Institution:
University of Cambridge

Unit of Assessment:
UoA15

Title of case study:
Rolls-Royce 3D compressor blades

1. Summary of the impact (indicative maximum 100 words)
Research in the University of Cambridge Department of Engineering (DoEng), which made it possible for the first time to design a 3D compressor blade as a single component, underpinned the design of compressors in Rolls-Royce civil aero engines. Blades designed using the research results yielded fuel efficiency improvements of 0.8% when deployed in Rolls-Royce Trent engines. The efficiency improvements in engines in service are estimated to have delivered savings of 460k tonnes in CO_2 emissions and USD 145 million in fuel costs during the assessment period. Rolls-Royce's outstanding order book for engines in which the technology made a significant contribution to efficiency is estimated to be worth GBP 27 billion at list prices as at 31 July 2013; orders received during the assessment period are estimated to be worth GBP 18 billion at list prices.

2. Underpinning research (indicative maximum 500 words)
Nick Cumpsty joined the University of Cambridge Department of Engineering (DoEng) in 1975 as a Lecturer, focussing his research principally on compressor aerodynamics, and collaborating with Rolls-Royce (sponsors of a portfolio of fundamental research in turbomachinery aerodynamics, noise and vibration, combustion, heat transfer and advanced cycles). Cumpsty became the Rolls-Royce Professor of Aerothermal Technology in 1989, leaving in 1998 on completion of the underpinning research described in this case study.

The key insight that prompted the new research came in 1993, when Cumpsty and his research team realised that combining a simple and elegant mental model of the 3D geometry of a compressor blade with the ability to rapidly explore the performance of such geometries would open the way towards the practical ability to design 3D blades within an industrial timescale. The research advances which followed from this insight built upon research and capabilities within the DoEng initially developed before 1993:

- The measurement capability provided by a single-stage experimental compressor facility (the “Deverson” compressor) capable of rapidly testing novel concepts. In 1993 this had recently been upgraded.
- The computational capability arising from work by DoEng academics Bill Dawes (then Lecturer; Francis Mond Professor of Aeronautical Engineering from 1996) and John Denton (Professor of Turbomachinery Aerodynamics until his retirement in 2005), whose research had produced the 3D computational fluid dynamics (CFD) codes which are now industry-standard for the design of turbomachinery worldwide.

Cumpsty's insight was that the advanced experimental measurements (which the Deverson compressor made possible), combined with the ability to accurately simulate viscous flow, turbulence and separation for a multistage compressor in three dimensions without excessive computational expense (based on Dawes and Denton's work), together created new opportunities for investigating the hypothesis that 3D blade shapes could be more efficient. This had been postulated, but without both measurements and modelling of 3D flow in multistage compressors, there had previously been no way of making informed decisions to change the design.

In 1993, therefore, Rolls-Royce and DoEng set up a joint programme to research 3D compressor blade technology and transfer it into the Rolls-Royce design system. Cumpsty created the underlying 3D design methodology, developed an optimal low-speed blade design and experimentally tested its performance in the test compressor at DoEng. Dr Simon Gallimore, then Rolls-Royce's Chief Compressor Aerodynamic Specialist, led a team in Rolls-Royce which translated the methodology into the company's design system, using it to design blades for high-speed testing of the technology.[1]

Cumpsty and his team visualised and described the 3D shaping of the new compressor blade in a simple and elegant way using the terms “sweep” and “dihedral” – which are analogous to the 3D rearward and upward curvature of birds’ wings in flight. These curvatures act to control the 3D structure of the flow, making the flow less likely to separate. The research was undertaken in three overlapping stages:

- In 1993-95, the fundamental methodology underpinning 3D compressor design was explored, using CFD codes to understand how sweep and dihedral affect endwall flow separation.
- In 1994-97, the parallel experimental research project was undertaken on the Deverson compressor at DoEng. A number of designs were tested and the performance improvement was measured. This gave Rolls-Royce the confidence that the technology worked.
- In 1995-98, DoEng worked closely with Rolls-Royce to develop the design method, transferring the technology to the company and enabling it to design 3D blading into the Trent 500 engine.

Publication of the results was delayed until the new blade design had been trialled successfully in engines at Rolls-Royce; shortly after the trials had been completed, in 2002, the key paper was published in two parts. Part I covered the basic research at DoEng and discussed the use of CFD techniques [1], and Part II covered the low-speed model testing and the high-speed engine compressor design and test [2].

