Institution: Imperial College London		
Unit of Assessment: 10 – Mathematical Sciences		
Title of case study: B10-4 Design and Optimisation of Laminar Flow Wing Technology for Next Generation Aircraft.		
Period when the underpinning research was undertaken: 2010-2020		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s): Professor Anatoly Ruban Dr. Shahid Mughal Professor Xuesong Wu Professor Philip Hall	**Role(s) (e.g. job title):** AR: Professor SM: Lecturer in Applied Mathematics XW: Professor of Applied Mathematics PH: Professor of Applied Mathematics	**Period(s) employed by submitting HEI:** AR: 2009-present SM: 2014-present XW: 1993-present PH: 1996-2018
Period when the claimed impact occurred: 2014-2020		
Is this case study continued from a case study submitted in 2014? Y		

1. Summary of the impact

Successful application of Laminar Flow Control (LFC) is a strategic pillar in the aerospace industry aimed at improving fuel and noise efficiency of next generation aircraft (military, civilian and unmanned), irrespective of future propulsion systems. Imperial Mathematics research has produced state-of-the-art modelling tools for geometrical shape optimisation of laminar wings to accurately predict transition to turbulence and open the way for significant economic and environmental impacts. These tools are being used by Airbus, for example, to analyse and interpret data from their €200 million project, Breakthrough Laminar Aircraft Demonstrator in Europe (BLADE). In September 2017, BLADE flew as part of the €4 billion EU Clean Skies II initiative and showed that the laminar-flow transonic wing could reduce drag by 10% and reduce fuel burn by 5%. Imperial's software has provided Airbus with key LFC design analysis tools for their product development.

2. Underpinning research

Researchers at Imperial Mathematics developed key breakthroughs in computational flow physics models that enable harnessing LFC technologies for the design of aircraft wings. These addressed crucial uncertainties of how to model and incorporate: (1) flow receptivity; (2) surface imperfections; and (3) fully three-dimensional (3D) wing geometry variations. Engagement with Airbus engineers and access to proprietary Airbus data created internationally unrivalled LFC modelling capability.

1. Flow Receptivity: Air flow disturbances are generated through resonance mechanisms arising from free-stream fluctuations coupling to wing roughness elements within a thin (<2mm) air boundary layer. This process, known as receptivity, plays a key role in the transition from laminar to turbulent flow. LFC wings are designed to push this transition front across the wingspan, as far downstream as possible. However, the stochastic nature of the freestream environment, coupled with small disturbances arising from gaps, fasteners, surface deformations and imperfections, as well as undesirable residues of dirt, de-icing fluid or rain droplets, make it immensely difficult to incorporate all such effects in laminar wing transition predictive tools. The Imperial team made theoretical breakthroughs in receptivity theory. Specifically, Ref **[1]** included the effect of wing vibrations; Ref **[2]** incorporates the random nature of the surface roughness field and Refs. **[3,4]** extend these approaches to the transonic regime in which commercial aeroplanes fly, adapt it to the wing geometry and sweep, and make the methods computationally efficient and feasible for the industrial design process.

2. Surface Imperfections - flow destabilisation due to steps, gaps and impact damage: Critical concerns for operational and LFC robustness are micron-scaled imperfections and misalignments of surfaces arising during wing manufacture, distortions due to aerodynamic pressure loads on longer and slimmer light carbon-fibre wings, and existence of small laminar separation bubbles (LSBs). The abrupt nature of these features means that local stability analyses are invalid or of little use in accurate design. The theory developed in **[5]** circumvents these limitations by characterising the transition via a transmission coefficient of disturbance amplitude across abrupt changes in surface topography. Such analytical findings underpinned novel computational tools that are fully capable of ascertaining flow destabilisation effects due to discontinuous changes in local geometry and presence of LSBs **[6]**. Publications **[5, 6]** enable, for the first time, quantitative predictions rather than empirical practices previously used in industry.

