Institution: Swansea University

Unit of Assessment: 10 - Mathematical Sciences

Title of case study: Techniques for Improved Electromagnetic Design in the Aerospace Industry

1. Summary of the impact

Research at Swansea University in the area of computational electromagnetics has led to better design of aircraft with respect to radar detection and the screening of internal systems from the effect of unwanted electromagnetic field ingress. A key issue was the development of an ability to accommodate electromagnetically large complex bodies having spatially small, but electromagnetically important, features. In addition, procedures for modelling RF threats, including lightning strikes and electromagnetic hazards, were also developed. Such progress has enabled significant improvement in electromagnetic performance of technology produced by BAE Systems reaching across its Advanced Technology Centre and its business units (Military Aircraft and Information, and Naval Ships). This research enabled two-orders-of-magnitude improvement in efficiency of BAE software compared to previously used techniques, significantly reducing design time. These developments were used on major international programmes such as TYPHOON, the Taranis UCAV (unmanned Combat Air Vehicle).

2. Underpinning research

The UoA and the College of Engineering have a long tradition of collaboration across the field of applied mathematics resulting in many joint publications. This interdisciplinary activity was officially formulised by the creation of WIMCS and the appointment of Prof Ken Morgan to lead the computational modelling activities at the University. Recently, a new appointment in the UoA (Arranz-Carreno) has further strengthened the collaborative programme, which is planned to continue into the future. Research carried out by Morgan, in partnership with BAE Systems, was initiated using applied mathematics and numerical methods to address specific industrial requirements in computational electromagnetics. The main problem of interest was the simulation of the scattering of electromagnetic waves by complex, electrically-large, multi–material objects (aircraft and sea-going vessels in particular). Also addressed was the major problem of electromagnetic field penetration into the interiors of bodies, and the threat of their coupling to internal systems. This problem is of particular relevance to electromagnetic hazards and compatibility.

The mathematical models and solution methods developed involved a novel combination of an unstructured grid continuous Galerkin formulation within material layers, and a discontinuous Galerkin approach at material interfaces which used a characteristics-based formulation ensuring phase accuracy [R1]. This approach resulted in a stable, phase-accurate time-domain algorithm for dealing with the electromagnetic jump conditions across curvilinear material boundaries. The basic Swansea grid generator was developed to enable the handling of both geometric detail and electromagnetic features, such as wires and thin resistive sheets via embedding techniques. The parallelisation and integration of grid generators and solvers was achieved in major European projects and enabled the modelling of electrically large, engineering problems [R2, R3], White–space reduction techniques were developed by hybridising solution methods with overlapping grids [R4]. This achieved an overall reduction of computational complexity with two-orders-of-magnitude improvements in efficiency over unstructured grid finite element methods previously used by BAE Systems. Stability analyses of hybrid schemes and their dependence on inter-grid interpolation was established, and limits obtained for phase accuracy for wave propagation over electrically-large bodies. Phase accuracy studies were performed to assess effectiveness of high-order and hybrid methods on near-resonant coupling to wires and dipole antennas. In later work, undertaken as part of the five year EPSRC/BAE Systems FLAVIIR project, a method for prediction of RF threats, including high intensity radiated fields (HIRF) and lightning strike, was developed [R5]. The FLAVIIR project was the winner of the Aerospace Category of the 2011 Technology and Innovation Awards in *The Engineer*.

Related frequency domain research [R6], undertaken with EPSRC support and in collaboration with the group of Professor Mark Ainsworth at Strathclyde University, led to significant insights into the application of hp-adaptivity in the solution of Maxwell's equations.

Main personnel involved:

- Academic Staff at Swansea University: Prof O. Hassan (1994-present), Prof K. Morgan (1991-present), N.P. Weatherill (1987- 2008)
- Research Staff at Swansea University: M. El hachemi (2000-2008), Z.Q. Xie (2004-12)
- Research Students at Swansea University: P. Brookes, J. W. Jones, P. D. Ledger (1999–2001, Research Staff 2002–2003, Academic Staff since 2006), R. Said

3. References to the research

Publications Swansea authors in **bold.** Publications 1, 2 and 4 best indicate the quality of the research.

R1. **K. Morgan, O. Hassan,** N. E. Pegg **and N. P. Weatherill,** The simulation of electromagnetic scattering in piecewise homogeneous media using unstructured grids, *Computational Mechanics*, 25:438–447, 2000.

R2. **K. Morgan, P. J. Brookes, O. Hassan and N. P. Weatherill**, Parallel processing for the simulation of problems involving scattering of electromagnetic waves, *Computer Methods in Applied Mechanics and Engineering*, 152:157—174, 1998.

R3. **K. Morgan, N. P. Weatherill, O. Hassan, P. J. Brookes, R. Said and J. Jones**, A parallel framework for multidisciplinary aerospace engineering simulations using unstructured meshes, *International Journal for Numerical Methods in Fluids*, 31:159—173, 1999.

R4. **M. El hachemi, O. Hassan, K. Morgan,** D. Rowse **and N. P. Weatherill**, A low-order unstructured mesh approach for computational electromagnetics in the time domain, *Philosophical Transactions of the Royal Society of London, Series A*, 362:445—469, 2004.

R5. C. Christopoulos, J. F. Dawson, L. Dawson, I. D. Flintoft, **O. Hassan**, A. C. Marvin, **K. Morgan**, P. Sewell, C. J. Smartt and **Z. Q. Xie**, Characterisation and modelling of electromagnetic interactions in aircraft, *Proceedings of the Institution of Mechanical Engineers Part G: Journal of Aerospace Engineering*, 224:449−458, 2010

R6. **P. D. Ledger,** J. Peraire, **K. Morgan, O. Hassan and N. P. Weatherill**, Adaptive hp finite element computations of the scattering width output of Maxwell's equations, *International Journal for Numerical Methods in Fluids*, 43:953—978, 2003.

