Institution: University of Bath

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

Title of case study: Efficient and robust rotating machines: Design innovations and international standards

1. Summary of the impact

Rotating machines are ubiquitous key elements for power generation. Research has led to impacts that have improved the design and performance of rotating machinery for component vendors, original equipment manufacturers and end-users:

(a) Siemens has adopted new designs of interstage turbine disc rim seals that reduce gas leakage paths and hence increase power efficiency/fuel savings in power based gas turbines. The impacts have protected 4-5 R&D jobs, improved seal product design, and enabled reallocation of corporate budgets.

(b) Integrated dynamic/thermal analysis has enabled preventive design against unstable shaft thermal bending, known as the Morton Effect in the field of turbomachinery.

(c) Research into the functionality of active magnetic bearings has been transferred into the standard ISO 14839 1-4 that has brought technology normalisation, involving changes to company design practices, to the field. Part 4 was published in 2012.

(d) An oil-free experimental facility has been delivered to GE Global Research (Munich) to aid in their compressor designs for subsea machines. GE has benefitted through knowledge transfer and the training of engineers for the design of new machines.

2. Underpinning research

Key researchers

Sustained research activity has been driven for more than twenty years in the rotating machines field by Professor CR Burrows (Professor from 1987, emeritus since 2007), Professor PS Keogh (Lecturer 1990-1996, Senior Lecturer 1996-2003, Reader 2003-2007, Professor since 2007), Gary Lock (Lecturer 1995-2001, Senior Lecturer 2001-2008, Reader 2008-2012, Professor since 2012), Mike Owen (Professor from 1989, emeritus since 2008), Necip Sahinkaya (Reader since 2001) and Mike Wilson (Lecturer 1996-2003, Senior Lecturer since 2003). Their activities cover gas turbine fluid flow and heat transfer, motion induced shaft heat transfer, and the functionality of active magnetic bearing and touchdown bearings for high speed machines. Their effort is focused in the Gas Turbine Research Unit and the Centre for Power Transmission and Motion Control.

Key insights and projects

Fundamental research has been funded mainly by the EPSRC in collaboration with industrial partners. Insights into the research and associated EPSRC projects (with project codes, dates, and collaborating industrial partners) are provided in the following text.

Owen led projects on heat transfer and cooling within turbine stage cavities (GR/J07907/01 from 1993-1996; GR/K27360/01 from 1994-1997 with European Gas Turbines; and GR/M08868/01 from 1999-2002 with European Gas Turbines). Lock provided a focus on turbine leakage/cooling/flows by leading projects GR/L48034/01 from 1997-2000 with European Gas Turbines; and GR/N33980/01 from 2000-2004 with Alstom/Rolls-Royce. This led to the formulation of two research projects on gas ingestion and ingress through novel designs of rim seals (EP/G069107/1 from 2009-2012; EP/J014826/1 from 2012-2015), both in collaboration with Siemens Industrial Turbomachinery, previously European Gas Turbines.

Keogh investigated the heat transfer from fluid film bearings to rotating shafts under dynamic motions (GR/J15568/01 from 1993-1997) to highlight the particular conditions under which a shaft may experience asymmetric heating that leads to runaway thermal bending. Burrows and Keogh led activities relating to the design of modern control strategies for magnetic bearing levitated rotors (GR/J15575/01 from 1993-1996; GR/L62238/01 from 1998-2001; and GR/R45277/01 from 2001-2005, both with Edwards High Vacuum). Research into high speed rotor/touchdown bearing contact control was led by Keogh through EP/D031389/1 from 2006-2009 in collaboration with

Goodrich, now part of Rolls-Royce as Aero Engine Controls.

Key outputs

Research embraces thermofluidic influences on the dynamics and control of rotating machines. The group embodies one of the world centres for experimental research in rotating-disc systems, particularly in the theory, calibration and application of thermal imaging techniques to measure the heat transfer on rotating surfaces [1]. The prediction and measurement of flows/ingress through turbine disc rim seals is exemplified in [2, 3], which has had important implications for gas turbine efficiency.

The first identification of the phenomenon of runaway thermal bending of a shaft within a hydrodynamic bearing, requiring machine shutdown, is given in [4]. This is now known as the Morton Effect to designers of turbomachinery. This can be negated through passive machine design. Studies on the active control of magnetic bearings and their associated touchdown bearings have realised contributions to enable system design and optimised rotating machine performance under contact-free levitation. An understanding of rotor/touchdown bearing contact modes has also been established in [5, 6]. When rotor/touchdown contact events occur, the mechanical and thermal integrity of the system may be compromised, hence these research outputs have provided a basis for preventative design.

