Institution: 10007822

Unit of Assessment: 12

Title of case study: Aerodynamic modelling saves development costs of Joint Strike Fighter (JSF)

1. Summary of the impact

Cranfield University has conducted research in jet aerodynamics, particularly for vertical or short take-off and landing (V/STOL) aircraft applications, for more than 20 years, with funding from the aerospace industry, MoD and RCUK, making a major contribution to the continuing development of the new Joint Strike Fighter aircraft.

The impact of the research has been:

- savings of many £M in development costs of the Lockheed Martin F-35B (Joint Strike Fighter) by reducing the development time, improving safety with less restrictive operating conditions, and enabling better design decisions.
- a series of continuing professional development courses on V/STOL aircraft design delivered internationally to more than 300 engineers and managers.

2. Underpinning research (indicative maximum 500 words)

The design of jet-lift vertical or short take-off and landing (V/STOL, or STOVL – short take-off and vertical landing) aircraft introduces significant aerodynamic complexities. In particular, in vertical flight the lifting jets point downwards and the entrained air flow induces a download on the airframe. This download is exacerbated close to the ground when the lift jets hit the ground and spread out to flow radially. This so-called wall jet has a number of consequences:

- it increases the entrained flow and, hence, the download on the airframe;
- it carries hot engine exhaust gases towards the engine intakes;
- in a relative head-wind the wall jet can separate from the ground and form an unsteady ground vortex that surrounds the aircraft, carrying hot gases towards the engine intakes and changing the air-loads on the airframe.

Understanding the characteristics of the wall jet and ground vortex – and how they vary with operating and design conditions – is crucial for the efficient design and safe operation of jet-lift V/STOL aircraft.

Over the past 20 years Cranfield University has studied jet-induced flowfields with the aim of understanding and reducing the adverse effects of these flows on V/STOL aircraft. Our projects have addressed various flow phenomena, including the development of wall jets from single and multiple impinging jets [P2], jet/intake interactions [P3, P6], jet mixing [G1, P6], coannular impinging jets, mean and fluctuating flowfields associated with the ground vortex [G2, P1, P4], and unsteady fountain flows [G3, P5].

Our initial studies were aimed at understanding factors that controlled the location and size of the ground vortex formed when a jet hits the ground in a cross-flow [P1]. Our results quantified the differences between impingement on fixed and moving ground planes, confirmed self-similarity rules for the size of the ground vortex, revealed the levels of unsteadiness of the ground vortex, and presented initial findings on multiple jet interactions in cross-flows. This work led us to more detailed studies of some of the fundamental flow features involved, starting with the wall jet that feeds the ground vortex.

In the next stage of our research we investigated wall-jet flows produced by jets hitting the ground

[P2]. This showed the influence of initial free-jet conditions on the development of the wall jet, and the significance of the angle at which the free jet strikes the ground on the growth of the wall jet. This led to Cranfield's subsequent studies on the detailed flowfields produced by multiple impinging jets [P5].

In parallel with our fundamental wall jet studies, we conducted more-applied research into the mutual interference between free-jet entrainment flowfields and aircraft intake-induced flows [P3, P6].

More recently Cranfield has used laser-based flow measurement techniques to investigate unsteady features of the ground vortex [G2, P4] and the fountain upwash flow produced by multiple impinging jets [G3, P5]. This work has revealed the stochastic nature of these flowfields.

Key Researchers	Post details and dates involved	Research
Dr D Bray	Lecturer (1988 – 2003); Senior Lecturer (2003 – date)	Aerodynamics; propulsion
Dr M V Finnis	Principal Research Fellow (1993 – to date)	Aerodynamics; instrumentation
Prof K Knowles	Senior Lecturer (1991 – 2007); Professor (2007 – date)	Aerodynamics; propulsion
Dr N J Lawson	Lecturer (1999 - 2002); Senior Lecturer (2002 - 2008); Reader (2008 – to date)	Aerodynamics; propulsion; instrumentation
Dr A J Saddington	Research Engineer (1993 – 1997); Lecturer (1999 – 2010); Senior Lecturer (2010 – to date)	Aerodynamics; propulsion

3. References to the research

Evidence of quality - Peer reviewed journal papers

P1***** *Ground Vortex Formed by Impinging Jets in Cross-flow.* K. Knowles and D. Bray.
Journal of Aircraft, **30** (6), pp. 872-878, 1993.
doi: 10.2514/3.46429

P2***** *Turbulence Measurements in Radial Wall Jets.* M. Myszko and K. Knowles.
Experimental Thermal and Fluid Science,**17**, pp. 71-78,1998. – ***Invited paper***
doi: 10.1016/S0894-1777(97)10051-6

P3 *Jet/Intake Interference in Short Take off, Vertical Landing Aircraft*.
A.J. Saddington and K. Knowles.
Journal of Aircraft, **38** (5), pp. 924-931, 2001.
doi: 10.2514/2.2853

P4 *Particle Image Velocimetry and Laser Doppler Anemometry Experimental Studies of a Compressible Short Take-off and Vertical Landing Ground Vortex Flow*.
N.J. Lawson, J.M. Eyles, and K. Knowles. Proceedings IMechE Part G: Journal of Aerospace Engineering, **216** (G4), pp. 171-187, 2002.
doi: 10.1243/09544100260369713

