Institution: University of Sussex

Unit of Assessment: UoA 15 General Engineering

Title of case study: Gas Turbine Internal Air Systems Research: Economic and Environmental Impact

1. Summary of the impact

There have been both direct and indirect contributions to cost savings, reduced fuel consumption and reduced CO_2 emissions through Sussex research into gas turbine engine technology. Rolls-Royce and GE Aviation have benefited from experimental measurements that have allowed improvements to internal air systems flow modelling. This has led to savings in engine testing of approximately £10M over the period; indirectly it has also led to substantial economic benefits through reduced costs for engine manufacturers and their airline clients, and to improved design of internal cooling and sealing systems, which has direct impact on reduced fuel consumption and emissions.

2. Underpinning research

A gas turbine's efficiency improves with increased turbine inlet temperatures; temperatures sufficiently high, ~1800^{o}C, as to melt the engine. Hence, air-driven component cooling and sealing are essential. The focus of this study is the improvement of cooling and sealing flows to critical components.

Engine Operation

The behaviour of the complex geometry and material mix comprising an aero-engine is affected by the passage of the gas and associated compression and ignition processes.

The main gas path flow is separated from the internal air system by the peripheral surface, shroud, of the compressor drum. The internal air system provides cooling to the rotating blades and stationary nozzle guide vanes; and aerodynamically seals the gap between rotating and stationary surfaces.

Once used, the cooling and sealing air is ejected into the mainstream flow which can have a detrimental effect on overall thermodynamic efficiency.

It is essential that results from simulations are experimentally validated; thus making acceptable simulated design changes. The wealth of expertise developed over thirty years, combined with strategic alliances with Rolls-Royce (1996-2009), and GE Aviation (2011-) has enabled significant research, both experimental and theoretical, to be undertaken on the internal air systems of gas turbine engines.

Fully Coupled CFD Model

There is a need to understand the effect of gas property changes on physical engine components. Prior to this work, circa 1995, two separate computer simulation codes were required: one to model the gas flow behaviour (velocities, temperatures, heat transfer by convection); a second to model engine component behaviour (displacement, stress, temperature, heat transfer by conduction).

The output from one code formed the input to the other. Transferring the data required significant manual intervention to compensate for the lack of coupling; for example for relative displacements, such as the gap between a rotating and stationary component, affected by thermal expansion, and directly linked through gas flow and component surface temperature, each calculated in different codes.

Research, initiated by Rolls-Royce, led to the seamless coupling of the two codes [R1], now used extensively within Rolls-Royce for engine design, as predicting surface temperatures inside an engine is crucial in forecasting thermally-induced stress and displacements; component life; and cooling and sealing air temperatures.

Measurement and Validation

High precision rigs and measuring techniques have been developed to provide insight and validation data.

The interaction of the internal air system flow with the compressor discs and drive shaft, and methods to enhance the heat transfer from compressor discs were studied experimentally providing:

- measurements and correlations of heat transfer from the disc, drive cone and peripheral surfaces of a typical high pressure compressor geometry [R2];
- measurements and correlations of the discharge coefficients from transfer holes in a rotating drive shaft [R3];
- measurements of the time constants of the discs under engine acceleration and deceleration transient conditions [R4].

A two-stage, high-pressure turbine test rig was used to investigate the flow and heat transfer within cavities adjacent to the main annulus section, leading to:

- measurements of sealing effectiveness over a range of cooling flows for different configurations of cooling hole design [R5];
- quantification, by CO_2 tracer gas, of ingestion, reingestion and interstage seal flows [R6].

3. References to the research

Authors who were staff at the time the research was carried out are indicated thus: CA Long. All other authors, with the exception of Childs in [R6], are (or were) employees of Rolls-Royce plc, Derby.

