Institution:	**University of Warwick**
Unit of Assessment:	**B9 Physics**
Title of case study:	**Engineering applications of ultrasonics research**

1. Summary of the impact

The techniques developed by the Warwick Ultrasonics Group focus on non-destructive testing (NDT) and address particular industrial needs as specified by industrial funders. These partners have included over 40 companies in the REF Impact period, ranging from SMEs to large multi-nationals operating in a range of sectors such as the heavy manufacturing, nuclear energy, food, petrochemical, transport, aerospace, power generation, equipment manufacturing and service industries. In particular, our spin-out company, Sonemat, has commercialised high-performance electromagnetic acoustic transducers (EMATs) developed by the research group, which has led to economic benefits for NDT equipment suppliers and their end users. Further industrial impact has arisen from novel NDT methodologies established by the Group.

2. Underpinning research

The Ultrasonics Group, led by Prof. Dixon in the Dept. of Physics, combines research in solid-state physics, materials science and engineering science for application in industry. Much of their research has been undertaken through the EPSRC-funded *Research Centre for Non-Destructive Evaluation* (RCNDE – www.rcnde.ac.uk) [8], a collaboration between sixteen major industrial partners and six UK universities. The RCNDE develops research projects that are targeted towards medium to long-term industrial needs. Dixon is the Academic Chairman and a Board Member of the RCNDE. There are a further twenty or so associated members who are mainly SMEs or micro-companies. The Ultrasonics Group has separately collaborated with a number of other multinational and international companies such as Corus, Alcan and Network Rail [9,10].

Electromagnetic acoustic transducers (EMATs) Since 1993, the Group's research has led to key discoveries in EMATs [1-6], particularly in broadband EMATs that make it possible to generate and detect a range of ultrasonic frequencies simultaneously [1,2]. The major progress in EMAT design achieved in Warwick has arisen from a thorough understanding of the underlying physics, both of the real EMAT device and of the material being tested in a real world application [2,3]; by meticulous design and building of both the transducers and associated electronics [4]; and through developing modelling and simulation of ultrasonic propagation in real materials. For instance, generic methods have been developed for measuring the thickness of thin Al sheets [1]; measuring surface coating thickness from bulk ultra-sound propagation [5]; assessing ferrous metals using an EMAT coil without a permanent magnetic [4]; introducing a ferrite backing to enhance eddy current generation and hence create a much larger ultrasonic wave amplitude [6].

Many of the Group's research outputs proceed to either commercialisation or licensing. There are other examples where the fundamental research interests in material property measurement, such as research developing dry acoustic couplants for ambient and high temperature applications [7], or know-how developed on research projects on system integration and signal processing, provide other industrial impact. In 2005, the Group established the spin-out company Sonemat, with support from the Dept. of Physics, as a vehicle both for the commercialisation of EMATs for NDT and to allow wider engagement in industrial-academic collaborative programmes than would be achievable by the academic group alone. The impact of Sonemat is discussed in Section 4.

The Group's pre-eminence in the NDT field was recognised by the establishment in March 2011 of a Research Chair (currently held by Professor Dixon) [11] sponsored by Elster, one of the world's largest electricity, gas and water measurement and control providers. Elster's Vice-President (Technology -Electronic), has stated that choosing Professor Dixon and the University of Warwick has enabled Elster 'to engage with one of Europe's leading researchers in the field and one of the UK's leading university research hubs' [tinyurl.com/lbxlqc9].

Transducers for gas flow - Since the establishment of the Elster Research Chair, the Group has been collaborating with the gas flow measurement industry to support a number of developments. This collaboration has already led to some major advances in industrial prototype design (although bound by strict confidentiality at this stage). The Group is now working with industry to improve the

current ultrasonic transduction methods and developing the next generation of transducers for gas flow measurement. Much of this experimental research is underpinned by finite element modelling, using the results from such models to inform and optimise transducer design.

Warwick researchers: The Ultrasonics Group currently consists of two academics Prof. S.M. Dixon (1993-2013) and Dr R.S. Edwards (Assoc. Prof. 2007-13); five postdoctoral research assistants; nine graduate students embarked on MSc/PhD/EngD degrees; and a secondment from Elster. A further 9 graduate students have completed their degrees since 2008. All of these people have contributed to parts of the research.

