Institution: University of Oxford

Unit of Assessment: 10 - Mathematical Sciences

Title of case study: Computational fluid dynamics: the Rolls-Royce HYDRA code for jet engine design

1. Summary of the impact

Rolls-Royce uses the HYDRA computational fluid dynamics (CFD) code for the design of all of its new gas turbine engines. The HYDRA CFD package, including the mathematical theory behind it, was developed by Professor Mike Giles and his research team in the period 1998-2004 at the University of Oxford, and subsequently transferred to Rolls-Royce, forming the basis of the RR corporate CFD strategy with an investment of over 100 person years in development.

Since 2009, HYDRA has become the standard aerodynamic design tool across Rolls-Royce, and has been used to design Rolls-Royce's Trent 1000 engine and the newer Trent XWB. HYDRA has enabled Rolls-Royce to save over **[text removed for publication]** in test rig expenses, provides superior accuracy compared to its competitors such as FLUENT, and has contributed to increases in engine efficiency of up to **[text removed for publication],** which in turn has led to higher sales and increased revenue for Rolls-Royce.

2. Underpinning research

In 1993, Professor Mike Giles of the University of Oxford established the Rolls-Royce University Technology Centre (UTC) in Computational Fluid Dynamics. Part of the Numerical Analysis Group, it was created to investigate and develop mathematical and computational techniques for use in the analysis and design of turbo-machinery.

The development of HYDRA, a programme of work at the University of Oxford running from 1998 to 2004, was led by Professor Mike Giles and was sponsored by Rolls Royce with supporting funding from EPSRC. Based on identified Rolls Royce requirements, Giles set four key goals for his team: that they should use efficient multi-grid iterative solvers on complex unstructured grids to model problems with complex engine geometries; that they should enable the efficient computation of linear and nonlinear unsteadiness due to blade flutter and forced response; that they should use adjoint design techniques to improve the speed of design optimisation; and that the whole computation should execute very efficiently on distributed-memory parallel clusters.

Turbomachinery flows have hydrodynamic shocks which can be modelled mathematically as discontinuities in the flow properties. In prior work, Giles was the first to show that linear perturbation methods could be used to analyse the effect of shock oscillations in inviscid flows. This was an important background result for the development of HYDRA at the University of Oxford, but new research was required to develop efficient multi-grid solvers for linear unsteady viscous flows [3].

Giles and his team also developed new adjoint techniques [2,4] to improve the efficiency of optimisation calculations. The team moved away from existing adjoint techniques, instead developing their own so-called “discrete" approach in which the nonlinear discretisation is linearised and then the transposed matrix defines the discrete adjoint equations. While other research groups were also working on the subject, HYDRA research pioneered many of the developments in the area, including the use of Automatic Differentiation software to construct discrete adjoint equations.

Taken as a whole, these advances were combined by Giles' team into a complete CFD package called HYDRA which offered:

- use of complex unstructured grids composed of a mix of different element types, to give maximum geometric flexibility to handle complex turbomachinery geometries, including tip gaps, disk cavities, cooling slots, and internal cooling passages;

- an efficient multigrid solver for time-averaged steady flow calculation, and for solving the implicit nonlinear system of equations which comes from approximating nonlinear unsteady flow calculations;
- the ability to analyse linearised harmonic unsteady flow perturbations for both forced response and flutter analysis;
- 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.

The parallelisation aspects were handled by building on preparatory research undertaken between 1993 and 1998. This made it possible to hide the parallelism, from both the HYDRA CFD users and crucially the HYDRA developers in Oxford, allowing them to concentrate their efforts on developing new features within HYDRA [1]. This was a forerunner of modern high-level abstraction techniques which are an active research topic today in computer science addressing the challenges of many-core computing.

Key researchers from the University of Oxford:
Mike Giles: Reader (1992-1997), Professor (1997-present); Paul Crumpton: PDRA (1993-1997); Niles Pierce: PDRA (1997-1998); Mihai Duta: PDRA (2002-2005); Jens Muller: PDRA (1997-2002)

3. References to the research

[1] P.I. Crumpton and M.B. Giles. ‘Multigrid aircraft computations using the OPlus parallel library'. pp.339-346 in Parallel Computational Fluid Dynamics: Implementations and Results Using Parallel Computers, A. Ecer, J. Periaux, N. Satofuka, and S. Taylor, editors, North-Holland, 1996. DOI: 10.1.1.48.9819.

Key paper on OPlus parallel framework on which HYDRA is built.