3. References to the research (* references that best indicate quality)

1. VU Kakade, GD Lock, M Wilson, JM Owen and JE Mayhew. Accurate heat transfer measurements using thermochromic liquid crystals. Part 2: Application to rotating disc, 2008, International Journal of Heat and Fluid Flow, **30**, 950-959. DOI: 10.1016/j.ijheatfluidflow.2009.04.005
2. JM Owen, OJ Pountney and GD Lock, Prediction of ingress through turbine rim seals. Part 2: Combined ingress, 2012, ASME Journal of Turbomachinery, **134**, 031013. DOI: 10.1115/1.4003071 (First published as a conference paper in 2010)
3*. CM Sangan, OJ Pountney, K Zhou, M Wilson, JM Owen and GD Lock. Experimental measurements of ingestion through turbine rim seals. Part 1: Externally-induced ingress, 2012, **135**, ASME Journal of Turbomachinery, 021012. DOI: 10.1115/1.4006609 [Received a Best Paper Award from the Heat Transfer Committee of the ASME Turbo Expo 2011]
4*. PS. Keogh and PG Morton, The dynamic nature of rotor thermal bending due to unsteady lubricant shearing within a bearing, 1994, Proceedings of the Royal Society: Mathematical and Physical Sciences, **445**, 273-290. DOI: 10.1098/rspa.1994.0061
5*. PS Keogh, MOT Cole, MN Sahinkaya and CR Burrows. On the control of synchronous vibration in rotor/magnetic bearing systems involving auxiliary bearing contact, 2004, ASME Journal of Engineering for Gas Turbines and Power, **126**, 366-372. DOI: 10.1115/1.1689362
6. IS Cade, PS Keogh and MN Sahinkaya. Transient rotor/active magnetic bearing control using sampled wavelet coefficients, 549-555, ASME Journal of Engineering for Gas Turbines and Power, **129**, 2007. DOI: 10.1115/1.2436570 [Received a Best Paper Award from the Structures and Dynamics Committee of the ASME Turbo Expo 2006]

4. Details of the impact

The specific cases (a) – (d) of section 1 fall under the general categories of ***'Economic impacts'*** and ***'Impacts on practitioners and professional services'***.

(a) Gas turbine rim seal design advances

Siemens is a large global company with an Energy product group. It has a vested interest in manufacturing more efficient power generation products so as to increase market share. Siemens Industrial Turbomachinery employs 1,600 people in Lincoln for the design, manufacture and maintenance of gas turbines in the power ranges from 5 MW to 15 MW. Research and design innovations at Bath have had significant economic and environmental impact at Siemens. The impact has contributed significantly to the company's current level of technology and competitiveness in the power generation industry has helped to protect jobs in Lincoln, supported the local and wider UK economy, and has created greener technology with a reduction in CO_2

through improved engine efficiency. The knowledge transfer of the research from Bath to Siemens has been facilitated by a Knowledge Transfer Associate (Teuber).

(i) *New rim seal components and improved thermal efficiency*

The Bath research [2, 3] has led directly to new rim seal components. These patented component designs ([A] and patent applications from Siemens: 2013P00020EP and 2013P00483EP, currently embargoed) evolved through a carefully organised programme of interaction between Siemens and Bath, via a Knowledge Transfer Partnership. ***Economic impacts have been evidenced through improved products, jobs protected, and reallocation of corporate budgets*** as the Director of Future Technology within Siemens (Lincoln) states that an improvement in thermal efficiency of 0.4% has been confirmed [B]. Furthermore:

> '*Internal funding directly from Technology looking at the development of seals and improved secondary air systems analysis will be in the region of €1M-1.5M over five years. To this I would add the indirect effort that comes about through related engine design and concept development activity. Here we have ~4 to 5 people full time equivalent @ approx €1M/annum.*'

(ii) *Changing and improving the design methods at Siemens*

The research at Bath has ***achieved impact on practitioners/engineers through changed and improved design practices used at Siemens***. Specifically, a new theoretical model for rim seal ingress has been developed at Bath and translated into a practical design tool (used in 2nd Flow) for the Siemens' secondary air system (SAS) [C]. It is stated in [B] that:

> '*Avoidance of a single instrumented engine test has reduced the engine development budget by over £250k and the development programme by 3 months. Reduced lead times for engine development can be equated to additional opportunity for engine sales.*' and
>
> '*Increasing the life of these parts therefore makes the company's service plans more attractive to the customer and secures the jobs in its service organisation. Each additional long term service agreement secured is a sale valued at between £250k and £500k per year for 5 to 10 years.*'

Each additional sale of a 15 MW class engine represents a sale valued at over £5M. Siemens branches in the USA, Sweden and Germany have validated their own SAS tools and have assessed 2nd Flow as the major SAS design tool [D]. This has enabled Siemens to reallocate corporate budgets towards research in the Energy sector.

