Institution: University of Cambridge		
Unit of Assessment: UoA 12 Engineering		
Title of case study: Compressor Elliptical Leading Edge		
Period when the underpinning research was undertaken: 2004 to 2014		
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:**
Prof Robert J. Miller	Professor of Aerothermal Technology	2001 to date
Dr Martin Goodhand	Research Fellow	2010 - 2014
Period when the claimed impact occurred: 1 August 2013 – 31 July 2020		
Is this case study continued from a case study submitted in 2014? No		

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

Collaborative research between University of Cambridge Department of Engineering's Whittle Laboratory and Rolls-Royce into gas turbine aerodynamics between 2005 and 2014 has led to a new compressor blade design that is now standard in all modern Rolls-Royce civil aero engines. The developed elliptical leading edge blade technology has been used in almost 2500 new aero engines delivered since 2014, with a further almost 2,000 engines on order as of December 2019. As well as being part of new engine designs, four older generations of engines have been revised and retrofitted with the technology. For two engines alone, 45 airlines are operating aircraft equipped with this technology. The technology delivers fuel savings of 0.5% to 0.7%, which can be estimated to be delivering savings of USD219,000,000 per year for airlines.

2. Underpinning research (indicative maximum 500 words)

There is a long-standing collaborative research relationship between University of Cambridge Department of Engineering's Whittle Laboratory and Rolls-Royce on fundamental research in turbomachinery. The research described below formed part of the University Gas Turbine Partnership with Rolls-Royce, which was inaugurated in 2001 and incorporates formal processes for technology and people transfer.

The compressor of a gas turbine is made up of many blades (around 4,000 in large civil engines). The air flow over each blade is highly sensitive to the geometry of the leading edge of the blade, and changes to the geometry of the leading-edge, and can cause the flow to separate. This separation causes the flow close to the surface to transition from laminar to turbulent and results in a significant detrimental impact on engine efficiency. Small changes in the design geometry, shape perturbations due to manufacturing variability, and in-service shape changes due to erosion can affect whether or not flow separation occurs, and consequently impact engine efficiency.

Computational investigations by Professor Miller in 2004 indicated that an elliptically shaped leading edge on a modern compressor blade could stop the separation that occurred with a standard circular leading edge. This allowed the flow close to the surface to remain laminar, reducing losses and therefore improving engine efficiency. Experimental investigations of the new leading edge profiles confirmed the performance benefits suggested by the simulations.

The findings of the experimental investigation, supported by further numerical simulations, were published in [R1], showing that by switching from the standard circular leading edge to an elliptical leading edge the flow remained attached, allowing the flow close to the surface to remain laminar. The mechanisms behind the flow features observed in [R1] ere investigated in [R2], both experimentally and computationally. It was shown in [R2] that the pressure close to the leading edge can exhibit a 'spike', and if the spike remains below a critical threshold then the separation does not occur and the engine efficiency will be unchanged. However, if the pressure spike exceeds a critical threshold, flow separation occurs, and the engine efficiency is negatively impacted. Building on the new understanding of the physical mechanisms, [R2] also provided design criteria for the shape of the leading edge, allowing designers to determine whether the flow over a given leading edge design would separate or not. Research in [R3] extended the understanding to the three-dimensional case, and investigated the sensitivity to small geometry variations, including surface roughness, at the leading edge. The shape of the leading edge evolves over the lifetime of a blade, and [R4] investigated how its design shape can be made insensitive to these changes. Research in [R3], through considering the three-dimensional case, showed that geometric details of the blade design, usually overlooked in the early design phases, are critical factors for overall performance and do need to be considered early in the design process.

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

R1. A. P. S. Wheeler, A. Sofia and R. J. Miller (2009). The Effect of Leading-Edge Geometry on Wake Interactions in Compressors, *Journal of Turbomachinery* 131(4):041013, doi:10.1115/1.3104617.
R2. **M. N. Goodhand and R. J. Miller** (2011). Compressor Leading Edge Spikes: A New Performance Criterion, *Journal of Turbomachinery* 133(2):021006, doi:10.1115/1.4000567.
R3. **M. N. Goodhand and R. J. Miller** (2012) The Impact of Real Geometries on Three-Dimensional Separations in Compressors, *Journal of Turbomachinery* 134(2):021007, doi:10.11151/1.4002990.
R4 **M. N. Goodhand, R. J. Miller** and H. W Lung (2015). The Impact of Geometric Variation on Compressor Two-Dimensional Incidence Range, *Journal of Turbomachinery* 137(2):021007, doi:10.1115/1.4028355.
Research quality evidence by rigorous peer-review. The research has been supported by competitively won grants: RG63118, RG65246, EP/C536207/1, RG48687 and RG4937. Value: GBP1,870,000. Funders: EPSRC and Rolls-Royce.

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

The collaborative research between University of Cambridge Department of Engineering's Whittle Laboratory and Rolls-Royce described in section 2 has increased engine efficiency, leading to fuel savings for the airline industry. It has also provided Rolls-Royce with commercial benefit in a market where engine efficiency is a key differentiator.