R1 Illingworth, J.B., Hills, N.J., Barnes, C.J. (2005) '3D fluid - Solid Heat Transfer Coupling of an Aero Engine Pre-Swirl System', *Proceedings of the ASME Turbo Expo, 3 PART A*, 801-811, DOI:10.1115/GT2005-68939

R2 Long, C.A., and Childs, P.R.N. (2007) 'Shroud Heat Transfer Measurements Inside a Heated Rotating Multiple Cavity with Axial Throughflow', *International Journal of Heat and Fluid Flow*, Vol. 28(6), 1405-1417, DOI:10.1016/j.ijheatfluidflow.2007.04.009

R3 Alexiou, A., Hills, N.J., Long, C.A., Turner, A.B., L., Wong, L-S., and Millward, J.A. (2000) 'Discharge Coefficients for Flow Through Holes Normal to a Rotating Shaft', *International Journal of Heat and Fluid Flow*, Vol. 21(6), 701-709, DOI:10.1016/S0142-727X(00)00068-0

R4 Atkins, N.R. (2013) 'Investigation of a Radial-Inflow Bleed as a Potential for Compressor Clearance Control', Proceedings of ASME Turbo Expo 2013, Volume 3A: Heat Transfer, Paper No. GT2013-95768, ppV03AT15A020-, DOI:10.1115/GT2013-95768

R5 Dixon, J.A., Valencia, A.G. Coren, D.D., Eastwood, D., and Long. C.A. (2012) 'Main Annulus Gas Path Interactions – Turbine Stator Well Heat Transfer', *Proceedings of ASME Turbo Expo 2012*, Paper No. GT2012-68588. Also in ASME Journal of Turbomachinery Vol. 136 (2), DOI: 10.1115/1.4023622

R6 Eastwood, D., Coren, D.D., Long, C.A, Atkins, N.R. Childs, P.R.N., Scanlon, T.J., and Guijarro-Valencia, A. (2012) 'Experimental Investigation of Turbine Stator Well Rim Seal, Reingestion and Interstage Seal Flows Using Gas Concentration Techniques and Displacement Measurements', *ASME Journal of Engineering for Gas Turbines and Power*, Vol. 134(8), pp 082501-1-082501-9, DOI:10.1115/1.4005967

Outputs R2, R4 and R6 best indicate the quality of the underpinning research.

Key researchers:

- A **Alexiou** at Sussex 1995 – 2002, Research Fellow, now Senior Researcher at the Laboratory of Thermal Turbomachines, National Technical University, Athens
- NR **Atkins** at Sussex 2007 – 2009, Lecturer, now lecturer at the Whittle Lab, University of Cambridge
- PRN **Childs** at Sussex 1987-2008, Professor, now Professor in Engineering Design at Imperial College
- DD **Coren** at Sussex 2002 – 2010, Research Fellow, now Senior Lecturer, School of Computing, Engineering and Mathematics, University of Brighton
- D **Eastwood** at Sussex 2006 – 2010, Graduate Assistant and PhD Student, now Development Engineer for PTL, Shoreham by Sea, West Sussex
- NJ **Hills** at Sussex 1998 – 2005, Senior Research Fellow, now Professor of Computational Engineering, University of Surrey
- JB **Illingworth** at Sussex 2001 – 2005, Tutor and PhD student now Powertrain Integration Engineer for Ford Motor Company, Essex
- V **Kanjirakkad** at Sussex 2011 – present, Lecturer and Early Career Researcher working on GE projects
- CA **Long** at Sussex, 1982 – present, Reader since 2001 at University of Sussex
- AB **Turner** at Sussex 1983 – 2009, Professor
- LS **Wong** at Sussex 1998 – 2002, Research Officer
- H **Xia** at Sussex 2011 – present, Lecturer and Early Career Researcher

4. Details of the impact

Improved understanding of internal air system flows and heat transfer has reduced engine development time and testing costs; and indirectly contributed to improvements in production and operating costs, component life and weight, efficiency, and CO_2 emissions.

The use of computational models in place of engine tests has allowed Rolls-Royce to save an estimated £10M on engine testing and contributed to the improvement of engine design models in a range of areas [C1].

