Institution: University of Sheffield

Unit of Assessment: 12A - Aeronautical, Mechanical, Chemical and Manufacturing Engineering: **Mechanical Engineering and Advanced Manufacturing**

Title of case study: New computational aerodynamics design tools for the aerospace industry.

1. Summary of the impact

Research from the Sheffield Department of Mechanical Engineering has led to major improvements in engineering analysis and design software for aerospace companies such as Rolls-Royce and Airbus. As a result of introducing new practices based on our research, the organisations have reported significantly reduced time input to design components as well as related economic benefits. For example: Rolls-Royce has reported an order of magnitude improvement in the time needed to mesh components. Similarly, by adopting our highly efficient computational aerodynamics solvers, Defence Science & Technology Laboratory has reduced the time its engineers spent evaluating concepts from many days to a few hours.

2. Underpinning research

The impact was underpinned by a body of research involving computational methods for the prediction of aerodynamic flow. In general, these computations require: a mesh to formulate the geometry of the physical problem, a solver to predict the flow; and an optimisation or design procedure that can interact with the computational model to achieve a desired performance. The impact was underpinned by research in all three of these areas:

(1) Meshing techniques: Delaunay mapping, buffer layer and zipper layer methods

Between 2003 and 2006, Professor Ning Qin (Sheffield since 2003) and Dr Xueqiang Liu (then a research student) developed an efficient moving mesh method [R1] funded by a Sino-British Fellowship. A moving mesh method is crucial for efficient design optimisation and for fluid structure interactions when the geometry deforms. Instead of using spring analogy based moving mesh methods, where partial differential equations are solved, the Delaunay-based method [R1] provides a fast moving mesh method using algebraic mapping for arbitrary topologies. Since aerodynamic designs, such as aircraft wings or engine compressor blades, require a large number of mesh deformations, this method can significantly shorten the engineering design process.

The method attracted strong interest from Rolls-Royce and the Sheffield team was invited to take part in the Centre for Fluid Mechanics Simulation (CFMS) (2007-2010) and Strategic Investigation in Low Emission Technology (SILOET) (2010-2012) projects funded by Rolls-Royce, in which the methodology was exploited in the industrial design software [text removed for publication].

The CFMS and SILOET projects led to two further underpinning research techniques:

- ***a)*** The buffer layer technique, developed by Qin, Carnie (postdoctoral research associate), Le Moigne (postdoctoral research associate), and Liu (research student), built on the Delaunay mapping method to use a buffer layer of mesh to link two dissimilar structured meshes through a divide-and-conquer approach.
- ***b)*** The zipper layer technique by Qin, Wang (research student), Carnie, and Shahpar (Rolls-Royce) [R2] improved further on this, by linking dissimilar quality multi-block structured meshes together without hanging nodes.

(2) Design and optimisation: 3D shock control bumps

From 2003-2008, Qin, Wong and Le Moigne invented a three-dimensional contoured shock control device through design optimisation to reduce transonic aircraft drag. This research was funded by BAE Systems. The Sheffield team demonstrated the drag reduction benefits and the robustness of the design around the design lift condition [R3, R4]. With further funding from Airbus, the mechanism of the three dimensional shock control was revealed through weakening the shock strength by replacing the shock wave with compression waves so as to reduce the entropy increase. The device was then parameterised and optimised for best performance. Substantial drag reduction at high transonic speed was achieved, typically 20-30%, in comparison with the baseline wing without shock control.

(3) Solver methods: Implicit parabolised Navier-Stokes solution (IMPNS) for supersonic/hypersonic vortical flow and adjoint based shape optimisation

Between 2003-2009, Qin, and DeFeo (PhD Student and then RA), further developed a multi-block multi-grid implicit space marching method with GMRES accelerations [R5], leading to an efficient aerodynamic analysis and design tool for a high speed slender body with or without fins. Compared with the conventional time marching approach, the IPNS approach results in significant saving in computing time and memory for fast product analysis and evaluation. Three dimensional flow fields can be solved at the Navier-Stokes level in minutes rather than hours or days for practical applications. This research led to the development of the software, IMPNS, and was funded by the Defence Science Technology Laboratory (DSTL).

During 2003-2006, Qin and Le Moigne (PhD student and then RA) developed a discrete adjoit solver for Reynolds averaged Navier-Stokes equations [R6]. This underpinned the adj-MERLIN software code, which has made an impact recently on DSTL design practice, enabling detailed shape design with many hundreds of design variables.

3. References to the research

References that best indicate the quality of the research are indicated with asterisks (***).

Meshing Techniques:

R1. **** X Liu, N Qin and H Xia, Fast dynamic grid deformation based on Delaunay graph mapping, Journal of Computational Physics, Vol.211, 2006, pp405-423,* http://dx.doi.org/10.1016/j.jcp.2005.05.025.

R2. *** Y Wang, N Qin, G Carnie, and S Shahpar, Zipper layer method for linking two dissimilar structured meshes, *Journal of Computational Physics*, Vol 255, 2013, pp 130-148, http://dx.doi.org/10.1016/j.jcp.2013.08.012.

Shock Control:

R3. *** N. Qin, W.S. Wong, A. LeMoigne, Three-dimensional contour bumps for transonic wing drag reduction, Proc. IMechE, Part G: *J. Aerospace Engineering*, 2008, 222(G5), 605-617, http://dx.doi.org/10.1243/09544100JAERO333

R4. W. S. Wong, A. Le Moigne and N. Qin Parallel Adjoint-based Optimisation of a Blended Wing Body Aircraft with Shock Control Bumps, *The Aeronautical Journal*, Vol.111, No.1117, 2007, pp165-174.

