Institution: Loughborough University

Unit of Assessment: B12 Aeronautical, Mechanical, Chemical and Manufacturing Engineering

Title of case study: Reduced Aero-engine Fuel Consumption via an Integrated Design Methodology for Combustor Aerodynamics

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

Starting in 1996 experimentally based research into combustor aerodynamic inefficiency at Loughborough University has been used by Rolls-Royce (RR) to ensure minimised combustor pressure loss for their entire Trent engine family. Five Trent engines, operating on more than 900 aircraft, have benefited. The latest engine – the Trent XWB - the world's most efficient and fastest-selling wide-body aero-engine (predicted fleet ~1000 aircraft) - began flight tests in mid-2013; this engine includes the latest Loughborough development, a novel approach to compressor/combustor interface management for reduced fuel burn [text removed for publication] improving both global competitiveness and carbon/pollutant emissions.

2. Underpinning research (indicative maximum 500 words)

Starting in 1996 experimental research at Loughborough University (LU) has been undertaken to improve the fundamental understanding of the aerodynamic interactions at an aero-engine compressor/combustor interface. This required measurements of mean and turbulent flow characteristics and analysis of how these influence combustor pressure loss and fuel injector flow quality. The first outcome of this research was identification of the benefit of an integer ratio of compressor Outlet Guide Vanes (OGVs) to fuel injectors and the fundamental reason for this. RR subsequently adopted this as best practice.

To design compressor OGVs to minimise the inefficiency in the downstream combustor aerodynamics, LU quickly realised that the ability to simulate engine-representative conditions but in an atmospheric pressure isothermal rig was essential to allow cost-effective but comprehensive understanding of the complex flow physics. In 1999 LU designed and commissioned a bespoke, fully-annular facility, incorporating a 1.5 stage compressor and a representative combustion system geometry – allowing use of scaled perspex models (or even engine hardware), high fidelity measurements and enabling rapid turnaround **[3.1, 3.2]**.

Further research (2003-2005) identified novel bleed-controlled pre-diffusers **[3.3]**, providing RR with further potential design gains, now protected by RR/LU shared international patents. Compressor/combustor interaction relevant to future lean-burn combustors for ultra-low NO_x was studied in 2006-08 **[3.4, 3.5]**. The measurements taken revealed an unwanted two-way aerodynamic coupling. The research paper written **[3.4]** received a 2006 Best Paper award from the ASME Combustion and Fuels Committee. The success of this experimental approach encouraged RR to expand use of fully annular rigs; three are now available at LU and in constant use by RR to support engine designs.

Between 2006 and 2011 research on the LU rigs identified the Integrated OGV concept **[3.4, 3.5, and 3.6]**. The OGV geometry was modified to generate secondary motions that re-energised the boundary layers in the pre-diffuser, enabling higher area ratios in a given length and reducing pressure loss. This concept was communicated to and transferred to RR, who adopted the idea for incorporation into its Trent XWB engine, which has now begun flight tests (June 2013).

The research has been conducted via a series of interrelated projects, funded from a variety of sources. Loughborough academic staff/researchers involved were: JF Carrotte (Research Fellow 1991–1996, Lecturer 1996–2003, RR Reader 2003–2013, Director LUTC 2012-present, R.A.Eng./RR Professor 2013–present); AG Barker (Research Associate 1993–present); PA Denman (Research Fellow 1991–present) ; J Luff (PhD student 1997–2003, Post-Doc Research

Associate 2003–2005); JJ McGuirk (Prof of Aerodynamics 1990-present, Director LUTC 1991–2012); and AD Walker (PhD student 1997–2002, Senior Research Associate 2003–2011, Lecturer 2011–present).

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

Publications:

3.1 AG Barker and JF Carrotte, "Influence of compressor exit conditions on combustor annular diffusers - Part I: diffuser performance", *AIAA J. of Propulsion & Power*, 17, 678–686, 2001. DOI: 10.2514/2.5795

3.2 PA Denman, "Aerodynamic evaluation of double annular combustion systems", ASME paper GT-2002-30465, *ASME Turbo Expo*., Amsterdam, Netherlands, 2002.

