Institution: Imperial College London

Unit of Assessment: 12 Aeronautical, Mechanical, Chemical and Manufacturing Engineering

Title of case study: 4. Rolls-Royce University Technology Centre on Vibration

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

Cost savings in the order of £130M over the REF period have been achieved by Rolls-Royce through the improvement of engine reliability of civil and military aero-engines, industrial machines used for electricity generation and gas/oil pumping applications through the use of techniques and processes developed by the Vibration University Technology Centre (UTC) at Imperial College London.

2. Underpinning research (indicative maximum 500 words)

A major problem in the design and use of gas turbines is the control of vibration. Excessive vibration in gas turbine components can lead to failure due to metal fatigue and in severe cases a component failure can threaten the integrity of the machine and possibly the aircraft. The Vibration UTC has operated throughout the period from 1993 to the present day in close collaboration with Rolls-Royce plc. Rolls-Royce works with the Centre to identify relevant research areas and provides financial and in-kind support through access to real aero engine geometry and engine test results. The underpinning research is organised in three inter-related themes (a) fluid-structure interaction (b) structural dynamics, and (c) engine design capability.

<u>Fluid-Structure Interaction</u>
The development of the fluid-structure interaction capability was led by Prof M. Imregun throughout the period from 1993 until 2010. The main research challenges were to understand and predict the complex vibration mechanisms which can occur within a gas turbine due to the air flow. An example of this is flutter of fan blades in which the blade motion causes aerodynamic changes which in turn affect the structural response [1]. The system behaviour is also influenced by interaction with the engine intake flow, including the wind conditions on the ground, and is known to vary from assembly to assembly for nominally identical fan sets. Other examples are the aerodynamic instability issues causing rotating stall and surge, which can lead to unacceptably high loads on gas turbine components. Forced vibration of compressor and turbine blades due to the aerodynamic unsteadiness from adjacent rows of blades is also a critical issue for design [2].

A new software based methodology (known as AU3D) was developed to model details of the interaction between the air flow and the structure. It calculates the instantaneous state of the fluid and structure and allows each to interact as the solution proceeds [3]. The approach, based on state-of-the-art unsteady compressible flow and structural dynamics was initially developed by Dr M. Vahdati (Senior Research Fellow and in the group from1993 to the present) and has continued to be developed and be applied with contributions from many other researchers within the VUTC. The approach has been transferred to Rolls-Royce and is used largely in the form supplied by Imperial.

<u>Structural Dynamics</u>
Understanding the structural dynamic behaviour is critical to predicting the material component integrity.

A team formed by Prof David Ewins (in post 1993-present; now a member of the Rolls-Royce Manufacturing, Materials and Structures Advisory Board) has focussed on non-linear contact and friction and their effect on overall system response (here system refers to the set of components in a turbine or compressor stage). A unique prediction method (JM62) has been developed to model structural interfaces with emphasis on the overall dynamic response [4] rather than the tribology of the contact. The approach has been transferred to Rolls-Royce and is in wide use, with frequent interaction on refinements and new features. Since 2011 the team is headed by Dr Christoph

Schwingshackl (Lecturer since 2011).

As an example, the High Pressure Turbine rotor is subject to very large unsteady gas loads and the vibration is controlled by use of a friction damper. The research has involved detailed investigation of the behaviour of such dampers, including extensive analysis supported by experimental system level testing [5] for validation and development of a friction measurement rig to determine the contact parameters at high frequency.

Engine Design Capability
The objective of the gas turbine design and analysis system ("Virtual Engine") is to provide detailed assessments of preliminary engine configurations at an early stage in the design process. The team was launched in 2005 and is headed by Dr Luca di Mare (Lecturer since 2011) and has developed a completely novel approach to gas-turbine design which includes the close linking of low-order modelling of physical effects adapted to the stage of the design process. There is a very close link between geometry and associated data in a unified approach enabling "water tight" geometry extraction to enable robust analysis of the aerodynamics performance and mechanical integrity of the machine [6].

3. References to the research (indicative maximum of six references)
* References that best indicate quality of underpinning research.

