Institution: University College London (UCL)

Unit of Assessment: 10 – Mathematical Sciences

Title of case study: Improving aircraft safety in icing conditions

1. Summary of the impact

The consultancy company AeroTex makes use of UCL research findings to design new and improved ice protection systems for fixed wing or rotor aircraft. These new designs enable AeroTex's customers (aircraft manufacturers and Tier 1 equipment suppliers) to comply with upcoming changes that are raising aircraft certification standards and to operate aircraft more safely in icing conditions. The increase in income to AeroTex resulting from this work was approximately [text removed for publication] per year between 2010 and 2013, representing around 15% of AeroTex's annual turnover.

2. Underpinning research

When an aircraft flies through cloud at or below freezing temperature, ice can accrete on its forward-facing parts. This can lead to detrimental performance, and has been a significant factor in a number of past incidents and accidents, some of which resulted in the loss of life. Icing occurs when supercooled water droplets suspended in the cloud impact on the body of the aircraft and freeze on to it. The rate, amount and location of ice accretion depend on parameters including temperature, speed, aircraft surface shape and droplet size. Existing mathematical models are reasonably accurate in predicting the shape and quantity of ice produced when droplets are small (≤40μm). However, for larger droplets (supercooled large droplets, or SLD) the models were inadequate and tended to dramatically over-predict the amount of ice produced and wrongly predict its location, partly because larger droplets tend to splash. This resulted in errors in predicting aerodynamic performance and safety.

Accurate modelling of aircraft icing is desirable as it can inform the design of aircraft and ice protection systems, resulting in improved aircraft safety. Between 2001 and 2013 researchers in UCL's Department of Mathematics investigated and modelled various aspects of impacts of relevance to aircraft icing, taking larger droplets into account and ensuring that models are realistic. Work on asymptotic expansions and matching, involving complex multi-phase fluids, irregular geometry, air-water interactions, shallow-layer impacts and ice-skimming, produced reduced-equation computations and code supported by comparisons with real-world findings.

Early work (2001-03) involved the development of models that simulate how a layer of air between a droplet and a water layer affects the impact of the droplet [1]; the effect of air on impacts – vital for real-world applications – had never been predicted before. Splashing of large droplets impacting onto a layer of water was then investigated in 2002 to 2005 [2, 3], with parameters such as air flow, water depth and droplet size being varied. Findings included the first-ever predictions of surface roughness effects after impact and how much of the water layer is splashed away. Some of this work [3] was written up jointly with a group from the Mathematical Institute in Oxford, the University of Nottingham and the University of East Anglia, who had arrived simultaneously at the same research conclusions. This work was followed in 2006 to 2008 by modelling of impacts involving a solid body approaching another solid body with two fluids (air and water) between them [4]; in an aircraft icing scenario this corresponds to an ice crystal impacting upon a solid aircraft surface covered by a water layer.

A related research strand (2008-13) involved skimming impacts and rebounds. A model was derived for a solid body (e.g. an ice crystal) undergoing an oblique skimming impact with a shallow liquid layer and then rebounding from it [5]; this work included explanations of both entries into and exits from water. An extension of this model included fluid-body interactions with multiple bodies and multiple impacts [6], of relevance to wind-blown ice particles travelling along an aircraft wing.

The above research generated new and simpler computational methodology. It also provided flexible mathematical predictions of the precise extent of a splash, rebound duration, effects of surrounding air motion, and shapes resulting from ice accretion or melting, which take into account highly variable parameter values including droplet size, impact speed and angle of incidence.

Site visits and discussions with QinetiQ and AeroTex, together with complementary experimental input from Cranfield University, were important for much of the above modelling work [1, 2, 3, 4].

Key UCL researchers: Frank Smith (Professor in Mathematics), Richard Purvis (PDRA 2002-05), Andrew Ellis (PDRA 2006-08) and Peter Hicks (PDRA 2010-11).

3. References to the research

[1] Air cushioning with a lubrication/inviscid balance, F. T. Smith, L. Li and G. X. Wu, *J. Fluid Mech.*, 482, 291-318 (2003) doi:10.1017/S0022112003004063

[2] Droplet impact on water layers: post-impact analysis and computations, R. Purvis and F. T. Smith, *Phil. Trans. R. Soc. A*, 363, 1209-1221 (2005) doi:10.1098/rsta.2005.1562

[3] Droplet impact on a thin fluid layer, S. D. Howison, J. R. Ockendon, J. M. Oliver, R. Purvis and F. T. Smith, *J. Fluid Mech.*, 542, 1-23 (2005) doi:10.1017/S0022112005006282

[4] Trapping of air in impact between a body and shallow water, A. A. Korobkin, A. S. Ellis and F. T. Smith, *J. Fluid Mech.*, 611, 365-394 (2008) doi:10.1017/S0022112008002899

[5] Skimming impacts and rebounds on shallow liquid layers, P. D. Hicks and F. T. Smith, *Proc. R. Soc. A*, 467, 653-674 (2011) doi:10.1098/rspa.2010.0303

[6] On interaction between falling bodies and the surrounding fluid, F. T. Smith and A. S. Ellis, *Mathematika*, 56, 140-168 (2010) doi:10.1112/S0025579309000473

References [1], [5] and [6] best indicate the quality of the underpinning research.

