Institution: Imperial College London

Unit of Assessment: 10 Mathematical Sciences

Title of case study: C9 - Modelling of bulk and guided waves in the Non-Destructive Evaluation of structures; software and implementation by industry

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

The waves group in the Mathematics Department at Imperial College London has developed methodology in several areas, including novel absorbing layer techniques and Hybrid methods (with Rolls Royce and CEA) for Finite Element software, and efficient techniques for finding the properties of waves in curved plates, bars and pipes. The impact is facilitated by a long-standing research collaboration with the Non-destructive Evaluation group in the Mechanical Engineering department, incorporated with industrial partners through the UK Research Centre in Non-Destructive Evaluation (https://www.rcnde.ac.uk). Our work has been directly implemented in DISPERSE - the world leading software modelling tool for guided stress waves (licensed by Imperial Consultants) - and by Rolls-Royce. [text removed for publication]. Rolls-Royce use the models for improved inspection techniques, resulting in reduced man hour costs and multiple £50Ks of equipment savings.

2. Underpinning research (indicative maximum 500 words)

The initial collaboration between the Non-destructive Evaluation (NDE) group (Mechanical Engineering) and Mathematics involved studying dispersion curves which are vital in the interpretation and understanding of guided elastic waves [G1]. A technical, but practically important, issue is the efficient and accurate evaluation of such curves for waveguide structures (such as pipelines) that is guaranteed not to miss any curves and which remains reliable and stable for the industrial user. The theory created in [1,2] does precisely this for the important class of circumferential guided waves in pipelines and is incorporated in the DISPERSE releases from 2002-present. DISPERSE is the world's leading modelling tool for guided stress waves, developed in Imperial College and licensed by Imperial Consultants. A further industry requirement is for dispersion curves for porous elastic media, anisotropy for fibre-reinforced composite pipelines, inhomogeneous media and buried pipelines. Again, progress in the theory [3] has been made and, for porous media, this has actively been taken up by the geophysics and petroleum engineering communities.

In practical terms, ultrasonic modelling in industry is dominated by ray modelling (the world leading code is CIVA, http://www-civa.cea.fr/en/, developed by the Commissariat à l'énergie atomique et aux énergies alternatives, CEA, in France) but this is not good for scattering for which finite element (FE) models are strongest; commercial FE codes such as ABAQUS are widely-available and well established. When modelling scattering by defects in practical structures of large size, the greatest limitation in numerical modelling is unwanted reflections from model boundaries that are manifest as additional reverberations in the ultrasonic signal that contaminate and poison the results. Arbitrarily extending the domain size to large extents requires high-cost computing and long-time solutions, and indeed is unfeasible for all but the simplest cases. The removal of unwanted reflections is a challenging practical problem, and a research area in its own right, but a key issue ignored by the academic literature is that implementation in industry must use finite element codes that are professionally accredited and meet industry standards. Contributions from Mathematics were to identify how perfectly matched layers (PMLs) can be used to address elastic waveguide modes that have negative group velocity [4], a technical point that destroyed applications of bespoke FE codes to ultrasonics in waveguides, and then use this knowledge to tackle the industry bottleneck. The primarily academic work then grew into an investigation of absorbing layers versus PMLs with the emphasis on how to actually implement these research ideas into the codes (ABAQUS) that Rolls-Royce [G2] and many others in industry actually use. We were successful in this, as described in [5], and our techniques are now implemented by Rolls-Royce.

In practice, scattering from defects may occur in large complex structures (rail tracks, components in nuclear plants etc, [G3]) with considerable separation between excitation transducer, defect and receiver and the subsequent numerical modelling can lead to vast memory requirements, particularly in 3D. This industry bottleneck motivated the group to develop hybrid methods whereby only the source, receiver and scatterer are modelled numerically and these small "boxes" then communicate mathematically with each other as described and implemented for commercial FE in [6]. These advances enable large scale realistic simulations, even in 3D, to be practical in CIVA and this is key to applications of modern ultrasonics. This success led to the invitation by CEA to join a consortium developing CIVA which is used by industry worldwide (http://www-civa.cea.fr/en/partners/).