3.3 AD Walker, PA Denman, "Hybrid diffusers for radially staged combustion systems", *AIAA Jnl. of Propulsion and Power*, 21, 264-273, 2005. DOI: 10.2514/1.6680

3.4 AD Walker, JF Carrotte, and JJ McGuirk, "Enhanced external aerodynamic performance of a generic combustor using an integrated OGV/diffuser design technique", *ASME Jnl. of Eng. For Gas-turbines and Power*, 129, 80-87, 2007. DOI: 10.1115/1.2364008

3.5 AD Walker, JF Carrotte, and JJ McGuirk, "The influence of dump gap on external combustor aerodynamics at high fuel injector flow rates", *ASME Jnl. of Eng. For Gas Turbines and Power*, 131, 011502-1-015502-8, 2009. DOI: 10.1115/1.3028230

3.6 A D Walker, A G Barker, J F Carrotte, J Bolger (RR), and M J Green (RR), "Integrated OGV design for an aggressive s-shaped compressor transition duct", *ASME Jnl. of Turbomachinery*, 135, 011035-1-011035-11, 2012. DOI: 10.1115/1.4006331

Evidence of Research Quality:

These research outputs were strategically targeted at:

(i) three journals that are widely read by both university academics and the global gas-turbine industry, viz.:

- *AIAA Journal of Propulsion and Power*
- *ASME Journal Of Engineering for Gas Turbines and Power*
- *ASME Journal of Turbomachinery*

The American Institute of Aeronautics and Astronautics (AIAA) and the American Society of Mechanical Engineers (ASME) are the world's leading technical societies dedicated to the global aerospace profession. Their journals are acknowledged as high quality technical publications for archival research papers disclosing new theoretical developments and/or experimental results. Paper [**3.4**] received the Best Application Paper Award from the ASME Combustion and Fuels Committee in 2006.

(ii) what is widely regarded as the premier annual international gas-turbine conference, *ASME Turbo-Expo*, organised by the International Gas-Turbine Institute, where conference papers are only accepted after 3 positive reviews of the full paper (from academia, industry and government research organisation referees).

Finally, this body of work led directly to Prof McGuirk being invited to deliver the prestigious 2013 Lanchester Lecture at the Royal Aeronautical Society, entitled: "The Aerodynamic Challenges of Aero-engine Gas-turbine Combustion Systems" (http://aerosociety.com/Events/Event-List/1003/Lanchester-Lecture-2013).

Grants

The quality of the research conducted may also be judged by the success of gaining continuous funding support worth £2.3M over a 17 year period in competitive environments and across a range of funders covering UK and European government sponsors as well as industry.

Grant Holders	Project Title	Sponsor	Period	Value
JFC	Annular Strutted Pre-diffuser Study	RR/MoD	95-97	£151k
PAD	Combustor External Aerodynamics (HTDU5)	RR/MoD	96-97	£102k
JFC	EJ200 External Aerodynamics	RR	99-01	£105k
JFC, JJM	Low Pollution Combustor Technology	EU (FP5)	01-05	£309k
PAD	ANTLE External Aerodynamics	DTI	04-05	£ 96k
JJM, JFC	Integrated Lean Low Emissions Combustor	EU (FP6)	04-08	£271k
PAD	Aerodynamic Performance of Trent1000	RR	07-08	£200k
PAD	EFE Combustion System Aerodynamics	TSB	06-08	£448k
PAD	Phase5/Trent1000/ANTLE Combustor Exit	RR/TSB	08-09	£132k
JFC	External Aerodynamics in Lean Systems	EU (FP7)	08-12	£514k
PAD	Trent XWB Fully Annular Rig Measurements	RR	09-10	£210k
JJM, JFC	KIAI – Pre-diffuser Unsteady Flow	EU (FP7)	09-11	£221k
PAD, JJM, JFC	SAMULET Projects 1, 2	EPSRC	09-12	£538k

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

The overall impact of Loughborough University's experimentally-based research into combustion system aerodynamics, as cited in Section 2 and Section 3, has had multiple impacts during the period 2008-2013 as listed below, of which three major ones are: (i) Decision makers at RR were convinced to undertake [text removed for publication] testing of all their high bypass ratio civil turbofan engines at bespoke facilities at Loughborough; (ii) The Integrated OGV design methodology, developed and validated at Loughborough, has been incorporated into the globally-significant RR Trent XWB engine, [text removed for publication] (iii) Improvement of RR combustor cooling technology – particularly for the Trent 900 engine this enabled more air to be dedicated to reduce combustion emissions.

