Institution: Cardiff University		
Unit of Assessment: Engineering (12)		
Title of case study: New tribology solutions for frigates, helicopters and aeroplanes		
Period when the underpinning research was undertaken: 1/1/2004 – 1/3/2019		
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:**
Henry Peredur Evans	Professor	01/09/1977 - 28/1/2021
Alastair Clarke	Senior Lecturer	01/07/2012 - present
Raymond Walter Snidle	Professor	01/09/1972 - 31/08/2020
Period when the claimed impact occurred: 2014 – 31/12/2020		
Is this case study continued from a case study submitted in 2014? No		

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

Gears and bearings employed in high-pressure environments, such as naval and aviation vehicles, necessitate precise design and monitoring. Cardiff's tribology expertise facilitated the development of accurate models of such components, enabling improved design of complex gear mechanisms by industry partners, leading to:

- improved naval gearbox design tools for David Brown Santasalo, supporting a £100M design and build contract for Type 26 Frigate propulsion systems;
- SKF Aerospace's accelerated development of a new range of helicopter composite liner bearings, enhancing international commercialisation;
- design tools improving Rolls-Royce high-pressure fuel pumps and reducing development costs.

2. Underpinning research (indicative maximum 500 words)

Gear contacts operating in high-pressure environments and at extreme failure conditions (e.g., highly loaded power transmission gears), generally have surface roughness asperities that are larger than the lubricant film thickness. In mixed-lubrication contacts, where load is supported partly by lubricant pressure (via elastohydrodynamic lubrication: EHL) and partly by direct contact of roughness asperities, asperity collision and lubricant film rupture can occur.

Cardiff University's 40-year research heritage in tribology culminated in a coupled solver **[3.1]** that can analyse mixed-lubrication contacts to reduce gear failure. The solver gives transient surface load history at asperity scale, leading to tooth surface fatigue analysis for real gear micropitting tests. The solver and design functionality was applied in multiple scenarios including military thrust cone design, modelling liner bearings, and Rolls-Royce fuel pumps.

2.1 Thrust Cone design tools for David Brown Santasalo

Cardiff's Thrust Cone Design Aids (TCDA) software for helical gear thrust cones used in high power transmissions has been mandated by the Ministry of Defence for all prospective military designs since 2003. The software was further developed through the 15-year R&D relationship between industrial gears specialist David Brown Santasalo (DBS) and Cardiff University, with a focus on thrust cone contact and tribology in high-performance naval ships and machinery.

The thrust cones (Figure 1) enable use of single helical gears rather than larger and more complex double helical arrangements. The overlapping cones react axial tooth loads (developed due to the helix angle) in an EHL-bearing contact. The TCDA tool was reconfigured and enhanced for DBS during the REF period, providing improved model film/contact thermal behaviour prediction **[3.2, 3.3]** allowing the tool to simultaneously model film thickness and substrate behaviour.

(a) (b)

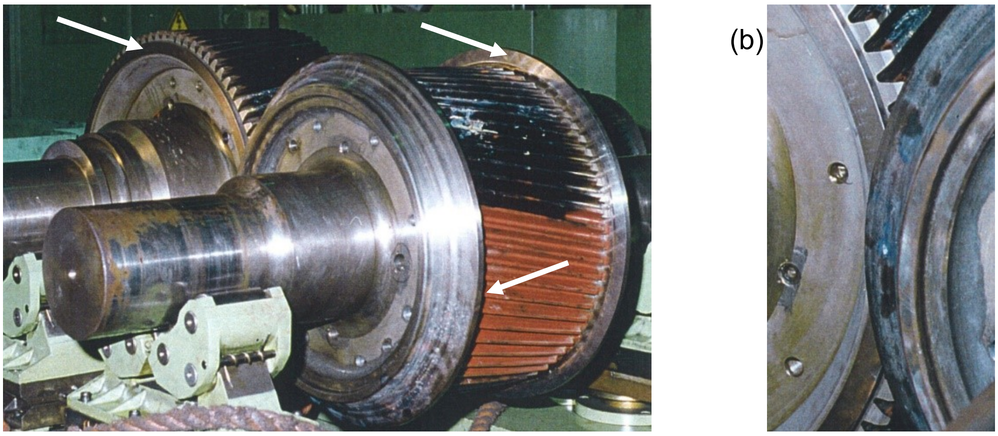

Figure 1: (a) Thrust cone bearings (arrowed) used in a low ratio single helical gear pair transmitting 6MW and (b) close-up of tooth meshing area showing the overlapping cones.

2.2 Modelling liner bearings with SKF Aerospace

Cardiff's expertise was also applied to development of new simulation tools and new liner materials for SKF Aerospace. Cardiff began testing and modelling friction and wear in composite liner bearings for SKF UK in 2009. The research developed a wear model for composite liner bearings, which are used in a wide range of control and actuation applications within both fixed and rotary wing aircraft. This new research direction updated the former approach for worm gears **[3.4]** and developed into an ongoing collaboration with SKF for testing, wear modelling, and condition monitoring of lubricant-free bearings **[3.5]**. The research was supported by a Knowledge Transfer Partnership award (TSB rated outstanding) **[G3.1]** and seven subsequent SKF grants totalling £850,000 (e.g. **[G3.2]**). Cardiff's research also led SKF to obtain development funding of £300,000 through the ADS National Aerospace Technology Programme.

