**Institution:** Cranfield University

**Unit of Assessment:** 12

**Title of case study:** F-35B: V/STOL Aircraft Design and Employment

**Period when the underpinning research was undertaken:** 2001 to 2019

**Details of staff conducting the underpinning research from the submitting unit:**

| Name(s): | Role(s) (e.g. job title): | Period(s) employed by submitting HEI: |
|---|---|---|
| Dr D Bray | Aerodynamics; propulsion<br>Senior Lecturer | 2003 – present |
| Dr N K Depuru-Mohan | Aeroacoustics; aerodynamics; propulsion<br>Research Fellow | 2017 – present |
| Dr M V Finnis | Aerodynamics; instrumentation<br>Principal Research Fellow | 2000 – present |
| Prof K Knowles | Aerodynamics; propulsion<br>Professor | 2007 – present |
| Miss L J Lacey | Airworthiness; safety<br>Lecturer | 2006 – present |
| Prof N J Lawson | Aerodynamics; propulsion; instrumentation<br>Professor | 2016 – present |
| Dr A J Saddington | Aerodynamics; propulsion; airworthiness<br>Reader | 2020 – present |

**Period when the claimed impact occurred:** August 2013 to December 2020

**Is this case study continued from a case study submitted in 2014?** Y

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

Cranfield's research has underpinned savings of tens of millions of pounds during the design and release to service of the F-35B Lightning (Joint Strike Fighter).

Modern aircraft design cycles take more than 20 years from initial concept to service entry; our research has contributed throughout this process for the F-35B. BAE Systems and Lockheed Martin used Cranfield's insights into vertical or short take-off and landing (V/STOL) aircraft applications to move development of the F-35B through flight testing to initial service entry during the current REF period.

Cranfield's research improved design decisions that are impacting on the operation of the aircraft in service with the Ministry of Defence, allowing for airworthiness clearance, improving safety, and saving operational costs.

**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 faces complexities posed by jet-induced flowfields. In particular, in vertical flight, lifting jets are pointing downwards and the entrained air flow induces a download on the airframe; this is exacerbated in ground proximity when the lift jets impinge on the ground and spread out to form a 'wall jet'. The wall jet increases the entrained flow and the download on the airframe; it carries hot engine exhaust gases; and, in a relative head-wind it can separate from the ground and form an unsteady horseshoe-shaped ground vortex surrounding the aircraft. This carries hot gases towards the engine intakes and changes the airloads on the airframe.

Over more than 20 years, Cranfield University has been researching jet-induced flowfields to reduce the adverse effects on V/STOL aircraft design and operation. Projects have addressed a range of flow phenomena, including the development of wall jets from single and multiple impinging jets, jet/intake interactions [R1, R2], jet mixing studies [R2, R6], coannular impinging jets, mean and fluctuating flowfields associated with the ground vortex [R4], and unsteady fountain flows (where wall jets from multiple impinging jets collide and flow back up towards the aircraft) [R3].

Our underpinning research included experimental studies of factors that controlled the location and size of the ground vortex formed by an impinging jet in a cross-flow. Our results quantified the differences between impingement on fixed vs moving ground planes, showing that the ground vortex was 20% further away from the aircraft in the latter case (simulating a rolling vertical landing vs hover in a head wind, simulated with a fixed ground). They also confirmed self-similarity rules for the size of the ground vortex, revealed the levels of unsteadiness associated with the ground vortex flow-field, and presented initial findings on multiple jet interactions in cross-flows [R4].

This work led us to more detailed studies of some of the fundamental flow features involved: the influence of initial free jet conditions on the development of the wall jet, and the significance of jet impingement angle on its growth. Wall jets grow in thickness both radially and with increasing nozzle height above the ground. Our new findings showed that the rate of growth with nozzle height is not linear and that above about 10 nozzle diameters the wall jet growth rate reduces significantly. This led to studies (2001-2013) on the detailed flowfields produced by multiple impinging jets [R3], and more-applied research into the mutual interference between free-jet entrainment flowfields and aircraft intake-induced flowfields [R1, R2].

A particular focus (2000 to 2013) has been flowfield unsteadiness - the unsteady features of the ground vortex [R4], and the fountain upwash flow produced by multiple impinging jets [R3] - revealing the stochastic nature of these flowfields. Our most recent work has focussed on jet mixing and aeroacoustic issues [R6] and on assuring airworthiness of complex systems such as F-35B [R5].

**3. References to the research** (indicative maximum of six references)


[R1] Saddington A.J., & Knowles K., (2001), Jet/Intake Interference in Short Take off, Vertical Landing Aircraft, *Journal of Aircraft,* 38 (5), 924-931. https://doi.org/10.2514/2.2853

[R2] Saddington A.J., & Knowles K., (2005), A Review of Out-of-ground-effect Propulsion-induced Interference on STOVL Aircraft, *Progress in Aerospace Sciences,* 41 (3-4),175-191, – *Invited paper* https://doi.org/10.1016/j.paerosci.2005.03.002

[R3] Saddington, A.J., Knowles, K., & Cabrita P.M., (2009), Flow Measurements in a Short Take-off, Vertical Landing Fountain: Splayed Jets. *Journal of Aircraft*, 46 (3), 874-882.

https://doi.org/10.2514/1.38296

[R4] Lawson, N.J., Knowles, K., Bray, D., Finnis, M.V. & Eyles J.M., (2014), Transient and Time-averaged Characteristics of a Compressible Ground Vortex Flow. *Proceedings IMechE Part G: Journal of Aerospace Engineering,* 228 (G3), 375-383.