Solver methods:

R5. A. Le Moigne and N. Qin, Variable-fidelity aerodynamic optimisation for turbulent flows using a discrete adjoint formulation, AIAA J. Vol. 42, No. 7, July 2004, pp1281-1192, http://dx.doi.org/10.2514/1.2109.

4. Details of the impact

The above research has solved practical problems for the aerospace industry, by improving engineering analysis and design software. This has involved direct engagement with the industrial end-user, providing a straightforward pathway to impact. The research has reduced the time taken to design components, and improved the final product. This has had a critical impact on the design processes of major aerospace companies in the following ways:

Meshing techniques

With the significantly increased use of computational flow field simulations in the industrial design process, quality mesh generation becomes even more important for accurate solutions, however it is very time consuming for industrial designers to generate such meshes for complicated geometries. The underpinning research on Delaunay mapping method [R1], the buffer layer method and the zipper layer method [R2] addresses this problem by shortening the mesh generation time for high quality meshes and allowing the linkage of quality multi-block structured meshes for industrial problems. In 2010, these methods were implemented in the Rolls-Royce turbomachinery/gas turbine analysis and design package, PADRAM, and had a critical impact on improving the design process.

The impact is twofold: a direct impact on practitioners (design engineers) at Rolls-Royce, and a consequent economic impact on the Rolls-Royce business, in terms of time savings associated with the faster software solution. This is evidenced by the supporting statement from Rolls-Royce [S1]:

> *"The buffer and zipper layer methods have significantly simplified quality mesh generation process for complicated engine geometries. These methods are now directly incorporated in the Rolls-Royce engine design optimisation suite... As a result we use the methods extensively for design and optimisation of the turbomachinery components for the next generation Jet engines. The methods are used by our design teams based at [text removed for publication]. The methods are particularly relevant to the investigation of engine casing treatment by grooves, open rotors, and engine cooling holes. I would estimate that we spend [text removed for publication] per year modelling these issues, and that the new methods represent an order of magnitude improvement to the time needed to mesh such components"*

In addition, there is evidence that the meshing techniques have influenced the strategic approach taken by Rolls-Royce for the design of future engines [S1]:

> *"As a direct result of the zipper layer method, we have developed an innovative casing treatment design. This un-conventional and novel distributed groove design [text removed for publication] was shown to improve the stall margin at no cost to the engine efficiency. Two patents have been filed by Rolls-Royce [with Qin et. al. as inventors] to protect the meshing technology and the innovative casing treatment design. Although this novel casing design is still at a low TRL level (4-5), I expect our future engine would also benefit from this design capability."*

3D shock control bumps

Drag reduction for transport aircraft is crucial for future greener aviation. Most large transport aircraft fly at the so-called transonic speeds (high subsonic near the speed of sound). However, in this transonic region there is a key problem of drag due to shock wave formation on the wing. The 3D contoured shock control bump developed by the research group [R3] substantially reduces this drag.

This development has had a significant influence on the design programmes in the aerospace industry, in particular Airbus, as evidenced by the following supporting statement [S2]:

> *"Due to the research undertaken by the Sheffield Team, our understanding of the behavior of the shock control bumps for practical application onto our aircraft wings, in particular in their robustness for different flight conditions and for laminar wings with different transition locations, has improved significantly. Their design and critical analysis of 3D bumps has led to further Airbus internal and Airbus led EU programmes, including wind tunnel testing."*
>
> *"…the use of shock control bumps is actively being pursued in our research for future Airbus wing concepts, in particular as part of our research into Laminar Flow wing designs. Here, shock bumps have a potential role to play in helping to optimise the wing design in terms of drag reduction, robustness to the effects of surface imperfections, and 'Mach flexibility' - being able to fly the aircraft above its design cruise speed without incurring a significant drag increase and buffet onset."*

Solver methods

The implicit space marching technique for supersonic/hypersonic vertical flows (IMPNS) software [R5, R6], can drastically reduce the solution time for complicated three dimensional supersonic/hypersonic external flows. The software has been widely used by Defence Sciences Technology Laboratory (DSTL), and the IMPNS code has been released through DSTL to [text removed for publication]. This has improved the performance of the organisation by providing a significant time saving in comparison to previous solutions. This is evidenced by the following supporting statement from DSTL [S3]:

> *"One of Prof. Qin's CFD solvers, IMPNS, is regularly used in DSTL to support a wide range of MOD projects. This solver is extremely efficient, robust and accurate and represents a truly world class capability. In comparison with commercially available*

CFD software, the IMPNS solver is dedicated to supersonic and hypersonic problems of particular interest to DSTL. The use of the IMPNS solver has reduced the time DSTL scientists/engineers spend evaluating high-speed concepts by at least one order of magnitude, from many days to a few hours.”.

The unique design tool based on the adjoint method (adj-MERLIN software code) developed by Qin and LeMoigne [R6], enabled detailed design with many hundreds of shape design variables. It has led to a number of novel designs (products) by DSTL and impacted on their design practice, evidenced by the following statement [S3]:

“Prof. Qin, along with his PhD student Joe Coppin, has developed a suite of wing design and optimisation tools that are already having a significant impact in the area of [text removed for publication] design and performance. The adjoint based optimisation tool provides us with an essential capability to conduct aerodynamic design with a very large number of design variables. A number of novel designs have been developed as a result of using this advanced capability, which would have been impossible with traditional methods.”.

5. Sources to corroborate the impact

S1. Supporting statement from Rolls-Royce (on file). This can corroborate the statement quoted in Section 4 regarding the practitioner impact at Rolls-Royce.

S2. Supporting statement from Airbus (on file). This can corroborate the statement quoted in Section 4 regarding the practitioner impact at Airbus.

S3. Supporting statement from DSTL (on file). This can corroborate the statement quoted in Section 4 regarding the practitioner impact at DSTL.