* [2] M.B. Giles, M.C. Duta, J.-D. Muller and N.A. Pierce. ‘Algorithm developments for discrete adjoint methods'. AIAA Journal, 41(2):198-205, 2003. DOI: 10.1.1.10.262.

Key paper, in international journal, on adjoint algorithms in HYDRA;59 Citations (Web of Science), 108 citations (Google Scholar).

* [3] M.S. Campobasso and 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: 10.1007/978-3-540-74460-3_24.

Key paper, in international journal, on linearisation problem; 13 citations (Web of Science), *23 citations (Google Scholar).*

* [4] M.B. Giles and NA Pierce. ‘An introduction to the adjoint approach to design', Flow, Turbulence and Combustion, 65(3-4):393-415, 2000. DOI: 10.1.1.135.6053.

Overview paper in international journal; 130 citations (Web of Science), 280 citations (Google Scholar).

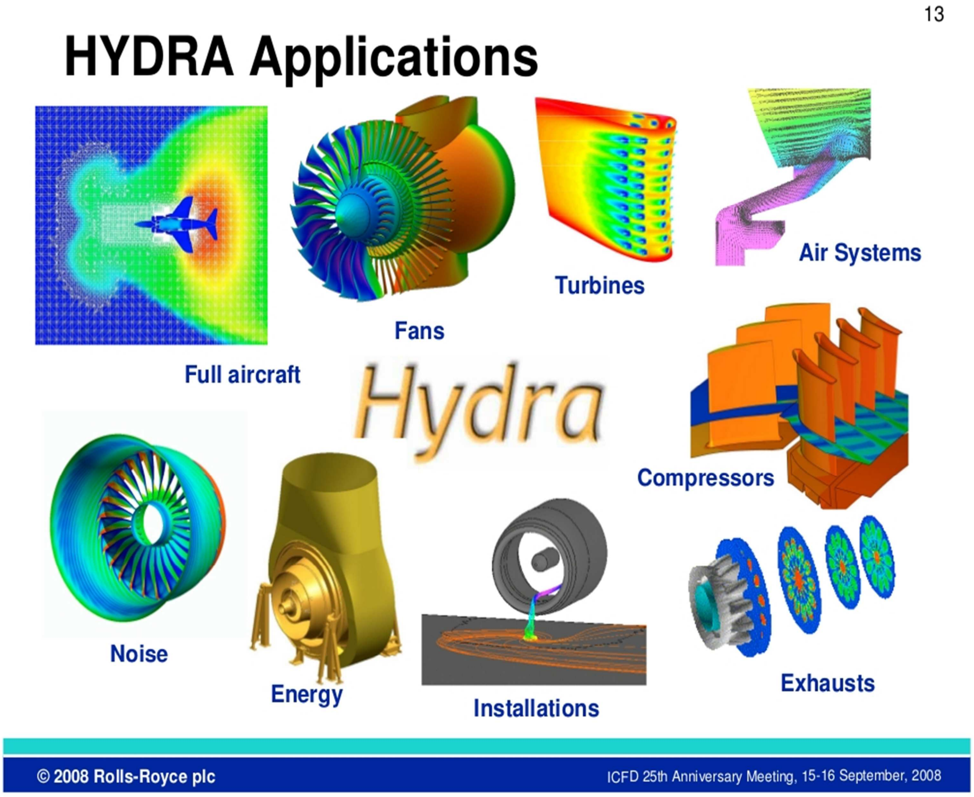
The three asterisked outputs best indicate the quality of the underpinning research. All these papers report research performed exclusively at the University of Oxford.

4. Details of the impact

The impact is economic: enhanced design capabilities based on the research have resulted in a superior product and substantial time and cost savings. The beneficiary is Rolls-Royce, a world leader in the design and manufacture of gas turbine engines for aircraft, ships, power generation and other applications. Rolls-Royce has been hailed as a star of the manufacturing sector by the UK Government, bucking the trend of many of its peers by achieving a total revenue of over £12.2 bn and record profits of £1.4 bn in 2012 [A], with 85% of its sales abroad [B] bringing valuable income to the country, as well as providing employment for almost 20,000 in the UK alone [C].

From research to impact. Rolls-Royce uses CFD codes to simulate the flow of fluids in and around all products, including the flow of air through all components of diesel or gas turbine engines and their installations [D]. In 2004, Rolls-Royce received from Oxford the first production version of the HYDRA CFD code for testing. In 2006 it was established as the company's compressor design tool, and by 2009 it had become the design tool for multiple businesses across Rolls-Royce – including gas turbines, air and thermal systems, and power generation [E]. It is one of the few codes that the company uses for CFD [D].

The many uses of HYDRA within Rolls Royce are illustrated in this diagram, taken from [F] and used with permission.



