Institution: Imperial College London

Unit of Assessment: 10 Mathematical Sciences

Title of case study: C7 - Research underpinning laminar airfoil design leading to revised aircraft wing design

1. Summary of the impact (indicative maximum 100 words)

Research at Imperial concerning the onset of turbulence in fluid flows provided the key theoretical underpinning of the design tools needed to produce the next generation of aircraft wings for both civil and military aircraft. This work facilitates the development of laminar flow wings, which, through reduced fuel consumption of up to 5%, has a significant economic impact, together with a similar environmental impact, associated with reduced engine noise. Carried out in conjunction with industry, most notably EADS/AIRBUS, the work is now part of the current design tools used by AIRBUS and has already influenced the design of the wing developed by AIRBUS for flight-testing in 2015. The financial impact in future for AIRBUS-UK will be measured in billions if and when the technology becomes part of future aircraft.

2. Underpinning research (indicative maximum 500 words)

The underpinning Imperial research concerned the onset of turbulence in fluid flows and provided the key theoretical underpinning of the design tools which are needed to produce the next generation of aircraft wings for both civil and military aircraft. The relevant research primarily concerned the following three areas:

(a) The Receptivity process. This is the mechanism by which atmospheric fluctuations, surface imperfections and acoustic waves combine to generate growing disturbances. In the absence of an understanding of the receptivity phase, the transition prediction becomes empirical and the consequent lack of precision historically meant that any drag savings were lost by the necessity to 'over-design' in order to avoid catastrophes. The papers [1,2,3] have quantified the receptivity process to the extent that the full benefits of flow control can be achieved.

A longstanding problem associated with transition was the question of whether wind tunnel experiments were ever able to reproduce conditions in flight. In [1], a theory to explain some long-standing experimental observations of the role in streaks was given; this paper was one of the first to explain the dangers of extrapolating wind tunnel results to the flight situation. In 2001, a major contribution to our ability to account for all possible disturbance generations was made [2]. The research in [2] has been developed further in [3] to a level where we can account for how the way in which wing surface is painted or rolled during manufacture influences the transition process. [3] is a major breakthrough in the deployment of our theoretical tools in a very applied industrial context.

(b) The Nonlinear Breakdown stage. This is the 'endgame' of disturbance growth where rapidly growing waves occur and turbulence is quickly generated. Paper [6] uses the ideas from secondary instability theory developed by Hall to describe the breakdown stage and to describe coherent structures, which form the backbone of turbulent flows. Paper [5] describes how suction can be used to prevent the nonlinear breakdown stage occurring and was the crucial step in the development of a control mechanism sufficiently compact to be deployed.

All the major aircraft manufacturers use the parabolised stability equation method (PSE) to calculate the linear growth of disturbances in 2D flows. Until recently, the approach was 2D whereas flows over real wings are 3D. In 2010 [4], the first tools for transition prediction in genuinely 3D flows were developed. Paper [4] was done in collaboration with BAE and Qinetiq [G1] and concerned a very 3D geometry relevant to an unmanned combat air vehicle (UCAV). The crucial input into this paper came from Mughal who had developed the 3D PSE capability.

In situations where laminar flow cannot be maintained by careful design of the wing, active means can be used to prevent disturbance growth. The most viable active method is suction. However, test flights in the 1980's showed that theoretical predictions of control by suction could be verified but the weight of the machinery to deliver the suction meant that no room would be left for passengers. Optimization methods that could be used to find the best strategies for deployment without the punitive weight penalties were demonstrated in [5]. That research was used for the suction strategy used in the TELFONA flight tests [G2] to verify the feasibility of suction control (see §4).

(c) 3D PSE approach. The PSE approach was developed in the 1980's following Hall's work on Gortler vortices. The development of variants of that approach allowed flows of practical importance to be investigated and, used in conjunction with (a) and (b), enabled us to provide accurate transition prediction tools now being used by EADS/AIRBUS as part of the design process. Paper [4] represents the first practical implementation of the approach for 3D flows.

The flow on swept wings breaks down to turbulence due to the growth and then secondary instability of crossflow vortices. Secondary instability theory used to predict the latter growth was developed by Hall and Horseman in the early 1990's. In [6], it was found that the Hall-Horseman theory described wave systems in turbulent flows, and so plays a role in the control of turbulence. The Hall-Sherwin theory [6] provided the first rational framework to describe coherent structures in turbulent flows.

Key personnel: The authors cited at Imperial College are Profs Hall (1996-present), Ruban (2009-present) and Wu (1995-present) and senior researcher Dr Mughal (1996-present). Hall is director of LFC-UK, a joint research programme involving EPSRC [G3] and EADS/AIRBUS [G4] created in order to provide the underpinning theoretical technology for the development of laminar flow wings.

