Institution: Imperial College London

Unit of Assessment: 10 – Mathematical Sciences

Title of case study: B10-5 Mathematical tools and software improved nuclear safety through characterisation of defects in nuclear power plant components

Period when the underpinning research was undertaken: 2002-Present

Details of staff conducting the underpinning research from the submitting unit:

Name(s):	**Role(s) (e.g. job title):**	**Period(s) employed by submitting HEI:**
Professor Richard V. Craster Professor Michael J.S. Lowe Dr Peter Huthwaite Dr Elizabeth A. Skelton Dr Fan Shi Dr Stewart Haslinger Dr Andrea Colombi Dr Daniel Colquitt	RVC: Professor of Applied Mathematics MJSL: Professor of Mechanical Engineering PH: Senior Lecturer in Mechanical Engineering EAS: PDRA in Applied Mathematics FS: PDRA in Mechanical Engineering SH: PDRA in Elastic and Seismic Metamaterials AC: PDRA in Elastic Metamaterials DC: PDRA in Multiscale Physics	RVC: 1998-Present MJSL: 1994-Present PH: L/SL 2016-Present, Fellow 2012-2016 ES: PDRA 1990-2018 FS: PDRA 2016-2019 SH: PDRA 2017-2020 AC: PDRA 2015-2018 (Marie Curie Fellowship) DC: PDRA 2014-2015

Period when the claimed impact occurred: 1 August 2013 – 31 December 2020

Is this case study continued from a case study submitted in 2014? N

1. Summary of the impact

Researchers at Imperial have developed a range of mathematical tools and software to address critical nuclear safety issues via ultrasonic non-destructive evaluation (NDE). These new tools enable the rapid inspection of critical nuclear components in confined and challenging environments, e.g. in nuclear submarines, and directly impact upon the safety of personnel and the timeliness and accuracy of inspection with end-users such as Rolls-Royce, Amec (now Jacobs), EDF, BAE Systems and the National Nuclear Laboratory. As noted in **[A]** "*The production of component safety justifications requires thousands of man hours that represents millions of pounds of cost. A small benefit provided to this effort will remove significant cost from the submarine enterprise.*" Additionally, driven by industry need, with ultrasonics and metamaterials at the fore, we helped create the UK acoustics network and we describe its impact at DSTL.

2. Underpinning research

Since 2002 Imperial researchers have created a suite of methodologies in wave modelling, oriented around ultrasonic inspection, including novel absorbing layer techniques and hybrid methods for Finite Element (FE) software, efficient techniques for finding wave properties in curved plates, bars and pipes, accelerated FE and imaging techniques, and more recently the analysis of scattering by rough elastic surfaces. There is a well-developed pipeline of theory, modelling, and numerical simulation moving from Imperial to industry, and demand from industry to academia being fed back, through the UK Research Centre in Non-Destructive Evaluation (RCNDE, https://rcnde.ac.uk). A succession of grants **[i-iv]** under the umbrella of RCNDE have

included financial support from industry (Rolls-Royce, Amec now Wood, EDF, BAE Systems and National Nuclear Laboratory).

As noted by the regulator **[B]**, a pressing and challenging issue in the nuclear industry is the characterisation of rough (real) defects; current state-of-the-art is, naturally, over-cautious. We have used our powerful array of techniques to pioneer, in **[1,2]**, the mathematical analysis of scattering by rough elastic surfaces and complemented this by experiments and comprehensive simulation: This was supported by industry through RCNDE projects (sponsors being EDF, NNL, Amec-Wood-Jacobs, BAE Systems and Rolls-Royce). In the words of **[C]** "*The work you have done to enable the prediction of the expected amplitude of reflection, using just the roughness statistics, is transformative*" allowing the overly cautious estimates currently in use to be replaced by tighter bounds. **[A]** describe this as "*a step change in the ultrasonic inspection modelling capability available to Rolls-Royce*".

Additionally, our work **[4]** is implemented in DISPERSE - the world leading software modelling tool for guided elastic waves - and in the GPU accelerated FE software, Pogo (also licensed by Imperial Consultants). New theory in **[4]** addressed a capability gap in DISPERSE, i.e., in dealing reliably with multiple layers each with anisotropy (for modern composites in aerospace), and viscoelasticity (for lossy media); this is now implemented in the latest version of DISPERSE. Interwoven with the above is unique scientific computing capability: Pogo GPU accelerated finite element scheme enables rapid simulation of complex geometries that are out of reach otherwise and this is used in rough surface scattering work **[1]** and utilised by Rolls-Royce amongst others **[6]**. We have developed further our hybrid methodology moving to incorporate new numerical schemes **[5]** and to enable our industry partners to better utilise it. Our research has also led to the development of elastic metasurfaces **[3]** that take advantage of ultrasonics.