The ability to simulate the flow of air through the engines is crucial to 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. Rolls-Royce uses HYDRA in various ways: to assess the aerodynamic efficiency of a design; to assess the unsteady aerodynamic forces acting on blades due to the passing of neighbouring blade rows; to assess the possibility of self-induced vibrations; and to quantify the heat transfer from the very hot gases coming out of the combustor into the high pressure turbine blades [F].

HYDRA offers Rolls-Royce unprecedented accuracy because of its ability to deal with shocks, and the company reports that it is now able to rank designs to better than 1% efficiency, consistently more impressive than rival packages such as FLUENT. As an example, it reports that calculated loss coefficients for industrial exhaust systems now differ from measured values by just 0.02%, compared to 0.16% when calculated using FLUENT [E].

Nature and extent of the impact. Of the many impacts of HYDRA to Rolls-Royce, the greatest has been on the design of its gas turbine engines for aircraft. The ‘soaring demand for more fuel-efficient engines for planes’ [G] helped the civil aerospace arm of the company deliver a 16% increase in annual revenue to over £6.4 billion in 2012 [A, G] and with Trent engines, which are designed using HYDRA, making up around 75% of all orders [A]. Furthermore, 'Rolls-Royce's order book rose 4% to £60.1bn thanks to strong demand for its Trent aircraft engines' [B].

HYDRA has given Rolls-Royce a single tool for aerodynamic, aero-acoustic and aero-elastic applications. Its novel multi-grid solvers allows the company to efficiently analyse complex engine shapes which were previously difficult to assess. Furthermore, the parallelisation of the software has cut analysis time, and Rolls-Royce attributes the decrease in design time for an intermediate turbine test rig, from **[text removed for publication]**, to the use of HYDRA's adjoint CFD code [E]. In total, the code has helped save Rolls-Royce at least **[text removed for publication]**, in test rig expenses [E]. Rolls-Royce technological development webpage openly credits HYDRA as one of the key pieces of technology that make up The Rolls-Royce Engineering System [D]; for example, "HYDRA has been used extensively in the design of recent RR products such as the Trent 1000."

The code was used to design Rolls-Royce's Trent 1000 series of engines, which power Boeing 787 aeroplanes. By way of illustration of the benefits of improved accuracy and design capability, improvements to the latest iteration of the Trent 1000, unveiled in 2012, over its predecessors include: **[text removed for publication]** more efficient intermediate pressure compressor; **[text removed for publication]** more efficient intermediate pressure turbine; shortened Boeing flight testbed schedule thanks to design being ahead of time; and a fan assessed as having "world class performance" in a Boeing Audit [E]. The Trent 1000 is also the quietest mode of powering the 787 — some 6 dB quieter than its competitors [C].

The newer Trent XWB, announced in 2007 and then first flown in 2012, powers the new Airbus A350 XWB and was also designed using HYDRA. As of May 2012, it was Rolls-Royce's fastest-selling engine to date, having achieved 1,100 orders from 34 customers worldwide [C]. Once again, HYDRA contributed to the improvement of its design, with its high pressure compressor seeing an improvement in efficiency of **[text removed for publication]**, and its intermediate pressure compressor seeing a **[text removed for publication]** improvement, both over the Trent 1000. All told, the Trent XWB is **[text removed for publication]** more efficient than the first generation Trent engines of 1995, making it the most efficient Trent engine to date.

5. Sources to corroborate the impact

[A] http://www.rolls-royce.com/investors/financial_reporting/financial_results/index.jsp

[B] http://www.guardian.co.uk/business/2011/nov/11/rolls-royce-engine-recovery-economy

[C] http://www.rolls-royce.com/Images/RR_full_AR_2011_tcm92-34435.pdf

[D] http://www.rolls-royce.com/about/technology/systems_tech/design_systems_tools.jsp

[E] A Brief History of HYDRA, Rolls-Royce internal presentation, supplied by Chief Design Systems Architect at Rolls-Royce (who can be contacted), showing the significance of the impact of Hydra at Rolls-Royce. Copy held by Oxford University.

[F] Rolls-Royce presentation at ICFD meeting, reading University, 2008, www.icfd.rdg.ac.uk/ICFD25/Talks/LLapworth.pdf

[G] http://uk.reuters.com/article/2013/02/14/uk-rolls-royce-idUKBRE91D0B720130214?feedType=RSS&feedName=businessNews

[C]-[F] give data about Hydra and its use at Rolls-Royce. [A], [B] & [G] give evidence of the economic success of Rolls-Royce engines designed using Hydra.