. In addition, highly-skilled engineers have been trained through an Engineering Doctorate programme and are now leading the industrial development of new array inspections based on underlying research performed at Bristol.

2. Underpinning research (indicative maximum 500 words)

The work described here was performed in the University's ***Ultrasonics & Non-Destructive Testing*** (***U&NDT***) group led by Drinkwater (UoB since 1996). The Group is now acknowledged as a world leader in the use of ultrasonic arrays for NDT, but its activity in this area stemmed originally from work by Drinkwater to develop dry-contact ultrasonic wheel probes using rubber as a coupling medium [1]. The first wheel probes were relatively narrow and contained a single ultrasonic transducer. This enables a property of the component (e.g. its thickness) to be measured along a line as the wheel is rolled along. However, by developing a wider wheel and replacing the single transducer with an ultrasonic array a ~100mm wide swathe of structure could be mapped in a single pass. The wheel array probe was patented [2] and licensed to Sonatest Ltd.

In 2003, the ***U&NDT*** group was one of the six founding academic partners of the UK Research Centre in Non-Destructive Evaluation (RCNDE). Under the RCNDE core research programme, the Bristol ***U&NDT*** group continued its array work with an increasing emphasis on array data acquisition and processing. In 2004, Holmes (UoB RA 1999-2007), Wilcox (UoB since 2002) and Drinkwater presented a paradigm-shifting paper at the main international NDT research conference (*Annual Review of Progress Quantitative NDE*) entitled *Signal Processing of Ultrasonic Array Data*. The thesis of the paper was that the traditional and widely-used beam-forming methods for ultrasonic array imaging that had been inherited from the medical community were sub-optimal for NDT. Rather than firing multiple array elements in parallel to emulate a monolithic transducer, it was proposed to fire each element separately, record all the data and perform processing off-line – a procedure that the ***U&NDT*** group termed Full Matrix Capture (FMC). The paper showed experimental proof that any of the imaging modalities currently obtained *live* from an NDT array imaging system could be exactly recreated off-line by post-processing the FMC data. More importantly, it was shown that with access to FMC data, superior imaging algorithms that were not possible with current array architecture became possible. Of particular note was the Total Focusing Method (TFM) – a term coined jointly by the University of Bristol and Rolls-Royce – that leads to image resolution very close to the theoretical diffraction-limit. The TFM can be cast in such a way that it can be adapted to almost any conceivable NDT configuration including for example: anisotropic materials; immersion inspection through irregular surfaces and mode-conversion imaging.

The pioneering conference paper was consolidated by two journal papers: the first [3] formally introduced the FMC concept and contained quantitative demonstrations of the superiority of the TFM imaging algorithm over other imaging modalities; the second [4] reviewed current array use in NDT and laid out the ***U&NDT*** group's vision of future array use in NDT being based around FMC and post-processing. Since then, the realisation of that vision has continued both in the ***U&NDT*** group at Bristol and numerous other groups internationally. Over the last decade, the ***U&NDT***

group has published around 30 journal papers on array usage in NDT based around the concept of FMC. Some important examples include a new technique for sizing sub-wavelength defects [5] and auto-focusing FMC data in post-processing to deal with unknown material or geometric properties [6].

3. References to the research (indicative maximum of six references)

[1] *B. Drinkwater, R. Dwyer-Joyce and P. Cawley, 1997. *A study of the transmission of ultrasound across solid-rubber interfaces.* Journal of the Acoustical Society of America, 101(2), 970-981, dx.doi.org/10.1121/1.418055.

[2] D. Brotherhood and B. Drinkwater, 2002. *Coupling element with varying wall thickness for an ultrasound probe*. US patent 7360427 B2.

[3] *C. Holmes, B. Drinkwater and P. Wilcox, 2005. *Post-processing of the Full Matrix of Ultrasonic Transmit Receive Array Data for Non-destructive Evaluation*. NDT&E International, 38(8), 701-711, dx.doi.org/10.1016/j.ndteint.2005.04.002.

[4] B. Drinkwater and P. Wilcox, 2006. *Ultrasonic Arrays for Non-destructive Evaluation: a Review*. NDT&E International, 39(7), 525-541, dx.doi.org/10.1016/j.ndteint.2006.03.006.

