HEFAT2010
7th International Conference on Heat Transfer, Fluid Mechanics and Thermodynamics
19-21 July 2010
Antalya, Turkey

IMPLICIT LARGE EDDY SIMULATION OF CHANNEL AND URBAN ENVIRONMENT FLOWS

Drikakis D.*, Shapiro E., Kokkinakis, I., Papachristou, C.
*Keynote Speaker
Department of Aerospace Sciences,
Cranfield University,
Cranfield, Bedfordshire,
MK43 0AL,UK,
E-mail: d.drikakis@cranfield.ac.uk

ABSTRACT

The paper presents implicit large eddy simulations (ILES) of low speed flows in conjunction with different computational methods raging from second to ninth order of accuracy. The simulations include channel and urban environment flows based on a model of an array of buildings. The aim of this study is to demonstrate the accuracy of several different ILES models against direct numerical simulations (DNS) and experimental data.

INTRODUCTION

Despite the rapid increase in computing power, DNS of turbulent flows still requires significant computational resources for modelling all turbulent flow scales [1].

Large Eddy Simulation (LES) has emerged as an alternative. In particular, there are increasing efforts in relation to ILES [2-7], where the large scales of motion are resolved and the small scales are implicitly modelled through the dissipative properties of high-resolution schemes.

Based on the authors' experience, ILES typically requires several orders of magnitude less computational resource than DNS, e.g., ILES simulations for flows around wings have been performed at Reynolds number of $2.1 \cdot 10^5$ using a grid of $1.27 \cdot 10^6$ nodes [5]; the simulations provided satisfactory accuracy with respect to the key flow features such as transition, separation and vortex development, and the numerical results were in very good agreement with the experimental data for the velocity and turbulent shear stress profiles.

The ILES properties have been previously explored for a number of numerical schemes for both compressible and incompressible flows. The early studies focussed on second- and third-order schemes such as flux-corrected transport (FCT) [8]; variants of Godunov-type schemes [9, 10], and the piecewise-parabolic method (PPM) [11]. Despite progress in the development of ILES methods, the computational requirements of turbulent simulations, which are governed by the need to resolve the inertial range of the turbulent energy cascade, are still high, thus motivating the application of refined high-resolution and high-order methods for compressible and incompressible flows.

A 5^{th}-order Monotone Upstream Conservation Laws (MUSCL) scheme for variables reconstruction [12] has been demonstrated to provide accurate representation of turbulent flows for both single [13-15] and multi-phase [4] problems. Further reduction of subgrid dissipation can also be obtained through the application of Weighed Essentially Non-Oscillatory (WENO) schemes [16]. The application of 5^{th} and 9^{th}-order WENO schemes to single and multi-phase, transitional and turbulent flows has been presented in [4, 14]. An additional control mechanism for subgrid dissipation is provided by the Low Mach Number Treatment (LMNT) proposed in [17]. This approach combines adaptive non-linear blending of the high-resolution reconstructed variables with a central difference scheme. LMNT improved the accuracy of single phase homogeneous turbulence and multi-species shock-induced turbulent mixing [17].

It is worth noting that although the ILES properties of the aforementioned numerical schemes have been explored predominantly in the context of compressible flows, a number of ILES schemes have also been developed specifically for incompressible flows, e.g., [18,19]. Furthermore, the artificial compressibility approach for incompressible flows [20] allows application of the schemes devised for hyperbolic systems to low speed gas as well as liquid flows [21]. A comprehensive review of the numerical schemes with appropriate subgrid dissipation exhibiting ILES properties can be found in [2, 3].

The aim of this paper is to present results from different ILES models for low-speed, effectively incompressible flows. All computations reported in this paper have been performed using the CFD code CNS3D which incorporate block-structured and unstructured grid solvers for single and multi-component flows. The simulations were conducted on Cranfield's Astral 7.2 Tflops HPC cluster.