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

*[1] Simon J. Gallimore, John J. Bolger, Nicholas A. Cumpsty, Mark J. Taylor, Peter I. Wright, and James M. M. Place, The Use of Sweep and Dihedral in Multistage Axial Flow Compressor Blading – Part I: University Research and Methods Development, Journal of Turbomachinery, Vol. 124, October 2002, pp 521-532. doi:10.1115/1.1507333

*[2] Simon J. Gallimore, John J. Bolger, Nicholas A. Cumpsty, Mark J. Taylor, Peter I. Wright, and James M. M. Place, The Use of Sweep and Dihedral in Multistage Axial Flow Compressor Blading – Part II: Low and High-Speed Designs and Test Verification, Journal of Turbomachinery, Vol. 124, October 2002, pp 533-541. doi:10.1115/1.1507334

* Papers that best represent the quality of the research

In 2006, in connection with this research, Gallimore won the Royal Academy of Engineering Silver Medal – see http://www.raeng.org.uk/news/releases/shownews.htm?NewsID=323

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

Dr Simon Gallimore FREng (now 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 critical contribution to the success of the several generations of the Trent aero engine. The groundbreaking work by Nick Cumpsty and his team changed the way that compressor blades are now designed in Rolls-Royce. The impact was first felt in 2002 and will continue to be felt as future generations of engines make use of the technology*.”[3]

The research established “sweep” and “dihedral” as the standard terms for movements parallel to the compressor aerofoil section chord line and movements normal to it. More importantly it gave designers a simple mental model for how “sweep” and “dihedral” affected the aerodynamic of the flow. For the first time this made 3D design of compressors relatively simple, which facilitated the uptake of the technology by industry; in Gallimore’s words, “*the research allowed industrial designers, for the first time, to undertake 3D compressor design in a time scale which was acceptable within an engine programme*.”[3]

Before the research, compressor blades were designed and manufactured in a number of 2D sections and thus were not able to fully exploit the 3D shape of the blade to improve performance. The DoEng research made it practically possible to measure and model 3D viscous flow in multistage compressors in such a way that 3D designs could be evaluated within timescales suitable for industrial development. The research gave Rolls-Royce this understanding, proposed a new shape for the blade and provided the tools for refining the design further.

The knowledge was transferred to Rolls-Royce primarily through DoEng academics working closely with Rolls-Royce engineers, and through PhD students and staff being employed by Rolls-Royce after the fundamental underpinning research had been completed (including Cumpsty, who became Chief Technologist of Rolls-Royce in 2000). The impact of the research began before the 2002 paper was published, as the first compressor blades designed according to the new methodology were certified and flight-tested, entering service in the form of the Trent 500 engine earlier in that same year. All subsequent generations of Rolls-Royce Trent engines (Trent 900, Trent 1000, Trent XWB) have also made use of 3D compressor blade design technology.

The impact during the period 1 January 2008 to 31 July 2013 can be quantified in two main ways: (a) in the fuel burn savings (and carbon emissions savings) achieved by the engines in service during that period; and (b) in the size and value of Rolls-Royce's order book for the relevant engines, for which fuel efficiency and emissions reduction are the key selling points.

Fuel burn and carbon emissions savings. According to Gallimore, "*3D blading achieved combined efficiency gains for both high pressure and intermediate pressure compressors of approximately 1%. This translates to an engine specific fuel consumption [SFC] reduction of about 0.8%. 1% of specific fuel consumption reduction represents a fuel burning saving of USD 240k per aircraft per year and a reduction in CO2 emissions of 765 tonnes per aircraft per year.*"[3] By the end of the assessment period, 214 aircraft powered by 3D-bladed Trent engines were in operation:

- The Trent 500 powers all Airbus A340-500/600 aircraft; 130 in service as at 31 July 2013.[4]
- The Trent 900 is one of the engine options for the Airbus A380; 56 Trent-powered aircraft in service as at 31 July 2013 (China Southern Airlines 5, Lufthansa 10, Malaysia Airlines 6, Qantas 12, Singapore Airlines 19, and Thai Airways International 4).[4]
- The Trent 1000 is one of the two engine options for the Boeing 787 Dreamliner; 28 Trent-powered aircraft in service as at 31 July 2013 (All Nippon Airways 20, LAN Airlines 3 and LOT Polish Airlines 5).[5]

The annualised fuel burn savings from these aircraft in service at the end of the period are therefore estimated to be approximately USD 40 million (240*0.8*214), with CO_2 emission reductions of approximately 130k tonnes (765*0.8*214). 123 of these aircraft (104 A340s and 19 A380s) were in service throughout the assessment period;[6,7] on the simplifying assumption that the other 91 aircraft entered service linearly in each of the intervening years, the fuel burn saving achieved in the whole period can be estimated as approximately USD 145 million, and the reduction in CO_2 emissions as approximately 460k tonnes.

