Institution: University of Southampton

Unit of Assessment: 15 General Engineering

Title of case study: 15-06 Turbulence Generation Method in Urban Environment and Wind Engineering Applications

1. Summary of the impact

Work by the University of Southampton's Aerodynamics and Flight Mechanics research group (AFM) has led to advances in the field of Computational Fluid Dynamics, a key element of the accurate and cost-effective modelling of airflow and turbulence. New techniques have been incorporated in commercial software releases (e.g. **CD-adapco**'s Star-CD v4) and adopted by leading design and engineering firms (e.g **Arup, Buro Happold**), giving UK businesses a significant edge over their international competitors. Specifically,

- **CD-adapco** with its client base of more than 7,000 users and 3,000 firms, using the new techniques, enjoy a competitive advantage;
- *AFM's work* has helped **Arup** to significantly improve the efficiency and accuracy of design, and **Arup**'s standing on projects.

The techniques have been increasingly influencing the design of wind-sensitive structures by facilitating the faster, cheaper and more precise prediction of factors such as peak wind loading and pollutant dispersion.

2. Underpinning research

Large-eddy simulation (LES) has been a cornerstone of the science of modelling airflow and turbulence for some decades. Its accurate and increasingly cost-effective use is of growing importance in a range of research fields and related industry sectors, including the clean environment, safety assessment, construction and engineering. In industry, simulations are usually conducted using commercial Computational Fluid Dynamics (CFD) codes, because of the absence of real-time predictive tools.

The University of Southampton's Aerodynamics and Flight Mechanics (AFM) research group is a recognised leader in CFD. This is evidenced not least by its long-standing leadership of the UK Turbulence Consortium, which coordinates the use of Britain's supercomputers for large-scale CFD simulations and seeks to maximise the potential of ever-increasing computer power in modelling turbulence. Supported by EPSRC, NERC, EU and industry, AFM has been at the forefront of efforts to apply LES to wind flows in urban environments, with a view to developing methods that are sufficiently accurate to compute the turbulence and consequent heat transfer and pollutant dispersion within urban canopies.

With funding from NERC via the Universities Weather Research Network, a forerunner of the National Centre for Atmospheric Science, Professor Ian Castro (Professor of Fluid Dynamics, AFM, 2000-present) launched this strand of research in 2003. He remains involved today. The key contributor is Dr Zheng-Tong Xie (Senior Research Fellow, AFM, 2004-2007; Lecturer, 2007-present). Other contributors have included Dr Venkata Bharathi Boppana (Research Fellow, 2008-present).

In 2008 Xie and Castro published a paper **[3.1]** that offered the first detailed description of a novel way of specifying the inflow boundary conditions for turbulence simulations using LES. Their proposal was based on a new Hybrid Forward Stepwise (HFS) method, a filter-based concept that was shown to be far more efficient and exact than previous methodologies. Xie and Castro argued that the shortcomings of earlier techniques, including the use of white noise and the need to run "precursor" simulations, not only tended to deliver notably inaccurate results but added to complexity and computational times. As well as the obvious benefits of improved precision, the comparative speed of their HFS method – around 500 times faster than the first filter-based approach, which entered the literature in 2003 – gave rise to clear implications for the cost-effectiveness of simulations.

The new method's high levels of efficiency, demonstrated in a series of tests that simulated flows over smooth walls and arrays of staggered cubes, were in large part derived from employing a digital filter technique that eschewed the use of three-dimensional data in favour of a two-dimensional alternative. The satisfactory validation of the results represented an important step towards addressing the longstanding problems associated with applying LES to areas consisting of streets, parks and other urban features.

Subsequent research demonstrated the power of HFS by computing various kinds of generic and field (i.e. "real-life") urban-type flows. These included an analysis of the Marylebone Road area of London, which led to significant predictive improvements (i.e. reducing errors and uncertainties down to one tenth of those without using this technology) of pollutant dispersion compared with experimental data **[3.2, 3.3].** These studies have provided confidence for coupling mesoscale meteorological models (e.g. the UK Met Office's Unified Model) with the street-scale LES of urban environments **[3.3].** Related work has addressed specific features of turbulence, pollutant dispersion and heat transfer in urban canopies and peak loading of tall building and bridge **[3.4-3.6]**, supported by ongoing grants and contracts (listed in **§3** below).

