Institution: University of Cambridge		
Unit of Assessment: UoA12 Engineering		
Title of case study: S-ducts for efficient aeroengines		
Period when the underpinning research was undertaken: 2003 to 2010		
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 Miller Prof Howard Hodson Dr John Longley Dr Edward Naylor	Professor of Aerothermal Technology Professor of Aerothermal Technology Senior Lecturer Research Fellow	2001 to date 1989 - 2012 1991 to date 2009-2011
Period when the claimed impact occurred: 1st Aug 2013 to date		
Is this case study continued from a case study submitted in 2014? Yes		

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

Research at the Whittle Laboratory at the Department of Engineering and at Loughborough University led to a new design for the ducts ('S-ducts') that link compressors in an aeroengine, improving engine efficiency and reducing emissions. Rolls-Royce incorporated the new design into the Trent XWB generation of engines, which were first delivered in 2014. The new S-duct provides fuel efficiency improvements of 0.25%. In 2019 alone this is estimated to have delivered fuel cost savings of USD19,200,000 for airlines. Rolls-Royce has delivered over 919 engines with the new S-duct design since 2014, and in 2020 there are 370 Airbus A350 aircraft in-service with the S-duct design.

2. Underpinning research (indicative maximum 500 words)

The research described below was developed in the EU FP6 project *Aggressive Intermediate Duct Aerodynamics for Competitive and Environmentally Friendly Jet Engines.* The University of Cambridge, Loughborough University and Rolls-Royce were partners in the project and collaborated on a new engine duct design.

In a modern civil aero engine, the intermediate- and high-pressure compressors are joined by S-shaped annular ducts. The Cambridge and Loughborough teams researched different aspects of the S-duct to improve engine performance, and it was the combination of the distinct underpinning research at each institution which allowed a new S-duct design to be developed. Cambridge research focussed on making the duct profile more aggressive, allowing a larger radius change or a shorter length, and Loughborough research focused on integration of the upstream blade row into the duct, also shortening the duct.

The starting point for the research at the Whittle Laboratory at the Department of Engineering was Miller's and Hodson's realisation in 2003 that, by developing an understanding of the aerodynamic failure mechanisms within strutted S-ducts, ducts with a larger radius change, shorter length, or with a thicker strut could be designed. Initially, the design space for S-ducts was explored. Computational fluid dynamics was used to explore the limits of the design space, with the limit cases then tested experimentally using large-scale aerodynamic test rigs. It was shown that a duct could be designed with a 24% larger radius change compared to the ducts used in engines at the time. These findings were published in [R1].

The research in [R1] was extended to more representative cases using a test facility with two independently powered compressor stages, one upstream and one downstream of the duct. This allowed the performance of ducts to be measured as the operating points of both stages are altered. This research demonstrated that the duct designed in [R1] could successfully operate in engine-representative environments [R2].

Building on [R1, R2], a new design method for 3D non-axisymmetric profiled ducts was developed [R3]. By allowing the duct walls to be designed non-axisymmetrically, the local diffusion imposed by the struts within the duct could be cancelled using curvature on the end walls. A numerical optimiser was used to optimise the profiled duct walls, which building on the earlier research now demonstrated that a 48% greater radius change for the same length was possible. The performance of the computationally optimised design was validated using a two-stage compressor duct test facility [R3]. The difference between the original ducts, and the final profiles developed through the research, is shown in Fig. 1. The final duct profile shows a cleaner flow, and reduced losses.

The 3D non-axisymmetric profiled technology is protected by a patent granted in November 2007 [R4].