Relevant research grants:

(i) Theory and computation in unsteady flow modelling (GR/S35394/01); £4,121; awarded to Professor Frank T. Smith; sponsor: EPSRC (CASE Award); 2003-2006

(ii) Faraday fast track proposal: droplet impact on water layers (GR/R91939/01); £103,456; awarded to Professor Frank T. Smith; sponsor: EPSRC (RA support); 2002-2004

(iii) Air and surface effects on water droplet impact (EP/D069335/1); £257,779; awarded to Professor Frank T. Smith; sponsor: EPSRC (RA support); 2006-2010

4. Details of the impact

Aircraft icing consultancy company AeroTex was founded in 2002, as an SME offshoot from QinetiQ. Since 2008, it has used UCL's research to underpin its specialist icing work, ranging from ice accretion physics to the design and certification of ice protection systems [A].

In 2010, the United States Federal Aviation Administration (FAA) proposed new aircraft icing regulations. The European Aviation Safety Agency (EASA) followed suit in 2011, proposing a similar update to their certification specifications for large aeroplanes. Since then, aircraft manufacturers have been working to ensure their designs meet these specifications, as the proposals will come into force imminently.

These proposals followed a number of accidents, including the October 1994 crash of American Eagle Flight 4184, which rolled out of level flight and crashed into a field in Indiana, killing all 68 people on board. Investigations found that the accident was caused by a build-up of ice on the wings during icing conditions that included freezing rain, or supercooled large droplets (SLD). At the time, the FAA required aircraft to be tested and certified for flight in icing conditions, but the rules were aimed at much smaller cloud-droplet diameters. The importance of SLDs, and their significant splash effects, was unknown, and was not even considered when certifying aircraft. Accidents including Flight 4184 and many since then highlighted the inadequacy of the icing certification standards and led to lengthy, complex discussions between authorities, manufacturers and designers about introducing updated regulations, and how these would be prepared for. This then resulted in the FAA introducing its proposals for new regulations that include SLD and ice crystals.

In 2002, the UCL group was asked by industry to conduct research into SLD. UCL's research described in section 2 helps AeroTex to design new ice protection systems that meet these regulatory requirements [A]. It also impacts upon AeroTex's customers by enabling them to operate aircraft more safely in icing conditions and to comply with improved safety legislation. The research came to influence AeroTex through research collaborations, including Research Associate placements, and meetings of the UK Icing Group, of which UCL and AeroTex are both members. The owner of AeroTex said: "We have been able to use the knowledge generated within our analysis phase so that there has certainly been a benefit to us. We flow the knowledge generated by UCL into designs for ice protection systems for commercial customers" [B].

AeroTex makes use of UCL research when advising customers on whether ice protection is needed and when designing new ice protection systems that comply with future and current regulations. The UCL research findings are an important part of a portfolio of methods and evidence used to make decisions, and have directly influenced the course of development of AeroTex's AID (Aircraft Icing Design) analysis tool, used in aircraft ice protection system design. UCL research also helps AeroTex to stay ahead of their competitive rivals; the company has become experienced at providing consultancy for manufacturers who need to conform to the new certification rules [A].

UCL's research has not only led to these important impacts on aircraft safety, but also has commercial benefits for AeroTex. [text removed for publication]

AeroTex's customers are confidential, but include several aircraft manufacturers and Tier 1 (the top approved) equipment suppliers. New sub-system designs have already been or are to be incorporated into manufactured aircraft, and are estimated to be included on thousands of aircraft over many years. UCL research has helped both AeroTex and their customers to understand the effects of ice on planes, and the safety implications associated with icing. It has helped AeroTex provide system designs that comply with proposed new rules, and enabled them to compete effectively against their rivals, supporting improved aircraft safety for the future. The financial figures as far as the customers are concerned are confidential but extend into the hundreds of thousands of pounds sterling.

5. Sources to corroborate the impact

[A] The Aircraft Icing Consultant at AeroTex UK can be contacted to corroborate all of the claims and details about AeroTex, including what the company uses the UCL research for and how it benefits from this, and the details of income generated and projects conducted. Contact details provided separately.

[B] Statement from the owner of AeroTex (contained within a document about the EPSRC funded Knowledge Exchange Programme – see page 1) – corroborates that the research is used by AeroTex and is beneficial to the company. Document available on request.