3. References to the research (* References that best indicate quality of underpinning research)

[1] Wu, X., Choudhari, M., '*Linear and nonlinear instabilities of a Blasius boundary layer perturbed by streamwise vortices. Part 2. Intermittent instability induced by long-wavelength Klebanoff modes*', J. Fluid Mech, 483, 249-286 (2003). DOI.

[2] Wu, X., '*Receptivity of boundary layers with distributed roughness to vortical and acoustic disturbances: a second order asymptotic theory and comparison with experiments*', J. Fluid Mech, 431, 91-133 (2001). DOI.

[3] Mughal, M. S. and Ashworth, R., '*Uncertainty Quantification Based Receptivity Modelling of Crossflow Instabilities Induced by Distributed Surface Roughness in Swept Wing Boundary Layers*' , AIAA 2013-3106, 43rd AIAA Fluid Dynamics Conference (2013) (available here)

[4] Arthur, M. T., Horton, H.P. and Mughal, M., '*Modelling of natural transition in properly three-dimensional flows*', AIAA, 2009-3556 (2009). DOI.

[5] Balakumar P, Hall P, '*Optimum suction distribution for transition control*', Theoretical and Computational Fluid Dynamics, Vol:13, Pages:1-19 (1999). DOI.

[6] Hall P, and Sherwin S, '*Streamwise vortices in shear flows: harbingers of transition and the skeleton of coherent structures*', J. Fluid Mech, 661, 178-205 (2010). DOI.

Research grants: Within the period 2007-1013 support for transition research includes:

[G1] Qinetiq (CU004-27172), PI: P Hall, 1/2/04-31/8/09, £240,206, 'Advanced swept wing transition modelling and control'.

[G2] Airbus via European Commission, AST4-CT-2005-516109, PI: P Hall, 1/5/05-31/10/09, €220,568, 'TELFONA - Testing for Laminar Flow on New Aircraft'.

[G3] EPSRC (EP/I037946/1), PI: P Hall, 1/3/11- 29/2/16, £4,219,574, 'LFC-UK: Development of Underpinning Technology for Laminar Flow Control'.

[G4] EADS/AIRBUS, PI: P Hall, 1/3/11- 29/2/16, £1.08m, 'LFC-UK: Development of Underpinning Technology for Laminar Flow Control'.

4. Details of the impact (indicative maximum 750 words)

The tools developed by Hall, Ruban, Wu and Mughal at Imperial have become a cornerstone of

AIRBUS UK's laminar flow research and were used to interpret flight test data from the TELFONA programme in 2009 [G2, A]. The group is at present working closely with EADS/Airbus on the design of the 'Smart Fixed Wing', to be flight tested in 2015 as part of the Clean Skies initiative [B]. The Imperial group will also be fully involved with the interpretation of the flight test data [C]. A major part of the collaboration with EADS is the secondment of staff between academia and industry to help translate the academic research to EADS, and onto Airbus, and enable Imperial researchers to be fully aware of the complications associated with real wings [D].

For commercial jets, the two major manufacturers are AIRBUS (owned by EADS) and BOEING. In 2011, EADS/AIRBUS invested ~£1m pounds in LFC-UK [G4] which, together with ~£4m from EPSRC [G3], enabled us to provide the theoretical tools to underpin the development of laminar flow wings. The commitment of AIRBUS was a result of our previous successful collaborations, which had, for example, involved the successful interpretation of flight test data from the TELFONA project [5, C, E].

Within the period 2008-2013, EADS/AIRBUS progressively deployed variants of the Imperial group's PSE methods to predict transition rather than use old-fashioned crude methods, and many areas of research from Imperial have "*proved invaluable to EADS*" [D]:

- The work on receptivity theory has given EADS a rational method to input disturbances into laminar flows. For example [1], shows how free stream turbulence and acoustic waves generate disturbances in predominantly 2D flows and, taken with earlier contributions by Ruban, "*provide the cornerstone for modelling receptivity in the industrial environment*" [D]. Paper [3] demonstrated how the receptivity ideas could be used to model flows over randomly distributed surface roughness typical of that found on airfoils. The results will play a "*key role in the specification of manufacturing tolerances for the next generation of wings developed at [EADS/Airbus UK]*" [D].
- The work on the 3D transition prediction method, paper [4], has had "*major impact*". This paper "*opened up the way for industry to predict transition within the RANS-Solar CFD method used for design purposes*" [D]. EADS is supporting Mughal at Imperial to take the work forward in order to understand the effect of 3D waviness induced by manufacturing on in flight loading on transition. This work will contribute to the flight test analysis of the EU JTI Clean Sky 'BLADE' wing in 2015 and represents "*the 'state of the art' of transition prediction in 3D flows*" [D].
- EADS and Airbus have also taken great interest in the work of Hall and Sherwin [6] on self-sustained processes and coherent structures. This work is "*important for acoustic issues in aerodynamics*" [D]. Paper [5] was the first rational attempt to optimise the deployment of suction on wings. Before that work, the 'sledgehammer approach' of sucking everywhere as hard as possible did indeed produce laminar flow, but the equipment needed to produce it meant the aircraft was too heavy to take off, let alone be commercially viable. The method provided the basis for the development of optimisation strategies for all kinds of instabilities on airfoils and produced a scenario where suction deployment is commercially viable.

