Institution:	Imperial College London
Unit of Assessment:	12 Engineering
Title of case study:	Structural Integrity of Aero-engine Bladed Discs
Period when the underpinning research was undertaken:	2011 - 2019

Details of staff conducting the underpinning research from the submitting unit

Name(s):	Role(s) (e.g. job title):	Period(s) employed:
David Dye	Professor of Metallurgy	2000 – present
Fionn Dunne	Professor in Micromechanics	2012 – present
Christoph Schwingshackl	Reader in Mechanical Engineering	2006 – present
Mehdi Vahdati	Principal Research Fellow	1992 – present

Period when the claimed impact occurred: 1 August 2013 – 31 December 2020

Is this case study continued from a case study submitted in 2014? Yes

1. Summary of the impact

The multidisciplinary teams in Materials and Mechanical Engineering at Imperial focusing on aero-engine performance have contributed pivotal understanding to the structural integrity of aero-engine discs and blades addressing the degradation and failure processes of cold dwell fatigue and salt corrosion, and to engine vibration optimisation.

The underpinning research into the mechanistic basis of the degradation and failure process termed **dwell fatigue** has delivered the safe envelope of conditions for aero-engine flight loading to avoid this catastrophic failure, and has enabled substantive retirement of high-cost (around GBP1,000,000 per test) engine disc spin testing programmes. It has enabled the relaxation of the disc inspection regime and additional engine overhauls, saving around GBP100,000,000/year in reduced maintenance regimes. The research has also facilitated the closing out of aero-engine 'red-tops' (urgent safety priority investigations) in 2015, 2019, and continuing in 2020. The international research standing led to membership of the USA FAA consortium (GE, P&W, RR, IHI, USAF) as the only UK academic group, influencing international aviation safety policy. The research in mechanistic understanding of salt corrosion of aero-engine components led to substantively reduced test programmes on the TP400 aero-engine programme, saving over GBP40,000,000 in 2014 alone, and the lifting of costly potential flight envelope restrictions. Research to improve the accuracy of computational fluid dynamics and in non-linear engine vibrations for gas turbines established cause of vibration with the Trent 1000 engine, which eliminated blade root cracking and thus lifted the grounding of the Trent 1000 fleet. High vibration levels were eliminated in a development engine (Br700NG) allowing certification to be achieved on time. The research in non-linear vibration was key to design of the new Rolls-Royce MMM (design method) directly impacting the design of next generation turbine blades for the UltraFan® engine.

2. Underpinning research

Prof Fionn Dunne (2012), Prof David Dye (2000), Dr Christoph Schwingshackl (2006) and Prof Mehdi Vahdati (1989) collectively bring their expertise in metallurgy, micromechanics and dynamics to focus on aero-engine structural integrity to ensure safety. Their underpinning research addressing fatigue, corrosion cracking and vibration delivers the structural integrity of safety-critical bladed disc components fabricated from titanium alloys. The research, reported in (R1 to R9), underpinning the impacts (I1 to I5) is summarised as follows.

1. **Cold dwell fatigue [R1 to R4; I1, I2]:** dwell fatigue is a defect nucleation and failure process in titanium alloys which may lead to uncontained aero-engine failure; uncontained failure can compromise the aircraft. The Figure shows a recent example (full report at https://www.bea.aero/uploads/tx_elydbrapports/BEA2017-0568.en.pdf) and the subsequent FAA investigation resulted in an airworthiness directive estimating a liability of USD780,000 per engine [E1]. Across the aircraft fleet, this gives a potential exposure of US$350,000,000 to the engine manufacturer. Our research in dwell fatigue has prevented this kind of failure in Rolls-Royce engines.

Uncontained engine failure [E1] causing emergency landing of an Airbus 380 flight in Goose Bay, Canada in 2017. Uncontained failure can compromise the aircraft. The flight carried 521 passengers and crew. The failure was demonstrated to be cold dwell fatigue. Our research prevents this kind of catastrophic failure which has been avoided in Rolls-Royce. engines.