The above developments and computational advances based on the linear harmonic Navier-Stokes (LHNS) direct and adjoint models developed during **[i,ii]** lead to Dr Mughal's development of the **MiPSecR** suite of high-fidelity computational tools.

3. Fully 3D modelling: Long-haul flight requires swept wings that produce 3D flows and must crucially accommodate Hybrid-LFC technology for active control. Hybrid-LFC involves suction through thousands of micron-sized laser-drilled holes on the surface, but current design tools use simplistic and unrealistic assumptions for Hybrid-LFC surface placement and 3D modelling.

Imperial research developed **PPM-PSE3D**, an efficient 3D surface-marching parabolised stability equations algorithm for the quantification of laminar flow instabilities over complete aircraft wings **[7, 8]**. These tools make no pseudo-3D assumptions and can model aerodynamic problems of practical importance and relevance to industry **[ii]**.

The work was supported by a variety of funding sources, including direct support from Airbus, EPSRC **[i]**, Innovate-UK through the ALFET project **[ii]**, and Bombardier via the SANTANA project **[iii]**. DSTL and BAe Systems supported the initial development of *PPM-PSE3D* **[7]**.

3. References to the research

[1] Ruban AI, Bernots T, Pryce D, 2013, *Receptivity of the boundary layer to vibrations of the wing surface.* J. Fluid Mech., **723**, Pages: 480-528, https://doi.org/10.1017/jfm.2013.119.
[2] Raposo H, Mughal MS, Ashworth R, 2018, *Acoustic receptivity and transition modeling of Tollmien-Schlichting disturbances induced by distributed surface roughness*, Physics of Fluids **30**, 044105, https://doi.org/10.1063/1.5024909.
[3] Raposo H, Mughal M, Ashworth R, 2019, *An adjoint compressible linearised Navier-Stokes approach to model generation of Tollmien-Schlichting waves by sound*, J. Fluid Mech., **877**, https://doi.org/10.1017/jfm.2019.601.
[4] Thomas C, Mughal S, Ashworth R, 2017, *On predicting receptivity to surface roughness in a compressible infinite swept wing boundary layer*, Physics of Fluids **29**, 034102; https://doi.org/10.1063/1.4977092.
[5] Wu, X., Dong, M. 2016, *A local scattering theory for the effects of isolated roughness on boundary-layer instability and transition: transmission coefficient as an eigenvalue*. J. Fluid Mech., **794**, https://doi.org/10.1017/jfm.2016.125.
[6] Thomas C, Mughal S, Ashworth R, 2017, *Development of Tollmien-Schlichting disturbances in the presence of laminar separation bubbles on an unswept infinite wavy wing*, Phys. Rev. Fluids **2**, 043903. https://doi.org/10.1103/PhysRevFluids.2.043903.
[7] Mughal, M. S. (2010). *Application of Transition Modelling for Spanwise Varying Three-Dimensional Flows*. Final Report, UK MOD contract C/EGC/N03507/C004 on "Critical Aerodynamic Technologies for ALUAV-Sensorcraft" (*available on request*).
[8] Ashworth R., Mughal S., 2015, *Modeling Three-Dimensional Effects on Cross-Flow Instability from Leading Edge Dimples*. Procedia IUTAM **14**, 201-210, https://doi.org/10.1016/j.piutam.2015.03.041.

Research grants:
[i] EPSRC (EP/I037946/1), PI: P Hall, Mar/11- Feb/16, £4,219,574, 'LFC-UK: Development of Underpinning Technology for Laminar Flow Control'.