3. References to the research

Publications:

1. **Dixon S, Edwards C, Palmer SB,** High accuracy non-contact ultrasonic thickness gauging of aluminium sheet using electromagnetic acoustic transducers, *Ultrasonics* **39**, 445-453 (2001) DOI: 10.1016/S0041-624X(01)00083-X
2. **Dixon S and Palmer SB,** Wideband low frequency generation and detection of Lamb and Rayleigh waves using electromagnetic acoustic transducers (EMATs), *Ultrasonics* **42**,1129-1136 (2004) DOI: 10.1016/j.ultras.2004.02.019
3. **Dixon S, Edwards RS and Jian X,** Inspection of rail track head surfaces using electromagnetic acoustic transducers (EMATs), *Insight* **46**, 326-330 (2004) DOI: 10.1784/insi.46.6.326.56379
4. **Jian X, Dixon S, Edwards RS and Fan Y.,** Coupling mechanism of electromagnetic acoustical transducers for ultrasonic generation, J*. Acoust. Soc. Am.* **119**, 2693-2701 (2006) DOI: 10.1121/1.2184288
5. **Dixon S, Lanyon B, Rowlands G,** Coating thickness and elastic modulus measurement using ultrasonic bulk wave resonance, *Appl. Phys. Lett.* **88**, 141907 (2006) DOI: 10.1063/1.2192144
6. **Dixon S and Jian X,** Eddy current generation enhancement using ferrite for electromagnetic acoustic transduction, *Appl. Phys Lett.* **89** 193503 (2006) DOI: 10.1063/1.2387125
7. **Dixon S, Edwards C, Palmer SB**, High-temperature thickness gauging using a highly deformable dry couplant material, *Insight*, **42**, 734-736 (2000) (Article available on request.)

Peer-reviewed grants/awards:

8. EPSRC GR/S09388/01 & EP/F017332/1 (PI: P. Cawley, Imperial College) Co-I: S.M. Dixon '*UK Research Centre in Non-destructive Evaluation*' (2003-2014), £4.3 M over 11 years, with partners Airbus, AMEC, BAE Systems, BP, EDF, DSTL, E.ON, Health & Safety Executive, GKN, National Nuclear Laboratory, Petrobras, Rolls-Royce, RWE npower, Shell, SKF, Tenaris and 6 UK universities.
9. EPSRC GR/S24435/01. PI: S.M. Dixon, *Non-contact dual probe using eddy current and ultrasonic techniques*, (2003-2006), £170,888, with Corus, Jarvis, OiS, TWL and University of Huddersfield
10. EPSRC EP/C534808/1. PI: S.M. Dixon, *New Instrumentation for the Scientific Study of Rail Defects*, (2005-2009), £269,827, with partners Corus, London Underground, NDT Solutions, Network Rail, RWL, Serco Railtest, Tata Steel, Universities of Birmingham and Bristol.
11. S.M. Dixon, Research Chair in Industrial Ultrasonics (with 7 supplementary PhD students), funded by Elster Group (2011-2015), £670,302

4. Details of the impact

Industry benefits from the Group's research work addressing key questions on the viability of new non-destructive testing (NDT) methodology, and developing equipment for their adoption.

The spin-out company Sonemat has operated continuously throughout the REF impact period. It has commercialised EMATs for NDT and engaged in a large number of industrial-academic collaborative programmes. During its 9 year existence, Sonemat has maintaining long-term sustainability as a small enterprise without the need to dilute equity with external investment. It has repaid the Dept.'s investment many times over, and made a year-on-year increase in profits that are invested in the protection of intellectual property of new strands of technology [12]. As an SME, Sonemat has also taken part as a validated EU Partner in several projects large EU projects,

such as 'I-Rail' www.i-railproject.eu, in which it has established itself in a key role in bringing leading technology to industry via collaboration.

Sonemat produces a range of off-the-shelf products for purchase by industry and industrial researchers; it also uses the expertise of its highly skilled researchers to provide bespoke products and consultancy tailored to customer's needs. Sonemat's Director writes [12]:

> "[A] fundamental understanding of ultrasonics [has led] to analytical advances for the non-destructive testing (NDT) industry. The research performed by Prof. Dixon into guided wave inspection of plates and pipes has led to a significant improvement in industrial capability, and a number of successful business collaborations with international NDT inspection companies as we work with them developing real-world inspection systems."

Companies are enthusiastic about the application of the research into industry, as this sample list of testimonies shows:

i. Senior Scientist [13] at TNO Netherlands writes "Corrosion is one of the most important mechanisms of structural damage…affecting the economy around the world (Oil and Gas, Chemical, Power generation, Civil infrastructure, Public assets). The current annual cost of corrosion worldwide is over 3% of the world's GDP (about US$2 trillion)"
TNO use EMATs designed and developed by Dixon and Sonemat: "Their in-depth knowledge together with their capability to translate our demanding requirement to working prototypes has turned out to be very valuable…led to a spin-off company called CiT (www.cit-corrosion-Group.com). TNO's investment over the last few years in this technology is about one million euros which is now generating a steady turnover of several million a year [since 2011] on a variety of related fields".