   Work by Dunne (2013-19) and Dye (2000-19) utilised microstructure modelling to explain the temperature sensitivity of dwell fatigue [R1], resulting from differing temperature sensitivities of slip strengths and thermally-activated dislocation escape, providing predictive modelling capability. The research also established the intrinsic slip system rate sensitivities of the two key phases in these alloys for the first time. This facilitated assessment of the microstructures which cause dwell fatigue and demonstrated that it is microstructure which is key to dwell sensitivity, as opposed to chemistry. Subsequent study on the performance of Rolls-Royce engine components showed the multiaxial stress states to be important and explained facet crack locations observed in disc spin tests. The resulting paper [R2] was awarded the Rolls-Royce UTC top publication prize in 2017. This and subsequent research established a predictive modelling capability for dwell, recently reported in Nature [R3], which explained the very different dwell fatigue observations in (isothermal) disc spin tests compared to in-service (anisothermal) disc performance. This research was underpinned by EPSRC programme grant 'HexMat' [R4] for which Dunne was PI, and the research recognised by the award of the IoM^3's Harvey Flower Prize (2016) for 'outstanding contributions towards the science and technology of titanium' [R5].

2. **Stress corrosion cracking [R5-R7; I3]:** research in titanium led by Dye (2014 to 2019) provided understanding of low-life spin test (GBP300,000/test) results in aero-engine discs for the TP400 engine programme. The research established mechanistic understanding of the chemo-mechanical events leading to corrosion degradation giving rise to the material defect characterised as 'blue spot' at the crack initiation site. The observations in aero-engine components were replicated by specimen testing, which facilitated the mechanistic investigations. It was found using FIB-SIMS that a region of enhanced Na and Cl developed adjacent to the crack initiation point, at levels that had previously been undetectable by SEM-EDX [R6]. In TEM, different dislocation structures were also observed [R7]. Confirmatory work by STEM-EDX on the fracture surface also helped determine the reaction sequence and rationalise why these failures are observed in elevated temperature, low pressure testing but not at compressor pressure in operating

jet engines. Further work to examine the effects of hydrogen during the corrosion reactions was difficult but has proved very important, and the amount of testing retired as a consequence of this programme of work was in excess of GBP40,000,000 in 2014 alone. The research in [R7] was recognised by the TMS Science Award 2018 'for notable contributions to scientific understanding' [R8].

3. **Engine vibration [R8, R9; I4, I5]:** research by Vahdati (2009-19) in aeroelasticity has improved accuracy of computational fluid dynamics models for gas turbines. Understanding of flutter and rotating stall [R9] was achieved and extreme events such as bird strike and engine 'blade-off' conditions have been addressed. Vahdati designed and implemented more efficient solvers which reduce computational time and allow investigation of a wider range of parameters. Schwingshackl (2008-2019) investigated phenomena associated with non-linear engine vibrations, understanding the behaviour of under-platform dampers, which control the vibration amplitude in turbines [R10]. This was achieved with a novel high order nonlinear dynamic modelling approach and new experimental methods giving improved understanding of the behaviour of frictional interfaces under oscillatory loading.

3. References to the research

[R1 Zheng, Z, Balint, DS, **Dunne, FPE**. Mechanistic basis of temperature-dependent dwell fatigue in titanium alloys. Jnl. Mech. Phys. Solids. 107, 185–2, 2017.

[R2 Cuddihy, MA, Stapleton, A, Williams, S, **Dunne, FPE**. On cold dwell facet fatigue in titanium aero-engine components. Intl. Jnl. Fatigue. 97, 177–189, 2017.

[R3 Xu, Y, …, **Dunne, FPE**, **Dye, D**. Nature Communications, 11, 5868, 2020. https://doi.org/10.1038/s41467-020-19470-w.

[R4 IoM[3] https://www.iom3.org/award/harvey-flower-titanium-prize-retrospective.html.

[R5 Chapman, TP, Chater, RJ, Saunders, EA, Walker, ARM, Lindley, TC, **Dye, D**. Environmentally assisted fatigue crack nucleation in Ti-6Al-2Sn-4Zr-6Mo. Corros. Sci. 96, 87-101, 2015.

