Institution: University of Oxford

Unit of Assessment: 10: Mathematical Sciences

Title of case study: Rolls-Royce HYDRA CFD code for gas turbine engine design

Period when the underpinning research was undertaken: 2000-2016

Details of staff conducting the underpinning research from the submitting unit:

Name(s):	Role(s) (e.g. job title):	Period(s) employed by submitting HEI:
Mike Giles	Reader / Professor	1992 - present
Jens-Dominik Muller	PDRA	1997 - 2002
Mihai Duta	PDRA	2002 - 2005
Gihan Mudalige	PDRA	2010 - 2016
Istvan Reguly	PDRA	2014 - 2015

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

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

1. Summary of the impact

During the entire REF2021 period, the HYDRA computational fluid dynamics (CFD) code has been Rolls-Royce's primary tool for the aerodynamic analysis and design of gas turbine engines powering a wide range of civil aircraft, as well as engines for military and power generation applications. As a notable example, HYDRA has helped Rolls-Royce to improve the efficiency of its Trent high-bypass civil aircraft engine by 15%, which has provided estimated fuel savings of USD2,900,000 per year per aircraft. HYDRA forms part of the set of computational engineering tools which significantly contribute to Rolls-Royce's commercial success with annual revenue of over GBP15,000,000,000, and around 50,000 employees worldwide.

HYDRA was initially developed by Professor Mike Giles and his research team at the University of Oxford between 1998 and 2006. Furthermore, from 2009 to 2016, Giles and his team developed new parallelisation software to enable HYDRA to exploit the latest many-core High Performance Computing platforms.

2. Underpinning research

Professor Mike Giles established the Rolls-Royce University Technology Centre in Computational Fluid Dynamics to develop and analyse mathematical and computational techniques for use in the analysis and design of turbomachinery for use by Rolls-Royce. The development of HYDRA, a programme of work at the University of Oxford which started in 1998 but was primarily carried out in the period 2000-2006, was led by Giles and was mainly funded by Rolls-Royce with additional support from EPSRC.

Between 2000 and 2003, Giles and his team developed new adjoint techniques [1,2] to improve the efficiency of design optimisation sensitivity calculations. While other research groups were also working on the subject, the research by Giles' group pioneered many of the developments in the area including, during 2004-2008, the use of Automatic Differentiation software to construct the discrete adjoint equations [3].

Another key research accomplishment was the development, in 2003 and 2004, of an efficient multi-grid solver to compute the linearised equations representing unsteady flow oscillations [4]. The modelling of these is very important to avoid the possibility of an undesirable blade flutter condition, and to minimise the degree of forced response vibration of blades due to the rotation of rotor blades close to stationary components. The computational challenge addressed in [4] was the stabilization of the numerical simulation, suppressing a numerical instability which was related to the natural instability of flow around a blunt trailing edge.

These advances were combined by Giles' team into a CFD package called HYDRA which uses complex unstructured grids composed of a mix of different element types to give (i) maximum geometric flexibility to handle complex turbomachinery geometries, (ii) an efficient multigrid solver for both steady and unsteady flow calculations, (iii) the ability to analyse linearised harmonic unsteady flow perturbations for both forced response and flutter analysis; and (iv) an "adjoint" design capability to efficiently compute the sensitivity of output quantities, such as engine efficiency, to changes in any one of possibly hundreds of design variables.

High performance computing (HPC) on the latest generation of supercomputers and compute clusters is a key requirement for CFD packages such as HYDRA. The original version of HYDRA used a parallelisation framework called OPlus which Giles and his team had developed between 1994 and 1997. However, this was based on execution on the single-core scalar CPUs which were in use then, not modern multicore CPUs. Between 2009 and 2016, largely with EPSRC funding, Giles and two new PDRAs developed a new parallelisation framework OP2 [5, 6], to enable HYDRA to exploit these new multicore CPUs and also GPUs. Building on mathematical insights into the computations required, and using an embedded domain-specific language approach common in computer science, this was achieved through mathematical abstraction by separating out the specification of what is to be computed from how it is to be computed.

