Institution: University of Glasgow (UofG)		
Unit of Assessment: UoA 12 – General Engineering		
Title of case study: Computational fluid dynamics changes aircraft policy guidelines, increases airport capacity and delivers new capability to industry engineers		
Period when the underpinning research was undertaken 2001–2017		
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:**
Prof George Barakos	Lecturer Professor	2001–2005 2015–present
Period when the claimed impact occurred: 2015–present		
Is this case study continued from a case study submitted in 2014? No		

1. Summary of the impact

New methods in computational fluid dynamics (CFD) developed by Prof Barakos have delivered enhancements in understanding of aircraft / wind turbine and aircraft / aircraft wake interactions that have: (i) impacted policy by defining new safe aircraft separations at major airports for fixed and rotary wing aircraft; and (ii) defined safe separations of aircraft and wind turbines. As a result, aircraft separations for landing and take-off have been reduced at Europe's largest airports, generating millions of pounds of additional revenue per year. The new CFD methods are now also embedded in the design and analysis of Leonardo's current and future helicopters, providing unsurpassed capability and securing the future of their helicopter division.

2. Underpinning research

Prof Barakos has researched methods to simulate flows around rotary wings of helicopters and wind turbines since his first appointment at UofG in 2001 [3.1–3.6]. The resulting UofG-based CFD code was transferred to the University of Liverpool with Barakos in 2005 [5.1]. Barakos rejoined UofG in September 2015 and has continued to develop his body of work centred around the original UofG CFD code from his 2001–2005 appointment. His CFD methods have impacted the design of new aircraft and have led to new policy guidelines in the regulation of aircraft take-off and landing at airports in the UK and Europe.

Barakos' innovative research models the complex interaction between fluids and structures. For example, the blades of helicopters and wind turbines experience large structural deformations that affect their efficiency. The methods developed include modules to trim helicopter or wind turbine blades for specific conditions, with an accuracy that reduces the required number of expensive wind tunnel tests and prototypes.

CFD research linked to wakes

Barakos' CFD research was identified by the Civil Aviation Authority (CAA) as a key technology to allow safe separation criteria to be established between light aircraft and wind turbines, and between light fixed-wing aircraft and helicopters [3.1–3.4]. Wakes are airflow disturbances produced by aircraft and wind turbines that have been implicated in aircraft crashes, where the aircraft inadvertently crossed a wake during landing. Such crashes triggered an investigation by the UK CAA using CFD, *in-situ* measurements of wakes at East Midlands Airport and flight simulators to quantify the wake encounter hazard and produce pilot guidance. In 2015, this prompted *The European Organisation for the Safety of Air Navigation* (EUROCONTROL) to use the Barakos CFD expertise at UofG to develop their *European Wake Turbulence Categorisation* *and Separation Minima on Approach and Departure* (RECAT-EU). These are guidelines that detail the minimum separations that should exist between different types of aircraft, and the CFD work has enabled separation reductions at major airports.

CFD in modelling flow around helicopters and tilt-rotor blades

Barakos' work in CFD has given engineers from multinational aerospace company, Leonardo, the ability to model flows around rotary-wing aircraft blades. His long-standing research collaboration with Leonardo to develop advanced CFD methods began at UofG in 2001. An example is their work on the tiltrotor, a type of aircraft that combines the capabilities of aircraft and helicopters. The primary advantage is their vertical take-off and landing capabilities, and they are faster than comparable helicopters. Work is ongoing to allow for efficient and competitive designs of tiltrotor vehicles to enter the market and be certified for civil operations. UofG research focused on blade design optimisation and performance using CFD, under the *Innovative Aerodynamic Design Solutions for High-Performance Tiltrotor Aircraft* (HIPERTILT) project funded by Leonardo and Innovate UK [3.5, 3.6]. This research is now embedded in the 'Helicopter Multi-Block' (HMB) CFD tool, extensively used by Leonardo in their design and analysis of helicopters. Consequently, their engineers have the capability to optimise the shape of the tiltrotor wing and blades to deliver higher speed and better fuel utilisation.

3. References to the research

3.1. Nayyar, P., Barakos, G. N. and Badcock, K. J. (2007) Numerical study of transonic cavity flows using large-eddy and detached-eddy simulation. Aeronautical Journal, 111(1117), pp. 153–164. (doi: 10.1017/S0001924000004413)

3.2. Beedy, J., Barakos, G., Badcock, K., & Richards, B. (2003). Non-linear analysis of stall flutter based on the ONERA aerodynamic model. The Aeronautical Journal (1968), 107(1074), 495–510. (doi: 10.1017/S0001924000134001)

3.3. Barakos, G.N. and Drikakis, D. (2003) Computational study of unsteady turbulent flows around oscillating and ramping aerofoils. International Journal for Numerical Methods in Fluids, 42(2), pp. 163–186. (doi: 10.1002/fld.478)

3.4. Allan, M. R., Badcock, K. J., Barakos, G. N. and Richards, B. E. (2004) Wind-tunnel interference effects on a 70 degrees delta wing. Aeronautical Journal, 108, pp. 505–513. (doi: 10.1017/S0001924000000336)

3.5. Wang, Y., White, M. and Barakos, G.N. (2017) Wind-turbine wake encounter by light aircraft. Journal of Aircraft, 54(1), pp. 367–370. (doi: 10.2514/1.C033870)

3.6. Barakos, G. N. and Gates, S. (2017) Tiltrotor CFD part I: validation. *Aeronautical Journal*, 121(1239), pp. 577–610. (doi: 10.1017/aer.2017.17)

4. Details of the impact

Prof Barakos' CFD research at UofG has delivered: a) aircraft safety and policy changes; b) increased airport capacity; c) enhanced design and analysis capability at Leonardo.