CHANNEL FLOW

The channel flow is one of the major canonical flows used in the validation of LES methods [22]. Incompressible DNS results for this benchmark are widely available. In particular, the DNS study by Kim et al. [23] is frequently used in LES simulations. ILES modelling of a channel flow at nominal friction Reynolds number Re_τ =395, based on the wall friction velocity is presented. The bulk-average Reynolds number can be calculated using the experimental correlation [24]:

$$Re=(Re_\tau /0.09)^{1/0.88} \quad (1)$$

The averaged wall-shear stress obtained from the computations yields the actual friction Reynolds number. The comparison between the actual and nominal wall friction Reynolds numbers can be used as an indicator of the near-wall turbulence resolution.

The compressible solver CNS3D was employed at Mach number of 0.2. The time integration was performed using the Total Variation Diminishing (TVD) variant of the third-order Runge-Kutta method [25]. The viscous fluxes were discretised using 2nd-order central differences. The Harten-van Leer-Lax-Contact (HLLC) approximate Riemann solver of [26] was used in the discretisation of the convective fluxes. The reconstruction methods included the MUSCL scheme with the 2nd-order Monotonised Central (MC) limiter [27] and the 5th-order limiter proposed by Kim and Kim [12] (M5), as well as the 9th-order WENO scheme [16]. Further refinement of the numerics was obtained through the application of the Low Mach Number Treatment (LMNT) [17].

A schematic of the geometry is shown in Figure 1. The channel dimensions are 2π x 2π x 2π, which correspond to the DNS study [23]. Symmetry boundary conditions were used in the streamwise (x) and spanwise (y) directions and no-slip condition was applied at the solid wall boundaries (z). A forcing term was added to the x-momentum equation in order to preserve the mass flux following [28]. The initial conditions were defined as a laminar parabolic profile with a 10% white noise perturbation. The results presented in this section correspond to a statistically steady state, as determined by the time history of the integral wall shear stress.

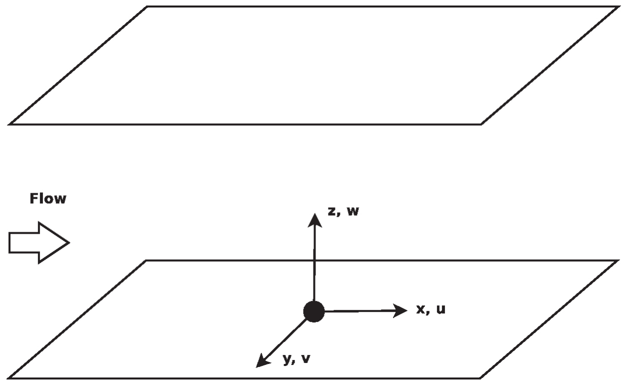


Figure 1 Schematic of the channel flow geometry

The details of the grids used in the present ILES and reference DNS study are given in Table 1.

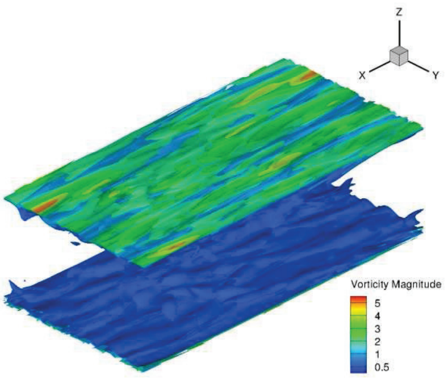
Grid	Nx, Ny, Nz	z+
G1	96 x 96 x96	1.0
G2	128 x 128 x 128	0.74
DNS	256 x 192 x193	0.03

Table 1 Computational grids employed in the present ILES and reference DNS [23] simulations .