Rolls-Royce order book. In a highly-competitive market focussed on fuel efficiency, the levels of improvement offered by breakthroughs such as Cumpsty's represent a key competitive advantage; the gain offered by this technology equates to almost one full year's-worth of the industry's average efficiency gains over time.[8] In the citation for the award to Gallimore of the Royal Academy of Engineering's Silver Medal in 2006, his introduction of these techniques is credited with enabling Rolls-Royce to grow its wide body aircraft share from less than 20% to 50% (figures quoted from the reference to the award in section 3).

The benefits to Rolls-Royce's order book have continued during the assessment period, and are most clearly demonstrated in the case of the Trent XWB (which will power all Airbus A350s as they enter service from 2014 onwards). Rolls-Royce markets the XWB as "*the world's most efficient aero engine flying today...* [with] *the lowest carbon emissions of any widebody engine*".[9] As at 31 July 2013, Rolls-Royce has an order book for the Trent XWB of more than 1400 engines.[10] 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.[11] This suggests that the whole Trent XWB order book, at list price, is worth approximately GBP 20 billion. If the order book for other 3D bladed engines (88 Trent 900s, 450 Trent 1000s) [4,5] is valued at the same rate, the list-price value of the order book for all such engines rises to over GBP 27 billion, a very significant proportion of the Rolls-Royce Civil Aerospace Sector's total order book of GBP 56 billion.[10] (If one takes the alternative view that orders placed between 1 January 2008 and 31 July 2013, rather than outstanding order book at the end of the period, should be considered, the figures are 36 Trent 500 engines, 128 Trent 900 engines, 270 Trent 1000 engines and 832 Trent XWB engines, with a list-price value around GBP 18 billion).[12]

Impacts beyond Rolls-Royce. 3D design and manufacture of compressor blades is now standard across the industry, with all major aero engine manufacturers (Pratt & Whitney and General Electric) and land-based gas turbine manufacturers (Siemens, General Electric and Mitsubishi) using 3D design methodologies, and the language to describe them, which are very similar to that developed and published by DoEng and Rolls-Royce. In addition to its role in the underpinning research, DoEng has continued to play a role in the dissemination of the 3D design methodology to the industrial community by means of the Cambridge Turbomachinery Course, the world's leading gas turbine course, which runs once every four years; in 2008 this attracted 92 delegates from 19 companies and government agencies from 11 countries, and in 2012, 97 delegates from 20 companies and government agencies from 8 countries.

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

[3] Statement from Chief of Global Aerothermal Technology and Senior Fellow of Thermofluids, Rolls-Royce (and Chairman of the Aerodynamics National Technical Committee)
[4] Airbus_July_2013_Orders_deliveries.xlsx downloaded from http://www.airbus.com/company/market/orders-deliveries/ *
[5] Boeing orders report downloaded from http://active.boeing.com/commercial/orders/displaystandardreport.cfm?cboCurrentModel=787&optReportType=AllModels&cboAllModel=787&ViewReportF=View+Report *
[6] Airbus-_OAD_-_2012Oct.xls retrieved from the Airbus website on 17 Nov 2012 and cited in table "Deliveries" at http://en.wikipedia.org/wiki/Airbus_A340 *
[7] Where is the A380 flying?, Airbus website, http://www.airbus.com/aircraftfamilies/passengeraircraft/a380family/a380-routes/ *
[8] The IATA Technology Roadmap Report, Issued June 2009, http://www.iata.org/whatwedo/environment/Documents/technology-roadmap-2009.pdf *
[9] Trent XWB, Rolls-Royce website, http://www.rolls-royce.com/civil/products/largeaircraft/trent_xwb/ *
[10] Civil aerospace order book, Rolls-Royce website, http://www.rolls-royce.com/Images/civil_aerospace_tcm92-50015.pdf *
[11] Rolls-Royce wins $1.1bn Trent XWB order from Air Lease Corporation, press release on Rolls-Royce website, 4 February 2013, http://www.rolls-royce.com/news/press_releases/2013/040213_air_lease_corporation.jsp *
[12] Statement from Market Analyst, Asia Pacific and Market Metrics, Civil Aerospace, Rolls-Royce

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