Key Contributors:
- Professor R Craster, Head of Department of Mathematics, Imperial College, Oct 1998-present
- Professor M Lowe, Professor in Mechanical Engineering, Imperial College, 1989-present
- Dr E Skelton, RA, Department of Mathematics, Imperial College, 1990-present

3. References to the research (* References that best indicate quality of underpinning research)

[1] J. Fong, M.J.S. Lowe, D. Gridin and R.V. Craster, "*Fast techniques for calculating dispersion relations of circumferential waves in annular structures*", Review of Progress in Quantitative NDE (American Institute of Physics conference proceedings), 22, 213-220 (2002). DOI.

[2] *D. Gridin, R.V. Craster, J. Fong, M.J.S. Lowe and M. Beard, "*The high frequency asymptotic analysis of guided waves in a circular elastic annulus*", Wave Motion, 38, 67-90 (2003). DOI.

[3] A.T.I. Adamou and R.V. Craster, "*Spectral methods for modelling guided waves in elastic media*", J. Acoust. Soc. Am. 116, 1524-1535 (2004). DOI.

[4] *E.A. Skelton, S.D.M. Adams, and R.V. Craster, "*Guided Elastic Waves and perfectly matched layers*", Wave Motion, 44, 573-592 (2007). DOI.

[5] P. Rajagopal, M. Drozdz, E. Skelton, M.J.S. Lowe and R.V. Craster, "*On the use of absorbing layers to simulate the propagation of elastic waves in unbounded media using commercially available Finite Element packages*", NDT & E International, 51, 30-40 (2012). DOI.

[6] *P. Rajagopal, E.A. Skelton, M.J.S. Lowe and R.V. Craster, "*A generic hybrid model for bulk elastodynamics, with application to ultrasonic Non-Destructive Evaluation*", IEEE Trans. Ultrasonics, Ferroelectrics and Frequency Control, 59, 1239-252 (2012). DOI.

Relevant Research Grants:

[G1] EPSRC, GR/R32031, "*Distorted Elastic Waveguides: Theory and Application*", PI: R. Craster, Co-Is: P. Cawley, M. Lowe, 01/10/01-30/09/04, £236,682

[G2] Rolls-Royce and MoD direct funding of research programme in Mech Eng (PIs: P Cawley, M Lowe), to develop ultrasonic inspection methods for nuclear plant components. Total >£3M over period 2004-2013

[G3] EPSRC, EP/I018948/1, "*Modelling of ultrasonic response from rough cracks*", PI: M. Lowe, Co-I: R Craster, 1/1/11-31/12/13, £292,750 + £90K Industrial from project partners (EDF-Energy, Rolls Royce Naval Marine), 01/01/11-31/12/13

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

DISPERSE software:

The theory work of [1,2] is incorporated into the commercial package DISPERSE [A] v2 which was released in 2002 and continues to be updated and developed by Imperial College, led by Prof M Lowe, Mechanical Engineering. DISPERSE was first released to external users in 1991 [text removed for publication] [C]. DISPERSE is an interactive Windows program designed to calculate dispersion curves for multi-layered flat or cylindrical structures. The facility to model accurately circumferential modes (added in 2002) is an attractive addition to the original code and has helped it to maintain its pre-eminent position in this area. [text removed for publication]. The spectral approach to generating dispersion curves accurately, developed in paper [3] drove the development of a porous elastic version by Karpfinger and colleagues at Schlumberger Oilfield Services and Shell International. This allowed real time completion modelling in deepwater oil wells

with the technique now widely utilised in those applications. An article in The Leading Edge, a magazine reporting new geophysical advances to the Society of Exploration Geophysicists, acknowledges the contribution of the spectral theory based on [3] to both experiments and the development of real-time completion modelling for oil fields [B].

Rolls-Royce Submarines:

Since 2004 Rolls-Royce has been working in collaboration with Imperial's departments of Mathematics and Mechanical Engineering on the development of the Finite Element Method (FEM) for the modelling of ultrasonic wave propagation and defect interaction [G2]. The aim of the work was to model capably the interaction of ultrasonic waves with small and geometrically complex flaws typical of the types found in nuclear plants due to manufacturing and service induced mechanisms. The limitations of existing models placed unnecessary cost on the company due to "*extended inspection durations and test piece trials*" [E]. An aim of the collaboration with Imperial was to "*provide a generic modelling capability to reduce inspection development costs through a greater emphasis on modelling rather than test piece trials*" [E]. The absorbing boundaries work [4,5] proved "*invaluable for the overall aims of Rolls-Royce as it allowed small regions of a component to be modelled using the FEM without wasting computing resources on unnecessarily large models*" [E]. These developments have "*delivered significant reductions in the model sizes required of typical inspection scenarios*" [E].