P5***** *Flow Measurements in a Short Take-off, Vertical Landing Fountain: Splayed Jets*.
A.J. Saddington, K. Knowles, and P.M. Cabrita[a].
Journal of Aircraft, 2009, **46** (3), pp. 874-882.
DOI: 10.2514/1.38296

P6 *A Review of Out-of-ground-effect Propulsion-induced Interference on STOVL Aircraft*.
A.J. Saddington and K. Knowles.
Progress in Aerospace Sciences, **41** (3-4), pp. 175-191. 2005. – ***Invited paper***
Doi: 10.1016/j.paerosci.2005.03.002

***** 3 identified references that best indicate the quality of the research

Evidence of quality – underpinning research grants

G1 MoD. Rapid Mixing Technologies for Exhaust Plume Suppression, £25,400, 1995-1997.
PI Prof K Knowles

G2 EPSRC (GR/N02504/01). *An Experimental Investigation of the STOVL Ground Vortex Transient Flow*, £50,300, 1999-2002.
PI Dr N J Lawson, CI Prof K Knowles

G3 EPSRC (GR/R42894/01). *Unsteady Features of Twin-jet STOVL Ground Effects*, £60,300, 2001-2004.
PI Dr A J Saddington, CI Prof K Knowles

Key to papers and grants

a: Rolls-Royce plc

4. Details of the impact

Cranfield's research on the ground vortex formed when jets hit the ground in a cross-flow [P1, P4] fed into the development of the Joint Strike Fighter (JSF) Our results showed that the ground vortex was 20% further away from the aircraft when a moving ground plane was used, simulating a rolling vertical landing vs hover in a head wind, simulated with a fixed ground plane. The wind-tunnel test programme for the JSF jet effects, involving over 4000 hours in a large multi-national facility, used a fixed ground plane. This programme alone is estimated to have cost some £5 million; a moving ground plane for such a facility would have cost an additional £4 million. Our findings allowed the fixed-ground results to be corrected by engineers in BAE Systems and Lockheed Martin, without the need for an expensive moving-ground simulation, [C1].

Similarly, BAE Systems used our work on wall-jet development [P2] to predict safe operating conditions for ground personnel working in the vicinity of a V/STOL aircraft [C2]. Wall jets, produced by propulsion jets hitting the ground, grow in thickness radially and with increasing nozzle height above the ground. Our work showed that the rate of growth with nozzle height is not linear, contrary to extrapolations from previously-published data, and that above about 10 nozzle diameters the growth rate of the wall jet reduces significantly. This allowed much more accurate predictions of the thickness of the wall jet produced by a landing aircraft. This, in turn, allows smaller exclusion zones for ground personnel and, hence, allows a less restrictive operating envelope for the aircraft.

Our research on jet/intake interactions showed that there was a mutual aerodynamic interference which would not have been accounted for by separate powered wind-tunnel model and independent intake tests. Nevertheless, this effect was shown to be sufficiently small that it did not require the expense and complexity of fully-powered wind-tunnel models with simulated jets and intakes to be mounted on force balances [C1]. These results fed into the development of the JSF to provide confidence in the separate testing of jets and intakes. A combined model, with both powered jets and powered intakes, would have been impractical and would have cost more than £1M. Our research saved this expense and gave designers increased confidence in the validity of their design, mitigating the risk of an overly restrictive operating envelope for the aircraft. Overall, an improved, more accurate design process allows for a shortened flight-test programme. For a complex V/STOL aircraft like the JSF, even a straightforward flight-test programme costs more than £100M; many times more if poor design decisions have been taken.

Cranfield's work on co-annular jet flows led to the conclusion that a gas-driven lift fan, producing a jet with a high-speed outer stream and a lower-speed inner stream, was not a viable solution for a V/STOL aircraft because of thrust loss when close to the ground. This allowed government and industry to drop this as a design possibility, saving many £billions in wasted development costs, [C3].

The impact of Cranfield's research was enhanced by the delivery of a series of continuing professional development courses to engineers and project managers from industry and government agencies. The course, "Fundamentals of V/STOL Aircraft Design with Joint Strike Fighter Applications", has so far been delivered by international experts eight times in the UK and the US, with Cranfield staff delivering lectures on V/STOL jet effects. The most recent courses ran in Fort Worth, Texas (2009), home of Lockheed Martin's Joint Strike Fighter engineering and assembly facility, and in Patuxent River Naval Air Station, Maryland (2010 [C4]), where the Joint Strike Fighter is undergoing flight testing. More than 300 delegates, primarily from industry and government agencies, attended these courses, which provided both broad and deep knowledge of the varied technical aspects of V/STOL jet aircraft design. The courses raised the competence levels of the design teams and helped them to ensure the validity of their designs [C1].

5. Sources to corroborate the impact

C1 Contact: Former Program Manager, Lockheed Martin Skunk Works

C2 Contact: Technologist Advisor, Propulsion Integration, BAE Systems

C3 Contact: Aerodynamics Lead, The Defence Science and Technology Laboratory (Dstl)

C4 2010 V/STOL course programme: http://www.paxpartnership.org/index.cfm?action=CL2&Entry=168 – accessed 14/10/13