Institution: Imperial College London

Unit of Assessment: 12 Aeronautical, Mechanical, Chemical and Manufacturing Engineering

Title of case study: 2. Commercialisation of Guided Wave Inspection for the Detection of Corrosion in Pipes

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

Research led by Professors Cawley and Lowe (employed at Imperial College over the whole 1993-2013 period) resulted in guided wave inspection being established as a new non-destructive evaluation (NDE) method. It is used worldwide to screen long lengths of pipework for corrosion, particularly in the petrochemical industry. A spin-out company has been established that employs seven PhD graduates in NDE from Imperial and the technology is also licensed to another company. Turnover on equipment sales 2008-2013 exceeds £50M and the service companies using the equipment generate about £75M pa in revenue worldwide and employ about 300 FTE staff to carry out the inspection. The oil companies benefit from greatly reduced cost of inspection, especially in areas such as insulated, offshore and buried pipes where access is difficult and expensive for conventional inspection methods. Furthermore, the reliability of inspection is significantly improved, leading to major improvements in safety.

2. Underpinning research (indicative maximum 500 words)

A major problem with conventional NDE techniques such as standard ultrasonic testing is that they only interrogate the part of the test structure directly beneath the transducer. This means that if a large structure is to be inspected, either test times become extremely long, so the inspection adds very significantly to operating costs, or the reliability of inspection is compromised due to sparse sampling of the local measurements. The problem can be overcome by using ultrasonic guided waves which propagate along a structure and therefore enable a large area to be inspected from a single transducer position, so giving 100% volume coverage and large savings in inspection time. The difficulty with guided wave inspection is that many guided wave modes exist (over 50 at 100 kHz in a typical 6 inch diameter pipe) and, unless the excitation and reception is carefully controlled, the received signals are too complicated to be interpretable. Understanding the modes and then investigating methods to control them was the first research task. The background research on the guided wave inspection of pipes started in the early 1990s and the main development was carried out under the CEC Thermie programme starting in 1994. This initial work was supervised by Professor Cawley.

Of the 50+ guided wave modes in a typical 6 inch diameter pipe at 100 kHz, only three are axially symmetric so the initial research led to a decision to excite only axially symmetric modes; two of these modes are longitudinal and one is torsional, and these mode types are not coupled so excitation in the circumferential direction will only excite torsional modes and excitation in the axial direction will only excite longitudinal modes. Excitation can efficiently be provided by an array of nominally identical transducers around the pipe, each transducer forcing in the required direction. This concept, together with a novel transducer design is the subject of the key underpinning patent [1] (authors Professor Cawley and RAs working on the project). The next step was to show how the chosen modes interact with defects, and the key initial study of this is reported in [2]; this was jointly supervised by Professors Cawley and Lowe in the mid-1990s.

A simple reflection measurement in an axially symmetric mode cannot distinguish between a benign, axially symmetric reflector such as a butt weld, and a corrosion patch that will typically be non-symmetric. We then showed that a symmetric feature will only reflect the incoming symmetric mode, whereas a non-symmetric feature will reflect both the incident axisymmetric mode and non-symmetric modes generated by mode conversion. The output of the individual transducers in the array can be processed to give both the symmetric and non-symmetric reflected modes and this, together with the relative amplitudes of the key modes for different circumferential extents of defects, is described in [3], a companion paper to [2]. A guide to using the relative amplitudes of the different reflections to diagnose corrosion is given in [4] and this is the procedure used commercially; again this work was jointly supervised by Professors Cawley and Lowe in the early 2000s. Further recent work [5] supervised by Professor Cawley has shown that the output of the transducer array can be processed to give a full unwrapped image of the pipe, so both the axial and circumferential location of defects is obtained, together with an indication of the lateral and axial extents of the defect; this is now implemented in the commercial product.

Pipes are frequently coated with highly viscoelastic materials such as bitumen to provide corrosion protection, so it is necessary to understand the influence of this on the wave propagation; a key fundamental study of this effect is given in [6] and informs the guidelines used for testing coated pipes. This work was supervised by Professor Cawley between 2000-2004.

3. References to the research (indicative maximum of six references)
* References that best indicate quality of underpinning research.

[1] P. Cawley, D.N. Alleyne, C.W. Chan," Inspection of pipes", Patent WO1996012951 A1, priority date 20-10-1994. http://www.google.co.uk/patents/WO1996012951A1?cl=en

[2] D.N. Alleyne, M.J.S. Lowe, P. Cawley, "The reflection of guided waves from circumferential notches in pipes", ASME J Applied Mechanics, Vol 65, pp. 635-641, (1998) DOI: 10.1115/1.2789105

*[3] M.J.S. Lowe, D.N. Alleyne, P. Cawley, "The mode conversion of a guided wave by a part-circumferential notch in a pipe", ASME J Applied Mechanics, Vol 65, pp. 649-656, (1998) DOI: 10.1115/1.2789107

[4] A. Demma, P. Cawley, M.J.S. Lowe, A.G. Roosenbrand, B. Pavlakovic, "The reflection of guided waves from notches in pipes: a guide for interpreting corrosion measurements", NDT&E International, Vol 37, pp.167-180, (2004) DOI:10.1016/j.ndteint.2003.09.004

*[5] J. Davies, P. Cawley, "The application of synthetic focusing for imaging crack-like defects in pipelines using guided waves", IEEE Trans UFFC, Vol 56, pp. 759-771, (2009) DOI: 10.1109/TUFFC.2009.1098

*[6] F. Simonetti, P. Cawley, "On the nature of shear horizontal wave propagation in elastic plates coated with viscoelastic materials", Proc Royal Soc Lond: Mathematical, Physical and Engineering Sciences, Vol 460, pp. 2197-2221, (2004) DOI: 10.1098/rspa.2004.1284

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

<u>Direct Economic</u>
Corrosion costs the petrochemical industry about $12 bn pa at 1999 prices [7] and it is essential to detect and manage it for the safe operation of plant and to avoid environmental disasters such as leaking pipelines in Alaska or subsea. Corrosion in pipe systems often happens at unpredictable locations and conventional inspection techniques require scanning over the whole surface to be inspected. Given the volume of pipes in service this is impractical. The guided wave inspection system described above solves this problem and makes it possible to do 100% screening of pipes that are otherwise prohibitively expensive to inspect.

