EPSRC CDT in Fluid Dynamics across Scales

Simulation of Complex Three-Dimensional Vortex Interactions using High-Order Computational Fluid Dynamics

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- Technical introduction and background

Airflows generated by missiles in free-flight commonly feature multiple vortices, e.g. as shed from the forebody and lifting surfaces. The close mutual proximity of these vortices means that they interact; these interactions can have a fundamental impact on the overall aerodynamic behavior of the missile. Accurate prediction of such vortex-dominated flows is of critical importance to the design of next-generation missile systems. However, current generation Computational Fluid Dynamics (CFD) tools have a limited capability in this regard.

Over the past five years we have been working to develop a new generation of CFD technology specifically designed for accurate simulation of such vortex-dominated flows in the vicinity of complex engineering geometries. Specifically, the technology combines the increased accuracy of so-called high-order Flux Reconstruction (FR) schemes with the capabilities of modern hardware platforms such as GPUs, and has been implemented in the open-source solver PyFR (www.pyfr.org). This technology has been demonstrated at extreme scale on some of the world's largest super computers for a range of test problems. However, its utility for the type of vortex-dominated flows associated with missile aerodynamics has yet to be assessed.

- Objectives and Methodology

The overall objective of the project is to assess the utility of GPU accelerated high-order FR schemes (PyFR) for the accurate simulation of turbulent and vortex dominated flows that are of relevance to missile design. In this regard, the project will have a focus on novel application and usage as opposed to numerical methods and software development – although such aspects may become pertinent depending on the results that are obtained.

The research will be constructed around the lessons learned from a test case on a generic missile airframe developed by MBDA: CFD_OTC1. This has been carefully designed to exhibit vortex interactions (illustrated in Figure 1) that, if not modeled accurately, will yield errors in predicted aerodynamic performance that are likely to have significant consequences for other system components (e.g. the autopilot).

The research will begin by building upon the lessons learned by MBDA regarding the limitations of contemporary CFD practice. Guided by the resulting understanding, a suite of increasingly challenging test cases will be devised to help isolate the constituents of the wider simulation problems and allow the potential utility of PyFR to be assessed. These test cases may begin by addressing unit problems (such as understanding the requirements for simulating the interactions of two vortices in isolation) but will progress to more challenging scenarios, with the ultimate goal of addressing CFD_OTC1 (which is a compressible flow - the freestream Mach number is 1.6 – at substantial - by contemporary standards – scale: the missile length is 4m).

- Main elements and rough schedule of work programme

- Y1 (MRes): Familiarisation in use of PyFR and capabilities of contemporary CFD tools as applied to CFD_OTC1.

- Y2 (PhD): Initial application of PyFR to vortex interaction test cases.

- Y3 (PhD): Progressively more informed application of PyFR to increasingly complex test cases.

- Y4 (PhD): First in-class, large-scale assessments of PyFR on CFD_OTC1, write up.

- Information sources and references

Literature concerning FR schemes:

- An Extended Range of Stable-Symmetric-Conservative Flux Reconstruction Correction Functions. P. E. Vincent, A. M. Farrington, F. D. Witherden, A. Jameson. Computer Methods in Applied Mechanics and Engineering, Volume 296, Pages 248-272, 2015

- Insights from von Neumann Analysis of High-Order Flux Reconstruction Schemes. P. E. Vincent, P. Castonguay, A. Jameson. Journal of Computational Physics, Volume 230, Issue 22, Pages 8134-8154, 2011

- A New Class of High-Order Energy Stable Flux Reconstruction Schemes. P. E. Vincent, P. Castonguay, A. Jameson. Journal of Scientific Computing, Volume 47, Number 1, Pages 50-72, 2011

Literature concerning PyFR:

- Towards Green Aviation with Python at Petascale. P. E. Vincent[†], F. D. Witherden, B. C. Vermeire, J. S. Park, A. Iyer. ACM Gordon Bell Finalist and Best Paper Finalist. Article 1. SC16 Proceedings of the International Conference for High Performance Computing, Networking, Storage and Analysis, 13-18 November 2016, Salt Lake City, Utah, USA

- Heterogeneous Computing on Mixed Unstructured Grids with PyFR. F. D. Witherden, B. C. Vermeire, P. E. Vincent. Computers and Fluids, Volume 120, Pages 173-186, 2015

- PyFR: An Open Source Framework for Solving Advection-Diffusion Type Problems on Streaming Architectures using the Flux Reconstruction Approach. F. D. Witherden, A. M. Farrington, P. E. Vincent. Computer Physics Communications, Volume 185, Issue 11, Pages 3028-3040, 2014

Literature concerning Missile Aerodynamics:

- Missile Aerodynamics, AGARD Special Course on Missile Aerodynamics, AGARD Report 804, May 1994

- Recent Advances in the Integration of CFD into the Missile Design Process, Dodds, M., Lawson, S. and Taylor, N., 50th 3AF International Conference on Applied Aerodynamics, Toulouse, March 2015

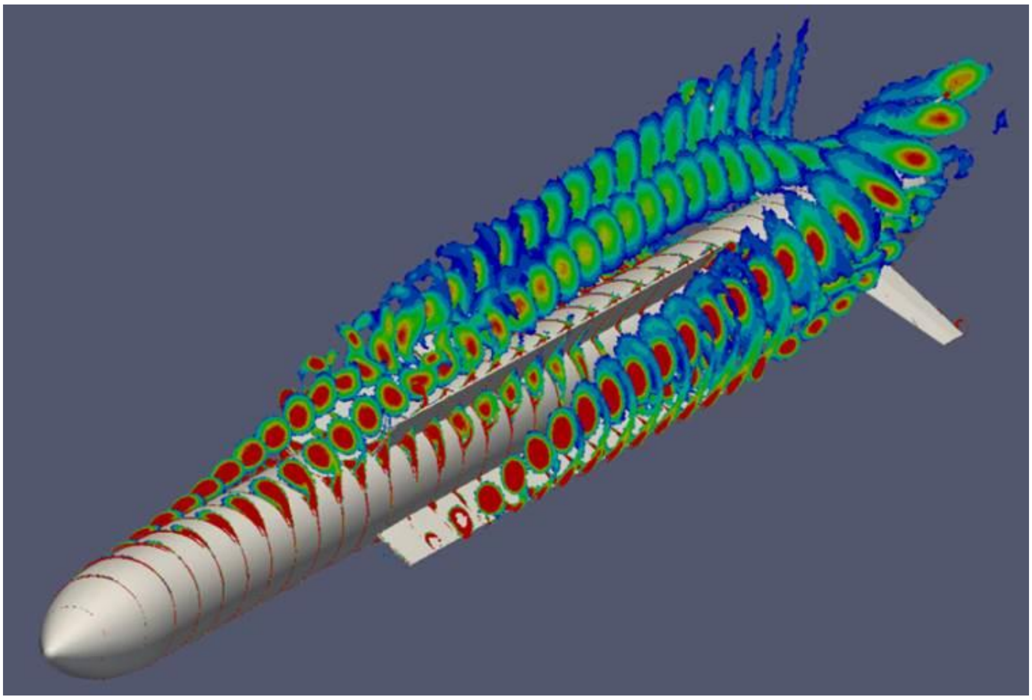

Fig 1: Image of vortex dominated flow field over generic missile configuration obtained using contemporary MBDA CFD tools.