In summary, EADS Innovation Works is "*already using a great deal of the work*" of the Imperial College group in their research activities "*directed at aerodynamic analysis and novel wing technology to support the Airbus Business*" [D]. For example, the collaborative work with EADS Innovation Works on "*a method for quantifying the effect of surface finish uncertainties on the transition location has been reported at the recent AIAA [American Institute of Aeronautics and Astronautics] conference in San Diego*" (paper [3]) and is of a "*clear world level standard*" [C].

Airbus considers the collaboration with Imperial and the LFC-UK project to be mutually beneficial for all parties. For example, "*industry takes on board the advanced and newer means of investigating complex flow phenomenon resulting from manufacturing realities while academic researchers benefit from exposure to real world problems*" [C]. Commenting on past collaboration, Airbus states "*the sharing of roughness data, flight test data (Smart Fixed Wing, and Blade projects) shows our commitment and belief in the excellence, novelty and timeliness of the work being undertaken in the LFC-UK project. Major aspects of the research highlighted in the September 2013 LFC-UK industry workshop are of real and practical use to Airbus in the UK*" [C]. As a final comment, Airbus states that it is "*fully supportive of the research, which has already had* *an impact on our current work and we fully expect the continuous stream of results coming from LFC-UK to influence our approach to the aerodynamic design and manufacture of the laminar flow wing concept*" [C].

In addition to the work already described above with EADS/Airbus, the Mathematics group has, or has had, collaborations with Qinetic [G1], BAE and the Aircraft Research Association (ARA).

The active collaboration with BAE is being taken forward within LFC-UK to develop a capability for BAE to design UCAVs having significant regions of laminar flow. Of "*particular importance to BAE Systems has been the work on the transition prediction on very 3D configurations*" [F]. Such configurations are "*relevant to UCAV design where increased range can be achieved if laminar flow can be achieved over as much of the wing as possible*" [F].

Here, the resultant reduced fuel burn enables vehicles to stay on mission for longer periods. In the civilian aircraft context, the reduced burn is primarily aimed at reducing fuel costs and the impact of emissions on the environment. Indeed the fuel reductions are one minor step towards the EU's planned goal of 50% reduction in aircraft emissions by 2050. LFC-UKs role in this area was reported by the Economist in 2011: "*Understanding what causes the transition from laminar to turbulent flow requires massive mathematical and computing power. But if Dr Serghides's colleague Philip Hall and his team can work out the details, they should be able to design wings whose shape maintains laminar flow from front to back, and thus lowers fuel consumption*" [G].

Scale of the impact:
It takes 20-25 years for an aircraft to go into service once a decision to produce it has been made. Impact in the aeronautics industry therefore occurs with long realisation timescales and it is difficult to assess the scale of the current impact precisely. However, wing design and production is a key capability for the UK and Airbus in the UK which, together with its supply chain, provides supplies and services worth nearly £1.5b annually to the UK economy. EADS Innovation Works comments that "*each contribution to the excellence of the product enables Airbus to complete both within Europe and on the global stage and as such the work at Imperial College is vital to the continued success of EADS and Airbus in the UK*" [D]. Additionally, BAE states that UCAV development is "*an activity involving tens of millions of pounds each year in the UK and any technical superiority obtained using leading edge contributions from academia helps to secure BAE Systems' position in this activity*" [F].

5. Sources to corroborate the impact (indicative maximum of 10 references)

[A] Telfona, AST4-CT-2005-516109, Final Technical Report, pages 2, 4, & 5 (available here)
[B] Flightglobal article, 26/7/11, "Smart wing design takes shape for next-generation narrowbody", http://www.flightglobal.com/news/articles/smart-wing-design-takes-shape-for-next-generation-narrowbody-359608/ (archived at https://www.imperial.ac.uk/ref/webarchive/8rf on 11/9/13)
[C] Letter from Transnational Senior Change Agent for Aerodynamics, Airbus Operations Ltd, 21/10/13 (letter available from Imperial on request)
[D] Letter from Head of Aeromechanics, EADS Innovation Works, 22/10/13 (letter available from Imperial on request)
[E] European Commission, Research & Innovation, TELFONA page, http://ec.europa.eu/research/transport/projects/items/telfona_en.htm (archived at https://www.imperial.ac.uk/ref/webarchive/9rf on 11/9/13)
[F] Letter from Executive Scientist, BAE SYSTEMS, Advanced Technology Centre, 7/10/13 (letter available from Imperial on request)
[G] Economist magazine article, 10/3/11, "Plane truths: How to build greener planes that airlines will actually want to fly", http://www.economist.com/node/18329444 (Archived here)