In 1999 a spin-out company Guided Ultrasonics Ltd was formed to commercialise the technology under licence from Imperial Innovations, the College technology transfer company. It now employs 7 PhD graduates in NDE topics from Imperial with a total staff of 15 in UK. It sells equipment to service inspection companies who do the inspection for the oil companies; the equipment and examples of applications are given in [8, 9]. The company has turned over £32M in the REF period 2008-2013 as confirmed by Operations Director, Guided Ultrasonics Ltd [B]. Imperial Innovations also licenses the technology to a Welding Institute subsidiary company, Plant Integrity Ltd, whose system is described in [10, 11]. This company has a similar turnover so during the REF period the turnover from the technology directly has been >£50M, over 80% of which is export [A].

The test systems last for 5-10 years and there are over 300 systems in service worldwide; they are typically charged at £2500/day [B]. Assuming 50% utilisation, revenue to service inspection companies is ~£75M pa and over 300 FTE inspectors are employed (crew of 2 per inspection). The income generated for the service inspection companies is therefore around £450M over the REF period.

End User – Economic and Safety
The benefit to the end user companies is reduced cost of inspection e.g. pipes buried under roads - excavation for conventional inspection costs upwards of £80k [C]; insulated pipes - stripping and re-instating insulation typically costs $100-2000/m depending on whether scaffolding etc. is required [B].

There are also significant safety benefits e.g.:

- Offshore risers - corrosion is most likely in the splash zone where safe access for conventional inspection is expensive to ensure; in contrast a guided wave test can be conducted from deck level where safe access is easy to provide [C].

- 100% volume inspection coverage gives much better probability of detecting severe, isolated defects than local inspection on a sampling basis.

- The technology also enables the end user companies to carry out more inspection of critical, inaccessible lines and so improve safety and environmental performance. An example of the use of the technology to inspect an oil transmission pipeline crossing a swamp in Mexico is given in [12]. The enhanced safety benefit is much more difficult to quantify but is clearly substantial. The technique is mainly used in the petrochemical industry but is also used in the power generation (especially nuclear) and gas transmission sectors.

Standards
Guided wave inspection has been recognised as a Method of NDE in its own right, and its worldwide use has grown steadily to the point at which it is appropriate to establish standards. This is important to ensure that the method is used correctly, and also that its capabilities are not over-sold, both vital ingredients to its long-term success. Professor Lowe is leading the development of standards, working with standards bodies, in close collaboration with Guided Ultrasonics Ltd and Plant Integrity Ltd. The British Standard [13] explicitly cites [4] above and there are also Italian [14], Japanese [15] and US [16] standards. Training of inspectors is also crucial to the successful application of the technology and certified training schemes are now in place e.g. PCN (UK), ASNT (USA), RINA (Italy).

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

[7] P. Cavassi, M. Cornago, 'The Cost of Corrosion in the Oil and Gas Industry', Journal of protective coatings & linings, (1999) pp30-40. This confirms the corrosion costs. ISSN 8755-1985 http://cat.inist.fr/?aModele=afficheN&cpsidt=10046432

The sources below give examples of the application of the technology in particular settings:

[8] D.N. Alleyne, B. Pavlakovic, M.J.S Lowe, and P Cawley. 'Rapid long-range inspection of chemical plant pipework using guided waves', Insight, Vol 43, pp93-96,101, 2001. DOI: 10.1063/1.1373757.

[9] Guided Ultrasonics Limited www.guided-ultrasonics.com (Archived at https://www.imperial.ac.uk/ref/webarchive/2rf on 6th September, 2013).

[10] P.J. Mudge 'Field application of the Teletest long-range ultrasonic testing technique', Insight Vol 43, pp74-77, 2001.

[11] Plant Integrity Limited www.plantintegrity.com (Archived at

https://www.imperial.ac.uk/ref/webarchive/3rf on 6th September, 2013)

[12] V.M.N. Ledesma, et al, 'Guided wave testing of an immersed gas pipeline' Materials Evaluation Feature Article pp102-115, (2009) ISSN: 0025-5327 WOS:000263371900003

The sources below corroborate the use of the research in the standards

[13] BSI ‘Non Destructive Testing - Guided Wave Testing’, (2011), UK (This standard cites ref #4), BS 9690 ISBN 978 0 580 73794 7 – British Standard

[14] UNI ‘NDT inspection of above-ground pipelines and plant piping using long range guided waves with axial propagation’, (2009) UNI/TS 11317 – Italian Standard

[15] ‘General principles of Guided Wave inspection for piping by pulse echo technique’, (2010), Japan. (in Japanese) JIS NDIS 2427 - Japanese Standard

[16] ASTM ‘Standard Practice for Guided Wave Testing of Above Ground Steel Pipework Using Piezoelectric Effect Transduction’, (2011), USA. DOI: 10.1520/E2775-11 – US Standard

Other sources for corroboration:

The sources below corroborate the financial impact of the technology on their respective companies:

[A] MD Technology Transfer, Imperial Innovations Ltd

[B] Operations Director, Guided Ultrasonics Ltd

[C] Inspection Consultant, Upstream Engineering Centre, BP plc – this source also corroborates the safety impact.