[R6 Chapman,TP, Vorontsov,VA,, Sankaran,A, Rugg,D, Lindley,TC, **Dye,D**. The dislocation mechanism of stress corrosion embrittlement in Ti6246. Met. Trans. A, 47, 282-292, 2016.

[R7] TMS EDP Award 2018 https://doi.org/10.1007/s11837-017-2720-0.

[R8] **Vahdati M**, Sayma AI, Imregun M. A integrated nonlinear approach for turbomachinery forced response prediction. Part II: case studies. Jnl. Fluids and Structures, 14, 103-125, 2000.

[R9] Pesaresi L, Salles L, Elliott R, Jones A, Green JS, and **Schwingshackl CW**, Modelling the nonlinear behaviour of an underplatform damper test rig for turbine applications. Mech. Systems and Signal Proc., 85, 662-679, 2017.

4. Details of the impact

Imperial College's Materials and Mechanical Engineering Departments have long been associated with the understanding, and the performance, of safety-critical aero-engine materials. As a consequence, we have had very close collaborations with Rolls-Royce (the Rolls-Royce Vibration and Nuclear UTCs; the RR Strategic Partnership) over decades facilitating research and technology transfer to Rolls-Royce directly. International impact and uptake results through membership of Federal Aviation Administration (FAA) partnerships with international industries including Pratt & Whitney, GE, TIMET, IHI and USAF. In addition, Rolls-Royce have recruited many of our graduating PhD students and two Royal Society Industry Fellowships, each over four years, have facilitated intimate, long-term collaborations (Dye from

Imperial to Rolls-Royce (2018 to 2022); Maclachlan from Rolls-Royce to Imperial (2018 to 2022); Dunne RAEng/Rolls-Royce research chair, 2015 to 2020 [Current and recent awards - Royal Academy of Engineering (raeng.org.uk)]). The five major impacts (**I1 to I5**) resulting, their links to the underpinning research, and the evidence to support them, are detailed in the following within three areas of aero-engine performance where national and international uptake have been achieved: A) eliminating **cold dwell fatigue**, B) assuring against **blue spot corrosion**, and C) optimising **engine vibration**.

A. Cold Dwell Fatigue Failures

Dwell fatigue is an aero-engine failure process associated with holds at load (e.g. during aircraft take off and cruise) in titanium fan and compressor discs. In a series of EPSRC-supported studentships and grants (EP/K034332), the Imperial team has developed world-leading understanding [R1, R2, R3] and then resolution of this safety issue, which is worth many millions of British Pounds to Rolls-Royce [E2, E3]. This impact arises in improved understanding of dwell providing **(I1) the safe envelope of conditions where dwell fatigue can be avoided**, **with consequent retirement of very high-cost spin testing programmes (GBP800,000/test), and the relaxation of the inspection regime (additional overhauls).** Rolls-Royce states:

> *"the reduced time taken for the tests means … the difference between actually being able to certify and use a new alloy, or not. The cost of a stand-alone alloy certification programme would be in the range £500M to £1B, and as a result, prohibitive"* [E2].

The underpinning research to allow this quantified safe stress limits in discs [R2], and explained the link between isothermal spin tests and in-service (anisothermal) behaviour [R1] through establishment of predictive modelling tools [R2, R3]. The research in dwell [R1, R2, R3] also facilitated **(I2) the close-out of several 'red-tops' (urgent safety priority investigations), with the impact of saving many millions of GBP**, **eliminating further disc testing programmes.** Rolls-Royce states:

> "*the research has provided sufficient mechanistic understanding to determine that we did not have to take draconian fleet management of … a recent major safety concern related to dwell fatigue behaviour in complex thermomechanical load regimes experienced in the engines. An overly conservative approach to cold dwell threatens the company on commercial grounds (multiple £100M) through engine removals and disc replacement, a non-conservative approach could result in significant loss of life*" [E2].