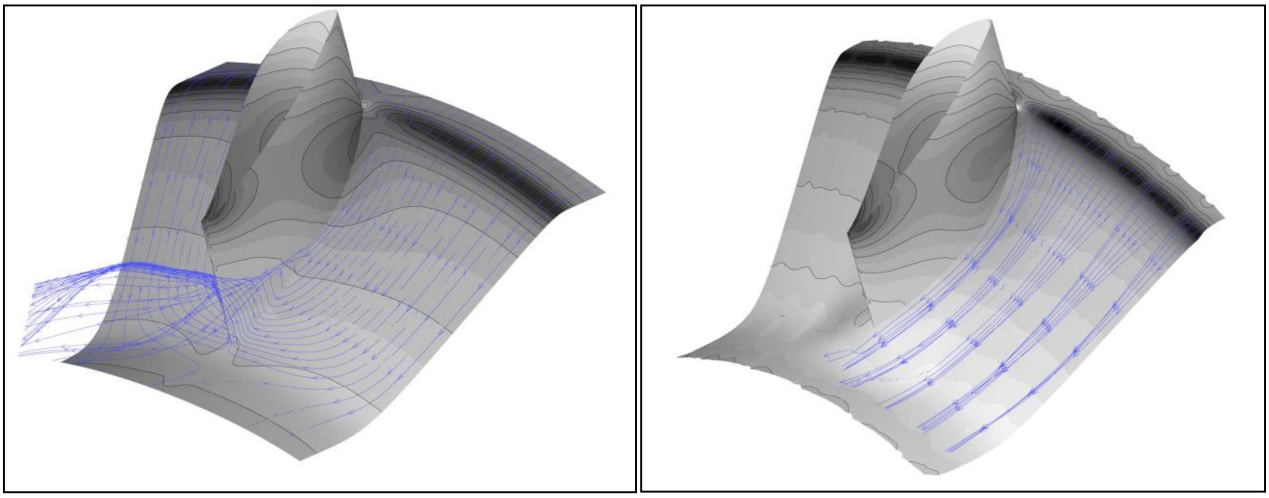

Fig 1: Original duct (left, high separation and losses) and a new duct (right, minimal separation; reduced losses) [R3].

3. References to the research (indicative maximum of 6 references**) bold = Cambridge**

R1. **Ortiz Duenas, C**., **Miller, R.J., Hodson, P. H. & Longley, J. P.** (May 2007). Effect of length on compressor inter-stage duct performance ASME GT2007-27752, ASME Turbo Expo, Montreal, doi:10.1115/GT2007-27752.

R2. **Karakasis, M. K., Naylor, M. J., Miller, R. J. & Hodson, H. P**. (June 2010). The effect of an upstream compressor on a non-axisymmetric s-duct ASME GT2010-23404, ASME Turbo Expo, Glasgow, doi:10.1115/GT2010-23404.

R3. **Naylor, E. M. J., Ortiz Duenas, C**., **Miller, R. J. & Hodson, H. P**. (2010). Optimization of non-axisymmetric endwalls in compressor S-shaped ducts, ASME Journal of Turbomachinery 132, 011011-1, doi:10.1115/1.3103927.

R4. United States Patent 20080138197 A1, (2007); Green, M., Harvey, N., **Miller, R. J., Ortiz-Duenas, C., Naylor, E.** and **Hodson, P. H.,** Transition duct for a gas turbine engine. http://www.google.com/patents/US20080138197.

Grants: EU; Rolls Royce AST3-CT-2003-502836 EU FP6 Project AIDA**;** University Gas Turbine Partnership (UGTP) “Aggressive Intermediate Duct Aerodynamics for Competitive and Environmentally Friendly Jet Engines” (2004 to 2009). EUR8,221,717 incl EUR5,607,325 from EU.

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

A new S-Duct design, made possible by the research, was incorporated into the Rolls-Royce Trent XWB engine and provides fuel efficiency and emission reduction benefits over the previous generation S-Duct design [E1]. The first Trent XWB engine was delivered in 2014 [E2, p.15], and the Trent XWB has been Rolls-Royce’s best-selling large civil aero engine by volume in each year since 2017 [E2, p.15]. The Trent XWB is marketed by Rolls-Royce as the “*the world's most efficient large aero engine*”, with fuel use cut by 15% compared to the original Trent engine and delivering fuels savings of USD2,900,000 per aircraft per year [E3]. It was selected by Airbus as the exclusive power unit for the Airbus A350 XWB aircraft, which entered service in 2015. Fuel accounts for approximately a quarter of airline operating costs, making engine efficiency a critical factor in the commercial success of an aeroengine.