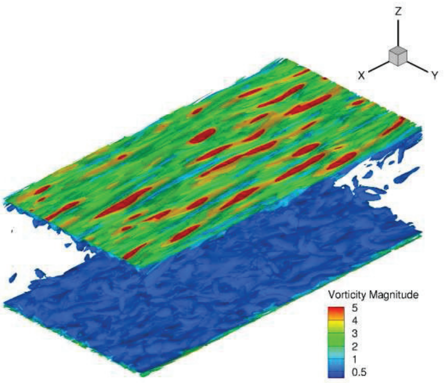
Figure 2 shows the instantaneous isosurfaces of vorticity for computations performed with the 2nd-order MC and the 9th-order WENO schemes on G2 grid. The near-wall streamwise vorticity streaks, typical for turbulent channel flows, are resolved with both schemes; however, finer structures seem to be captured by the 9th-order scheme.

The friction Reynolds number as obtained from the simulations varied from 291 (MC with no LMNT) to 415 (WENO 9th with LMNT). The reduction of dissipation obtained by increasing the accuracy in the variables reconstruction and/or by using LMNT consistently leads to higher friction Reynolds number. Figure 3 shows results from different ILES models for the turbulent velocity profile based on wall co-ordinates.

The second-order scheme is dissipative, especially on the coarser grid; however, the results obtained with the 5th and 9th order schemes are in good agreement with the DNS data, especially when they are used in conjunction with LMNT, whereas the 9th-order WENO scheme gives better results without LMNT. This is shown both for the friction velocity (Figure 3c) and for the Reynolds stress (Figure 4). The discrepancies between ILES and DNS data in the proximity of channel's centreline are attributed to the coarser grid in this region, which is due to the grid clustering in the near wall region.

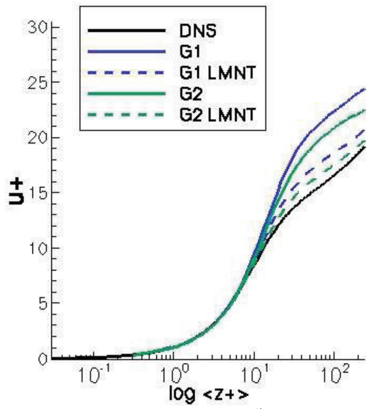


(a) 2nd-order MC scheme

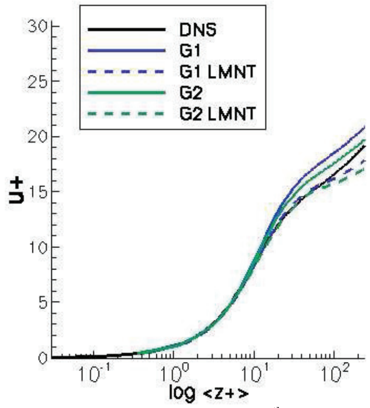


(b) 9th-order WENO scheme

Figure 2 Instantaneous vorticity isosurfaces for the channel flow.

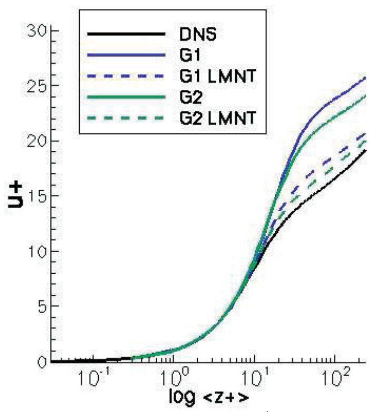


(b) M5 scheme, 5th-order



(c) WENO scheme, 9th-order

Figure 3 Streamwise velocity profile in channel flow; ILES vs DNS.



(a) MC scheme, 2nd-order

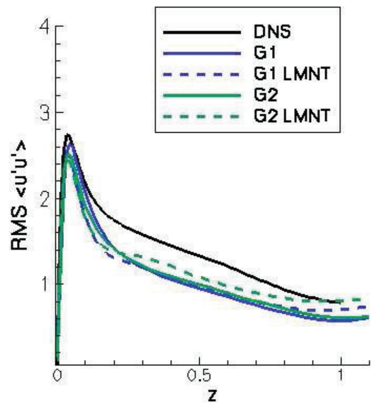


Figure 4 Streamwise Reynolds stress obtained by the 9th-order WENO variables reconstruction.