The industrial impact is also evidenced by the Sir Henry Royce Award 2017 [E4] for Technical Innovation by Rolls-Royce for our work on dwell fatigue [R2]. Dunne and Dye are the only UK dwell experts to be invited to join the USA's FAA dwell fatigue partnership of aero-engine manufacturers Pratt & Whitney, GE, Honeywell, Rolls-Royce, and IHI, influencing the management of aero-engine dwell fatigue internationally [E3, E5].

B. Blue Spot Corrosion

In the testing campaign supporting the qualification of the TP400 jet engine for the A300M transport aircraft, some low-life failures occurred associated with a characteristic corrosion defect (termed 'blue spot') on the fracture surface. This raised concerns about this alloy and its use across a much broader jet engine fleet in service. An EPSRC-supported CASE PhD studentship on this topic resulted in the determination that this feature was associated with NaCl hot salt stress corrosion cracking; the mechanistic understanding generated [R5, R6] allowed this safety concern to be resolved, with the impact **(I3) of saving over GBP40,000,000 in retired testing on the TP400 programme in 2014** alone, and much more across Rolls-Royce as a whole including the lifting of potential flight envelope restrictions. Rolls-Royce state "*reducing the cyclic life of Ti6246 alloy discs by ~25% would have cost us in excess of £500M*" [E2]). The industrial impact is evidenced by the **Rolls-Royce Engineering Excellence Award 2014 [E6] for our work on Blue Spot Corrosion [R5, R6].**

C. Engine Vibration

Research has been pivotal in developing understanding of key aspects of the cause of vibration issues with the Trent 1000 engine, relying on our unique capability to accurately simulate blade forced response [R8]. This understanding identified design changes which **(I4) eliminated blade root cracking and thus lifted the grounding of the Trent 1000 fleet, and delivered the AU3D code to eliminate high vibration levels on a development engine (Br700NG) through unique virtual engine testing** at Imperial, allowing certification to be achieved on time. Rolls-Royce states: "*during 2018, I was deployed to lead part of the Trent 1000 problem investigation team and we relied heavily on work done at Imperial College to (i) reach an understanding of the root cause, (ii) map out the main risk factors (iii) redesign the components and (iv) support certification of the redesigned parts. The cost of this issue with Trent 1000 has been reported in the Rolls-Royce Annual Report (February 2020) to be $2.4 billion*" [E7]. The underpinning research carried out led to very substantial financial savings. The research also contributed to subsequent engine development and provided design improvements which go significantly beyond that which would have been available through testing alone [E7]. Our work on non-linear vibration has included explicit modelling of under-platform dampers (UPDs) [R9] resulting in a fully validated approach to reliably capture damping performance due to frictional slip at the damper/platform interfaces. This delivered **(I5) the development of a flutter free design system which has been embodied within the UltraFanR engine**, **and which formed a key input to the new Rolls-Royce MMM (design method) for UPDs having direct impact on the design of next generation turbine blades in this engine,** resulting in significant cost saving and significant competitive advantage [E7]. Safer and more reliable operation has enabled Rolls-Royce to obtain increased performance for the new turbine core design in the UltraFan®. Rolls-Royce said "*the Rolls-Royce UltraFan® is an exciting technological leap. The knowhow and tools developed by the Imperial team has allowed the vibration threats to be understood from the outset, particularly flutter. This allows the fan system to be optimised without adding conservatism for unknown vibration risks, freeing the design space to deliver a reduction in CO2, NOx*" [E7].

5. Sources to corroborate the impact

[E1] FAA Report EASA_AD_US-2019-18-08_1: https://www.bea.aero/uploads/tx_elydbrapports/BEA2017-0568.en.pdf PDF archived here.

[E2] Letter from (formerly) Senior Fellow and Engineering Specialist, Rolls-Royce, Derby, UK.

[E3] Letter from Senior Materials Engineer, US Air Force, Dayton, Ohio, USA.

[E4] Sir Henry Royce Awards 2017 for Technical Innovation in Dwell Fatigue.

[E5] Letter from, Senior Fellow Discipline Lead, Pratt and Whitney, USA.

[E6] Rolls-Royce Engineering Excellence Award for Blue Spot Corrosion 2014.

[E7] Letter from Fellow, Rolls-Royce, Derby, UK.