ii. Ritec Inc., an established US equipment manufacturer and global leader in high-power ultrasonics, whose Director [14], states "We do not manufacture transducers … arguably the most important component in an ultrasonic measurement. This is where Sonemat comes in. … Not only does Sonemat make EMATs well, but they are willing to design EMATs tailored to a customer's application. Over the last two years, approximately 5% of the systems we have sold are being used in conjunction with EMATs manufactured by Sonemat."
Ritec are developing a tool for a large petroleum company for detecting corrosion and wall thinning in pipelines. Corrosion is responsible for at least a quarter of failures in the oil and gas industry, costing ~ $1.4 billion in 2013. This project represents 8% of Ritec's total revenue in 2012-13; it has "potential for significant growth over the next few years, and it would have been difficult without Sonemat and Professor Dixon's expertise" [14].

iii. Director of Spectrum Subsea Inspection Services [15], a US company specialising in NDE technologies for the petroleum industry writes:
"The significance to our customers can be put into perspective when considering the EMAT inspection service we provide to our customers on their oil platforms and oil refineries that cost billions of dollars to build and maintain. The health, safety and future of these structures relies of the quality and innovative methods and technologies we supply. The EMAT advancements from the Dixon Group and through Sonemat have enabled my company to develop world leading technology and successfully perform EMAT inspections never before accomplished."

iv. Senior Integrity Engineer [16] at Sonomatic, a worldwide organisation providing inspection services , writes "our largest client base is in the challenging oil and gas industry, both upstream and downstream…such customers include Shell, BP, Marathon, ConocoPhillips and Chevron. We have invested over £50,000 in producing a commercial EMAT inspection product based on the technology developed within the Dixon Group at Warwick…the EMAT system that has been developed provides information on the condition of subsea and top-side pipelines that may otherwise be un-inspectable".

Dixon's research, undertaken through the RCNDE, which led to the development of a new design of EMATs that can generate large ultrasonic compression waves, has benefitted US manufacturer of non-destructive testing solutions, Innerspec Technologies Inc.. The CEO states [17]:

> "The device has been incorporated into a novel, patented, ultrasonic system designed to measure liquid levels in beverage cans on-line. Innerspec have invested in this development as we see it as a complete change in technology and process in which we have focussed a stream

of our company strategy due to the overwhelming potential in the beverage industry application and wider. We see this as a revolutionary approach to fill level inspection - a transformation of the on-line measurement of fill levels in beverage cans compared to previous practice and a significant step change, based from the research of Professor Dixon."

Research in eddy current driven testing [6] has brought important economic benefits to several significant companies. In 2007, the Group began a collaboration with Cummins Turbo Technologies, a global power leader (with sales over $1 bn p.a.), on the eddy current inspection of turbocharger components. This has benefited Cummins by incorporating the improved techniques for sub-surface flaw detection in their casting foundry, as suggested by the research work and introducing batch modifications and processes that reduce scrap materials and field failures and thereby provide long-term cost savings. A former Warwick EngD student, now Senior Materials Engineer [18] leads the development of new inspection techniques at Cummins and states:

"The research provided Cummins with a detection method for the identification of critical surface and sub-surface casting defects, through the novel use of eddy current technology, which has previously not been possible. The availability of this detection tool has enabled us to quantify the quality of our supplier castings with a greater resolution and as a result has driven multiple casting improvement initiatives which aim to improve the turbocharger durability, improving our reputation for reliability and reducing warranty costs. Multiple other benefits stemmed from the research, reaching beyond the objectives of the original project, including a greater understanding of how the casting defects are distributed within a casting and … when and how life-limiting defects can be introduced into the casting process."

Other companies to benefit from this eddy current testing research include Rolls Royce and RWE npower. Rolls Royce are starting to implement eddy current array scanning technology, on the basis of a firm understanding of its strengths and limitations; this will provide significant cost savings and improved reliability [19]. RWE have developed their own Inspection Management Service www.nde.rwepi.com, using specialised NDT applications from the Group's research. This has provided significant savings in time and surface preparation costs. Head of NDT [20]) states

"The original work we have benefitted from in this field resulted in significant process cost and time savings during plant shutdowns. The ability to use EMAT transducers to monitor boiler tube thicknesses without having to surface prepare the component has saved on average £10,000 per unit shutdown."

Many more collaborations occurred in the 2008-13 period from which companies have derived impact; however, confidentiality restrictions (and space) mean that not all can be described in detail. Those expounded on above thus represent a sample to illustrate the breadth of our impact.

5. Sources to corroborate the impact

12. Letter received from Director, Sonemat confirming details of the company http://www.sonemat.co.uk/
13. Letter received from Senior Scientist TNO Netherlands
14. Letter received from Director (and Senior Applications Scientist) at Ritec Inc.; www.ritecinc.com
15. Letter received from Director of Spectrum Subsea Inspection Services
16. Letter received from Senior Integrity Engineer, Sonomatic Ltd.
17. Letter received from CEO, Innerspec Technologies Inc.
18. Letter received from Senior Materials Engineer, Cummins Turbo Technologies.
19. www.rolls-royce.com/nuclear/services/inspection_services/ndt/#Ultrasonic_inspection
20. Letter received from Inspection Management Group Head, RWE npower