3. References to the research (the best 3 are starred)

[3.1]* Xie, ZT, and Castro, IP (2008): Efficient Generation of Inflow Conditions for Large-Eddy Simulation of Street-Scale Flows, *Flow, Turbulence and Combustion*, **81**, 449-470.

[3.2]* Xie, ZT, and Castro, IP (2009): Large-Eddy Simulation for Flow and Dispersion in Urban Streets, *Atmospheric Environment*, **43**, 2174-2185.

[3.3]* Xie, ZT (2011): Modelling Street-Scale Flow and Dispersion in Realistic Winds – Towards Coupling with Mesoscale Meteorological Models, *Boundary-Layer Meteorology*, **141**(1), 53-75.

[3.4] Boppana, B, Xie, ZT, and Castro, IP (2013): Large-Eddy Simulation of Heat Transfer from a Single Cube on a Very Rough Wall, *Boundary-Layer Meteorology,* **147**, 347-368.

[3.5] Kim, Y, Castro, IP and Xie, ZT (2013) Divergence-free turbulence inflow conditions for large-eddy simulations with incompressible flow solvers. *Computers and Fluids*, **84**, 56-68.

[3.6] Daniels, SJ, Castro, IP and Xie, ZT (2013) Peak loading and surface pressure fluctuations of a tall model building. *Journal of Wind Engineering and Industrial Aerodynamics*, **120**, 19-28.

Grants

Castro, IP, Bluff Bodies in Boundary Layers, EPSRC, 2002-03 – £262,203

Castro, IP, Modelling the Urban Atmospheric Environment, UWERN, NERC, 2003-07 – £186,000

Castro, IP, Turbulent Flows over Rough Walls, EPSRC, 2006-09 – £374,528

Xie, ZT, and Castro, IP, Modelling the Urban Atmospheric Environment, NCAS, NERC, 2007-13 and ongoing – £510,000 so far

Xie, ZT, Industrial CASE PhD Studentship: Evaluation of Vortex Shedding of Slender Structures, EPSRC and Arup, 2011-15 – £93,000

Xie, ZT, Thomas TG, Castro IP, Dispersion of localised releases in a street network (DIPLOS), EPSRC, 2014-17, £220,000

4. Details of the impact

The improved accuracy and cost-effectiveness of large-eddy simulations in urban environments gives rise to a number of benefits. Firstly, the companies that supply the Computational Fluid Dynamics (CFD) codes that facilitate a cutting-edge approach in this field enjoy a competitive advantage **[5.1-5.3].** Secondly, enhanced understanding and numerical prediction lead to better and more efficient design and superior safety assessment **[5.4, 5.5].** Thirdly, *AFM*'s research has significantly strengthed the companies' modelling capability **[5.6-5.9].** Details of all this are given below.

CD-adapco is the world's largest independent provider of engineering simulation software, support and services. Based in the UK and with 30 offices around the world, it employs 700 staff and has a client base of more than 7,000 users and 3,000 firms. In 2010, in direct response to its customers' needs, the company implemented AFM's new inflow turbulence generation method as a plug-in for its CFD software **[5.1-5.3],** which is specifically geared towards satisfying the growing legislative emphasis on sustainability and emissions.

In May 2011 CD-adapco released a beta program, STAR-CD v4.16, which included a User Manual relating to the new method. This Manual was developed in collaboration with Xie and Castro. A month later the company made AFM's method available to its client base in an official version of STAR-CD [5.3]. A number of CD-adapco's users have been using the method. Dr Fred Mendonca, CD-adapco's Director of Aeroacoustics, has remarked that

> "We appreciate indeed the successful collaboration with your *Southampton University* group in the last few years… We view *your research* in this area as being of direct value to the sectors. … Utilisation of our software with *your sub-models* implemented enhances fundamental learning and numerical prediction in these sectors", adding: "Our software use among a worldwide client-base exceeds 7000, an increasing proportion of which uses LES modelling where *your methodology* has a direct impact " **[5.1].**

One of the major companies to have used AFM's method is **Ove Arup and Partners Ltd. (Arup)**, which is widely recognised as among the world's leading design and engineering firms. Arup is based in the UK and employs over 11,000 people worldwide, with 10,000 projects active at any one time. On 20th September 2007, Prof *Castro* presented an invited talk for Arup on CFD/LES approaches to a Wind Engineering Design Workshop for architects and urban & city planners, held at Tate Modern. In November 2011, Arup invited *AFM* to help with the preliminary estimation of wind loads on the Gerald Desmond Bridge Replacement, a structure with a 1000ft main span and a unique cross-section planned for construction in California **[5.4].** The replacement bridge will be two miles long, including over 6,000ft of elevated approach viaducts up to 200ft high. Dr Ngai Yeung has commented that

> "Having looked into *your group's* very helpful simulations, we have more confidence to use such aero-coefficients for preliminary sizing before a sectional model wind tunnel testing is carried out…".