The initiative taken at Loughborough in its research into gas-turbine combustion system external aerodynamics **[3.1-3.6]** was based on the development of bespoke (and unique) experimental facilities, acquisition of detailed high quality measurements and detailed analysis of these to produce the understanding that helped industry identify improved design methods and reduced the cost of validating their designs as fit for purpose. The analysis of the data generated has enabled Loughborough to achieve a series of important industrial impacts over the last 15 years. The most natural route for industry exploitation of Loughborough's research outputs in this field is RR, a world-leader in aero-engine technology.

Loughborough University has hosted one of RR's University Technology Centres (UTCs) since 1991. Whilst the usual academic dissemination route of publication in high quality journals was followed for the underpinning research **[3.1-3.6]**, to maximise impact and optimise the speed of technology transfer, use was made of established UTC mechanisms for rapid transfer of ideas and results. Quarterly review meetings and regular (on average once per month) presentation of Loughborough research work at internal RR discussion forums and design reviews are a standard feature of the UTC framework.
Once RR had been convinced that research carried out in University-based laboratory facilities was representative of engine operating conditions, the uptake by RR of ideas and recommendations generated from Loughborough in this research area followed rapidly, as illustrated below:

- Confidence in the engine relevant status of data on combustion system pressure loss from LU fully-annular rigs has lead RR to adopt the practice that the combustors of all its high bypass-ratio large turbofan engines undergo [text removed for publication] testing at LU [text removed for publication] **[5.1]**.
- The Integrated OGV (IOGV) design methodology – developed and validated at Loughborough – was adopted for use in the RR Trent XWB engine. RR estimates for the aerodynamic benefit of the IOGV [text removed for publication]

The projected aircraft number is ~1,000 with a life of 20 years; the benefit is thus considerable for increasing product competitiveness, reducing carbon footprint, and lowering environmental impact **[5.1]**.

- Use of high fidelity aerodynamic measurements on LU fully annular facilities helped to develop minimum pressure loss designs for turbine cooling air and benefit engine specific fuel consumption **[5.1]**.
- LU has made full use of the unique fully annular aerodynamic facilities developed to undertake research that has helped RR understand data taken on EU and UK Government sponsored full-scale RR demonstrator engine projects: Affordable Near Term Low Emissions (ANTLE) and Environmentally Friendly Engine (EFE) **[5.1]**.
- LU has developed design rules from its laboratory facilities that have contributed to improved cooling technology on the Trent 900 engine **[5.1]**
- Recommendations from LU on the aerodynamic benefits of designs incorporating an integer number of OGVs to fuel injectors have influenced RR 'best practice' **[5.1]**.
- LU ideas on a novel diffuser design have led to a shared patent, now being investigated for future designs **[5.2]**.

In summary, we are claiming that our research, as cited in Section 2 and Section 3, has achieved substantial change in a world-leading aero-engine manufacturer with major consequential economic and environmental benefits. Their latest engine, the Trent XWB - the world's most efficient and fastest-selling wide-body aero-engine, with a predicted fleet of ~1000 aircraft - began flight tests in mid-2013 and includes the latest Loughborough developments as cited here.

5. Sources to corroborate the impact (indicative maximum of 10 references)
The following sources can be made available at request:

5.1 Letter from RR Senior Engineering Staff - Head of Civil Large Engine (CLE) Sub-Systems, Chief of Aero-thermal (CLE Combustion Sub-System), Chief Design Engineer (CLE Combustion Sub-System) - indicating:

- How LU experimental facilities in combustor aerodynamics have been recognised as high quality benchmark facilities, superseding all internal RR rigs/test facilities in this technical area.
- Adoption based on LU work of integer number of OGVs to injectors as RR 'best practice'.
- Adoption of the LU IOGV concept to achieve associated operational fuel savings for Trent XWB.
- LU work in support of RR Engine Demonstrator Project "ANTLE": Support on Air-blast Lean Modules – Influence of Pre-diffuser Efflux on Fuel Injector Mixing, 2007.
- LU work in support of RR Engine Demonstrator Project "EFE": Support on Combustion System Aerodynamics – Lean Module Scaling - Part 1 Fuel Injector Scalar Mixing Experiments, 2007.

5.2 RR patent on novel combustor diffuser system originating from Loughborough research and including named LU research staff:

- Rolls-Royce plc. Patent on: "A Diffuser Arrangement" - EU Patent EP1431516 B1, (Patent granted Nov. 2009).