2.3 Evaluation of fuel pumps within Rolls-Royce engines

In research sponsored by Goodrich Control Systems (now Rolls-Royce) in 2006, Cardiff's work on mixed lubrication was extended to plain bearing applications in aerospace fuel pumps. The initial application of the EHL model to the sealing surfaces of the pump was subsequently developed into a general approach for mixed lubrication in plain bearings based on calculating flow factors to quantify the average effect of the measured surface roughness on lubricant flow. This required a loaded contact analysis of the bearing surfaces, taking the 3D surface roughness into account, and was achieved using the methods of the coupled solver **[3.1]** in an elasto-plastic analysis **[3.6]**.

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

[3.1] Holmes MJA, **Evans HP**, **Snidle RW** (2005). Analysis of mixed lubrication effects in simulated gear tooth contacts, *Trans ASME Jn of Tribology*, 127(1), pp61-69. doi: 10.1115/1.1828452

[3.2] Sharif K, **Evans HP**, **Snidle RW**, Newall, JP (2004). Modelling of film thickness and traction in a variable ratio traction drive, *Trans ASME Jn of Tribology*, 126(1), pp92-104. doi: 10.1115/1.1609490

[3.3] Clarke A, Sharif KJ**, Evans HP**, **Snidle RW** (2006). Heat partition in rolling/sliding elastohydrodynamic contacts, *Trans ASME Jn of Tribology*, 128(1), pp 67-78. doi: 10.1115/1.2125867

[3.4] Sharif K, **Evans HP**, **Snidle RW**, Barnett, D, Egorov, IM (2006). Effect of elastohydrodynamic film thickness on a wear model for worm gears. *Proc. Instn. Mech. Engrs Part J, Jn of Engng Tribology*, 220(3), pp295-306. doi: 10.1243/13506501JET122

[3.5] Cockerill A, **Clarke A**, Pullin R, Bradshaw T, Cole P and Holford KM (2016). Determination of rolling element bearing condition via acoustic emission. *Proc. Instn. Mech. Engrs Part J, Jn of Engng Tribology*, 230 (11), pp 1377-1388. doi: 10.1177/1350650116638612

[3.6] Manoylov AV, Bryant MJ, **Evans HP** (2013). Dry elasto-plastic contact of nominally flat surfaces. *Tribology International*, 65, pp248-259. doi: 10.1016/j.triboint.2013.02.029

Selected grants:

[G3.1] PI: **Evans HP**, 'To develop and implement a design methodology for textile tribological materials based upon first principle research and utilise the methodology in design of new materials', TSB KTP009059. March 2013 to February 2015, total award £145,631.

[G3.2] PI: **Evans HP**, 'Development of wear modelling capability for self-lubricating plain bearings', SFK UK. October 2015 to March 2019, total award £32,500.

4. Details of Impact

Gear mechanisms in high-powered machinery are subject to significant forces and require precise design and monitoring to ensure performance. Cardiff's research in tribology and elastohydrodynamic lubrication (EHL) led to tools and methods improving the design of gear mechanisms, which in turn:

1. aided the design of naval thrust cone contacts and influenced global naval investments;
2. reduced friction and wear in helicopter composite liner bearings and enabled faster product development cycles; and
3. improved the design of Rolls-Royce aircraft fuel pumps and allowed more efficient modelling of prospective gear designs.

4.1 Aided the design of naval thrust cone contacts

David Brown Santasalo (DBS) are a global producer of gear mechanisms, and develop thrust cones for specialised applications, providing significant benefits to gearbox power density, noise reduction and energy efficiency in high power (multi MW) capital plant applications **[5.1]**. Having discussed a programme with Cardiff on thrust cone design solution performance modelling in 2014, DBS contracted the University to improve the Cardiff Thrust Cone Design Aid (TCDA) tool, mandated by the Ministry of Defence (MoD) for military applications since 2003 **[5.2]**. Completed in 2016, with extended modelling in 2018, the revised TCDA tool now simultaneously models film thickness and substrate behaviour, which enabled DBS to design and develop more efficient thrust cone propulsion systems.

Scott Tran, Engineering Director for DBS stated: "*The advances in analytical design and validation technologies enabled by the research and computational methods developed by Cardiff have strongly supported the creation of class leading engineered solutions for large scale power transmission equipment*" **[5.1]**. DBS noted how the advanced TCDA tool enabled them to engineer solutions with ***"****increased accuracy and confidence"*, highlighting that the ability to predict oil film thickness in the micron scale was vital to define the required manufacturing requirements and assure a long and reliable transmission life in service **[5.1]**.

