Institution: Loughborough University

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

Title of case study: Acoustic damping systems for leaner, greener aero-gas turbine combustion

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

Since 2002 researchers at Loughborough University have developed facilities and methods that have led to novel damping configurations being incorporated within Rolls-Royce's next generation low emission demonstrator engines [text removed for publication]. The work was required since future aircraft emissions legislation requires radical changes to the combustion system, which makes it inherently more unstable. The instability issues have been overcome using novel acoustic damping systems that are also capable of operating in the harsh aero-engine environment. The damping technology is therefore an enabler to Rolls-Royce producing greener gas turbines that meet future legislative requirements and ensure access to the predicted $3.7 trillion aerospace market over the next 20 years.

2. Underpinning research (indicative maximum 500 words)

To optimize the damping that can be achieved within the complex environment of a gas turbine combustion system (i.e. highly unsteady flow field, hot gases, limited space, etc.) requires improved understanding of the fundamental mechanisms by which acoustic energy is absorbed.

The research undertaken at Loughborough University initially commenced in 2002 with the development of a baseline facility in which loudspeakers were used to simulate the acoustic waves produced by combustion instabilities and unsteady heat release **[3.1, 3.2]**. This provided a controlled environment, with known boundary conditions, in which the aerodynamic response of individual combustor features (e.g. fuel injectors, dampers, etc.) to incident pressure oscillations could be evaluated. Since 2005 this approach allowed the amount of incident acoustic energy absorbed to be accurately determined, under these idealised conditions, for both conventional and novel damping designs **[3.2]**. A damping system typically consists of an array of apertures and so more fundamental experiments were subsequently conducted (2008 onwards) on various hole sizes and shapes of *practical* engineering relevance that could be incorporated within a damping system. Hence detailed measurements were undertaken to quantify the amount of acoustic energy absorbed by individual orifices of various designs under different operating conditions **[3.3]**.

Since the energy absorbed by the creation of unsteady flow field structures cannot be converted back into acoustic energy, the acoustic measurements were complemented by measurements of the unsteady flow field (2009-11). New analysis techniques were applied to these measurements to enable the acoustically generated flow field structures to be identified from the unsteady flows and turbulence associated with other features **[3.3, 3.4]**. This improved capture of the aero-acoustic processes enabled identification of the transition regime between linear and non-linear absorption for various geometries, the unsteady flow fields that provide peak absorption and the conditions where gas will be ingested into an aperture.

Within the gas turbine environment space is extremely limited whilst the harsh operating environment is also problematical. For example, high levels of acoustic absorption are often associated with large unsteady damper flows, but this increases the potential for the ingestion of hot gas from the combustor. This, in turn, compromises acoustic performance and mechanical integrity. In addition, the damper is exposed to a highly complex unsteady aerodynamic flow field, such as that generated by a fuel injector, which can impact on the absorption processes. Facilities were therefore developed (2008-present) that enabled complete damping systems to be characterised within a more complex aerodynamic environment representative of that found within a gas turbine combustion system **[3.5]**.

The experimental investigations have also enabled the development and validation of analytical models (2009 onwards) which simulate both the damping of individual apertures and the performance of the complete damper system **[3.2, 3.3, 3.5]**. Although prior to this work some models were available, these were typically based on idealised configurations (e.g. an infinitely thin circular hole). The new models predict the performance of more practical engineering configurations that have been developed and validated against the experimental measurements in a representative environment. Once validated, these models also enable the design of more optimised configurations and enable scaling from atmospheric conditions (i.e. as used within the research programme) to the high pressure and temperature conditions found within a typical engine operating envelope. In addition to articles in the public domain, applications of the underpinning research to more commercially sensitive configurations and operating conditions has been passed onto Rolls-Royce in a number of commercial in confidence reports **[3.6]**.

Loughborough University personnel engaged in this research: JF Carrotte (Lecturer 1996 – 2003, Reader 2003 – 2013, RAEng/RR Chair 2013 – present, Director LUTC 2012-present); C A'Barrow (Research Assistant 2005 – 2011); AG Barker (Research Associate 1993 – present); J Rupp (PhD Student 2008 – 2012); and A Spencer (Lecturer 1991 –2008, Senior Lecturer 2008- present).

