Institution:	The University of Liverpool
Unit of Assessment:	UoA12 Engineering
Title of case study:	Modelling and Simulation to Support UK Naval Ship Design and Aircraft Operations
Period when the underpinning research was undertaken:	2003 – 2020

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:**
MD White	Professor	1996 – present
I Owen	Emeritus Professor	1983-2011, (Em. 2016 – present)
GD Padfield	Emeritus Professor	1999-2011, (Em. 2011 – present)

Period when the claimed impact occurred: 1st August 2013 – 31st July 2020

Is this case study continued from a case study submitted in 2014? N

1. Summary of the impact

The University of Liverpool (UoL) has developed advanced modelling and flight simulation tools for the assessment of ship aerodynamics and its impact on pilot workload when flying aircraft to naval ships. UoL is internationally leading in this research field, using these tools for the first time during the design phase in ship building. The impact of this research is seen in the improved design of the UK's new Type 26 frigate leading to greater operational capability. Further impact has been achieved through reducing the risk, cost and carbon footprint associated with at-sea testing of the UK's new aircraft carrier HMS Queen Elizabeth. These outcomes were achieved by integrating our research with BAE Systems' new world-class flight simulator to improve the efficiency and reduce the risk associated with F35B aircraft flight trials operating to the aircraft carrier. The impact extends to export activities (Hunter Class ship, Australia) and informing best practise in NATO working groups.

2. Underpinning research

Launch and recovery of aircraft to ships at sea can be a risky and demanding task for pilots. The combination of a confined landing area, moving ship and the airflow over and around the ship's superstructure (i.e. the "airwake") are hazardous during aircraft operations at sea. UoL has been at the forefront of research to develop methods to integrate computational ship airwakes into flight simulators to assess their impact on pilot workload and safety. The computational and flight simulation tools developed at Liverpool [3.1, 3.2], provide the ability to inform ship design processes, to enhance aircraft operations and to prepare pilots for real-world trials, improving efficiency whilst reducing risk, cost, and fuel consumption.

The foundation of the experimental work was funded by EPSRC (EP/C009371/1) in 2006. In 2011, Owen developed an instrumented model-scale helicopter, the 'AirDyn' (Airwake Dynamometer) [3.3], that could be placed around the flight deck of a model ship to measure the magnitudes of the aerodynamic loads acting on the helicopter to assess the effect of ship design changes on helicopter operations [3.4]. Based on this research, a new computer-based simulation tool, the Virtual AirDyn, was developed in 2013 [3.5] to assess the unsteady loads on a simulated aircraft in the presence of an airwake generated by Computational Fluid Dynamics (CFD). Using the geometry of a real ship, CFD airwakes have been computed for various wind angles on a high-performance computer cluster. These airwakes have been integrated into an aircraft simulation environment which imposes time-varying velocity effects onto complex nonlinear aircraft simulation models. The Virtual AirDyn allows analysis of the design of a ship's superstructure from the perspective of the helicopter and pilot workload, which represents a step-change in ship design practices.

Validation of the CFD methodology was accomplished, through funding from two BAE Systems ICASE awards, using Acoustic Doppler Velocimetry to measure the flowfield around a scale model of the UK's new aircraft carrier, HMS Queen Elizabeth, in a 90,000-litre recirculating water tunnel [3.6]. Excellent agreement between the computed and measured results was achieved, which was important to provide confidence in the methodology.

Padfield joined the University in 1999, establishing an internationally leading flight simulation research group. Collaborating with Owen (2003), techniques were established [3.1, 3.2] to integrate computational ship airwakes into a flight simulation environment allowing pilots, to assess their impact on workload and safety. As with the CFD validation methodology described previously, it was also important to have a similar understanding of the fidelity of the flight simulation methods that have been developed. In 2003 Padfield commenced research on the assessment of simulation fidelity requirements for maritime operations [3.2]. Additional research funding from QinetiQ allowed White in 2016 to undertake a structured assessment of the various flight simulator components e.g. visual and motion system, on pilot performance to provide confidence in the current methodology as well as defining requirements for future simulations [3.7, 3.8]. Confidence in the underlying simulation methodology was essential for the design and operational assessment tools to be accepted and deployed.