DBS confirmed that Cardiff's TCDA was used within the transmission design process for the most recent Naval vessels under build for the MoD **[5.1]**, including the DBS contract to design and supply the main propulsion gear units of the new Type 26 (T26) Frigate, developed by BAE Systems **[5.3]**. The T26 design attracted considerable domestic and international demand:

- in 2017, the Royal Navy confirmed purchase of eight T26 Frigates, starting with an investment of £3.7BN for three ships **[5.4]**;
- in 2018 the Australian Navy confirmed an £18.1BN investment in nine T26 Frigates **[5.5]**;
- in 2019 the Canadian Navy ordered 15 ships based on the T26 design at total cost of around £32.5BN **[5.6]**.

Steve Watson, Managing Director of DBS noted that the contract to supply the gearboxes for the Type 26 ships is the largest single order in the firm's 150-year history **[5.3]**. The contract resulted in DBS making significant investments in infrastructure which *"transformed a semi-derelict area of our Huddersfield site into new state of the art manufacturing, assembly, and test facilities*" **[5.3]**. DBS confirmed the T26 contract created commercial opportunities that *"collectively measure in the scale of £100m+*" **[5.1]**.

4.2 Reduced friction and wear in helicopter composite liner bearings

SKF Aerospace are an international supplier of commercial aeroengine components. Cardiff's expertise modelling, simulating and testing composite liner systems improved SKF's capability to develop new self-lubricating composite liner bearings within critical flight controls for helicopters, highlighted by SKF as a significant commercial market **[5.7]**. Through collaborative research with Cardiff, Grant Dennis, Business and Product Development, SKF Aerospace stated that "*SKF have been able to accelerate the development of a new product line of improved performance self-lubricating plain bearings***"** that can typically take years between development and installation **[5.7]**. At the time of writing, SKF noted that the bearings are currently at TRL 8 and would fly on aircraft within 2020, with expectations of global commercialisation within 2021 **[5.7]**.

Cardiff research also enabled SKF to bring to market new condition monitoring solutions by developing algorithms to support early detection of the end-of-life for products. SKF confirmed the research "*has brought the technology to TRL 4, where SKF can embark on technology and product development activities to bring the solution to market*" **[5.7]**. SKF noted that condition monitoring is a growing market, and "*building on the strong foundation*" of work with Cardiff has given them a "*competitive advantage*" to penetrate the US market, forecasting increased revenue by "*tens of millions of pounds annually*" as a result **[5.7]**.

SKF stated that the collaborative research undertaken with the Cardiff *"had a significant impact on the development activities carried out by SKF, consolidating the company's strong position in the European market and developing competitive new products for the US market*" **[5.7]**. The materials have numerous other applications in aerospace and other high performance, high value markets such as motorsport.

4.3 Improved design of Rolls-Royce aircraft fuel pumps

In 2005, Cardiff University partnered with Goodrich Control Systems (now part of Rolls-Royce) to explore methods of modelling mixed lubrication within the fuel control systems in their aero engines. Of essential importance is the high-pressure fuel pump, a component that includes several tribological interfaces lubricated by the fuel itself. Martin Yates, Engineering Associate Fellow at Rolls-Royce stated: "*This is a particularly challenging interface to engineer […] should these interfaces fail, this can lead to an inflight shutdown of the engine*" **[5.8]**.

Cardiff developed several methods (e.g. **[3.6]**) to model the complexity of mixed-film lubrication within critical components including the thrust and journal bearings of the pump and in the shaft seal. The shaft seal prevents fuel leaks, and Cardiff's methods have been deployed by Rolls-Royce to better understand the performance of this shaft seal, which helped the company to *"improve the performance of an existing in-service design*" **[5.8]**.

Rolls-Royce highlighted how Cardiff developed "*an essential tool*" **[5.8]** for investigating materials within fuel pumps, specifically the suitability of new materials to facilitate the company's move away from undesirable legacy materials (e.g. lead and copper) while meeting challenging requirements. Rolls-Royce stated: "*Without the use of this type of sophisticated modelling a* *purely experimental approach would be required which would be far more expensive and time consuming than approach lead [sic] by analysis and validated by testing."* **[5.8]**

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

[5.1] Testimonial: Scott Tran, Engineering Director, David Brown Gear Systems Ltd.

[5.2] Ministry of Defence, Defence Standard 02-305, *Requirements for Gearing - Main Propulsion*. Issued January 2003, updated 2010.

[5.3] 'UK Type 26 programme powers ahead', BAE Systems news article,6 July 2015.

[5.4] 'Multi-billion pound deal signed for first three new Type 26 Frigates', Royal Navy, 2 July 2017.

[5.5] 'Australia officially announces $26B frigate contract. Here are the build details', defensenews.com, June 29 2018.

[5.6] 'Canadian surface combatant', Government of Canada website.

[5.7] Testimonial: Grant Dennis, Product Development Manager, SKF Aerospace.

[5.8] Testimonial: Martin Yates, Rolls-Royce Engineering Associate Fellow – Fuel System Design & Integration.