Fuel savings

The global airline industry fuel bill has been estimated at USD188,000,000,000 in 2019, with fuel costs accounting for 23.7% of airline operating costs [E1]. Therefore, small fuel efficiency gains lead to enormous cost savings for aircraft operators and major competitive benefits to engine suppliers. The elliptical leading edge technology developed provides fuel savings of between 0.5% to 0.7% [E2, E3]. Based on the industry's average 12.3 daily hours of utilisation for wide-body aircrafts and an average fuel cost of USD5000 per hour, a 0.7% fuel use reduction equates to a cost saving of USD157,000 per aircraft per year [E4, E5]. For the nearly 1,400 aircraft in service with elliptical leading edge turbine blades, this equates to estimated fuel savings of USD219,000,000 per year that can be attributed to the developed technology.

Engine designs and deliveries

The elliptical leading-edge technology, published in [R1, R2], was introduced first in the Trent 1000 engine (first delivered in 2011) after being presented to the Trent 1000 design team by Professor Miller in 2004 [E6]. All later generation Rolls Royce engines for wide-body aircraft (Trent XWB, first delivered 2014; Trent 7000, first delivered 2018) and the latest generation of engines for business jets (Pearl 15, first delivered 2018; Pearl 700, first delivered 2019) were designed with the elliptical leading edge blades [E6, E7]. In the period since 2014, Enhanced Performance packs for the earlier generation Trent 500, 700, 800 and 900 engines have been available [E3] and include the elliptical leading edge blades [E6].

The Trent engines power some of the world's best-known aeroplanes, including the Boeing 777 and 787, and the Airbus A330, A330neo, A340 and A380. Over the period 2014-2020 Rolls Royce delivered nearly 2,500 engines with the elliptical leading edge (including new designs and updates of earlier models) [E7, p.15], with a further almost 2,000 engines on order as of December 2019 [E7, p.14]. Deliveries in the period 2014-2019, orders at December 2019 and engines in service at December 2019 for wide-body engines that were designed with the elliptical leading edge blades are summarised in Table 1. Of the 510 wide-body aircraft engines delivered by Rolls-Royce in 2019, over 90% (466) were designed from the outset with the elliptical leading edge blades [E7, p.15].

Engine	Aircraft	Year of first delivery	Engine deliveries 2014-2019	Engines on order (Dec 2019)	Engines in-service (Dec 2019)
Trent 1000	Boeing 787	2011	667	246	658
Trent XWB 84/97	Airbus A350	2014/2017	846	1,133	660
Trent 7000	Airbus A330-800/900 (neo)	2018	114	576	80
TOTAL			1627	1955	1398

Table 1: Deliveries, orders and number in service for the Rolls Royce wide-body Trent 1000, XWB and 7000 engines equipped with the elliptical leading edge [E7, p.14, p.15].

The elliptical leading-edge technology has been added to Enhanced Performance pack (EP) revisions of the earlier generation Trent 500 (powers the Airbus A340), Trent 700 (powers the Airbus A330), Trent 800 (powers the Boeing 777) and Trent 900 (powers the Airbus A380) engines [E6]. EP packs are retrofitted to existing engines and included with new deliveries of older generation designs. All 216 Trent 900 engines delivered since 2014 [E6] have been fitted with the elliptical leading edge [E2]. The EP for the Trent 700 has been available since 2009, and over the period 2014-2019 Rolls Royce delivered 595 Trent 700 engines [E7, p.15]. As of

December 2019, there are 1,606 Trent 700 engines in operation [E7, p.14] and the majority are fitted with the elliptical leading edge. The fuel savings of between 0.5% and 0.7% provided by the elliptical leading edge can be quantified by measuring the efficiency of the Trent 700 and 900 engines without (original design) and with the elliptical leading edge blade EP packs [E2, E3].

Airline operators

Airlines around the world operate aircraft with engines fitted with the elliptical leading edge. The Trent XWB (exclusive power unit for the A350) and Trent 7000 (exclusive power unit for the A330-800/900 (neo)) engines alone are operated by 45 carriers as of June 2020 [E8]. The Trent XWB powered Airbus A350 was rated in 2017 as the most fuel-efficient aircraft used on transatlantic routes [E9, p.9].

Efficiency is a key differentiator in the aircraft engine industry, and the elliptical leading-edge technology has helped Rolls-Royce gain commercial benefit in this market.

"In 2004 Rob Miller spent his summer in Rolls-Royce investigating the impact of leading-edge shape on compressor performance. This computational work showed that leading-edge shape could cause a 20%-30% change in the profile loss of a blade row. This led to the Trent 1000 project funding testing in the Whittle Lab that showed that leading-edge shape could change profile loss of a blade row by 24%, and helped to support the Trent 1000 team's confidence that Elliptical Leading Edges should be implemented on the Trent 1000. This is a great example of how the long relationship between Rolls-Royce and the Whittle Laboratory helps to ensure that technology is successfully transferred into product."

Engineering Fellow (Aerodynamics), Rolls Royce [E6]

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

E1. International Air Transport Association Fact Sheet (December 2019).

E2. Flight Global article, June 2013.

E3. Aviation International News, Rolls-Royce Trent 700 Benefits from Technology Development Flow-Back (June 2013).

E4. Reported utilisation of wide-body aircraft from www.Planestats.com

E5. Reported operating costs for wide-body aircraft from www.Planestats.com

E6. Letter from Engineering Fellow (Aerodynamics) at Rolls Royce.

E7. Rolls Royce 2019 Full Year Results (Data Appendix).

E8. Airbus Commercial Order and Delivery figures June 2020 (excel file available for audit on request).

E9. Trans-Atlantic Airline Fuel Efficiency Ranking 2017, The International Council on Clean Transportation.