Fully Coupled CFD Model

The computational fluid dynamics model was coupled to the Rolls-Royce in-house thermo-mechanical analysis program SC03 in 2006; and has a capability which is still at least four years ahead of that available commercially [C1]. The fully coupled model is used extensively by Rolls-Royce and has been applied effectively to many engine projects including the V2500, Trent 700, 900 and 1000 engines.

In some very specific cases [C1] the code has been validated against engine test data, and used with Certification Authority approval, in support of life predictions of critical engine components. It is estimated that the use of the code has prevented four engine tests from having to be carried out, a direct saving of £8M.

The use of this Certification Authority approved method has increased the accuracy of component life predictions and increased the operating periods between recalls; thus Rolls-Royce, as well as their customers, have seen considerable reductions in cost and disruption. The value is impossible to calculate, but has been informally estimated at around a billion pounds over a ten year period.

Measurement and Validation

Correlations of heat transfer data acquired from the experimental work, since the early 1990s and subsequently built upon, have been adopted by Rolls-Royce for use in computational models predicting surface temperature, displacement, stress and critical component life. These have been applied to the internal rotating surfaces of high pressure compressor drums, where the use of computational models of the fluid flow, CFD, to acquire heat transfer data are impractical due to the unsteady nature of the flow field coupled with buoyancy effects.

The correlations are used extensively in current thermal models of Trent series engines. The main benefit to Rolls-Royce is more accurate predictions of the life of critical components, which can be used to determine service and replacement intervals, resulting in improved operation with the accompanying financial benefits [C1].

The work on the interaction of the internal air system flow with the drive shaft provided discharge coefficient data for the holes in the drive shaft used to transfer the internal air system flow to the turbine stages. This allowed Rolls-Royce to proceed with the design of the Trent series contra-rotating turbine section, allowing a 0.5% improvement in Specific Fuel Consumption (SFC), without having to carry out a £2M engine test.

The study that investigated enhancement of heat transfer from compressor discs has provided very comprehensive design data for future generations of actively-cooled engines. At the very least, this would allow a 30% reduction in the clearance between compressor blades and engine casing at cruise conditions with a corresponding 0.2% reduction in SFC. An appreciation of the value of this data can be obtained from the fact that Rolls-Royce are exploiting the findings and applying the results to current and new engine designs [C1].

Rolls-Royce has used the turbine rim seal flow and heat transfer data to validate computational predictions of flow structure and convective heat transfer for some (Trent series) engine components. The understanding gained through this research is being used to optimise cooling air consumption in Trent series engines, and to determine turbine disc integrity and cyclic life. The results from this work have not allowed engine tests to be replaced with modelling but it does have the potential to do so [C2]. A direct impact of the work is a reduction of 0.1% in SFC of Trent XWB engines now on order, this amounts to an extra passenger on each plane.

GE Aviation Impact

A new research partnership was formed with GE Aviation in 2011. This was motivated by the unique test capabilities and skills at Sussex, as described in the open literature, [R2, R4-R6]. Work carried out for GE has already had an effect on processes and productivity improvements leading to a direct saving of $0.55M (£0.34M) [C2].

Environmental Benefits

The environmental impact of the research described, beyond the economic benefits to Rolls-Royce and GE, is to contribute towards a 2% reduction in SFC from reduced turbine cooling flow, improved turbine and compressor efficiency, and a 2% reduction in CO_2 emissions, by the engines currently in use. Broadly, the benefits of research into gas turbine technology are indicated by an improvement of 1% in cruise specific fuel consumption (SFC) on a single aircraft engine being worth around $100,000 (£62,000) / year, 2013 prices, in reduced fuel costs. The improvement in SFC is matched by an equal saving in CO_2 emissions and a 1% reduction in CO_2 is equivalent to a saving of about 600 tonnes of CO_2 per engine / year. To put this in perspective, the current fleet of British Airways aircraft has over 600 engines, and Virgin Atlantic has about 150.

5. Sources to corroborate the impact

C1 Chief of Thermal Systems, Rolls-Royce.

C2 Advanced Testing Leader, GE Aviation