Taken together this comprehensive range and breadth of ultrasonic modelling is widely used in the NDE industry to investigate complex scattering scenarios **[A, C]**; the nuclear regulator notes our effectiveness in directly addressing topics of direct interest to the nuclear industry **[B]**. In terms of wave modelling in ultrasonics for elastic waves the UK is undoubtedly in a world-leading position in part as a result of the theoretical underpinning provided by the Mathematics grouping.

3. References to the research

[1] S. Haslinger, F. Shi, P. Huthwaite, R. V. Craster and M. J. S. Lowe, “Appraising Kirchhoff approximation theory for the scattering of elastic shear waves by randomly rough defects” Journal of Sound and Vibration 460, 114872, 2019, doi:10.1016/j.jsv.2019.114872.

[2] F. Shi, M.J.S. Lowe and R.V. Craster, ``Recovery of correlation function of internal random rough surfaces from diffusely scattered elastic waves'', J. Mech. Phys. Solids, 99, 483--494, 2016, doi:10.1016/j.jmps.2016.11.003.

[3] A. Colombi, V. Ageeva, R. J. Smith, A. Clare, R. Patel, M. Clark, D. Colquitt, P. Roux, S. Guenneau, R. V Craster, "Enhanced sensing and conversion of ultrasonic Rayleigh waves by elastic metasurfaces" Scientific Reports, 7, 1-9, 2017, doi:10.1038/s41598-017-07151-6.

[4] F. Hernando Quintanilla, M. J. S. Lowe and R. V. Craster, ``Full 3D Dispersion Curve Solutions for Guided Waves in Generally Anisotropic Media'', J. Sound Vib., 363, 545--559, 2015, doi:10.1016/j.jsv.2015.10.017.

[5] W. Choi, E. A. Skelton, J. Pettit, M. J. S. Lowe and R. V. Craster ``A generic hybrid model: Three-dimensional bulk elastodynamics in non-destructive evaluation'', IEEE Trans. Ultrasonics, Ferroelectrics and Frequency Control 63, 726--736, 2016, doi:10.1109/TUFFC.2016.2535369.

[6] J. R. Pettit, A. E. Walker and M. J. S. Lowe "Improved detection of rough defects for ultrasonic nondestructive evaluation inspections based on finite element modeling of elastic wave scattering" IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control 62, 1797 - 1808, 2015, doi:10.1109/TUFFC.2015.007140.

Grant support:
[i] Rolls-Royce and MoD direct funding of research programme in Mech Eng (P Cawley, M Lowe), to develop ultrasonic inspection methods for nuclear plant components. Total £2M over period 2004-2011

[ii] M. Lowe and R. Craster Modelling of ultrasonic response from rough cracks: EPSRC EP/I018948/1 01/01/2011-31/12/2013 (EPSRC 292K + 90K Industrial) project partners EDF and Rolls-Royce Plc

[iii] 2011-2014 EU Project SIMPOSIUM €5.99million administered by CEA Labs, Saclay http://www.simposium.eu/

[iv] M. Lowe and R. Craster Stochastic ultrasonic scattering from the tips of rough cracks EPSRC EP/P01951X/1 01/04/2017-31/3/2020 415K project partners Amec Foster Wheeler, BAE Systems, EDF, National Nuclear Laboratory and Rolls-Royce Plc

[v] K. Horoshenkov and R. Craster, UK Acoustics Network, EPSRC EP/R005001/1 561k (13 industry partners). 06/11/2017-31/03/2021 and UK Acoustics Network Plus, EPSRC EP/V007866/1 1.4M (36 industry and external partners contribute additional 1.1M). 01/11/2020-31/10/2024

[vi] R. Craster (PI) plus 8 Co-I EPSRC EP/L024926/1 Programme Grant: Mathematical fundamentals of Metamaterials for multiscale Physics and Mechanics. 2.55M EPSRC + 0.7M Industry Sponsors. 30/07/2014-31/01/2020

4. Details of the impact

Our work directly impacts upon civilian nuclear inspections and safety as evidenced in **[C]**; it also impacts the UK nuclear deterrent by ensuring that the UK submarine capability remains safe and available for operation; it ensures the health and safety of personnel; and by delivering improved estimates for component lifetimes and defect characterisation yields savings in inspection development costs **[C, A]**. Focussing in on improving the inspection capability for critical components, that are hard to access in confined space, has provided substantial cost savings **[A]**. These advances also have broad reach and significance as many of the UK, and international, nuclear facilities are ageing and the accurate inspection of difficult to access components is critical to ensuring that they continue to operate safely **[B]**.