Major Relevant Research Grants

G1. **K. Morgan,** High frequency CEM simulation, BAE Systems, 1997–1998, £60K.

G2. **N. P. Weatherill**, Joint industrial interface for end–user simulations (JULIUS), EU, 1998–2001, £270K,

G3. **K. Morgan**, Adaptive finite element procedures for electromagnetic scattering, EPSRC, 1999–2002, £170K,

G4. **K. Morgan,** Error estimation applied to FE methods for CEM, EPSRC Visiting Fellowship for Professor J. Peraire from MIT, 2000, £20K.

G5. **O. Hassan**, Time domain CEM solver developments suitable for hybrid and overset structured grids, BAE Systems, 2000–2003, £130K.

G6. **O. Hassan**, Grid enabled computational electromagnetics, BAE Systems and EPSRC, 2003–2005, £103K.

G7. **K. Morgan**, Integrated programme of research in aeronautical engineering, EPSRC and BAE Systems, 2004–2009, £267K.

4. Details of the impact

The close interaction and collaboration with BAE Systems resulted in the creation of a computational electromagnetics technology that has empowered design engineers to use computational modelling to shorten design cycle times. In addition, engineering insight, hitherto unavailable, has been gained through the comparison of high fidelity modelling results with trials data. The adoption and use of robust, low-order, Galerkin-based schemes, using unstructured grids, for the time-domain solution of Maxwell's equations for the analysis of scattering from complex multi-material bodies, resulted in a step-change in capability for modelling electromagnetic systems within BAE Systems. The work guided the adoption of mesh refinement strategies at BAE Systems, resulting in increased accuracy in Radar Cross Section (RCS) prediction for problems involving scattering from electrically large objects with localised small-scale features. The accurate modelling of multi-material, multi-layer structures enabled the optimisation of radar absorbing material, the characterisation of *in situ* frequency selective surfaces by means of full-field optimisation and the investigation of sophisticated Jaumann absorbers for low observable platforms.

"BAE Systems has worked very closely with the Swansea group both defining the requirements and guiding the research. This has involved co-working and the exchange of research personnel between Swansea and the Advanced Technology Centre (ATC), including the recruitment of experienced research personnel from Swansea as an adjunct to technology transfer. The success of the high-risk research undertaken by Swansea has resulted in developed technology being taken in-house and further developed by BAE Systems' personnel for business-specific requirements, not least of these being the inclusion of sophisticated frequency dependent material's models. Given the scale of BAE Systems and its diverse interests, the enormity of the breadth and scope of problem to which the resulting time-domain capability has been applied is extensive and its geographic application international. The technology has enabled the analysis of problems across the broad spectrum of the Electromagnetic Engineering (EME) domain."
[Former Executive Scientist and Technology Fellow, BAE Systems, ATC, Filton]

The results of electrically large simulations were also used to devise trials for complex engineering platforms. The modelling process was used, and further developed to a high degree of sophistication, by BAE Systems Military Aircraft and Information. This led to savings, in both time and money, on the radar range and in the quantification of the manufacturing and engineering tolerances required to avoid spurious scattering from features on low observable platforms.

The developed capability was used on such diverse programmes as TYPHOON and the Taranis UCAV. In 2009, the four nations of the Eurofighter consortium signed the contract for the first 112 of the Tranche 3 production aircraft.

The underpinning modelling capability developed by Swansea assisted BAE Systems participation in European Framework projects FULMEN, CATE and EMHAZ which addressed aircraft protection from the direct and indirect effects of lightning, issues of electromagnetic compatibility and protection against electromagnetic interference. The ability of the approach to model non-coordinate aligned wires and cables, contributed to analyses performed in the pan-European 26M€ HIRF-SE (High Intensity Radiated Field Synthetic Environment) 7th Framework project.

"*In the area of electromagnetics, financial support from, and close technical liaison with, BAE Systems ATC led to the adoption of the Swansea unstructured mesh approach as a design tool within BAE Systems at the ATC, at Naval Ships and at Military Air and Information. The technology has had critical impact on:*

(a) unmanned Combat Air Vehicle (UCAV) design, demonstrating the principle of rapid full field solutions, showing the art of the possible and formulating the future technology direction for key programmes for the MoD;

(b) testing and evaluation for the analysis of design options prior to trials and subsequent comparison with experimental range results;

(c) the modelling of frequency selective surfaces (FSS) for radomes and aperture windows;

(d) the analysis of lightning strike induced arcing and sparking phenomena for product reliability;

(e) EMC analysis and meshing for aircraft and naval vehicles, radiation hazard (RADHAZ) analysis for naval platforms including Type 23 and Future Aircraft Carrier (CVF, Elizabeth Class);

(f) greater integration of EM and CFD modelling as the commonality of unstructured numerics ensured that the subsequent development and industrialisation cost of the delivered codes was greatly reduced, enabling BAE Systems to capitalise on its expertise and deliver tighter integration between electromagnetic and aerodynamics, which is the key to BAE Systems core competencies in integrated design and utilised on the Taranis UCAV programme for example."

[University & Collaborative Programmes Relationship Manager, BAE Systems, ATC, Filton]

5. Sources to corroborate the impact

(i) Letter from University & Collaborative Programmes Relationship Manager, BAE Systems, Advanced Technology Centre, Filton, Bristol BS34 7QW

(ii) Letter from Former Executive Scientist and Technology Fellow, BAE Systems , Advanced Technology Centre, Filton, Bristol BS34 7QW