[5] *J. Zhang, P. Wilcox and B. Drinkwater, 2008. *Defect Characterization Using an Ultrasonic Array to Measure the Scattering Coefficient Matrix.* IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, 55(10), 2254-2265, dx/doi/org/10.1109/TUFFC.924 (listed in REF2).

[6] C. Lane, A. Dunhill, B. Drinkwater and P. Wilcox, 2010. *3D Ultrasonic Inspection of Anisotropic Aerospace Components*. Insight, 52(2), 72-77, dx.doi.org/10.1784/insi.2010.52.2.72. *Winner of John Grimwade medal*.

* References that best indicate the quality of the underpinning research.

Grants

- B. Drinkwater, 2001-3. *Ultrasonic Wheel Array Sensor Instrument*, EPSRC GR/N33843/01, £160k.
- B. Drinkwater (PI at Bristol), 2003-14. *Intelligent Inspection Systems Using Array Data (part of core research programme of UK Research Centre in NDE - a collaborative research programme involving 6 universities)*, EPSRC (GR/S09388/01 and EP/F017332/1) ~£1M, industry (~15 partners) ~£400k.
- B. Drinkwater, 2005-11. *Nuclear Propulsion Critical Technology Programme – Improved Inspection of Reactor Components Using Ultrasonic Arrays*, MoD, ~£600k.
- P. Wilcox, 2008-11. *Two-Dimensional Arrays for the Quantitative Characterisation of Complex Defects*, EPSRC (EP/F005032/1) £263k, industry (Airbus, BNFL, Rolls-Royce, Serco and Shell), £48k.
- P. Wilcox, 2010-3. *Enhanced Ultrasonic 3D Characterisation Of Composites Using FMC Data*, EPSRC (EP/H010920/1) £224k, industry (Airbus and Rolls-Royce) £90k.
- B. Drinkwater, 2013-. *Ultrasonic Array Inspection Optimisation for Non-Destructive Evaluation*, EPSRC (EP/J016438/1) £308k, industry (EDF, Rolls-Royce, Serco, BAE Systems and Sellafield Sites), £90k.
- P. Wilcox, 2011-2. *Future Submarine Programme Enhanced NDE Technology Demonstrator Programme - Full Matrix Capture*, BAE Systems, £230k.

4. Details of the impact (indicative maximum 750 words)

Routes to impact

The most important routes to industrial impact since 2003 have been through RCNDE and the linked Engineering Doctorate NDE Centre. These routes have enabled the major end-users of NDT in the UK to be intimately involved throughout the development of the technology. The result has been industrially-funded trials, application-specific development, inward and outward secondments and the continued, rapid transfer of the new technology into industry. A second route to impact has been through academic publications stimulating interest from companies outside RCNDE seeking to solve particular NDT problems, most significantly Ontario Power Generation.

The main end-users of NDT tend to be large multi-national companies (e.g. in the power generation, aerospace, petro-chemical or defence sectors) while NDT equipment tends to be manufactured by specialist SMEs. The ***U&NDT*** group's work on ultrasonic arrays has impacted on (1) the NDT supply chain, (2) the end-users of NDT and (3) the NDT workforce. Key examples are detailed in the following sections.

Impact on the NDT supply chain

- *Sonatest* have an exclusive license to the patented [2] wheel array probe technology developed in the ***U&NDT*** group. Sales of the wheel array probe (marketed as RapidScan) have been *[text removed for publication]* [a].
- *Peak NDT Ltd.* was one of the first companies to realise the potential of the Group's FMC concept and provide an array controller instrument (MicroPulse PA) that could perform FMC without modification. As demand for FMC capability has grown, they have developed a special instrument optimised for acquiring FMC data (MicroPulse FMC). *[text removed for publication]*.

