Institution:
University of Cambridge

Unit of Assessment:
UoA15

Title of case study:
Rolls-Royce compressor S-ducts

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

Research in the University of Cambridge Department of Engineering (DoEng) between 2003 and 2010 investigated the technical feasibility and efficiency benefits of an innovative design for the S-shaped ducts linking the two compressors in a modern civil aero engine. Rolls-Royce incorporated this technology in its latest generation of engines (Trent XWB); the benefits in terms of increased fuel efficiency which the new design of S-duct brings are a significant selling-point for what is marketed as “the world’s most efficient engine”. As at 31 July 2013 Rolls-Royce has an order book of more than 1400 such engines (worth, at list price, approximately GBP 20 billion), of which 832 orders were received within the assessment period.

2. Underpinning research (indicative maximum 500 words)

Rolls-Royce has sponsored a major portfolio of fundamental research in turbomachinery and combustion science in the University of Cambridge Department of Engineering (DoEng) since 1972. The research described below formed part of the University Gas Turbine Partnership (UGTP), inaugurated in 2001, which incorporates formal processes for technology and people transfers; Rolls-Royce provides half of the annual funding for research projects and supports two professors and two lecturers, with matching funding from EPSRC, the TSB and the EU. Matching funding for the research described below came from EU FP6 Project AIDA.

The research was undertaken between 2003 and 2010 under the leadership of Robert Miller (who joined DoEng as a Lecturer in Turbomachinery in 2001 and became Professor of Aerothermal Technology in 2013) in collaboration with Howard Hodson (appointed as a Lecturer in 1989 and was Rolls-Royce Professor of Aerothermal Technology from 2000 until his retirement in 2012).

In a modern civil aero engine, the two compressors (intermediate-pressure and high-pressure) are joined by S-shaped annular ducts. The mean radius necessary to achieve maximum efficiency differs for the two compressors. Traditionally the radius change has been split between the duct and the rear stages of the intermediate-pressure compressor, reducing its efficiency. Research in DoEng developed the technology necessary to achieve the radius change across the duct alone. The starting point was Miller 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. This would enable compressors to be designed with potential efficiency benefits in the form of reduced fuel consumption and reduced CO_2 emissions.

The research was conducted in three parts, and published at the largest peer-reviewed international conference in the field and in a paper in the *Journal of Turbomachinery* which summarised the whole programme of work from theoretical concept, through experimental trials, to key conclusions about how the research could be used to safely increase the size of the design space in which aero engine duct designers can operate. The three parts of the research, and the associated papers, were as follows:

- Firstly, between 2003 and 2006, the S-duct design space was explored, and a better understanding of the aerodynamic failure mechanisms achieved, by using computational fluid dynamics (CFD) to determine the rough location of the limits of the design space. These were then explored experimentally by building a number of low-speed large-scale aerodynamic test rigs. The work showed that ducts could be designed which had a 24% larger radius change, with the same length, than ducts currently used in engines [1].

- Secondly, between 2005 and 2009, the impact on duct performance of ‘real’ engine representative inlet and exit flows to the duct was investigated, using an internationally unique duct-test facility built at DoEng and funded by EU-FP6 Project AIDA. The facility consists of two independently powered compressor stages, one upstream and one downstream of the duct, allowing the performance of ducts to be measured as the operating points of the upstream and downstream stages are altered. The research demonstrated that the duct designed in the first stage of the research could successfully operate in the engine-representative environments [2].

- Thirdly, between 2006 and 2009, a new 3D non-axisymmetric profiled duct design method was developed. By allowing the duct walls to be designed non-axisymmetric, the local diffusion imposed by the struts within the duct could be cancelled using curvature on the endwalls. A numerical optimiser was used to optimise the profiled duct walls. This achieved ducts with an additional 24% higher radius change for the same length. This technology, used in conjunction with the technology developed in the first part of the research, allows a 48% higher radius change for the same length. This technology was then validated using the two-stage compressor duct test facility [3].

Under the terms of the UGTP, Rolls-Royce staff members Matt Green, John Bolger and Neil Harvey were involved with all stages of the research, by means of regular personal visits, link calls and data transfer, ensuring that the test cases were appropriate to modern engines, that the technology and knowledge were successfully transferred into the company, and that the technical know-how was defended through a patent. Rolls-Royce protected the 3D non-axisymmetric profiled technology by a US patent granted in November 2007 [4]. This patent – filed in the names of Miller, Hodson and members of their team (together with Green and Harvey) – protects the company's competitive advantage, enabling S- ducts to be designed with a 24% larger radius change, or 24% shorter length, compared to previous designs.

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

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

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

*[3] Naylor, E. M. J., Ortiz Duenas, C., Miller, R. J. & Hodson, H. P. Optimization of nonaxisymmetric endwalls in compressor S-shaped ducts. ASME Journal of Turbomachinery, Vol 132, 011011-1, 2010. doi:10.1115/1.3103927

[4] United States Patent 20080138197 A1, Nov 26, 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

* References which best reflect the quality of the underpinning research.

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

The immediate beneficiary of the research is Rolls-Royce plc. The S-duct for Rolls-Royce's latest engine, the Trent XWB, was designed at DoEng using the understanding developed in the research. Key design investigations for the Trent XWB were undertaken by Miller and Hodson's team, in consultation with Green, in 2008 and 2009. The engine received certification from the European Aviation Safety Agency (EASA) in February 2013, and will enter service in 2014 as the sole option available to power the new Airbus A350 XWB aircraft [5].

The increased fuel efficiency which the new design of S-duct brings is a significant selling-point for the Trent XWB, which is marketed as "*the world's most efficient aero engine flying today... [with] the lowest carbon emissions of any widebody engine*" [6]. As at 31 July 2013, Rolls-Royce has an order book for the Trent XWB of more than 1400 engines [7], of which 832 were received during the period 1 January 2008 to 31 July 2013 [8]. Although the company does not publish the value of this order book, an estimate can be made using announcements on the value of specific orders.

