Institution: Manchester Metropolitan University (MMU)

Unit of Assessment: B7 Earth Systems and Environmental Sciences

Title of case study: Offshore Renewable Energy Deployment

1. Summary of the impact

Examples are provided of significant impact by the Centre for Mathematical Modelling and Flow Analysis (CMMFA) upon the Marine Renewables and Offshore Wind communities. In particular, CMMFA informed the design of a novel wave energy converter being commercialised for connection to the national grid. CMMFA has also contributed to a study of the design parameters for an offshore wind power station as part of a larger interdisciplinary collaborative research effort. This work responds to and informs the RCUK Energy Programme via underpinning research, capacity building and provision of trained personnel thus enacting UK Government Energy Policy.

2. Underpinning research

The context for the Impact case study is the UK Department of Energy and Climate Change 2007 Energy White Paper and its UK Renewable Energy Roadmap and 2012 update. These documents set out the UK Government policy and target to deliver 15% of UK energy from renewables by 2020. Eight technology areas are identified: onshore wind, offshore wind, marine energy, biomass electricity, biomass heat, ground/air source heat pumps and renewable transport. Responsibility for delivering the technology rests in part with the RCUK Energy Programme, which, through its funded programmes, seeks to position the UK to meet its energy and environmental targets and policy goals through world-class research with impact, capacity building and training. The RCUK programme, with £625M invested thus far, is helping the UK to make evidence-based policy decisions on energy addressing the climate change agenda, including changes to regulatory mechanisms and impact assessments. CMMFA's research and Impact case study is linked to 2 of the above 8 technology areas, namely marine energy and offshore wind.
Active in the area of free surface hydrodynamics since 1995, CMMFA has developed in-house advanced computational fluid dynamics (CFD) models and software. The work cited relates to the environmental impact assessment arising from climate change, sea level rise and increased storm activity in the offshore environment. This has critical implications for the safe deployment and survivability of past, existing and proposed offshore structures for both wind and wave power, which in deep water are increasingly likely to be novel floating structures. The design and survivability of these structures depends critically on the reliability of hydrodynamic impact load predictions. These are a key component of a fully integrated design solution for offshore marine structures involving other disciplines such as electrical power engineering, materials science, rotor aerodynamics and condition monitoring as well as environmental impact, regulatory and socio-economic issues.
Supported by experimental studies conducted in collaborating partner laboratories at Bath, Edinburgh, Hull, Lancaster, Manchester, Oxford, Plymouth and Queen's Belfast universities, work was focused upon constructing a detailed, validated, computational model in the form of a so-called numerical wave tank (NWT). This simulates both laboratory-scale and full-scale devices in realistic wave climates and led to the development of the CMMFA's AMAZON suite of flow codes. CMMFA brought novel developments in numerical techniques over the discipline boundary from its pre-1995 work in aeronautical CFD. CMMFA pioneered their use in the sister discipline of hydrodynamics. These included optimized adaptive mesh generation that preserves the favourable properties and simplicity of rectangular grids whilst combining these with so-called cut (trimmed) cells **[1]** that align with stationary irregular boundaries/terrain, or objects moving with up to six degrees of freedom (DoF); and, Riemann-based flow solvers that provide high resolution of cell-interface fluxes **[2]**. The suite of codes developed included i) a numerical wave flume based on the shallow water equations (a depth-integrated form of the Navier-Stokes equations) suitable for calculating wave run-up in near-shore regions **[3]** and, ii) a 3D NWT based on a full two-fluid viscous Navier-Stokes solution in both air and water regions above and below the free (water) surface. This can model wave generation, steepening, overturning and breaking over a structure **[4, 5]**. In the NWT, numerical wave paddles move, either singly or in groups, to generate the required wave characteristics, e.g. directionally focussed waves. Boundary conditions eliminate reflections or allow waves to pass through. Outputs are a full set of flow variables e.g. pressure and velocity fields, water surface elevations, forces and body motion response. These supplement laboratory experiments and prototype testing. The result is a fully detailed flow model incorporating