Impact on the end-users of NDT

- Since 2009, Airbus has endorsed the RapidScan instrument for various in-service inspection procedures performed on its aircraft, including, for example, A320 trailing edge corrosion: ten RapidScan devices held within the Airbus maintenance store in Hamburg are loaned to maintenance facilities worldwide to perform this inspection procedure. RapidScan enables large areas to be scanned with a 50-75% reduction in inspection time compared with conventional methods and provides added benefits such as the ability to record data. Since 2011, Airbus has also permitted a number of its suppliers of Carbon Fibre Reinforced Plastic (CFRP) components to use RapidScan as a post-production inspection tool; previously such inspections would have been performed on expensive automated/semi-automated immersion scanning facilities [d].
- *[text removed for publication]*.
- Shortly after the publication of the early work [3, 4] a team from *Ontario Power Generation* (OPG) visited the ***U&NDT*** group to gain understanding of FMC/TFM. In their CANDU (CANadian Deuterium Uranium) reactors there was an urgent need to map wall thickness around welds in several hundred reactor feed-water pipes with complex 3D geometries. Working with UK array-controller manufacturer Peak NDT Ltd., they subsequently developed a complete FMC/TFM system. This was deployed in two inspection campaigns on the Pickering power station Units 1 and 4 in 2010-1 where a total of 66 welds were completely mapped [f,g].
- The in situ detection of cracks in gas turbine blade roots is critical for the efficient operation of aircraft fleets by *Rolls-Royce Aerospace*. Although a turbine blade failure is not safety-critical (as it is contained) the estimated cost is £5M per incident. Prior to using arrays for blade root inspection Rolls-Royce suffered about three such failures per year but with inspection and a new design of blade there have not been any [h]. In particular, a special 2D array system using FMC and a modified form of the TFM algorithm was created through the doctoral work of a former Bristol EngD Research Engineer (now a Rolls-Royce employee). This work developed an auto-focus technique to deduce blade crystallographic orientation from the measured FMC data prior to imaging. A paper describing one aspect of this work [6] won the John Grimwade Medal for best paper published in the NDT journal Insight in 2010 and the Research Engineer won the John Bush award for "*engineers in the early part of their career who have made an outstanding technical contribution of value to Rolls-Royce*" [h].
- The work has impacted on the activities of QinetiQ in several areas where advanced NDT inspections have been required to keep military aircraft flying beyond their initial design lives. In those cases, the enhanced resolution achievable with the Total Focusing Method (TFM) has allowed smaller cracks to be detectable in wing spar flanges under a wing skin layer. This has been applied to three different aircraft types in the UK, enabling them to achieve the required life extensions and bringing a total of £450k of extra business to QinetiQ to implement fleet-wide surveys in two cases, the third being on-going. Another programme to look at ply-wrinkling that exploits FMC has been worth £90k to QinetiQ so far, in funding from Rolls-Royce and Airbus. QinetiQ estimate the benefit to the industry to be at least £10M per year after the initial implementation phase [i].

Impact on the NDT workforce

- In the Engineering Doctorate Centre in NDE (led by Imperial College) Bristol has so far trained four research engineers who have worked / are working on industrial projects to develop FMC capability for specific applications (three with Rolls-Royce, one with BAE Systems).
- The Argentinian company *Tenaris*, which manufactures high grade pipes for the petrochemical industry seconded an employee to the ***U&NDT*** group for three months in 2012 to learn how FMC could be applied to improve the inspection of safety-critical pipework at manufacture.
- A post-doctoral research associate from the ***U&NDT*** group was seconded to the Inspection Validation Centre at *AMEC* (formerly Serco Assurance) to develop a procedure for the application of FMC/TFM to reactor pressure vessel welds in the nuclear industry. This secondment was funded by the University Impact Acceleration Account and AMEC.

5. Sources to corroborate the impact (indicative maximum of 10 references)

[a] Sonatest annual sales and royalty reports held by Research Commercialisation Manager at the University of Bristol.

[b] 2012 UK price list of Peak NDT equipment from their distributor UTEX.

[c] Technical Director, Peak NDT Ltd.

[d] Senior NDT Aerospace Engineer, Airbus.

[e] NDE Manager, BAE Systems.

[f] R. Ten-Grotenhuis and A. Hong, 2012. *Imaging the Weld Volume Via the Total Focus Method*. Proc. of 4th International CANDU In-service Inspection Workshop and NDT in Canada Conf.

[g] R. Ten-Grotenhuis, A. Hong and A. Sakuta, 2012. *Inspection of Complex Geometries Using the Full Matrix Capture Technique.* Proc. of 4th International CANDU In-service Inspection Workshop and NDT in Canada Conf.

[h] Company Associate Fellow NDE, Rolls-Royce.

[i] Senior Fellow, QinetiQ, Farnborough, UK (email correspondence, 10 November 2012). Subsequently appointed to University of Bristol, 24 April 2013.