3. References to the research

[1] M.B. Giles, N.A. Pierce. ‘An introduction to the adjoint approach to design’, *Flow, Turbulence and Combustion*, 65(3-4):393-415, (2000). DOI: 10.1023/A:1011430410075

[2] M.B. Giles, M.C. Duta, J.-D. Muller, N.A. Pierce. ‘Algorithm developments for discrete adjoint methods’, *AIAA Journal*, 41(2):198-205, (2003). DOI: 10.2514/2.1961

[3] M.B. Giles, D. Ghate, M.C. Duta. ‘Using automatic differentiation for adjoint CFD code development’, *Computational Fluid Dynamics Journal*, 16(4):434-443, (2008). (Available on request).

[4] M.S. Campobasso, M.B. Giles. ‘Stabilization of a linear flow solver for turbomachinery aeroelasticity by means of the recursive projection method’, *AIAA Journal*, 42(9) 1765-1774, (2004). DOI: 10.2514/1.1225

[5] G.A. Mudalige, M.B. Giles, I.Z. Reguly, C. Bertolli, P.H.J. Kelly. ‘OP2: An active library framework for solving unstructured mesh-based applications on multi-core and many-core architectures’, in *2012 Innovative Parallel Computing (InPar), IEEE*, 1-12, (2012). DOI: 10.1109/InPar.2012.6339594

[6] I.Z. Reguly, G.R. Mudalige, C. Bertolli, M.B. Giles, A. Betts, P.H.J. Kelly, D. Radford. ‘Acceleration of a full-scale industrial CFD application with OP2’, *IEEE Transactions on Parallel and Distributed Systems,* 27(5):1265-1278, (2016). DOI: 10.1109/TPDS.2015.2453972

Research funding:
Multi-layered abstractions for PDEs, EPSRC Research Grant EP/I006079/1, GBP237,881, 2010 – 2014. PI Mike Giles

4. Details of the impact

The impact is primarily economic, with HYDRA being part of the technology which significantly contributes to the success of Rolls-Royce, one of the UK’s premier engineering companies and a world leader in gas turbine engines for aircraft and naval propulsion, as well as for power generation. According to its 2019 Annual Report [A], published in March 2020, Rolls-Royce Holdings plc (the official name of the company) achieved annual revenue of over GBP15,000,000,000 with approximately 51% coming from Civil Aerospace, 22% from Power Systems, 20% from Defence, and 7% from other sources [A, page 2]. Rolls-Royce employs around 50,000 people in 50 countries [B], with approximately 24,000 of those being in the UK [B], and the company estimates that they contribute GBP12,000,000,000 annually to the UK economy and support over 135,000 jobs [B]. As well as contributing to these economic benefits, HYDRA has contributed to very substantial benefits to the environment and to airlines due to the fuel savings achieved.

