Institution: Durham University

Unit of Assessment: 15 General Engineering

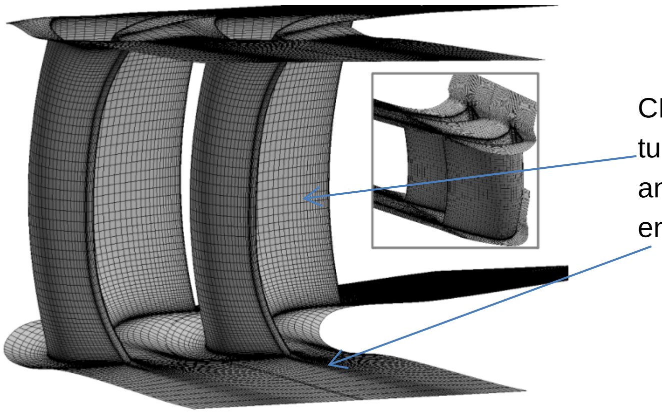
Title of case study: Profiled Endwalls for Reduced Fuel Burn

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

This impact is the improvement of aircraft engine efficiency by the application of profiled endwalls to turbine blades. The technology was researched by Durham University and exploited by Rolls-Royce by deploying the technology on airframes. Engines with profiled endwalls include the Trent 900 (A380 airframe), Trent 1000 (787 Airframe) and Trent XWB (A350 airframe). This (as of April 2013) totals around 2000 aircraft engine orders with profiled endwall technology applied. A saving of 1750 litres of fuel per flight from Zurich to Singapore was estimated when profiled endwalls are applied. This gives a 4400 kg reduction in carbon dioxide emissions for such a journey with a fuel cost saving of over $1100. In addition to the environmental benefit and the obvious cash savings for airlines an economic benefit for UK industry has arisen as Rolls-Royce is able to sell engines with a reduced fuel burn as well.

2. Underpinning research (indicative maximum 500 words)

David Gregory-Smith at Durham carried out research on “secondary flow” turbine aerodynamics throughout the 1990s examining the complex 3D flow patterns around turbine blades in aircraft engines. In the early 21st century this fundamental understanding was used to improve the aerodynamic efficiency of blades by applying profiled endwalls, i.e. using profiled surfaces within the turbine to optimise fluid flows as shown in the figure below.



CFD model of turbine blades and profiled endwall

The first contribution was to demonstrate that profiled endwalls would work in a simplified model of a turbine [Outputs 1 & 2]. Further studies explained how the performance gains arose by making a detailed examination of the flow structures present inside a turbine blade row [Output 3]. These papers were the first reported tests on systematically designed profiled endwalls.

Durham research also defined the boundaries of application by running a test campaign on “aggressive” endwall geometries, that deliberately pushed the performance of these devices to the point they were no longer aerodynamically effective (essentially pushing the device into a “stall” type condition) [Output 4]. A key aspect of the research was managing imperfect numerical calculations of the fluid flow within the turbine blades. Precise computations of the Navier-Stokes equations are impossible without accurate modelling of turbulence and transition. Such a model does not exist and remains one of the major unsolved problems in physics. The solution was to use a proxy parameter based on inviscid flowfield parameters to infer viscous losses. The obvious drawback of such a method is that the range of application of these proxies is very limited. The approach of using “Secondary Kinetic Energy” as the design variable is described in of our joint papers with Rolls-Royce [Output 1].

Ingram, who assisted with significant parts of this research is now a fulltime member of academic staff at Durham.

3. References to the research (indicative maximum of six references)
The underpinning research comprised a series of tests in the Durham thermofluids lab using cascades, and subsequent analysis of the results, also at Durham. This research was largely funded by Rolls-Royce in two projects:

- October 1999- July 2003 Brochure B1D1-1501DC with funding from the then DTI and MoD CARAD programme. PI: Dr David Gregory-Smith
- July 2003 - July 2007 “Three Dimensional Turbine Blade Passage Design.” Brochure: R-RAEPS2001 DPC5752 (Budget: £249k) PI: David Gregory-Smith (retired 2005) Grant Ingram (2006 to contract end).