Financial impact to Rolls-Royce can be summarised in two ways:
- The modelling improvements described above "*will significantly reduce the number of ultrasonic test pieces required during inspection development*" where a typical test piece adds in the region of £50,000-100,000 to inspection costs;
- The "*production of component safety justifications requires thousands of man hours that represents millions of pounds of cost*" and a small benefit provided to this effort removes "*significant cost from the submarine enterprise*" [E].

The projects that the Imperial group delivered "*provided Rolls-Royce with a significant improvement in modelling capability*" and have led to two sponsored EngD projects to further refine the ideas and transfer the technology into Rolls-Royce. Additionally, one of the collaborators for this work, M. Drozdz, is now a fulltime employee at Rolls-Royce.

SIMPOSIUM:
The hybrid technique [6] has similarly been implemented in code by Rolls-Royce and this successful implementation has created momentum with the impact on-going and developing internationally. For instance, it led CEA (the developers of CIVA, the pre-eminent ray code used in ultrasonics) to invite Imperial College to join the EU project 'Simulation Platform for Non Destructive Evaluation of Structures and Materials' (SIMPOSIUM) that it project manages [F]. SIMPOSIUM started in September 2011 and will develop over a period of 3 years. The cost of Project is €5.99m and involves Volkswagen, European Aeronautic Defense and Space Company (EADS), SKF and Serco amongst others as industrial partners [D]. The key objective of the SIMPOSIUM project is to "*build interoperable tools based on hybrid modelling, for ultrasonic and electromagnetic NDE, in order to solve very complex industrial cases from different fields (steel nuclear, energy, aeronautics), software solution providers, and academic teams*" [F]. The "*expertise, skills and know-how concerning both NDE and mathematics from Imperial College*" is leading the developments based on hybrid modelling for ultrasonic simulation, for which it is "*necessary to combine mathematical and physics knowledge to develop efficient hybrid and coupling formulations*" [F]. The core of the work being delivered by Imperial College relates to "*a hybrid code dedicated to ultrasonic simulation, based on the CIVA beam module (prediction of the incident ultrasonic beam) and a "scattering box", based on the well-known ABAQUS software, which contains a complex flaw*" [F].

The advantage of the absorbing boundaries work combined with the hybrid work is profound. For the first time, industrial companies such as Rolls-Royce are able to perform realistic simulations of the scattering of ultrasound from defects, using FE codes that are accepted in the industry. The realism includes thick and complex-shaped components, containing complex-shaped defects,

including fatigue cracks with rough surfaces (collaborative research is on-going on this aspect too). This means that they can make cases to justify proposed inspection of safety-critical components at much-reduced expense. The cost reductions include the reduced need to make experimental test (justification) samples, and the possibility to replace radiographical inspections with ultrasound inspections, avoiding the need to evacuate personnel during inspection and the attendant health and safety issues.

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

[A] DISPERSE software website - An Interactive Program for Generating Dispersion Curves http://www3.imperial.ac.uk/nde/products%20and%20services/disperse (archived at https://www.imperial.ac.uk/ref/webarchive/g9f on 15/11/13)

[B] A. Bakulin, F. Karpfinger and B. Gurevich, '*Understanding the acoustic response of deepwater completions*', The Leading Edge: special section on permanent monitoring, smart oil fields and reservoir surveillance, December 2008, 1646-1653. DOI. (archived here) [N.B. Reference to Craster in the acknowledgments]

[C] Letter from Imperial Consultants (ICON), June 2013. [text removed for publication] (available from Imperial on request).

[D] Simposium project, partners webpage, http://www.simposium.eu/imperial-college (archived at https://www.imperial.ac.uk/ref/webarchive/fpf on 26/7/13)

[E] Letter from NDE Development Engineer, Rolls-Royce Submarines, May 2013 (available from Imperial on request)

[F] Letter from NDE Senior Expert and Coordinator of the SIMPOSIUM project, CEA, 17/7/13 (available from Imperial on request)