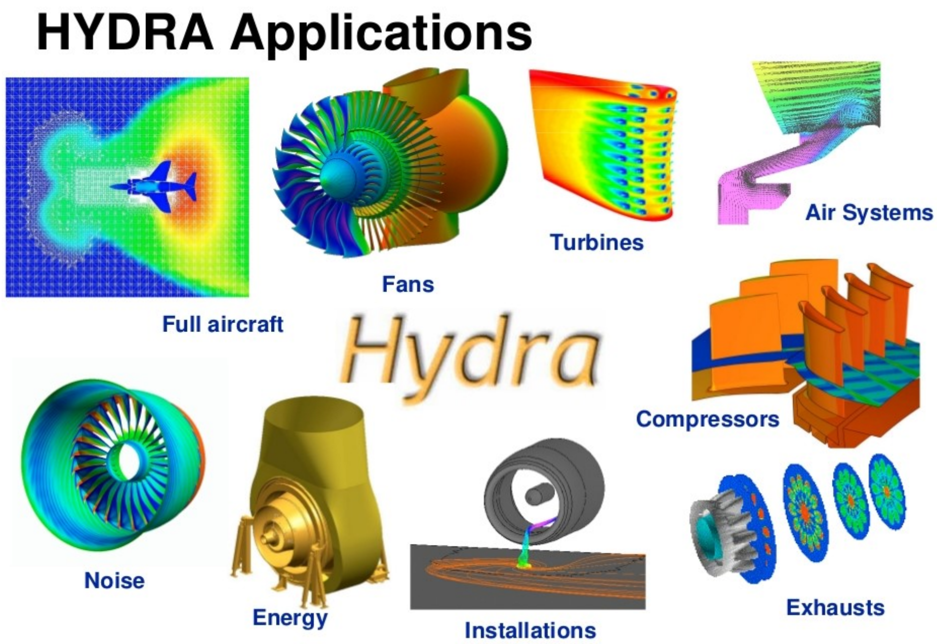
In addition to other key software tools for combustion analysis, structural analysis and heat transfer, the ability to simulate the flow of air through the engines is an important part of Rolls-Royce's design capability, as engines are now designed almost exclusively through computer simulation, with experimental testing carried out afterwards to verify the performance of the final design.

Pathway to impact:

The initial development of HYDRA was carried out in Oxford up to 2002. The initial code was then transferred to Rolls-Royce, and, over the following years, was further developed internally by Rolls-Royce and, until 2006, by Giles' group in Oxford. It was also used by university research groups at Cambridge, Loughborough, Southampton, Surrey and Sussex who were also funded by Rolls-Royce, with these groups adding additional features in some cases, such as for the flow through internal cooling passages. This history is partially documented in paper [C], written in 2004 by the Rolls-Royce engineer leading the further development of HYDRA within the company, which states: *"HYDRA-CFD is a unique suite of steady, unsteady, harmonic and adjoint solvers for turbulent CFD, built on a common input, output, multi-grid acceleration, parallelization and visualization core."*

HYDRA was gradually introduced into service within Rolls-Royce from 2008, becoming the primary corporate CFD code in 2012. Rolls-Royce's Chief Design Systems Architect [D] states: *"I can confirm that HYDRA has been the company's primary aerodynamic CFD code for the whole REF period 2014-2020. It has been used extensively in the design of all recent engines; and, today, is run over 1,000,000 times per year."*

The many uses of HYDRA within Rolls-Royce are illustrated in this diagram which is used with permission from Rolls-Royce.



Nature and extent of impact:

The greatest impact within Rolls-Royce has been in the design of its gas turbine engines for major civil aircraft manufactured by both Airbus and Boeing. At the beginning of the REF impact period in August 2013, there were two main civil aerospace engines [E] which had been designed using HYDRA, the Trent 1000 for the Boeing 787 and the Trent XWB for the Airbus A350. As mentioned above, all further development has also used HYDRA, with new variants of the Trent 1000 being certified in 2015 and 2016 [F], and a new variant of the Trent XWB certified in 2017 [F].

The Rolls-Royce Chief Design Systems Architect's letter [D] states: *"HYDRA contributed directly to the technology developed for the Trent XWB, the world's most efficient aero engine which delivered a 15% improvement in fuel consumption relative to the original Trent engine and provides USD2,900,000 savings per year per aircraft in fuel alone. HYDRA specifically contributed to the aerodynamic design of the fan, compressor and turbine – the fan design delivered world-beating levels of performance and the turbine has the highest efficiency of any Trent engine."*

In July 2020, Rolls-Royce data on the Trent XWB [E] shows that over 1,600 engines have been purchased or are on order, powering more than 800 Airbus A350 aircraft. This corresponds to total airline fuel savings of more than USD2,300,000,000 per year. In addition, the 15% improvement in fuel consumption provides huge environmental benefits in reduced CO_2 emissions. The global aviation industry produces 2-3% of global CO_2 emissions and IATA has targeted a 1.5% improvement in fuel efficiency per year over 2009-2020 [G].