Outputs 1 & 2 describe the design and test of the first ever systematically designed profiled endwall geometry for loss reduction.

- *Output 1: Harvey, NW, Rose, MG, Taylor, MD, Shahpar, S, Hartland, J and Gregory-Smith, DG Nonaxisymmetric Turbine End Wall Design: Part I - Three-Dimensional Linear Design System J. Turbomach. 122, 278 (2000).*
- *Output 2: Hartland, JC, Gregory-Smith, DG, Harvey, N.W. and Rose, MG Nonaxisymmetric Turbine End Wall Design: Part II - Experimental Validation J. Turbomach. 122, 286 (2000)*

Output 3 explores the underlying flow physics behind the performance enhancements seen and contains detailed measurements inside the blade row.

- *Output 3: Ingram, G., Gregory-Smith, D., Rose, M., Harvey, N. & Brennan, G. 2002, The effect of end-wall profiling on secondary flow and loss development in a turbine cascade, ASME Turbo Expo 2002 Land, Sea and Air (GT2002). GT2002-30339.*

Output 4 provided an indication as to the limit of the technological application by designing an endwall for maximum performance but instead introducing flow separations. This reduced the risk of application of endwall profile technology in real machines.

- *Output 4: Ingram, G., Gregory-Smith, D. and Harvey, N. Investigation of a Novel Secondary Flow Feature in a Turbine Cascade With End Wall Profiling J. Turbomach. 127, 209 (2005).*

Outputs 5 & 6 cover an extension of the profiled endwall concept to combine with blading modifications and won the 2008 PE Publishing Award for the best paper in Part A of the IMechE Journal of Power and Energy. This work was also the subject of a Rolls-Royce patent which Durham staff (Bagshaw, a research associate on the project) were named inventors.

- *Output 5: Bagshaw DA, Ingram GL, Gregory-Smith DG & Stokes MR 2008. An experimental study of three-dimensional turbine blades combined with profiled endwalls. Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy 222(1): 103-110.*

- *Output 6: Bagshaw DA Ingram GL, Gregory-Smith DG, Stokes MR & Harvey NW 2008. The design of three-dimensional turbine blades combined with profiled endwalls. Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy 222(1): 93-102.*

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

The impact of this research is that profiled endwalls in turbomachinery such as aircraft engines provide both economic and environmental benefits. Durham's research has given manufacturers confidence to apply profiled endwalls to engine representative test rigs and then into real products. Without the underpinning research outlining the benefits in simple test rigs these concepts would not have been put into production engines.

The early research (Outputs 1 & 2) gave the industrial partner (Rolls-Royce) confidence to apply this in cold flow engine test rigs (with a running cost of around £1M per test point) and then in aircraft engines for sale (first application in the Trent 500 performance upgrade). The limits established by Durham University in the test campaign on aggressive endwall geometries (Output 4) were incorporated into Rolls-Royce's in-house design codes.

The environmental benefit of this research is via reduced fuel burn in aircraft engines due to a 0.6% to 0.9% increase in turbine stage efficiency. The quantification of the level of improvement was obtained from cold-flow full scale rig testing at Rolls-Royce. This has been translated into a saving of 1750 litres of fuel per flight from Zurich to Singapore by Prof. Patrick Jenny, Institute of Fluid Dynamics at ETH. A similar order of magnitude effect can be estimated from Cumpsty's book "Jet Propulsion" which quotes a 1.13% change in sfc for a 1% change in high pressure turbine efficiency.

In financial terms the fuel saving on the Zurich to Singapore flight equates to $1192 per flight. If the route runs once per way in each direction this gives annual fuel saving of around $870,160 per year. In carbon dioxide terms this equates to a 4448 kg reduction per trip using the 2013 UK Government conversion factors published by DEFRA. These factors include other influences than simply the combustion process. For the route as a whole this is a reduction of 3247 tonnes.