[1] M. Vahdati, G. Simpson, M. Imregun, "Mechanisms for Wide-Chord Fan Blade Flutter", Journal of Turbmachinery- Transactions of the ASME, Vol 133, paper 041029 (2011) DOI: 10.1115/1.4001233

*[2] M. Vahdati, A.I. Sayma, M. Imregun, "An integrated nonlinear approach for turbomachinery forced response prediction. Part II: Case studies", Journal of Fluids and Structures, Vol 14, pp. 103-125, ISSN:0889-9746 (2000) DOI: 10.1006/jfls.1999.0254

*[3] A.I. Sayma, M. Vahdati, M. Imregun, "An integrated nonlinear approach for turbomachinery forced response prediction. Part I: Formulation", Journal of Fluids and Structures, Vol 14, pp. 87-101, (2000) ISSN:0889-9746 DOI: 10.1006/jfls.1999.0253

*[4] E.P. Petrov, "Method for direct parametric analysis of nonlinear forced response of bladed disks with friction contact interfaces", Journal of Turbomachinery, Vol 126, pp. 654-662, (2004) ISSN 0889-504X. DOI: 10.1115/1.1776588

[5] I.A. Sever, E.P. Petrov, D.J. Ewins, "Experimental and numerical investigation of rotating bladed disk forced response using under-platform friction dampers", Journal of Engineering for Gas Turbines and Power, Vol 130, pp. 042503, (2008) 042503/1-042503/11. ISSN 0742-4795. DOI: 10.1115/1.2903845

[6] L. Di Mare, D.Y. Kulkarni, F. Wang, et al., "Virtual Gas Turbines: Geometry and Conceptual Description", Proceedings Of The Asme Turbo Expo 2011, Vol 1 pp347-358 (2011).DOI: 10.1115/GT2011-46437

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

The problem of Vibration
Excessive vibration in gas turbine components can lead to failure due to high cycle fatigue (HCF). In extreme cases, it can lead to loss of the aircraft, such as the Kegworth Air Disaster [7] in 1989 in which 47 people lost their lives and the financial cost ran into tens of millions of pounds. The failure was caused by flutter (fluid-structure interaction) of the fan at high engine speed due to a change in the non-linear dynamic properties of the part-span shroud.

More typically a turbine or compressor blade may be released which causes difficulty for operators of civil and military engines because they require predictable availability in which all engine problems can be managed through scheduled maintenance. However, HCF can lead to sudden, unexpected component failure which can be very disruptive and expensive (e.g. additional aircraft and crew, ferrying damaged engine to base + cost of repair). For ground based gas turbines, used for gas/oil pumping or electricity generation, then the financial cost can be very high through lack of revenue, and the remote location of the units (e.g. on an oil platform) adds to the maintenance difficulties. The US Air Force reported that 56% of its “Class A” engine related mishaps were due to HCF, requiring an expenditure of 850,000 maintenance man-hours for risk management inspections, with the total cost of HCF being quoted as $400 million per year [8].

<u>The Impact of the Vibration UTC</u>
The Vibration UTC is a strategic partner of Rolls-Royce for the development of a prediction capability for vibration [9]. The research programmes completed by the Vibration UTC are delivered as fundamental investigations of behaviour, processes for prediction, software modules and supporting measurements. By controlling the vibration behaviour the risk of High Cycle Fatigue is dramatically reduced. The delivery of the impact is also assisted by consultancy undertaken by the academic staff and by PhD graduates and postdocs being employed by the company; 10 UTC researchers have joined Rolls-Royce since 1996, including 3 since 2008.

<u>Fluid-Structure Interaction</u>
The research on fluid-structure interaction has revolutionised the approach to predicting the vibration behaviour and is in routine use at Rolls-Royce across the major sites throughout the world. This was confirmed in a keynote lecture given by Dr M. Goulette (then Director of Rolls-Royce Engineering Systems) at the International Symposium on Unsteady Aerodynamics, Aeroacoustics and Aeroelasticity of Turbomachines in London during September 2009 [A]. Processes and software (AU3D/JM62) developed by the Vibration UTC have been applied to the design of the majority of Rolls-Royce civil & military aero-engines, including:

- All versions of theTrent family for the large civil engine market since the early 1990s (i.e Trent 700 / 800 / 500 / 900 / 1000 / XWB).
- BR710 / BR725 / V2500 / AE3007 for the small civil / corporate market.
- Main engine and LiftFan for the Joint Strike Fighter, TP400 for the A400M transporter, Pegasus for the vertical take-off Harrier and AV8-B.