all relevant physics above and below the water surface. This includes the fluids, air and water, aeration as waves break and impact a structure, wind effects on waves and the motion response of the structure. In contrast contemporaneous diffraction models and potential flow codes were not suitable for breaking waves whilst previous NWTs based on the full Navier-Stokes equations did not include compressible phenomena such as aeration and cavitation. This may be important in quantifying loadings under extreme wave conditions in which structures must survive **[6]**.
Since 1999, the group's work in the hydrodynamics area has been funded continuously by the EPSRC via 12 research grants and two Joule Centre grants, (total > £10M). Seven of these are within the current REF period (four are current). The majority of awards involve collaboration with leading laboratory-based groups (as stated above) or are multi-disciplinary consortium-led collaborations, e.g. with project partners in the EPSRC SUPERGEN programmes. The group has produced over 60 peer-reviewed publications in the underpinning area.

Key CMMFA Researchers

Professor Derek Causon, 1986 – present.
Professor Clive Mingham, 1989 – present

3. References to the research

[1] Causon DM, Ingram DM and Mingham CG (2001). A Cartesian Cut Cell Method for Shallow Water Flows with Moving Boundaries. Advances in Water Resources. **24**:899-911. **DOI:** 10.1016/S0309-1708(01)00010-0, *(48 citations)*
[2] Mingham CG and Causon DM (1998). A High Resolution Finite Volume Method for the Shallow Water Equations. Journal of Hydraulic Engineering. **124**(6):605-614. **DOI:** 10.1061/(ASCE)0733-9429(1998)124:6(605), *(137 citations)*
[3] Hu K, Mingham CG, Causon DM, (2000). Numerical simulation of wave overtopping of coastal structures using the non-linear shallow water equations. Coastal Engineering **41**(4):433-465. **DOI:** 10.1016/S0378-3839(00)00040-5, *(113 citations)*
[4] Qian L, Causon DM, Mingham CG and Ingram DM (2006). A Free-Surface Capturing Method for Two Fluid Flows with Moving Bodies. Proceedings of the Royal Society of London: A **462 (2065)**:21-42. **DOI:** 10.1098/rspa.2005.1528, *(47 citations)*
[5] Hu ZZ, Causon DM, Mingham CG and Qian L (2011). Numerical Simulation of Floating Bodies in Extreme Free Surface Waves. Natural Hazards and Earth Systems Science 11(2): 519-527. **DOI:** 10.5194/nhess-11-519-2011, *(2 citations)*
[6] Causon DM and Mingham CG (2013). Finite Volume Simulation of Unsteady Shock-Cavitation in Compressible Water. International Journal of Numerical Methods in Fluids. **72**(6): 632-649.

Research Grants:

1) EPSRC GR/M42428: Impulsive Wave Overtopping of Seawalls and Related Coastal Structures – Numerical Simulation: 05/99 – 09/02. £168,385. PI: Causon.
2) EPSRC GR/N24162: Numerical Prediction of Multi-Component Fluid Systems Using a Cartesian Cut Cell Method: 02/01 – 01/03. £78,190. PI: Causon.
3) EPSRC GR/S12333: An Experimental and Numerical Study of Oscillating Wave Surge Converters (OWSC's): 01/03 – 12/05. £120,377. PI: Mingham.
4) EPSRC GR/S23827: Violent Waves at the Coast- Are we safe at the seaside? (Public Engagement): 04/03 – 10/05. £41,412. PI: Causon.
5) EPSRC GR/T18622: Free Surface Simulation of Wave Overtopping during Storms: 04/05 – 03/07. £92,296. CI: Causon.
6) EPSRC EP/D077621: Extreme Wave Loading on Offshore Wave Energy Devices Using CFD: A Hierarchical Team Approach: 02/07 - 01/10. £116,530. PI: Causon.
7) EPSRC EP/D034566: Supergen Wind Energy Technologies Phase 1: 03/06 – 03/10. £2,552,788. PI: Mingham.
8) EPSRC EP/F069162: A Hybrid Turbulence Approach for Simulation of Breaking Waves and Their Impacts on Coastal Structures: 01/09 – 7/11. £223,956. PI: Qian.
9) EPSRC EP/H018662: SUPERGEN WIND ENERGY TECHNOLOGIES-CORE, Towards the Offshore Wind Power Station: 03/10 – 03/14. £4,834,191. PI: Mingham.
10) EPSRC EP/J010197: SUPERGEN MARINE: Modelling Marine Renewable Energy Devices; Designing for Survivability: 6/12 – 6/15. £1,039,617. PI: Causon.
11) EPSRC EP/J012793: FROTH: Fundamentals and Reliability of Offshore Structure Hydrodynamics: 11/12 – 10/15. £241,712. PI: Causon.
12) EPSRC EP/K037889: Virtual Wave Structure Interaction (WSI) Simulation Environment: 5/13 –