3. References to the research

3.1 Roper DM, Owen I, Padfield GD, & Hodge SJ, "Integrating CFD and piloted simulation to quantify ship-helicopter operating limits", *The Aeronautical Journal,* 110:(1109), 419-428 (2006). doi:10.1017/S0001924000001329 – **Royal Aeronautical Society Bronze Medal award**

3.2 Hodge S, Forrest J, Padfield GD, & Owen I, "Simulating the environment at the helicopter-ship dynamic interface: research, development and application", *The Aeronautical Journal,* 116:(1185), 1155-1184 (2012). doi:10.1017/S0001924000007545 - **Royal Aeronautical Society Gold Award**

3.3 Wang Y, Curran J, Padfield GD and Owen I, "AirDyn: An instrumented model-scale helicopter for measuring unsteady aerodynamic loading in airwakes", *Meas. Sci. Tech.*, 22 (4), 045901 (2011). doi:10.1088/0957-0233/22/4/045901

3.4 Kaaria C, Wang Y, White MD and Owen I, "An experimental technique for evaluating the aerodynamic impact of ship superstructures on helicopter operations", *Ocean Engineering*, 61: 97 – 108, (2013). doi: 10.1016/j.oceaneng.2012.12.052

3.5 Kaaria C, Forrest J and Owen I, "The Virtual AirDyn: a simulation technique for evaluating the aerodynamic impact of ship superstructures on helicopter operations", *The Aeronautical Journal,* 117: (1198) 1233-1248, (2013). https://doi.org/10.1017/S0001924000008836

3.6 Watson NA, Kelly MF, Owen I, Hodge S and White MD, "Computational and experimental modelling study of the unsteady airflow over the aircraft carrier HMS Queen Elizabeth", *Ocean Engineering,*172: 562-574, (2019). https://doi.org/10.1016/j.oceaneng.2018.12.024

3.7 Memon, WA, Owen I, and White MD, "Motion Fidelity Requirements for Helicopter-Ship Operations in Maritime Rotorcraft Flight Simulators", *AIAA Journal of Aircraft*, 56: (6), 2189–2209, (2019). https://doi.org/10.2514/1.C035521

3.8 Memon WA, Owen I, and White MD, "SIMSHOL: A Predictive Simulation Approach to Inform Ship-Helicopter Clearance Trials", *published online AIAA Journal of Aircraft 11 May 2020*. https://doi.org/10.2514/1.C035677

4. Details of the impact

Background: Previously, the effect of a ship's superstructure aerodynamics on the operational envelope of a helicopter was not assessed until after the ship had been built and evaluated through expensive sea trials. By this time, it is too late to make any structural changes. From 2012, working with BAE Systems (Surface Ships and Military Air and Information), White and Owen developed modelling and simulation tools to improve the design of new naval ships to improve operational capability (Type 26 frigate) [5.1, 3.2] and also reduce the cost and risk of at-sea testing (HMS Queen Elizabeth aircraft carrier (QEC)) [5.2, 3.6]. The validated tools have also been used to inform the placement of ship's anemometers which measure the at-sea wind conditions. Earlier ships have suffered from inadequate anemometer placement leading to poor predictability of the measured wind and to reduced helicopter operating capability. Liverpool's research has informed the deployment of anemometers for current and future ships. The following sections indicate that impact has been achieved in the current REF assessment period.

International Reach: Recognising the impact of this research area, further collaboration was forthcoming with Westland (now Leonardo) Helicopters, the UK Ministry of Defence (MoD), BAE Systems and EPSRC. Wider collaboration with international defence agencies, particularly in the US, Canada and Australia, and membership of international bodies and working groups further extended the reach of the research. As the Liverpool research matured, the modelling and simulation methods were adopted in two projects:

- Firstly, the design of frigates including the Type 26 (GBP8 billion); the Australian Hunter class [5.3] (AUD35 billion) and the Canadian Type 26 (CAD69.8 billion) ship programmes.
- Secondly the development and application of a full motion simulator by BAE Systems to prepare for the integration of the F-35B Lightning stealth fighter with the aircraft carrier HMS Queen Elizabeth, a combined programme costing approximately GBP16.7 billion.

The research has led to improved ship designs and to more effective at-sea flight trails, so improving operability, saving time and expensive resources. To date, the direct beneficiaries have been BAE Systems Surface Ships, BAE Systems Air Warfare, and the UK MoD.

Influencing government policy and practice: The impact of the research was identified in its early years by the MoD. Owen and White were invited [5.4] to be UK representatives (the only ones from academia) on the Aerospace Systems Group of The Technical Cooperation Programme (TTCP), a body with representatives from the UK, US, Canada, Australia and New Zealand, which coordinates and disseminates international research into maritime helicopter operations. Owen and White were also invited by the MoD to represent the UK on a NATO working group (AVT-217) which coordinated international efforts in ship design guidance for aircraft operations. In 2017, the Group received a NATO AVT Panel Excellence Award in recognition of their "extraordinary scientific contribution".