The first application of profiled endwalls was the Trent 500 performance improvement package applied to the A340 airframe. The first new engine with profiled endwalls was the Trent 900 for the Airbus A380. Profiled endwalls are now used as a routine design tool and are also applied on the Trent 1000 (787 Airframe) and Trent XWB (A350 airframe).

As of April 2013 there have been fifty one A380 aircraft delivered with Rolls-Royce engines for a total of 204 engines in service on that airframe. Rolls-Royce engines have been selected for 238 of Boeing 787 orders for a total of 476 engines and Rolls-Royce make the only powerplant for the A350 which has 616 orders for a total of 1232 aircraft engines. Each of which are more efficient as a result of the underpinning research.

Profiled endwalls can also potentially improve the efficiency of any rotating machine and Rolls-Royce has also applied profiled endwalls to stationary gas turbines used for pumping applications, the Avon engine. This technology is offered as an upgrade kit for existing engines and allows operators to reduce fuel burn whilst providing additional business for the manufacturer.

A second important impact of this research has been to provide improved products for industry and keep the products that UK industry offers at a competitive efficiency level. Rolls-Royce have also applied for patents based directly on the results of Durham research e.g: Rolls-Royce plc. Aerofoil members for a turbomachine. Pat. GB0704426.6, date lodged 08.03.2007, 2007.

Other engine manufacturers have sponsored research programmes on profiled endwalls including Pratt and Whitney with Carleton University and MTU with ETH Zurich and Stuttgart. Although there is no direct link between Durham and these organisations the presentation of the Durham and Rolls-Royce work at conferences has led to a worldwide impact.

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

1. Source for 0.6-0.9% efficiency gain: Rose et al. (2001) reporting a stage efficiency increase of 0.59%±0.25% and Harvey et al. (2002) reporting a stage efficiency increase of 0.9%±0.4%.
Rose, M., Harvey, N., Seaman, P., Newman, D., and McManus, D. (2001). Hp turbine using non-axisymmetric end walls. part ii: Experimental validation. ASME Paper 2001-GT-0505.
Harvey, N., Brennan, G., Newman, D., and Rose, M. (2002). Improving turbine efficiency using non-axisymmetric end walls: Validation in the multi-row environment and with low aspect ratio blading. ASME Paper GT-2002-30337.

2. Source for 1750 litres fuel saving from: Philipp Jenny, Laboratory for Energy Conversion ETH Zurich. http://www.esc.ethz.ch/events/frontiers/10_Jenny_FiER.pdf Accessed 1st May 2013.

3. 1.13% change in sfc for a 1% change in high pressure turbine efficiency is from: N. Cumpsty, Jet Propulsion: A Simple Guide to the Aerodynamic and Thermodynamic Design and Performance of Jet Engines, ISBN-10: 0521541441, 2nd Edition, 2003.

4. Source for fuel cost is from the International Air Transport Association (IATA) fuel price analysis web page. http://www.iata.org/publications/economics/fuel-monitor/Pages/price-analysis.aspx Accessed 13th September 2013.

5. The conversion from litres of fuel to carbon dioxide is taken from the Department for Environment Food & Rural Affairs' Greenhouse Gas Conversion Factor Repository. Accessed on the 13th of September 2013 http://www.ukconversionfactorscarbonsmart.co.uk/

6. Source for A380 and A350 airframe sales: http://www.airbus.com/company/market/orders-deliveries/ Accessed 15th of May 2013.

7. The engine breakdown for A380 sales is from http://www.rolls-royce.com/civil/products/largeaircraft/trent_900/ Accessed 15th of May 2013.

8. Source for 787 sales: Boeing website: http://active.boeing.com/commercial/orders/ Accessed 15th of May 2013

9. Rolls-Royce Website Advertising the use of “3D profiled end wall aerodynamics” in Trent 1000 engine. http://www.rolls-royce.com/civil/products/largeaircraft/trent_1000/ (Under Technical Tab, HP/IP turbine)

10. Rolls-Royce Brochure Advertising the application of profiled endwalls to the Avon 200 Stationary Gas Turbine. http://www.rolls-royce.com/Images/Avon200_112011_tcm92-15721.pdf Accessed 1st May 2013