(b) Design against runaway shaft thermal bending in rotating machines

The dynamic process of runaway shaft thermal bending, known as the Morton Effect, was first explained in reference [4]. Since that publication, design and field engineers have reported numerous instances of problematic turbomachines that were not meeting specification due to excessive vibration. These engineers now design against occurrence of the Morton Effect by reducing a thermal-orbit loop gain system parameter below a definable threshold value. Impact of this research is therefore evident through ***traceable references from practitioners (engineers) to reference [4]***. Cases of the Morton Effect have been reported through the Pump/Turbomachinery Symposia, organised by the Turbomachinery Laboratory, Texas A&M University, and held annually in Houston. The Director of the Turbomachinery Laboratory, who has extensive industrial engagement with the oil and gas sector, comments [E]:

> '*After their work, a stream of papers appeared involving case studies of real machines with "synchronously unstable" vibration characteristics. The outcome was comparable to the discovery of a previously undiagnosed disease that — once recognized — was found to be widely distributed and now predictable, avoidable, and curable.*'

(c) International standards for Active Magnetic Bearing (AMB) based rotating machines

The group has led research into the rigorous design of active magnetic bearing (AMB) control strategies for the stable levitation of flexible rotors, and has addressed the understanding of the dynamics of rotor drop onto touchdown bearings [5, 6]. The impact of this research is now evident through its incorporation into ***new and modified professional standards***.

A degree of standardization was required following the early industrial application of AMBs over the 1980s and 1990s, when failures were reported. Recognition of the Bath research became evident

through invitations to serve on the International Organization for Standardization (ISO) TC108/SC2/WG7 AMB Project committee (Burrows, 1996; Keogh, 1998; Sahinkaya, 2003) with other academic researchers and industrial technologists from the USA, Switzerland, Germany, France, and Japan. Bath is now the only institution with three representatives. This committee has encouraged the expansion of applications from vacuum pumps, motors, generators, flywheel energy storage, to compressors for the oil and gas sector. The Bath group pioneered the technique of automatic balancing of levitated flexible rotors and has been central to the understanding of AMB touchdown dynamics that arise from rotor de-levitation. The Bath input has been embedded into the standard, ISO 14839 (Parts 1-4) [F]. Since 2009, Keogh has led ISO/TC108/SC2/WG7 as Convenor and Part 4 was published in 2012. Beneficiaries include vendors (S2M, MECOS, Calnetix, Waukesha), original equipment manufacturers (Siemens, GE, Solar Turbines, Edwards) and end-users (Shell, Total, Statoil, Exxon). The Director of Technology, Calnetix, states [G]:

> '*As Director of Technology of Calnetix, an innovation led company based near Los Angeles, USA, I know well that important technical issues must be overcome to ensure that high performance machines operate reliably and safely in their intended environments. The input from the Bath team has contributed significantly to the development of rigorous standards for AMB operation in a range of industrial applications. The performance metrics required by the standard are very useful and practical, enabling Calnetix to advance the robustness of its machine designs. This has helped Calnetix increase market penetration – in fact, annual revenues of Calnetix have tripled over the past five years.*'

(d) Oil-free compressor design

International recognition of the Bath input is attested by the invitation of GE Global Research (Munich) in 2012 for the Bath team to design and deliver an experimental facility for oil-free compressor dynamic investigations. The research from Bath has also underpinned collaboration and impact with GE through ***knowledge transfer***. The Principal Engineer: Electric Drivetrain, GE Global Research, states [H]:

> '*I was aware of the previous Bath AMB research into the control of levitated flexible rotors. Such rotors are pertinent to the oil and gas compressor rotors manufactured by GE. A contract was therefore arranged for Bath to design and deliver an experimental rotor/AMB facility to GE Global Research (Munich) to enable investigation of the system requirements for compressors, particularly in subsea applications. Professor Keogh and Dr Sahinkaya have since interacted with and guided the GE engineering team from April 2012 to July 2013 through knowledge transfer of the principles that are embedded within ISO 14839 guidelines.*'

The experimental facility has been used to train five practitioners (design engineers) for the development of oil-free compressors.

5. Sources to corroborate the impact

A. *Finned seal for gas turbine*, Patent 2012P08852, JM Owen, CM Sangan, GD Lock, KM Tham, VP Laurello and CP Lee, 2012.
B. Corroborative statement from Director of Future Technology Siemens (Lincoln), 12 April 2013.
C. *Implementation of rim sealing Orifice Model in 2nd Flow*, R Teuber, Siemens Technical Report TR 12/124, July 2012.
D. Corroborative statement from Siemens (Core Competence Owner Secondary Air System), 4 October 2013.
E. Corroborative statement from Director of Turbomachinery Laboratory, Texas A&M University, 13 September 2013.
F. ISO 14839 Mechanical vibration - Vibration of Rotating Machinery Equipped with Active Magnetic Bearings: Part 1: Vocabulary (2002); Part 2: Evaluation of vibration (2004); Part 3: Evaluation of stability margin (2006); Part 4: Technical guidelines (2012).
G. Corroborative statement from Director of Technology, Calnetix Technologies LLC (Los Angeles), 16 August 2013.
H. Corroborative statement from Principal Engineer: Electric Drivetrain, GE Global Research Centre (Munich), 8 August 2013.