For example, the order for 25 aircraft from Air Lease Corporation on 4 February 2013 cited a list-price order value of USD 1.1 billion (GBP 714 million) for 50 engines [9]. This suggests that the whole Trent XWB order book at the end of the assessment period, at list price, is worth approximately GBP 20 billion (of which GBP 12 billion represents orders achieved during the period). Even when commercial discounts (which are not published) are taken into account, this represents a significant proportion of the Rolls-Royce Civil Aerospace Sector's total order book of GBP 56 billion, and indeed of the Company's whole order book of GBP 69 billion [7,10].

In all Rolls-Royce Trent engines prior to the Trent XWB, the radius dropped across the rear stages of the intermediate-pressure compressor. This reduced the efficiency of the compressor, increasing engine specific fuel consumption (SFC). The technology developed by DoEng in partnership with Rolls-Royce led directly to the duct in the Trent XWB having a larger radius change. This allowed the radius of the rear stages of the intermediate-pressure compressor to remain high, maintaining optimal performance and resulting in a 0.15% reduction in engine SFC [11] (a significant contribution, given the historical rate of engine reduction of ~1% SFC per year [12,13]).

According to Rolls-Royce estimates, the benefits from this improvement in duct technology are expected to be *"a fuel burn saving of USD 30k per aircraft per year, which represents a* CO_2 *reduction of 120 tonnes per aircraft per year."* [11]. Once the Trent XWB engines currently on order enter service – on the 682 twin-engine A350 XWB aircraft on order as at 31 July 2013 [14] – this will translate into an annual fuel burn saving in excess of USD 20 million per year, and a CO_2 emissions reduction of more than 80k tonnes per year. These benefits, however, will accrue outside the assessment period; within the period, the impact is the way in which the expectation of these benefits has contributed to the competitiveness of the engine.

Chief of Global Aerothermal Technology and Senior Fellow of Thermofluids, Rolls-Royce plc, and Chairman of the Aerodynamics National Technical Committee, commented: "*Research in Cambridge's Department of Engineering has made a significant contribution to the huge success of the Trent XWB engine. The team led by Rob Miller and Howard Hodson developed the understanding of S-duct aerodynamics necessary to achieve improved compressor efficiency, and the incorporation of this into the Trent XWB. This has contributed to Rolls-Royce's ability to present the engine to the market as the world's most efficient engine. In a highly-competitive market focussed on fuel efficiency, the levels of improvement offered by such breakthroughs represent a key competitive advantage, and can make all the difference to winning a contract. The Trent XWB has become the fastest-selling widebody engine ever, with over 1400 engines on order from 34 customers – more than twice the number of orders for any comparable engine, at this stage of the programme*" [15].

The Technical Lead for Trent XWB Compression System Aerodynamics at Rolls-Royce, added: *"The way of working with the Cambridge Engineering Department within the UGTP made a critical contribution to Rolls-Royce being able to realise the benefits of the research. As well as being able to spend lots of time working closely with the research team, the unique duct test facility allowed us to conduct testing to a technology readiness level of 4, higher than could be achieved with CFD or with a facility with non-engine representative boundary conditions – effectively, to test that the technology would work in real engines. The technology has opened up areas of the design space which could not otherwise have been achieved"* [11].

Please note that the DoEng case studies for Rolls-Royce 3D Compressor Blade and Decision Rationale Editor (DRed) also reference the success of the Trent XWB engine among other impacts. The lines of research in each case study are entirely separate and carefully defined in each case study. The impacts for each line of research are also accurately delineated.

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

[5] Rolls-Royce Trent XWB achieves important milestone with award of EASA type certification, Rolls-Royce website, 7 February 2013, http://www.rolls-royce.com/news/press_releases/2013/070213_easa_type_certification.jsp *

[6] Trent XWB, Rolls-Royce website, http://www.rolls-royce.com/civil/products/largeaircraft/trent_xwb/index.jsp *

[7] Civil Aerospace Order Book, Rolls-Royce website, http://www.rolls-royce.com/Images/civil_aerospace_tcm92-50015.pdf *

[8] Statement from Market Analyst - Asia Pacific and Market Metrics, Civil Aerospace, Rolls-Royce plc, 13 August 2013

[9] Rolls-Royce wins $1.1bn Trent XWB order from Air Lease Corporation, Rolls-Royce website, 4 February 2013, http://www.rolls-royce.com/news/press_releases/2013/040213_air_lease_corporation.jsp *

[10] Rolls-Royce Holdings plc Half Year Results, Rolls-Royce website, 25 July 2013, http://www.rolls-royce.com/news/press_releases/2013/25072013_half_year_results.jsp *

[11] Statement from Tech Lead for Trent XWB Compression System Aerodynamics at Rolls-Royce plc, 14 August 2013

[12] Rolls-Royce Holdings plc Annual Report 2012, R-R, http://www.rolls-royce.com/Images/rolls_royce_annual_report_2012_tcm92-44211.pdf *

[13] The IATA Technology Roadmap Report, issued 2009, IATA, http://www.iata.org/whatwedo/environment/Documents/technology-roadmap-2009.pdf *

[14] Airbus_July_2013_Orders_deliveries.xlsx, downloaded from Airbus website, http://www.airbus.com/company/market/orders-deliveries/ *

[15] Statement from Chief of Global Aerothermal Technology and Senior Fellow of Thermofluids, Rolls-Royce plc (and Chairman of the Aerodynamics National Technical Committee), 24 September 2013

*These sources were accessed by the DoEng in August 2013 and saved in its audit file as they are subject to updates