AFM's work has also helped Arup to generate a better cost estimation in time. The joint venture - which includes Arup (who is the design lead) - submitted a design-build proposal earlier in 2012 that was selected as the "best-value" proposal, and was awarded a US$649.5 million design-build contract in July 2012.

As a result of this successful collaboration, in July 2012 Arup began to adopt *AFM's methods* in all LES applications for commercial projects, beginning with a stadium being designed in Doha, Qatar, for the 2022 World Cup **[5.5].** More recently, Arup has used these methods for the Vanquish high-rise building project in the City of London. Dr Ender Ozkan has commented that

> "The initial computational flow simulations that were carried out with the support of *Dr Xie's team* have helped provide a vital understanding of wind-related issues by the client ahead of

the wind tunnel tests. This in turn improved the efficiency of the subsequent wind tunnel tests and Arup's standing on the project. This has demonstrated that we have been paving the way for using *such tools* more regularly in the future" **[5.5].**

Dr Ender Ozkan has also commented that

"For many years the ability to accurately simulate turbulent wind flows around bluff structures has been outside the grasp of commercial firms such as ours. But nowadays, with the help of collaborations such as the current industrial CASE project with *University of Southampton*, we are starting to use such computational techniques for various projects across the world", adding "*This (AFM) calibrated inflow method* improves the accuracy of our simulations greatly" **[5.5].**

Dr Ozkan has indicated Arup's intention to reduce its dependence on wind-tunnel labs and instead focus on LES, using *AFM's* turbulence inflow techniques **[5.5].**

AFM researchers have also worked to raise awareness of the value of precise and cost-effective LES across a wider range of sectors, e.g., **Buro Happold** and German SME Ingenieurbüro **Lohmeyer** GmbH & Co. KG **[5.6-5.8].** Dr Marcus Letzel, a Senior Scientist at Lohmeyer, has commented "Without *your method*, we would not be able to produce satisfactory OpenFOAM LES results with our limited computational resources" **[5.7]**.

Wider outreach efforts have included lectures and presentations to the **Atmospheric Dispersion Modelling Liaison Committee** (Didcot, September 2009), the **Environment Agency** (Cardiff, March 2011) and the **UK Wind Engineering Society** (London, September 2011). The editor of Benchmark, the magazine for members of the **National Agency for Finite Element Methods and Standards**, described an article by *Dr Xie* in the October 2011 edition as

"…of interest to all readers, regardless of the technologies or industries you focus on", adding "This is what NAFEMS is all about - the sharing and discussion of new techniques, applications and findings within a community of like-minded individuals who share a passion for analysis and related technologies" [5.9].

5. Sources to corroborate the impact

[5.1] *Factual statement*: Dr Fred Mendonca, Director of Aeroacoustics, CD-adapco.

[5.2] *CD-adapco Report*: http://www.cd-adapco.co.uk/pdfs/articles/Urban_Scale_Weather_Modeling.pdf

[5.3] *CD-adpaco User Manual*: Supplementary notes for STAR-CD v4.16, May 2011.

[5.4] *User and beneficiary*: Dr Ngai Yeung, Associate, Arup.

[5.5] *Factual statement*: Dr Ender Ozkan, Advanced Technology and Research Associate, Arup's London headquarters. Dr Steven Downie, Senior Engineer of Advanced Technology and Research, Arup's London headquarters.

[5.6] *Factual statement*: Dr Bernardo Vazquez, Associate, Buro Happold.

[5.7] *Factual statement*: Dr MarcUs Letzel, Senior Scientist, the German SME Ingenieurbüro Lohmeyer GmbH & Co. KG.

[5.8] *Lohmeyer Report*: http://www.lohmeyer.de/en/openfoam.

[5.9] *Report:* Article in NAFEMS Benchmark Magazine, October 2011, http://www.nafems.org/publications/benchmark/archive/oct11/.