FLOWS AROUND AN ARRAY OF BUILDINGS

Turbulent flows in an urban environment are characterised by large scale separation and turbulence. The development of turbulence models for flows around buildings is frequently studied using benchmark configurations. For example, an array of buildings represented by wall-mounted cubes has been widely used as a benchmark designed to represent typical characteristics of flows in urban areas. Extensive experimental data for a staggered array of uniform height cubes can be found in the studies of Cheng and Castro [29] and Castro et al. [30]. The flow conditions selected for ILES correspond to a constant streamwise pressure gradient of 1.59 Pa/m and a Reynolds number of 5000 based on the free-stream velocity and cube height.

Following previous DNS [31] and classical LES [32] studies, a subdomain of the array is modelled based on a periodical repeating unit as illustrated in Figure 5. The coordinates are non-dimensionalised by the height of the buildings (h). The dimensions of the resulting computational domain are $(4h)^3$. In the reference DNS study of Coceal et al. [31], the grid resolution of 64^3 cells per unit cube was employed. The ILES simulations reported in this section have been performed on a grid comprising 24^3 cells per unit cube. In both cases, the grids were clustered near the solid boundary.

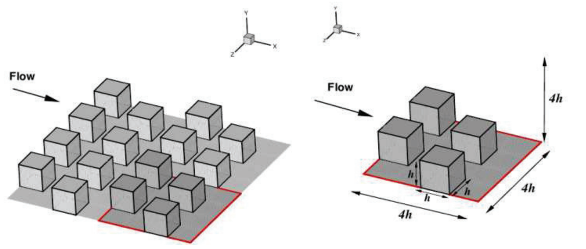
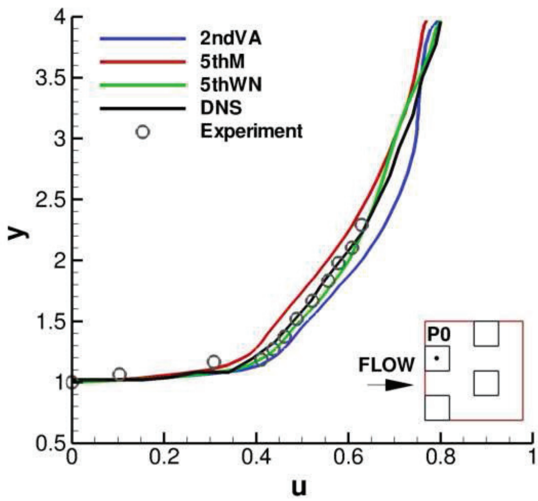


Figure 5 Computational domain for an array of buildings

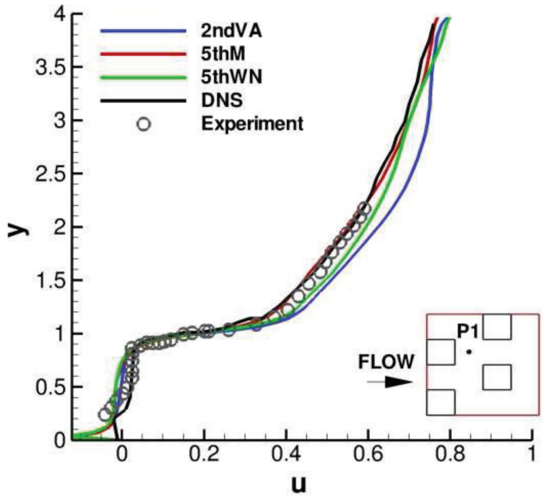
The symmetry boundary condition was used at the top of the computational domain and the periodic boundary condition was used in the streamwise (x) and spanwise (z) directions. The flow was driven by the application of the constant pressure gradient in the form of a forcing term. The CNS3D code used for the channel flow was also used in the present flow case.