An entirely new engine, the Trent 7000 [E], has also been designed using HYDRA. The Trent 7000 powers the Airbus A330neo and replaces the Trent 700 used on earlier A330 models; as of 31 December 2020, 57 Trent 7000-powered A330neos have been delivered, and 331 are on order [F].

HYDRA has also been used to develop other Rolls-Royce products, such as ground power installations for electricity generation, and the Pearl 700 engine for the Gulfstream G700 business jet. In reference to this engine, the Chief Design Systems Architect's letter [D] also says: *"HYDRA is a global system used by engineers in the UK, US, Germany and India, and has therefore been used on a wide range of engines including, for example, our recently* [November 2019] *unveiled Pearl 700 engine for the Gulfstream G700 ultra-long-range business jet. This engine has 3.5% less fuel burn and 5% greater efficiency than the previous BR725 engine for the G650."*

Impact of parallel computing implementation:

The Rolls-Royce website [E] describes the design process for the Trent XWB as: *"The most intense/comprehensive development programme ever undertaken by Rolls-Royce. Six times the computing power applied than the previous generation."*

The emphasis on the computing power is significant because of the huge computational resources required for large-scale simulations. In reference to this, and the more recent HYDRA research on improving its parallel performance on modern computing architectures, the Chief Design Systems Architect's letter [D] states: *"Simulation and modelling, enabled by High Performance Computing (HPC), have transformed the way our products are designed and engineered and will continue to do so. In 2018, we invested* [text removed for publication] *in an HPC upgrade based on the strategic importance of simulation and modelling to the company. HYDRA continues to have world class parallel performance which is a testament to your vision in designing the code."*

Conclusion

HYDRA is a key part of the suite of computational engineering tools which has been used by Rolls-Royce to design its gas turbine engines, helping Rolls-Royce to maintain its position as one of the UK's premier engineering companies, and has provided downstream additional benefits to airlines and the environment due to improved fuel efficiency.

5. Sources to corroborate the impact

[A] Rolls-Royce Annual Report 2019 (March 2020) https://www.rolls-royce.com/~/media/Files/R/Rolls-Royce/documents/annual-report/2019/2019-full-annual-report.pdf

[B] Rolls-Royce corporate website pages with details of its employment and contributions to the UK economy:
https://careers.rolls-royce.com/united-kingdom
https://careers.rolls-royce.com/our-locations/uk

[C] Rolls-Royce conference paper: "HYDRA-CFD: A Framework for Collaborative CFD Development", Leigh Lapworth, International Conference on Scientific & Engineering Computation, 2004.

[D] Letter from Rolls-Royce Chief Design Systems Architect, and Head of University Relations (2020)

[E] Rolls-Royce corporate website pages with details of the design and performance of the Trent 1000, XWB and 7000 engines
https://www.rolls-royce.com/products-and-services/civil-aerospace/airlines/trent-1000
https://www.rolls-royce.com/products-and-services/civil-aerospace/airlines/trent-xwb
https://www.rolls-royce.com/products-and-services/civil-aerospace/airlines/trent-7000

[F] Wikipedia pages on Rolls-Royce engines and Airbus A330neos ordered or delivered (p.25-26 gives numbers for deliveries and orders of A330neos; p.28 confirms use of Trent 7000 in the A330neo):
https://en.wikipedia.org/wiki/Rolls-Royce_Trent_1000
https://en.wikipedia.org/wiki/Rolls-Royce_Trent_XWB
https://en.wikipedia.org/wiki/Airbus_A330neo

[G] IATA website information on aviation and climate change, stating the fuel efficiency target:
https://www.iata.org/en/programs/environment/climate-change/