Institution: **10007822**

Unit of Assessment: **12**

Title of case study:

Optical fibre sensors: improved design of commercial superconducting magnets

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

Optical fibre sensor technology developed at Cranfield has supported development and subsequent sales of state-of-the-art superconducting magnet systems made by Oxford Instruments. The sensors provide detailed information on the magnets' performance that is critical to successful and safe operation. The fibre sensors have been deployed in:

- High-field NMR and high-density research magnets to 22 Tesla, a world leading product, a dozen of which have been installed at a total value of over £6 million.
- Magnets for beam-line facilities worldwide with 15 installed over the last five years at a total value of over £7.5 million.

Cranfield's research contributed to a doubling of the engineering and design staff at Oxford Instruments and 20% increases in turnover and technical staff at an instrumentation company, AOS Technology.

2. Underpinning research (indicative maximum 500 words)

For over 20 years, researchers at Cranfield have investigated, developed and deployed optical fibre Bragg grating sensors (FBGs) across a range of engineering disciplines to provide measurements that are not possible using other techniques.

The impact of our work arises from three areas of research undertaken by the Cranfield team in collaboration with multidisciplinary teams of academics and industrialists. The first established that FBGs were capable of monitoring transient events of microsecond duration [P1]. The second showed that the FBG technology successfully operated at cryogenic temperatures where they exhibited zero temperature response below ~100K and could measure strain at temperatures down to 2.2K [P2]. Conventional strain monitoring techniques cannot match these specifications, particularly in the presence of large and varying magnetic fields. The third area of research was the development of instrumentation [P3] to facilitate the measurement of loads using FBGs embedded within fibre reinforced composites [P4]. This led to the measurement of dynamic strain effects within a superconducting magnet coil during a quench, i.e., becomes resistive following a small release of energy within the coil [P5].

The ability of optical fibre sensor technology to monitor transient events, with rise times of <10 µs, was first demonstrated under a programme commissioned by the Defence Evaluation and Research Agency (DERA) [P1]. In this work FBGs – fabricated at Cranfield using a novel combination of UV laser and interferometer to achieve precise control over the reflected (Bragg) wavelength of the sensor [P6] - were used by Cranfield and DERA to measure transient strains induced by a 100mm diameter shell as it travelled along a gun barrel with an exit velocity of ~1km/s [P1]. The sensors were interrogated using instrumentation that was purpose designed and built by the Cranfield team.

Cranfield has significant expertise in monitoring thermosetting resins as they cure. Limitations to the use of dielectric sensors in carbon fibre reinforced composites, led us to explore the use of optical fibre sensors to monitor the curing of resins. This lead to the first demonstrations of the measurement of internal strain developed both along and transverse [P5] to the axes of FBGs embedded in curing composite components.

The dissemination of this work led to a research programme funded by Oxford Instruments. The company had a requirement for dynamic strain measurement in superconducting magnets. Cranfield undertook a collaborative research programme with Oxford Instruments and, for the first time, demonstrated that FBGs could measure strain in cryogenic environments [P2].

Further collaborative investigations – supported by grants G1, G2, G3 – used FBG sensors embedded into the composite structure of the superconducting magnet coil, to monitor dynamic loading when a superconducting magnet "quenches", i.e. becomes resistive following a small release of energy within the coil, due, for example, to cracking of the resin matrix [P5]. Coil designers need to understand the loads imparted during a quench and the influence of those loads on the lifetime of the coil. The rapidly changing magnetic field experienced during a quench precludes the use of conventional electrical strain gauges. The dielectric nature of the FBG yields measurements and insights that were previously unavailable.

Key Researchers	**Post details and dates**	**Research**
Dr E Chehura	Research Fellow (2003 – present)	Fibre Optic Sensors and instrumentation
Dr S W James	Research Fellow (1993 - 1997); Lecturer (1997 – 2002); Senior Lecturer (2002 - 2007); Reader 2007 – present)	Fibre Optic Sensors and instrumentation
Prof I K Partridge	Reader (1998 - 2004); Professor (2004 - present), from 1/10/12 Professor at the Advanced Composites Centre, Faculty of Engineering, Bristol University	Polymer composites, cure monitoring
Prof R P Tatam	Senior Lecturer (1992-1995); Reader (1995-1998); Professor (1998 – present)	Fibre Optic Sensors and instrumentation

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

Evidence of quality - Peer reviewed journal papers

P1. S W James, R P Tatam, S J Fuller[a] and C Crompton[a], *Monitoring transient strains on a gun barrel using fibre Bragg grating sensors,* Measurement Science and Technology, **10**, pp. 63-67, 1999.
doi:10.1088/0957-0233/10/2/002

*P2. S W James, R P Tatam, A Twin[b], M Morgan[b] and P Noonan[b], *Strain response of fibre Bragg grating sensors at cryogenic temperatures,* Measurement Science and Technology, **13**, pp. 1535-1539, 2002.
doi:10.1088/0957-0233/13/10/304

P3. C-C Ye, S E Staines, S W James and R P Tatam, *A polarisation-maintaining fibre Bragg grating interrogation system for multi-axis strain sensing,* Measurement Science and Technology, **13**, pp. 1446-1449, 2002.
doi:10.1088/0957-0233/13/9/310

*P4. E Chehura, M Kazilas, S W James, I K Partridge and R P Tatam, *Strain Development in Curing Epoxy Resin and Glass Fibre/Epoxy Composites Monitored by Fibre Bragg Grating Sensors in Birefringent Optical Fibre*, Smart Materials and Structures, **14**, pp. 354-362, 2005.
doi:10.1088/0964-1726/14/2/009