Underpinned by the research funded in **[i-iv]** we developed the first characterisation of scattering by rough cracks within reactor pipework -- previous algorithms assume smooth flat cracks and generate overly cautious estimates. Our work revises these estimates and is implemented by our industry partners **[6, A, C]**.

EDF Energy and Rolls-Royce Submarines
Both Rolls-Royce Submarines and EDF actively deploy the Finite Element Method for modelling of ultrasonic wave-defect interaction **[A,C,i,iv,6]**, aiming to provide a capability to model the reflection of ultrasonic waves from small and geometrically complex flaws typical of the types found in nuclear plants due to manufacturing, fatigue, or service **[A, C]**. Both Rolls-Royce and EDF highlight the cost-savings associated with accurate simulation versus the "*notoriously expensive*" standard approaches and that simulation is "*invaluable*", "*as it allowed small regions of a component to be modelled using the FEM without wasting computing resources on unnecessary and currently un-solvable models*" **[A]**. The economic benefits to Rolls-Royce and EDF are most keenly felt as cost savings as "*The production of component safety justifications requires thousands of man hours that represents millions of pounds of cost. A small benefit provided to this effort will remove significant cost from the submarine enterprise"* **[A]**.

Our impact draws upon a suite of specialised software some of which is commercialised: DISPERSE software is used by [redacted from public version] different organisations/companies and we evidence its impact via **[D]** where Disperse is a key capability underpinning the R&D development of that company. Additionally, our hybrid method is now standard in industry partners as evidenced in **[A]**; this has facilitated Pogo a finite element solver designed for GPU computation.

Software

- the latest version of software DISPERSE contains the algorithms in **[4]**. DISPERSE is licensed by Imperial College Consultants. Since 2013, [redacted from public version] different companies/ organisations purchased licences, across [redacted from public version] countries, generating a revenue of [redacted from public version] **[E]**.
- Customers include [redacted from public version] **[E]**.
- The hybrid **[5]** method we developed with sponsorship from Rolls-Royce, Amec now Wood, EDF, BAE Systems and National Nuclear Laboratory is now a standard tool for these sponsors and other industry partners. **[A, C]**.
- Pogo is a high-speed finite element package for ultrasound simulation that we have combined with the hybrid method **[1,2]**. This combination of PoGo/Hybrid method is now used internationally by industries operating in nuclear, oil and gas, and to [redacted from public version] for space exploration. Since 2017, [redacted from public version] licences have been supplied, with [redacted from public version] of these to private companies and [redacted from public version] to universities giving a total revenue of [redacted from public version] **[E]**.

Acoustics Network

The industry-academic relationships we built in NDE/ultrasonics **[iv]**, and in metamaterials **[3, vi]**, led, through workshops and community events, directly to the EPSRC UK Acoustics Network **[G]** (RVC is Co-Director). Starting in Nov 2017 UKAN has rapidly grown to >1200 members (500+ from industry) and extended to an EPSRC Network Plus **[v]**, with significant industry input, in 2020; there are special interest groups in both NDE and metamaterials.

This extensive network has broad impact, here we focus on a single exemplar of the impact that UKAN has on training industry staff in one organisation, DSTL **[F]**. Staff were trained at a UKAN workshop in machine learning (ML) for acoustics and "*Dstl has been able to use its new expertise in ML to contribute to a number of high impact projects that support the RN operational advantage in the underwater battlespace.*" UKAN has become "*an important part of the ecosystem being used by Dstl to maintain and develop internal capability in underwater acoustics.*" DSTL is just one of the many companies and external organisations (including Thales, GlaxoSmithKline, AECOM, DEFRA, Meridian Audio, Precision Acoustics, QinetiQ) that have been actively involved in UKAN. Using its industry connections, the network is actively involved in policy work for acoustics with the report **[H]** highlighting its value to industry, the economy, and society.

5. Sources to corroborate the impact

[A] Letter from Head of NDE at Rolls Royce Submarines Ltd
[B] Letter from Principal Inspector for Nuclear Safety at the Office for Nuclear Regulation
[C] Letter from Specialist Engineer at EDF Energy Nuclear Generation Ltd
[D] Letter from CEO at Guided Ultrasonics Ltd
[E] Letter from Imperial Consultants Ltd
[F] Letter from Senior Principal Scientist at DSTL Porton Down
[G] UK Acoustics Network weblink www.acoustics.ac.uk (Archived here)
[H] Sound Economics report. Authors, J. Lincoln, RVC, K. Horoshenkov
https://acoustics.ac.uk/?resources=acoustics-sound-economy-the-value-of-acoustics-report
(Archived here)