New S-duct design

The new duct design introduced two changes that improved engine efficiency. In previous generation engines the radius of the intermediate pressure compressor, upstream of the S-duct, dropped across its rear stages making its performance non-optimal. In the Trent XWB engine the intermediate pressure compressor was maintained at its optimal radius across all stages, increasing its efficiency. This was achieved by the new S-duct having a larger radius change over the S-ducts in previous engines. The second performance improvement was due to the length of the new S-duct being reduced by 60mm, reducing overall engine weight and length. The Cambridge research allowed final S-duct design to have an increased radius change and a reduced length. The Loughborough research allowed a further reduction in length. Without the combination of the two technologies the new development of the new S-duct would not have been possible.

Engine deliveries and operation

The Trent XWB-84 engine was first delivered in 2014, and the more powerful XWB-97 was first delivered in 2017 [E2, p15]. From 2014 to the end of 2019 Rolls Royce delivered 846 Trent XWB engines to customers. As of December 2019, 660 XWB engines were in service and a further 1,133 engines were on order [E2, p14]. The Trent XWB accounted for 46% of all Rolls-Royce large civil aero engines deliveries in 2019 and 57% of all orders at the end of 2019 [E2]. The Trent XWB powers all Airbus A350 aircraft [E2, p14], with 370 A350 aircraft delivered to operators since 2014 and up to 31 July 2020 [E4]. As of 31 July 2020, the A350 is operated by 36 airlines; the airlines operating the most A350 aircraft as of July 2020 are Qatar Airways (49), Singapore Airlines (48) and Cathay Pacific (36) [E4].

Fuel cost savings due to the S-duct design

The new S-duct design, an integration of the Cambridge and Loughborough research developments, reduces specific fuel consumption by 0.25% [E1]. Improved compressor performance accounts for a 0.15% fuel saving and the reduction in duct length accounts for a 0.1% fuel saving [E1]. Analysis by the Oliver Wyman consultancy of the US widebody fleet in 2019 reported that widebody aircraft operated 13.0 hours per day on average, and typical fuel costs for a large widebody aircraft were USD4,500 per hour [E5]. Based on 4,745 flying hours per year (13 hours per day) and fuel costs of USD4,500 per hour, a fuel efficiency improvement of 0.25% due to the s-duct technology equates to a fuel cost saving of USD53,300 per aircraft per year, and a saving of USD19,200,000 per year across 370 in-service A350 aircraft [E4]. The Trent XWB powered Airbus A350 was rated in 2017 as the most fuel-efficient aircraft used on transatlantic routes [E6, p.9]. The efficiency of the Trent XWB engine has contributed to Singapore Airlines operating scheduled Singapore to New York flights, the world’s longest by distance, which commenced in October 2018 [E7]. Fuel efficiency is a key differentiator in the competitive aeroengine market and the new S-duct design contributes to the efficiency of the XWB engines and to Airbus selecting the XWB engine as the exclusive power unit for the A350.
“*The Trent XWB engine is the world’s most efficiency aeroengine. In a highly competitive market focussed on fuel efficiency, the levels of improvement offered by the S shaped duct technology represent a key competitive advantage, and can make all the difference in winning a contract. The Trent XWB has been the fastest-selling widebody engine ever, with over 919 delivered as of 30 June 2020*.”

Engineering Fellow, Rolls-Royce plc [E1].

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

E1. Letter from Engineering Fellow, Rolls Royce.

E2. Rolls Royce 2019 Full Year Results (Data Appendix), https://www.rolls-royce.com/~/media/Files/R/Rolls-Royce/documents/investors/fy-2019-appendices.pdf.

E3. Rolls Royce Trent XWB product information, July 2020, https://www.rolls-royce.com/products-and-services/civil-aerospace/airlines/trent-xwb.aspx.

E4. Airbus Commercial Order and Delivery figures July 2020, https://www.airbus.com/content/dam/corporate-topics/publications/o&d/ODs-July-2020-Airbus-Commercial-Aircraft.xlsx.

E5. Wyman Oliver analysis of US widebody fleet in 2019, https://www.planestats.com/bhsw_2019sep.

E6. Trans-Atlantic Airline Fuel Efficiency Ranking 2017, The International Council on Clean Transportation, https://theicct.org/sites/default/files/publications/Transatlantic_Fuel_Efficiency_Ranking_20180912.pdf.

E7. The world's longest non-stop flight takes off from Singapore, BBC news article https://www.bbc.co.uk/news/business-45795573.