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

Publications:

3.1. Barker, AG, Carrotte, JF, and Denman, PA, "Analysis of Hot-wire Anemometry Data in an Acoustically Excited Turbulent Flow Field", *Experiments in Fluids,* 39(6), 1st December 2005, 1061-1070, ISSN 07234864 DOI: 10.1007/s00348-005-0039-z

3.2. Zhao, D, A'Barrow, C, Morgans, A and Carrotte, JF, "Acoustic Damping of a Helmholtz Resonator with an Oscillating Volume", *AIAA Journal,Vol.47,2009,*1672-1679, DOI: 10.2514/1.39704

3.3. Rupp, J, Carrotte, JF and Spencer, A, "Interaction between the acoustic pressure fluctuations and the Unsteady Flow Field through Circular Holes", *ASME Jnl. Of Engineering for Gas Turbines and Power,* Vol 132(6), June 2010, DOI: 10.1115/1.4000114

3.4. Rupp, J, Carrotte, JF and Spencer, A, "Methodology to Identify the Unsteady Flow Field Associated with the Loss of Acoustic Energy in the Vicinity of Circular Holes", *ASME Turbo Expo 2010,* Glasgow, UK, June 2010, ASME-GT2010-22178

3.5. Rupp, J, Carrotte, JF and Macquisten. M, "The Use of Perforated Liners in Aero Gas Turbine Combustion Systems", *ASME Jnl. Of Engineering for Gas Turbines and Power,* Vol.134(7), July 2012, DOI: 10.1115/1.4005972

3.6. LU Commercial in Confidence Reports, Report numbers TT06R04 (2006), TT09R08 (2008), T11R18 (2011) and TT12R13 (2013). *These reports can be made available at request.*

The ASME research outputs were strategically targeted at the premier annual international gas turbine conference (ASME Turbo-Expo organised by the International gas Turbine Institute), and the 2 ASME journals are recognised by both university academics and the global gas-turbine industry as the world-leading publications relevant to aero-engine propulsion. *Experiments in Fluids* is a world renowned publication involving the application of existing instrumentation techniques to provide fundamental understanding of the physics of fluid flows. The American Institute of Aeronautics and Astronautics (AIAA) is the world's largest technical society dedicated to the global aerospace profession and this is its leading technical publication for archival research papers disclosing new theoretical developments and/or experimental results. In addition, elements of the work have been presented in invited lectures at the Von Karman Institute (2010, 2012), the Royal Aeronautical Society Lanchester Lecture and at various seminars/meetings within UK/Europe.

Grants:

EU (FP5): Modelling of Unsteady Combustion in Low Emission Systems (2002-04) £180k (PI: JF Carrotte)
RR(UK): EFE Compact Resonators, Passive Damper and hot gas ingestion (2004-06) £43k (PI: JF Carrotte)
EMDA/RR(UK)/SRIF: Unsteady Fluids Mechanic laboratory (2006) £2.5M (PI: JJ McGuirk)
RR(UK): Interaction between the acoustic energy and the velocity fields associated with circular holes (2007) £47k (PI: JF Carrotte)
EU (FP7): Technology Enhancement for Clean Combustion in Aero-Engines (2008) £514k (PI JF Carrotte)

RR(D): Acoustic damper specification (2010) £34k (PI: JF Carrotte)
RR/TSB: Alecsys external aerodynamics testing (2011) £51k (PI: JF Carrotte)
RR(UK): Alecsys acoustic damper design (2011) £26k (PI: JF Carrotte)
RR/EPSRC: Development of enhanced damping configurations (2012) £119k (PI: JF Carrotte)

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

The ACARE (year 2020) aircraft emissions legislative targets require significant reductions in fuel burn (50%) and NOx emissions (80%) relative to the year 2000. To meet these challenging targets requires the introduction of lean burn technology within the combustion system. However, this technology is intrinsically more unstable than the rich burn technology currently in use. The technology is particularly susceptible to thermo-acoustic instabilities associated with the potential for feedback between unsteady heat release and acoustic interactions at the combustor boundaries. This can lead to large amplitude pressure oscillations that severely impact structural integrity and operational performance, so preventing the introduction of lean burn technology and the development of next generation 'leaner and greener' gas turbine engines. However, researchers at Loughborough university have been at the forefront of research undertaken to understand and overcome these problems **[5.1]**.