The numerical reconstructions schemes for this flow included the 2nd-order MUSCL with the van Albada limiter (2ndVA) [3], the 5th-order MUSCL (5thM) [12] and the 5th-order WENO (5thWN) [16]. The effect of LMNT was also investigated. Although good agreement with the DNS was obtained for the velocity profiles (Figure 6) using the 2nd-order scheme, application of the 5th-order schemes leads to slight improvement; the 5th-order WENO yields more accurate results in comparison with the 5th-order MUSCL scheme (Figure 6).

The differences between the 5th-order schemes are more pronounced in the Reynolds stresses distribution (Figure 7). The peak value of the Reynolds stress corresponds to the shear layer above the buildings. The 5th-order WENO yields better prediction of the peak Reynolds stress. LMNT, denoted by the "_LM" in the plot legend, does not provide significantly improved results in this case.



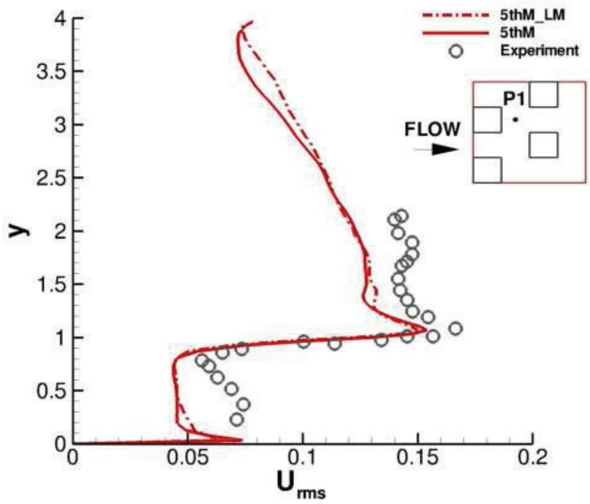
(a) Velocity distribution above the building at position p0 (see inset)



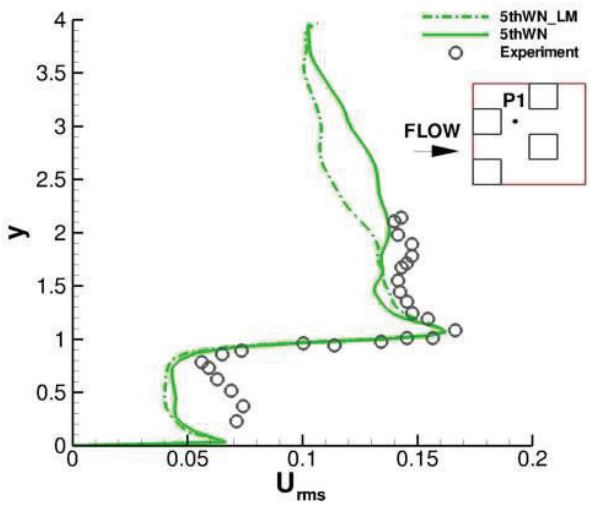
(b) Velocity distribution in the wake at position p1 (see inset)

Figure 6 The effect of the variables reconstruction scheme on the streamwise velocity component at two different positions.

The ILES results in a good agreement with the experimental and DNS data and a consistent improvement is observed with increasing the order of numerical accuracy.



(a) 5th order MUSCL



(b) 5th-order WENO

Figure 7 Comparison of the streamwise Reynolds stress magnitude obtained by different 5th-order schemes in the wake of the building at position p1 (see inset).

CONCLUSIONS

Over the past decade, the ILES approach has been advanced through the development and analysis of high-resolution and high-order schemes. The results presented in this paper concern attached and separated low-speed flows. Good agreement between ILES and DNS/experimental data was found for substantially coarser grid resolutions compared to DNS, e.g., 4.5 and 19 times coarser grids than those used in the reference DNS studies for a channel and an array of buildings flow geometries, respectively.

The assessment of a range of ILES models showed the effect of the subgrid dissipation on the computational results and prompted to the use of higher-order methods.

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