https://doi.org/10.1177/0954410012472421

[R5] Farnell, G.P., Saddington, A.J., & Lacey, L.J., (2019), A New Systems Engineering Structured Assurance Methodology for Complex Systems, *Reliability Engineering and System Safety*, 183 (March) 298-310 https://doi.org/10.1016/j.ress.2018.11.024

[R6] Godbersen, P., Manovski, P., Novara, M., Schanz, D., Geisler, R., Depuru Mohan N.K., & Shroeder, A., (2019), Flow-field Analysis of Subsonic Jets at Mach 0.5 and 0.84 using Multi-Pulse STB. *13th Int Symp on Particle Image Velocimetry – ISPIV, Munich, Germany 22-24 July* - later developed as https://doi.org/10.1016/j.expthermflusci.2020.110346

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

Development of the F-35B Joint Strike Fighter (JSF) involved substantial aerodynamics challenges [S1] because of the required increase in energetic jets compared with legacy aircraft. The complexity of the aircraft and the multi-national nature of its development made airworthiness assurance a major challenge [S3].

**Ground vortex location, wind tunnel simulation and aircraft landing technique**

Our research on the ground vortex [R4] generated data used in the design process for development of the JSF [S1]. Cranfield's research findings allowed the fixed-ground results to be corrected without the need for an expensive moving ground simulation as part of the jet-effects wind tunnel test programme, saving at least GBP4,000,000.

A senior Lockheed Martin engineer confirmed:

> *"This saved GBP millions in testing costs and enabled us to proceed to flight test with confidence"* [S2].

A senior BAE Systems engineer said:

> *"subsequent successful flight trials and entry into service without any serious operational limitations on STOVL operations prove that we got that aspect of the design right"* [S1].

Our research has led to the adoption (successfully demonstrated in 2018) of the shipborne rolling vertical landing (SRVL) for operations with the F-35B by UK forces. Such a manoeuvre markedly increases the "bring back" capability, reducing the likelihood of aircraft having to jettison unused payload (saving many tens of millions of pounds over the lifetime of the aircraft, and multiplying the force effectiveness). A senior BAE Systems engineer confirms*:*

> *"the work on strength, shape and penetration of the [ground jet horseshoe] vortex done by [Cranfield University at] Shrivenham gave a lot of confidence to designers to initially propose the SRVL solution…What you might call one of the underpinning technologies"* [S1].

**Reducing the extent of the flight test programme**

Our research on jet/intake interactions provided the evidence needed to allow for separate jet and intake testing on the JSF [S1]. This led to savings of approximately GBP1,000,000 - and gave designers increased confidence in the validity of their design, mitigating the risk of an overly restrictive operating envelope for the aircraft. As a senior Lockheed Martin engineer confirms:

> *"Cranfield identified that the flow into the intakes above the airframe was little affected by the jets below the airframe, saving more GBP millions in unneeded testing costs"* [S2].

An improved, more accurate design process allowed for a shortened flight test programme for this highly complex V/STOL aircraft. Even a straightforward flight test programme costs many hundreds of millions of pounds, which can be multiplied many-fold by poor design decisions.

**Wall jet development and safe ground operations**
Our research insights on wall jet development have been used by BAE Systems to predict safe operating conditions for ground personnel in the vicinity of a V/STOL aircraft [S1]. The findings provided the necessary evidence to allow exclusion zones for ground personnel to be reduced, meaning a less restrictive operating envelope for the aircraft [S1]. This approach has been adopted for operational trials and has been particularly important in shipboard operations that began in 2018.

**Assuring airworthiness**
Cranfield's original research delivered the systems engineering assurance framework needed to allow the UK MOD to go ahead with testing and operations from July 2012, following its acquisition of the F-35B aircraft. This was critical in overcoming the inconsistencies between US and UK socio-technical policies and technical standards. Our holistic approach to systems engineering ('Systems Engineering Structured Assurance' or SESA) was used by the UK's F-35B buying and certifying team to determine system threats and appropriate controls [S3].

The SESA arrangement allowed for a continuation of flight testing under restricted employment, the development of operator and maintainer techniques, and responses to the incremental addition of capability until November 2017 when the UK F-35B was formally granted a Release to Service by the UK military regulator. A senior RAF engineer said:

> *"I am able to confirm that the research provided direct benefit to the UK F-35B programme in enabling a means for the MOD to consciously approve the safe operation of the UK F-35 during 2012-2017; the experience gained during this period of operation, along with the evidence derived from further testing, enabled the subsequent release to service to be enacted"* [S3]

**Enhancement of the impact**

Knowledge and learning from the application of research has been shared via a series of continuing professional development courses for engineers and project managers from industry and government agencies in the UK and the US [S2]. Overall, more than 300 delegates attended courses on 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. A senior engineer for Lockheed Martin has said:

> *"It gave everyone involved in the [F-35B] program the same understanding of the issues and the solutions being developed"* [S2].

V/STOL aircraft design and operation has been incorporated into the MSc and CPD programme on Military Aerospace and Airworthiness (2009 onwards) run by Cranfield University largely for MOD and industry (including operators and procurers of the F-35B) working in the field of airworthiness and safety.

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

[S1] Technologist Advisor, Propulsion Integration, BAE Systems (currently Consultant Aerodynamicist)

| | |
|---|---|
| [S2] | Program Manager, Lockheed Martin Skunk Works (currently retired) |
| [S3] | Director, Combat Air, RAF (currently Engineering Director, BAE Systems) |