*P5. E Chehura, S Buggy, S W James, A Johnstone[c], M Lakrimi[c], F Domptail[b], A Twin[b] and R P Tatam, *Multi-component strain development in superconducting magnet coils monitored using fibre Bragg grating sensors fabricated in highly linearly birefringent fibre*, Smart Materials and Structures, **20**, 125004, 2011.
doi:10.1088/0964-1726/20/12/125004

P6. M L Dockney, S W James and R P Tatam, *Fibre Bragg gratings fabricated using a wavelength tuneable laser source and a phase mask based interferometer*, Measurement Science and Technology, **7** , pp. 445-448, 1996.
doi:10.1088/0957-0233/7/4/001

<u>*Key to papers*</u>

*: 3 identified references that best indicate the quality of the research

a: Defence Evaluation and Research Agency (DERA), Fort Halstead, UK; b: Oxford Instruments, UK; c: Siemens Magnet Technology, UK

Further evidence of quality – underpinning research grants

G1 PLATFORM GRANT: EPSRC (GR/T09149/01). *Development & Application of Photonic Instrumentation & Sensors*, £443,604, 06/2004 – 05/2009. PI Prof R P Tatam, CIs: Dr S W James, Prof C P Thompson, Prof G J Ashwell, Prof P Ivey, Prof I K Partridge, Prof P E Irving.

G2 EPSRC: Cranfield Innovative Manufacturing Research Centre (IMRC): Sub project - *Composite material process monitoring using optical fibre gratings,* £480,200, 10/2004 – 09/2007. Partners: Oxford Instruments, GKN Aerospace, Siemens, FibreLogix. PI: Prof RP Tatam, CI: Dr S W James, Prof I K Patridge

G3 PLATFORM GRANT: EPSRC (EP/H02252X*). Engineering Photonics: Development and Application of Instrumentation and Sensors*, £1,135,303, 10/2010- 09/2015. PI Prof R P Tatam, CIs: Dr SW James, Dr J Hodgkinson, Dr N J Lawson, Prof S P J Higson, Prof I K Partridge

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

Cranfield's research has supported the leading position of Oxford Instruments in magnet technology, with average magnet sales over £10 million a year over the last five years, and with a marked upward trend. These sales are enabled by the worldwide promotion and dissemination of Oxford Instruments' magnet performance using measurements conducted using the fibre optic technology developed by Cranfield [C2]. The unique combination of a non-electrically conducting sensor technology that is insensitive to temperature and magnetic field has facilitated unique measurements in the cryogenic regime [C1]. When holding workshops in China and India over the last year, the use of optical sensors was again used by Oxford Instruments to champion the superiority of their high-end technology, enabling magnet and consultancy sales [C2].

Underpinned by the fibre-optic technology derived from Cranfield's research, Oxford Instruments magnet design and production activities in the UK have grown over the last five years. The company has doubled its engineering and design staff and has seen a marked improvement in the profitability of these high-technology systems [C2].

Global markets

Oxford Instruments installs FBG sensor technology to measure strain on high-field magnet systems for nuclear magnetic resonance (NMR) and high-density research magnets with fields of up to 22 Tesla. The latter is a unique world leading product with up to a dozen installed worldwide over the last 5 years, at a total value of over £6 million. The technology is also a part of split-pair magnets used in beam-line facilities worldwide, another world leading activity with 15 installed over the last five years, at a total value of over £7.5 million.

The FBG sensors provide detailed information on the performance of the high-field magnets that is critical to successful and safe operation. These products have been exported worldwide, predominantly to the USA, Germany and Japan but increasingly to China, India and the emerging economies [C2].

Cranfield's research also had direct impact on the scientific instrument manufacturer, AOS Technology Ltd, which developed and supplied a state-of-the-art (at that time) interrogator for Bragg gratings as well as subsequently supplying FBG sensors to Oxford Instruments for several years. The technology developed within AOS led to the company's subsequent involvement with major programmes for Rolls-Royce and the Atomic Weapons Establishment (AWE), which contributed to the success of the company. Since 2008 AOS has seen increased turnover (20%) and their staff numbers by some 20%, [C3].

Fully superconducting magnets

Cranfield's FBG expertise is also supporting Oxford Instruments as it moves to fully superconducting very high field magnets for use in national facilities around the world. Traditionally, resistive water cooled magnets have been used to generate magnetic fields over 30Tesla. These resistive magnets consume GW of electricity and require huge quantities of cooling water. The fully superconducting magnets under development will run with 20 litres of liquid helium per day and run off a single phase 240V power supply with no water cooling. These magnets will transform the environmental footprint and operational 'up-time' of these national facilities. Fibre optic strain monitoring systems are unique in that they can be fitted to these complex high field magnets without compromising the electrical isolation of the high-voltage energy management and heater systems deployed throughout the magnet coil set. FBG strain sensors have been integrated into this new class of magnets, which will be installed at the National High Magnetic Field Laboratory in the USA in 2014 with subsequent installations planned in Asia and Europe, [C2].

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

C1 A Twin, J Brown, F Domptail, R Bateman, R Harrison, M Lakrimi, Z Melhem, P Noonan, M Field, S Hong, K Marken, H Miao, J Parrell, and Y Zhang, *Present and Future Applications for Advanced Superconducting Materials in High Field Magnets*, IEEE Trans. Applied Superconductivity, **17**, pp. 2295-2298, 2007. (DOI: 10.1109/TASC.2007.898430)

C2 Contact: Technical Team Leader Environments, Oxford Instruments Omicron Nanoscience, UK.

C3 Contact: Managing Director, AOS Technology Ltd, UK.