Through these engine programmes, the process and tools developed at Imperial have enabled improvement in reliability against tightening constraints on engine cost, weight, noise and performance, leading to savings. Designers tend to compromise the design due to unquantified concerns about HCF failure, but the research has enabled better understanding of the design space and allowed improved engine performance. [A] states, “The understanding and tools developed by the VUTC have enabled improved efficiency of fan system of Trent XWB by around 0.1%, which is equivalent to a saving of £100 million in fuel costs alone over the lifetime of the fleet. It has also enabled integrity assessment of damage cases such as bird impact and novel engine architectures such as the Lift Fan used in the F-35B Joint Strike Fighter”.

One very tangible benefit is the significant reduction in cost of testing because the analysis procedures (and software) are used to replace engine testing. Testing on rotating parts requires expensive engine telemetry experiments and can cost in the order of £1million per test, therefore the research has directly led to the saving of several millions of pounds per engine programme. [C] states, “AU3D has revolutionised the way Rolls-Royce assesses the mechanical integrity of compressor aerofoils. The code is in routine use within the company and with the support of the VUTC, has led to a factor of 5 reduction in test costs, a total saving of around £30M over the last five years for the Trent programme alone”. It is also now successfully deployed for the corporate jet market via Rolls-Royce Deutschland and is already making large savings [D].

<u>Structural Dynamics</u>
Work on modelling of non-linear contact and friction has improved the understanding of the influence of contact on the vibration characteristics and the mechanical damping of the system. The early focus (1998-2005) was on behaviour of turbine “under-platform” dampers to reduce

vibration levels and prevent high cycle fatigue failures.(Note: these blades are about 100mm long, produce ~800 HP, operate in gas flow several hundred Celsius above the material melting point and operate for millions of miles). Turbine failures in service create costs running into millions of pounds due to repair and warrantee payments and claims due to flight schedule disruption. There were problems in the 1990's which led to the introduction of a design change [10]. According to [B], "Rolls-Royce have routinely used JM62 for optimisation of the turbine blade damper system to control vibration and we have seen blade HCF failures reduce to virtually zero giving savings of tens of millions of pounds over the past five years".

Engine Design Capability

The Engine Design aspects are still at an early stage of deployment, but there are already programmes in place to transfer the developed methods into Rolls-Royce. The preliminary geometry generation tools are planned to become an integral part of the Rolls-Royce design system, allowing more rapid and broader studies of new engine architectures which are expected to give a better performance, reduced weight and cost. The low order modelling tools will also be used to identify vibration problems (and solutions) at an early stage in the design phase leading to significant savings in engine design and development costs.

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

[7] Accidents Investigation Branch - Aircraft Accident Report "Report in the Accident to Boeing 737-400 G-OBME near Kegworth, Leicestershire on 8 January 1989". http://www.aaib.gov.uk/cms_resources.cfm?file=/4-1990%20G-OBME.pdf Air 4/90 pp 7, 117-119. Archived here on 19/09/1013

[8] High Cycle Fatigue (HCF) Science and Technology Program 2001 Annual Report. AFRL-PR-WP-TR-2002-2060. http://www.dtic.mil/dtic/tr/fulltext/u2/a408071.pdf . Archived here on 19/09/1013

[9] "UTC & key academic partnerships" http://www.rolls-royce.com/about/technology/uni_research_centres/key_academic_partnerships.jsp (Archived at https://www.imperial.ac.uk/ref/webarchive/9qf on September 5th, 2013)

[10] P. Gilchrist, "Boeing 747-400" (1998), p44. ISBN 1853109339 (pbk.)

Source contact details

[A] Rolls-Royce Engineering Fellow – Mechanical Technology to corroborate the content of a keynote lecture given by Dr M. Goulette (then Director of Rolls-Royce Engineering Systems) at the International Symposium on Unsteady Aerodynamics and how the research enabled better understanding of the design space and allowed improved engine performance.

[B] Rolls-Royce Associate Fellow –to confirm use of unique prediction method (JM62) that resulted in giving savings of tens of millions of pounds over the past five years.

[C] Engineering Manager, Rolls-Royce – Compressor Mechanical Technology to confirm the a total saving of around £30M over the last five years for the Trent programme alone resultant from Imperial research

[D] Chief of Aeroelasticity, Impact and Thermals, Rolls-Royce Deutschland to confirm that the developed code is successfully deployed for the corporate jet market via Rolls-Royce Deutschland and is already making large savings.