Impacts on CAA policy guidance and enhanced safety

Barakos' CFD research expertise, founded on work from his initial UofG appointment [5.1], has directly led to new guidance from the CAA in the CAP 764 document, *'CAA Policy and Guidelines on Wind Turbines'* (2016), stating that light aircraft pilots should remain 5 rotor diameters away from wind turbines with diameter of less than 30m [5.2 pp32–34, 5.3]. This is a new rule based entirely on Barakos' research. This policy influences the activity of aircraft pilots, wind farm developers, local planning authorities and farmers using crop-spraying aircraft operating close to the ground and near wind turbines [5.2, 5.3]. The guidance enhances the safety of all parties and outlines a means of approving planning of wind farm development [5.2 p38]. This is important to the UK government as it tries to balance priorities of safety, renewable energy and the economic importance of aviation to the UK [5.2 p8].

Barakos' research featuring CFD to understand the effects of wakes has been adopted by EUROCONTROL to develop RECAT-EU (European Wake Turbulence Categorisation and Separation Minima on Approach and Departure) [5.3, 5.4]. In September 2015, RECAT-EU guidelines, which replaced previous wake vortex separation rules, were informed by Barakos' CFD models of aircraft separations to define new safe aircraft separations [5.3, 5.4 p7 para 6]. RECAT-EU has been adopted by air traffic control in Europe's largest airports, including Paris Charles de Gaulle (CDG) where RECAT-EU has been operating 24/7 since March 2016 [5.5, 5.6]. Heathrow, Schiphol, Leipzig-Halle and Le Bourget also use RECAT-EU. Deployment has enhanced airport safety and capacity, resulting in a significant increase of aircraft movements [5.6, slide 4].

Barakos' research and the RECAT-EU guidelines also enable helicopters to blend efficiently and safely with fixed-wing traffic (the US equivalent of RECAT-EU does not allow this), promoting better use of airports and higher safety standards. Recognising this, Barakos was awarded funding for a research project from the *Network for Innovative Training on Rotorcraft Safety* (NITROS; 2017) [5.7], focussed on using CFD and resulting wake information to determine the safe proximity of aircraft to wind turbines [5.6].

<u>Enhanced design capability at Leonardo</u>

Barakos' blade optimisation research (HIPERTILT) programme has provided high fidelity CFD design tools which allow engineers at Leonardo to explore new design concepts in the development of tiltrotor aircraft [5.8, p1 para 4]. The tiltrotor vehicle is a concept that with modern technology is set to change the way we fly, covering the gap between helicopters and fixed-wing aircraft in range and speed. Tiltrotor vehicles present capabilities to emergency and relief operations including air-ambulances and the distribution of humanitarian aid. This vehicle has been the top priority in the UK National Aerodynamics Committee agenda and top priority for Leonardo within CleanSky and CleanSky2 (EU programmes developing innovative technology to reduce the environmental impact of aircraft) [5.8, p1]. Barakos' UofG research was shared with Leonardo to enable optimal rotor analysis and design [5.8, p2 para 1]. Within the HIPERTILT project, training sessions for Leonardo engineers ensured that new designs were tested using Barakos' CFD tools [5.8, p2 'Approach to Impact']. The 700 tiltrotor engineers are part of a team of 3,000 Leonardo staff working in Yeovil (Somerset, UK) [5.8, p1 para 3]. The relationship with Prof Barakos at UofG is 'strategically important' to Leonardo [5.8, p3 para 5], securing their future and the UK's tiltrotor industry.

<u>Increased airport capacity</u>

RECAT-EU allows airports to recover more rapidly from adverse weather conditions and can increase runway throughput by over 5% [5.4 p21]. RECAT-EU has increased the number of aircraft taking off from European airports, which is linked directly to considerable economic impacts. The Director of Navigation Services for Paris CDG explained that the airport now has an increased throughput of aircraft [5.9]. *"We are very proud of having deployed this new operational concept at one of the busiest airports in Europe. This project is the result of close cooperation with EUROCONTROL. It has brought quick wins in terms of safety and capacity: thanks to RECAT-EU, runway throughput at Paris-CDG has increased by 2−4 aircraft movements per hour at peak periods."* Given that each flight landing and taking off from CDG must pay a fee in the region of EUR400, CDG alone has seen an increased annual revenue of several million euros from RECAT-EU [5.10 p1]. Similarly, Heathrow have an average of an extra 17 aircraft movements per day (6,205 movements/year), generating increased revenue from RECAT-EU [5.11, p19].

5. Sources to corroborate the impact

[all available as PDFs unless otherwise indicated]

5.1. University of Glasgow CFD code transfer acknowledgement
5.2. CAP 764 document ‘CAA Policy and Guidelines on Wind Turbines’
5.3. Testimonial: Head of Airports, EUROCONTROL
5.4. RECAT-EU information for stakeholders document
5.5. EUROCONTROL Press Release: RECAT-EU now in use at Paris Charles de Gaulle 24/7
5.6. Presentation: RECAT EU for Paris-CDG and Le Bourget
5.7. Publication: NITROS: An Innovative Training Program to Enhance Rotorcraft Safety
5.8. Testimonial: Head of UK Strategic Development, Leonardo Helicopters,
5.9. EUROCONTROL Press Release: RECAT-EU at Paris-CDG, a first in Europe
5.10. Groupe ADP (Aeroports de Paris): Landing fees in Paris
5.11. NATS Briefing for Heathrow Crew: Enhanced Time Based Separation (ETBS) & RECAT EU