Transforming Flight Simulation Methods: White and Owen were invited by UK MoD in 2014 to produce a strategy document for the use of modelling and simulation in support of future aircraft ship clearance activities. Modelling and simulation are now being used more extensively to support aircraft clearance activities. This has impacted government (MoD) policy and practice as evidenced by its application in the first ever simulated flight trials of an aircraft to a ship, involving both the air and ship's crews, so setting the trend for the future. White and Owen were engaged by BAE to apply their research to the new QEC aircraft carriers (Figure 1) to help prepare crews and reduce the risk in F-35B operations to the QEC; the first time modelling and simulation had successfully been employed to achieve this [5.2, 5.5]. The validation methodology described in Section 2 [3.6] was instrumental in the development of the flight simulator at BAE Systems Warton which was used in 2018/19 to optimise, in terms of time and cost, the F35 flight trial programme. The success of this approach was acknowledged by the pilots, "*Our trial preparation was extensive, and the simulator unequivocally formed the backbone of our efforts giving us the utmost of confidence from Day One onwards. As I hovered alongside for the first time, I felt an overwhelming déjà vu. That's testament to the team creating a world class simulator – a test pilot's dream*", RAF F35 Test pilot [5.6]. The impact of the research at Liverpool was acknowledged by a BAE Systems Chairman's Innovating for Success Award (2018) and a BAE Systems Executive Committee Innovating for Success Award (2019) for Liverpool's contribution to the joint BAE/Liverpool activity, indicating that the impact of the work has "*delivered a competitive advantage*…to the (BAE) *business*." The award was made recognising that the "*innovative models have inspired the highest levels of confidence in simulated conditions around the ship and helped ensure that F-35B flight trials could take place safely*".

Figure 1 The first ever F-35B Lightning II jet take off from HMS Queen Elizabeth on Sept. 25, 2018 – *"Coming into land for the first time on Tuesday…the interaction between the aircraft and the ship is exactly as expected, as we've simulated thousands and thousands of times….,"* the pilot said. "*There were no surprises*." [5.7]

Owen and White are currently leading a new NATO working group (AVT-315) which is determining best practice for modelling and simulation methods in this domain, extending the impact of Liverpool's research internationally [5.8].

Professional practice in design: Based on Liverpool's previous research, Owen and White were commissioned by BAE Systems Surface Ships in 2012 to provide design advice for the new Type 26 frigate [5.1]. To maximise the wind conditions under which the ship's helicopters can operate it is essential that the superstructure does not unnecessarily shed excessively large and unsteady flow features into the flight path. Initial designs presented to Owen and White showed that the ship had a 'stealthy' superstructure, but with several features which were of concern because of their aerodynamic profile and their emitted thermal signature. Using UoL's modelling and simulation methodologies, a comprehensive aerodynamic and thermal analysis of the ship's design was undertaken for a full range of helicopter and ship operating conditions. UoL's analyses led to design changes for the ship's superstructure and placement of its measurement equipment to provide more capability for the ship and reduce the cost and risk associated with remedial changes due to poor initial designs. This represents a step change in ship design practices and has produced a new methodology for future ship design processes. Construction of two Type 26 ships commenced in 2017 with six more on order [5.9]. This new design practice was included in BAE System's successful bid for Australia's Hunter Class frigate [5.3], an AUD35 billion ship design and build programme, and the new Canadian Type 26 programme. This experience has also been fed into TTCP and NATO projects [5.8], so extending the reach of the impact.

5. Sources to corroborate the impact

5.1 Letter from BAE Systems Surface Ships, Type 26 Global Combat Ship to corroborate input to Type 26 design.

5.2 Letter from BAE SYSTEMS Global Engineering Fellow, Aircraft-Ship Integration Lead and F-35/QEC First of Class Flight Trials Lead, BAE Systems Air to corroborate input to Queen Elizabeth Class aircraft carrier project

5.3 Letter from BAE Systems Surface Ships, Hunter Class Team to corroborate input to Hunter Class design.

5.4 Letter from Defence Science & Technology Laboratory of the UK MoD to corroborate statement relating to TTCP and MoD Modelling and Simulation strategy document

5.5 BAE website describing collaboration with University of Liverpool in modelling and simulation for virtual reality training, 02/10/20 .pdf
https://www.baesystems.com/en-uk/feature/virtual-reality-training-for-the-toughest-challenges

5.6 Video from RAF Museum of test pilot describing the first landings by F-35 aircraft on air craft carrier HMS Queen Elizabeth in 2018 https://rafm.tours/experience/it-was-a-walk-in-the-park-18485

5.7 News report for U.S. Naval Institute https://news.usni.org/2018/09/28/first-f-35bs-operate-off-hms-queen-elizabeth-u-k-works-toward-native-carrier-strike-group

5.8 Letter, Co-Chair AVT-315, Research Officer, Institute for Aerospace Research, National Research Council Canada to corroborate internationally leading AVT-315 activity 20/11/20.

5.9 Royal Navy web site describing the structure and use of the new Type 26 Frigate:
https://www.royalnavy.mod.uk/the-equipment/ships/frigates/city-class