Increasing the absorption of acoustic energy within the combustion system can overcome the instabilities inherent to lean burn technology. [Text removed for publication] In response to this researchers at Loughborough developed a strategy using isothermal facilities and artificial noise sources to simulate the engine environment along with the relevant damping system processes. However, the removal of unsteady heat release limits the acoustic power that can be generated. To simulate the required range of conditions a facility that puts up to 10 kW of acoustic power into the test section was developed using pneumatic energy as a noise source. Such noise sources of this type and size are more typically used to assess the ability of satellites to withstand the acoustic noise and vibrations associated with rocket launches. The facility was the centrepiece of the £2.5M Unsteady Fluids Mechanic Laboratory (opened in 2008) and is unique, since sectors of a complete combustion system can be exposed to relevant aerodynamic and aero-acoustic processes at noise levels representative of those encountered throughout the engine operating range. Together with other developments, the new laboratory provides a range of isothermal facilities that has enabled multi-facetted research to be undertaken aimed at understanding and overcoming the problems associated with flow field unsteadiness and instabilities **[5.1]**. This includes the response of fuel injector flows to acoustic forcing through to technology for damping of the acoustics. In addition to enabling more fundamental studies, damping systems for specific engine configurations can be evaluated, developed and optimised relatively cheaply (e.g. less than £100/day) prior to testing at high pressure and reacting engine representative conditions (in excess of £150,000/day).

[Text removed for publication] A novel cooling system was therefore developed to reduce the propensity of damping systems to ingest hot gas. The final concept was successfully tested on a high pressure test unit within Rolls-Royce and then incorporated within the ANTLE demonstrator engine. This is now embedded in all damping designs of this type used by Rolls-Royce for aerospace applications **[5.1]**. The experimental facilities also enabled the generation of high quality advanced data sets which have been used to validate models of the observed processes. These models have flowed into the companies design systems for use within its next generation engines **[5.1]**. The design tools enable the rapid optimisation of damping configurations for given operating conditions, engine space envelope, etc. These geometries are then further evaluated using low order thermo-acoustic network models (developed elsewhere) which characterise the acoustic performance of the complete combustion system.

The developed technology has been successfully demonstrated by Rolls-Royce within various engine programmes. This includes the EU/UK sponsored research programme ANTLE (Affordable Near Term Low Emission), with more complex and optimised damping configurations (including both conventional and novel concepts) being incorporated within the UK funded EFE (Environmentally Friendly Engine) and German public funded E3E engine programmes [5.6]. In addition, this technology is now embedded within Rolls Royce design processes to enable its application within future aerospace combustion systems. The ability to suppress instabilities means that it is a potential enabler to the introduction of lean burn technology for next generation engines. This will ensure the compliance of Rolls-Royce products with future legislative directives and maintain its competitive position within the aerospace market by being able to produce leaner and greener engines. The impact of the work is further reflected in a number of patents taken out by Rolls-Royce aimed at protecting the intellectual property delivered by the research at Loughborough **[5.3-5.5]**.

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

The following sources of corroboration can be made available at request:

5.1 Joint letter from (i) Head of Combustion and Turbine systems, Rolls-Royce plc, PO Box 31 Derby DE24 8BJ and (ii) Corporate Specialist- Combustion, Rolls-Royce plc, PO Box 31 Derby DE24 8BJ which corroborates the following:

- Loughborough University has been at the forefront of the research into the mechanisms and solutions to unsteady processes and noise production associated with lean burn technology

- During initial rig testing within Rolls-Royce of the ANLTE combustion system the damping performance deteriorated as the acoustics became more aggressive.

- The complexity of the problem demanded a new unsteady fluids facility that was developed which could generate noise levels similar to those experienced within real combustion systems and allowed various areas of research to be explored.

- Novel cooling schemes demonstrated within the ANTLE demonstrator programme enabling damping technology to work as its design intent. This is now embedded for use in Rolls-Royce combustors for aerospace applications

- Advanced data sets have been obtained from the facilities and used to develop/validate models of the processes observed and these have flowed into the companies design systems for onward use.

Example Engine demonstrator programmes:

5.2 http://www.rolls-royce.com/about/technology/research_programmes/gas_turbine_programmes/efe.jsp

Three RR patents relating to damping within gas turbine combustion systems originating from Loughborough Research and including named LU Research staff

5.3 Rolls-Royce plc, “Helmholtz resonator for a combustion chamber for a gas turbine engine” and “Combustion chamber for a gas turbine engine” Europe/USA Patents EP1669670 (2007), US7448215 (2008) (LU staff: AG Barker, JF Carrotte)

5.4 Rolls-Royce plc, “Combustion Chamber for a Gas Turbine Engine”, Europe/USA Patents US7857094 (2010), EP1862739 (2008) (LU staff: AG Barker, JF Carrotte)

5.5 Rolls-Royce plc., “Brennkammerkopf einer Gasturbine mit Kuhlung und Dampfung” EP11006812.9 NB. Patent currently applied for *(Europe (2011), US (2012)* (LU Staff AG Barker and J Rupp)