[ii] UKRI (113022), Airbus led ALFET project, Imperial investigators: P Hall, Mughal, M. S. Jan/14 – Mar/19, £621,952, 'https://gtr.ukri.org/projects?ref=113022'

[iii] UKRI (113001), Bombardier Aerospace led SANTANA project, Imperial investigators: P. Hall, D. Papageorgiou, Jan/14 – Mar/18, £306,355, 'SANTANA: System Advances in Nacelle Technology AerodyNAmics'

4. Details of the impact

Demand for air travel (despite the current pandemic) will continue to increase **[A, B]**, with low drag airframes forming a cornerstone of design philosophy. Airbus continues to invest in LFC for the next generation of narrow body, hydrogen fuelled and battery–powered aircraft **[C]**. LFC technology offers up to 5% lower CO_2 emissions corresponding to 3,000 tons of CO2 saved per aircraft annually **[D]**. Airbus states that:

> *"Wing design and production is a key capability for the UK. The supply chain impact of Airbus to the UK economy is worth £5 billion annually."* **[E]**

Imperial research contributed to key new technologies for the optimal design of laminar-flow wings for Airbus's next generation aircraft programmes. This is a long-standing collaboration which resulted in co-authored publications, both in the underpinning research **[2,3,4,6]** and applied studies **[F]**. Airbus is using these advanced theoretical and computational tools in the industrial process of laminar wing design optimisation:

> *"Our collaborations with Imperial College have been ongoing for some time, but the period from 2015-onwards has been the most significant for us regarding its impact on our research direction in the field of Laminar flow wing design. This is due to the* ***progression of the Imperial research from crucial fundamental aspects into an enhanced suite of theoretical tools that we are using in an industrial wing design setting****."* **[E]**

The quality of methods is rated highly by Airbus

> *"The measure and scope of the work has been truly impressive due to (i) the robustness of Imperial software models enabling investigations of practical engineering problems, and (ii) the advanced physics fidelity of the Imperial software."* **[E]**

These tools allow Airbus to conduct investigations that have been previously impossible.

> *The Imperial state-of-the-art modern transition prediction methods for industrial design,* ***have enhanced Airbus's laminar flow analysis capability enabling the solution of previously intractable problems."*** **[E]**

The new tools also aid LFC tests in industrial transonic wind-tunnel testing **[G]** led by the Aircraft Research Association (ARA).

Airbus invested €200 million towards the LFC BLADE project where the outer sections of an A340 aircraft had specially designed laminar flow wings **[H]**. This was part of the €4 billion EU Clean-Skies II initiative to reduce noise and emissions between 65-90% by 2050. Methods developed at Imperial were used in the analysis of the test flights:

> *"The computational suite comprising the 3D surface marching PSE algorithm (PPM-PSE3D) developed at Imperial and delivered to Airbus, was used by Airbus to analyse and interpret the data of its laminar flow wing demonstrator project using a A340-300 MSN001 "flight lab" aircraft. The flight tests (in 2017) were part of the Breakthrough Laminar Aircraft Demonstrator in Europe (BLADE) project sponsored by the EU Clean-Skies II initiative."* **[E]**

The impact of the analysis is the furnishing of a high-fidelity design tool for Airbus:

> *"The position of the laminar-turbulent front on the wing was predicted exceptionally well by PPM-PSE3D, making the software a high fidelity design tool that can be used alongside traditional empirical methods."* **[E]**

A major industry-wide barrier in predictive laminar wing performance has been the inability of modelling small-scale manufacturing and environmental uncertainties. Viability of LFC technology requires extremely tight control of manufacturing finishing standards and maintenance of tolerances during lifetime operation of aerodynamic surfaces. Imperial delivered to Airbus the *MiPSecR receptivity software suite*. The development has allowed several key areas (stochastic receptivity, steps–gaps, surface-roughness) to be investigated **[2,3,4,6]** and incorporated into advanced transition prediction software. Airbus state:

> *"Imperial's receptivity software suite MiPSecR allows us to utilise its adjoint framework to simulate thousands of stochastic realisations and use uncertainty quantification to predict transition due to tolerances and imperfections."* **[E]**

Capabilities facilitated by Imperial's research offers Airbus significant time and cost savings in the development of optimised LFC aircraft (for both Hybrid LFC and natural LFC). This is achieved by facilitating faster design cycles using the developed advanced tools, and reducing the need for unnecessary and costly wind-tunnel tests, as corroborated by the supporting evidence:

> *"It is vital for Airbus to simulate such features in a controlled manner, so that the tolerances for building a laminar wing can be understood. The BLADE demonstrator flew over a hundred hours and collected such data. Imperial's receptivity software suite MiPSecR allows us to utilise its adjoint framework to simulate thousands of stochastic realisations and use uncertainty quantification to predict transition due to tolerances and imperfections. Such state-of-the-art theoretical capabilities offer the potential to incorporate knowledge of manufacturing tolerances and real world limitations into future wing shape optimisation processes prior to expensive experiments and flight tests, again saving time and money."* **[E]**

The Imperial research has contributed to the competitiveness of Airbus and its UK operations, as well as the broader position of the UK in advanced technologies and manufacturing:

> *"Each contribution to the excellence of the product enables Airbus to compete on the global stage and as such the Imperial College research is vital for the continued success of Airbus in the UK."* **[E]**

The process of developing and building a new aircraft is long, complex and costly. For example, the Airbus A380 "superjumbo", announced in 1990, was delivered in 2005 with a cost of €25 billion. The design and manufacturing pipeline relies on fundamental knowledge and new technologies to provide a crucial competitive edge, and that is exactly what the research from Imperial has delivered and will continue to do as part of Airbus' plan to include LFC as a defining technology of a potential next-generation aircraft from the late 2020s.

5. Sources to corroborate the impact

[A] https://www.hlfc-win.eu/environmental-impact (Archived here)
[B] https://www.carbonbrief.org/guest-post-planned-growth-of-uk-airports-not-consistent-with-net-zero-climate-goal (Archived here)
[C] https://www.flightglobal.com/analysis/analysis-why-airbus-foresees-laminar-wings-on-next-gen-aircraft/128247.article (Archived here)
[D] https://www.hlfc-win.eu/environmental-responsibility (Archived here)
[E] Testimonial by the Research Project Leader for Virtual Product Engineering and the Partnerships Manager of Airbus.
[F] Applied papers co-authored with Airbus employees. (Archived here)

- Ashworth R, Lawson S, Lowry S, Martinez-Cava A, Mughal M, Thomas C., et al., 2016, *Numerical and experimental study of the tolerance of natural laminar flow on a wing to TS destabilisation at the leading edge /wing-box junction*, Royal Aeronautical Society Applied Aerodynamics Conference, 19-21 July 2016, https://spiral.imperial.ac.uk/handle/10044/1/37402.
- Kang, K. L., Ashworth, R., & Mughal, M. S. 2019. *Stabilization of crossflow instability with plasma actuators: Linearized Navier–Stokes simulations. Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering,* https://doi.org/10.1177/0954410019842033.

- Cooke, EE, Mughal, MS, Sherwin, S, Ashworth, R and Rolston, S. (2019). *Destabilisation of Stationary and Travelling Crossflow Disturbances Due to Steps over a Swept Wing*. AIAA Paper 2019-3533, http://dx.doi.org/10.2514/6.2019-3533.
- Appel T, Mughal MS, Ashworth R, 2019, *Global stability analysis of a boundary layer with surface indentations*. AIAA paper 2019-3537, https://doi.org/10.2514/6.2019-3537.

[G] Use of research by the Aircraft Research Association (ARA)
Ciarella, A, Lawson, S., Wong, P. and Mughal, MS, 2019. *Aerodynamic and Transition Analysis of the Hybrid Laminar Flow Control Wing Experiment at the ARA Wind Tunnel.* AIAA Paper 2019-3598. http://dx.doi.org/10.2514/6.2019-3598 (Archived here)

[H] BLADE test flight (Archived here)

- https://www.flightglobal.com/news/articles/ila-airbus-encouraged-by-laminar-winged-a340-trial-448031/
- https://www.airbus.com/newsroom/press-releases/en/2018/04/airbus-presents--flight-lab--blade-test-aircraft-to-eu-clean-sky.html
- https://www.ainonline.com/aviation-news/air-transport/2018-07-18/airbus-blade-runner-exceeds-expectations