4/16. £323,344. PI: Causon.
13) Joule Centre F-60024: A Numerical Study of a Novel Wave Energy Converter (Neptune): 03/07 – 02/08. £99,000. PI: Mingham.
14) Joule Centre F-60042: A Joint Numerical and Experimental Study of a Surging Point Absorber Wave Energy Converter (WRASPA): 04/08 – 03/09. £105,000. PI: Mingham.

4. Details of the impact

1) Marine Energy

On EPSRC grants GR/S12333 and GR/S12326 CMMFA and project partners, Queen's University Belfast (QUB) carried out a linked experimental and numerical study of Oscillating Wave Surge Converters (OWSCs). The Marine Renewables Energy Group at QUB are acknowledged world-leading device developers within the wave energy community credited with the development and installation of LIMPET, the world's first grid-connected wave energy converter (WEC). The OWSC was a novel hybrid of the LIMPET oscillating water column device and a pendulor-type system with a hinged paddle surge converter. The work involved wave tank tests at QUB and numerical modelling with CMMFA's AMAZON suite of codes to extensively map the parameter space of the device. This enabled particular parameters such as the hinge point location and position of an inclined back plane to be isolated, studied in detail and revised. The models allowed realistic scenarios to be explored to provide device productivity results. **The impact was design guidance for OWSC devices and the OYSTER WEC was developed as a direct result of this project [A]**.

Subsequently, Aquamarine Power plc with a team of 45 people was formed in 2005 to bring the OYSTER technology to the commercial market **[B]**. Since 2010, two full-scale prototypes of OYSTER 800 have been built and tested. In May 2013, the Scottish Government granted a license for Aquamarine Power plc to develop the world's largest grid-connected commercial wave power array deploying around 50 OYSTER devices with a combined capacity to power almost 30,000 homes **[C]**. **In 2012, RCUK cited OYSTER as one of its Impact exemplars of UK energy research and capacity building [D]**.

2) Offshore Wind

The CMMFA was Co-Investigator on the Phase 2 EPSRC SUPERGEN WIND ENERGY TECHNOLOGIES-CORE Consortium project EP/H018662, 'Towards the Offshore Wind Power Station' [2010-2014]. This involved 26 academic and 7 industrial partners undertaking research to achieve an integrated, cost effective, reliable and available Offshore Wind Power Station. CMMFA was also a Co-Investigator on Phase 1 of the SUPERGEN WIND Energy Technologies Consortium project EP/D034566 [2006-2010]. The focus of the SUPERGEN WIND project was on the technological challenges related to the exploitation of the UK's extensive offshore wind resource through interdisciplinary research consisting of all relevant branches of engineering embracing environmental impact, socio-economic and regulatory aspects. In particular, this included electrical power engineering; condition monitoring; use of innovative materials and active load reduction; rotor aerodynamics; lighting and radar visibility; subsea foundations and hydrodynamics.

The project had 2 parallel themes. The first dealt with the underlying physics and engineering of the offshore wind turbine farm whilst the second looked specifically at the wind turbine itself, building upon SUPERGEN Phase 1. The results of the two themes are now feeding into a third Gathering Theme, which is developing the wind farm as an offshore power station. Development focuses upon how the station should be designed, operated and maintained for optimum reliability. It also considers what form future developments should take such as the up-scaled facilities on novel floating structures and the economics associated with their implementation.

CMMFA was the only UK CFD group involved as Investigators in SUPERGEN WIND Phases 1, 2 with sole project responsibility for the subsea foundations and hydrodynamics areas. Working with partners at Lancaster and Hull universities, it combined numerical modelling with laboratory studies of foundation scour at wind turbine mounts and wave loading on fixed and floating mounts.

Knowledge transfer (KT) in SUPERGEN WIND Phase 1 and 2 occurs outside of the traditional dissemination routes of academic publications. In SUPERGEN WIND KT occurs through i) formal Consortium Management Group Meetings, which are attended by all academic partners and the 7 industrial project partners (e.g. E.ON plc, GL Garrad Hassan, Alstrom Grid Ltd) **[E]**, ii) Research Monographs targeted at knowledge transfer to industry **[F]** and iii) development of future industrial energy leaders through EPSRC Doctoral Training Centres (DTCs). These DTCs are part-funded by industrial partners who are also involved in project selection, placement and recruitment of doctoral students **[G]**. Knowledge transfer also occurs via the SUPERGEN WIND Annual Assembles **[H]** at which CMMFA have presented their research. Annual Assemblies are attended by over 50 industrial players in the wind energy sector and EPSRC Programme Managers and Policy Makers, who set and revise the agenda for the RCUK Energy programme. CMMFA were invited participants at the January 2013 Wind Energy Scoping Workshop convened by EPSRC **[I]**. This workshop defined the research areas to be prioritised for funding in Phase 3 of the 5-year programme from 2015, leading to the current Call for Proposals under SUPERGEN WIND. The new areas in Phase 3 include further work proposed by CMMFA on improved and adventurous foundation concepts to increase understanding of the dynamics of floating platforms in deeper water underpinned by the work carried out by CMMFA and partners in Phase 2 of the programme. CMMFA is the only UK university research group involved as investigators and project partners in both SUPERGEN WIND and SUPERGEN MARINE **[J]** programmes.

5. Sources to corroborate the impact

[A] Text attributed to EPSRC Grant EP/K041010: Pathways to Impact, page 1. [Confidential Source: available].

[B] Source: Aquamarine Power plc website: http://www.aquamarinepower.com/about-us/

[Accessed: 20-11-13].

[C] Source: BBC News Scotland Business: Ministers approve plans for world's biggest wave farm in Western Isles: http://www.bbc.co.uk/news/uk-scotland-scotland-business-22611317 [Accessed: 20-11-13].

[D] Source: Research Councils RCUK: Impact of energy research and capacity building. New technology will the harness power of the sea: http://www.rcuk.ac.uk/research/xrcprogrammes/energy/impactenergy/Pages/Newtechnologywillharnessthepowerofthesea.aspx [Accessed: 20-11-13].

[E] The SUPERGEN Wind Energy Technology web site provides details of project academic and industrial partners: http://www.supergen-wind.org.uk/partners.html [Accessed: 28-05-13].

[F] The cited knowledge transfer Research Monograph can be found via the link: http://www.supergen-wind.org.uk/dissemination.html [Accessed: 20-11-13].

[G] Details of the cited current Doctoral Training Centre can be found via the link at the Impact of RCUK Energy Programme 'Impact of energy research and capacity building' site: http://www.rcuk.ac.uk/research/xrcprogrammes/energy/impactenergy/Pages/Breathingnewlifeintowindenergy.aspx [Accessed: 20-11-13].

[H] The programme for the most recent SUPERGEN Wind Phase 2 – 3rd General Assembly can be found via the link: http://www.supergen-wind.org.uk/assembly2013.html Other General Assembly meetings, Events; publications; project information; details of Consortium Management Group Meetings can be found at the Supergen Wind Energy Technologies Consortium main project web site: http://www.supergen-wind.org.uk Copies of industrial dissemination and presentations can be found via the Downloads link. [Accessed: 20-11-13].

[I] Details of the EPSRC Wind Energy scoping workshop held on 18 April 2013 that defines Phase 3 and subsequent Call for Proposals for SUPERGEN WIND Phase 3 [2015-2020]: http://www.epsrc.ac.uk/SiteCollectionDocuments/Calls/2013/SUPERGENWindHubCallDocument.pdf [Accessed: 20-11-13].

[J] The SUPERGEN Marine Energy Research Consortium web site: http://www.supergen-marine.org.uk/drupal/ provides full details of the funded projects; academic partners; industrial partners; Consortium Management meetings, Grand Challenge projects and Annual Assembles. [Accessed: 20-11-13].