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On the computational efficiency of LES and hybrid RANS-LES models in building aerodynamics

Aly Mousaad Aly
Louisiana State University and Agricultural and Mechanical College, aly.mousaad@polimi.it

Faiaz Khaled
Louisiana State University and Agricultural and Mechanical College

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On the computational efficiency of LES and hybrid RANS-LES models in building aerodynamics

Md Faiaz Khaled[a,*], Aly Mousaad Aly[b]

[a]*WISE Research Lab, Louisiana State University, Baton Rouge, LA, USA, mkhale7@lsu.edu*
[b]*WISE Research Lab, State University, Baton Rouge, LA, USA, aly@lsu.edu*

ABSTRACT:
Large-eddy simulation (LES) has proven to offer superior accuracy in regards to predicting surface pressures compared to the Reynolds-averaged Navier Stokes (RANS) models. However, the primary impediment is the high computational cost associated with LES. The authors attempt to investigate the computational cost and accuracy by employing different sub-grid scale (SGS) models in LES and hybrid RANS-LES models. One of the prerequisites of accurate pressure estimations is to ensure a horizontally homogeneous empty computational domain. This study aims to compare the computational competence qualitatively and quantitatively using an empty domain in regards to the ability to maintain horizontal homogeneity. The Wall-adapting eddy viscosity (WALE) SGS model in LES exhibits a significant reduction in computational time. Moreover, the application of detached eddy simulation (DES) and its modified versions manifest encouraging results in reducing computational time and retaining accuracy.

Keywords: Large-eddy simulation (LES), horizontal homogeneity, sub-grid scale (SGS), Detached eddy simulation (DES), computational cost, Wall-adapting eddy viscosity (WALE).

1. INTRODUCTION

Improving buildings' resiliency against frequently occurring powerful windstorms is becoming more critical with evolving demands rooted in climate change. Computational fluid dynamics (CFD) has a growing reputation in the engineering community as a robust tool to model wind flow around a built environment. The performances of CFD applications vary with the turbulence model that is being employed. Reynolds-averaged Navier Stokes (RANS) models are commonly used by CFD practitioners to model and predict mean flow variables. In one of their previous studies, the authors demonstrated the superior performance of $k - \omega\, SST$ model in estimating mean surface pressures in the zone of flow separation. However, local peak pressures are considered to cause extreme suction on roofs leading to considerable damage to buildings' envelope. The large-eddy simulation (LES) model has attained the reputation of offering better accuracy while modeling mean and instantaneous flow fields around bluff bodies than RANS models. However, LES is computationally expensive for near-wall complex flow problems [1]. Besides, some studies have identified discrepancies while predicting peak pressure coefficients with LES. A few of them scrutinized the efficacy of LES in building aerodynamics and highlighted the importance of precise replication of turbulence intensity and length scales in the inflow [2]. Therefore, estimating peak surface pressures and high computational cost are the two core impediments for LES. Furthermore, ensuring minimum artificial acceleration in the computational domain is critical to predicting atmospheric flow fields accurately, which is a commonly encountered challenge in CFD [3].

One of the objectives of this study is to prepare an empty domain with acceptable horizontal

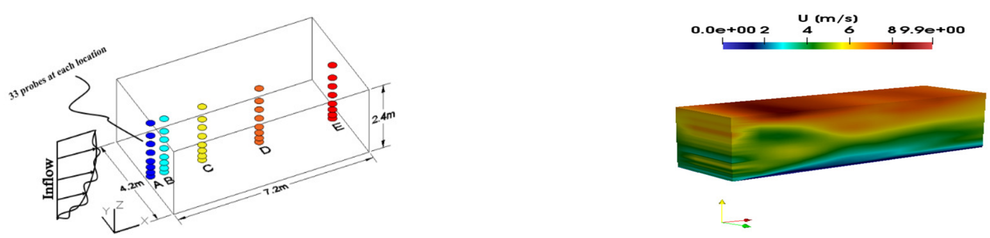
* Lead presenter

homogeneity and integral length scale of turbulence, which are fundamental for the precise prediction of surface pressures. Another side of the study deals with the comparison of computational times to achieve the desired computational domain. LES is accompanied by the application of subgrid-scale (SGS) models. LES can generate dissimilar flow fields even with a similar grid system depending on the SGS model; moreover, the computational time varies with the change in SGS models. Different SGS models are proposed based on the way subgrid eddy viscosity, ν_{SGS}, is computed. As for the hybrid RANS-LES models, three versions of detached eddy simulation (DES)s are used in this study; apart from DES, delayed detached eddy simulation (DDES), and improved delayed detached eddy simulation (IDDES) are adopted. The hybrid models combine the favorable features of RANS and LES, depending on the requirement; also, they use a different transport equation to compute the eddy viscosity. Moreover, the filter width and length scale terms are defined uniquely in different versions of DES. The computational time and accuracy in regards to maintaining horizontal homogeneity are investigated for the hybrid models.

2. METHODOLOGY IN BRIEF

All the simulations are conducted using OpenFOAM 5.0 with identical hardware configurations. The simulations are initiated with LES accompanied by a dynamic one-equation eddy viscosity model as the SGS model. A grid independence study was conducted with this numerical setup. The conditions for accuracy and computational cost in any LES study are closely associated but paradoxical. Finer cell distribution near the walls is necessary for achieving horizontal homogeneity and precise pressure predictions. However, such an arrangement of smaller control volumes adds to the computational cost of LES. The time step was kept constant at 0.004 sec. The upper limit of maximum Courant number ($\cong 1.3$) was settled by balancing between acceptable accuracy and stability of the investigated flow problem.

The optimal grid is employed to investigate the efficacy of different SGS and hybrid models. Velocities are recorded at five streamwise locations identified in Figure 1 (a). The mean velocity and turbulence intensity profiles obtained from the measured data are compared for different SGS and hybrid models; concurrently, the computational durations are recorded. The qualitative comparisons are made based on figures of vertical profiles and the quantitative comparisons are done based on four validation metrics. A Factor of 2 (FAC2), modified normalized mean bias (MNMB), fractional gross error (FGE), and linear correlation coefficient (R) are the four validation metrics. Moreover, the qualitative analysis is reinforced in the form of scatter plots. The qualitative comparison is made with respect to the profile at the inlet and theoretical profiles. However, the quantitative one is done relative to the inlet profile for investigating homogeneity.

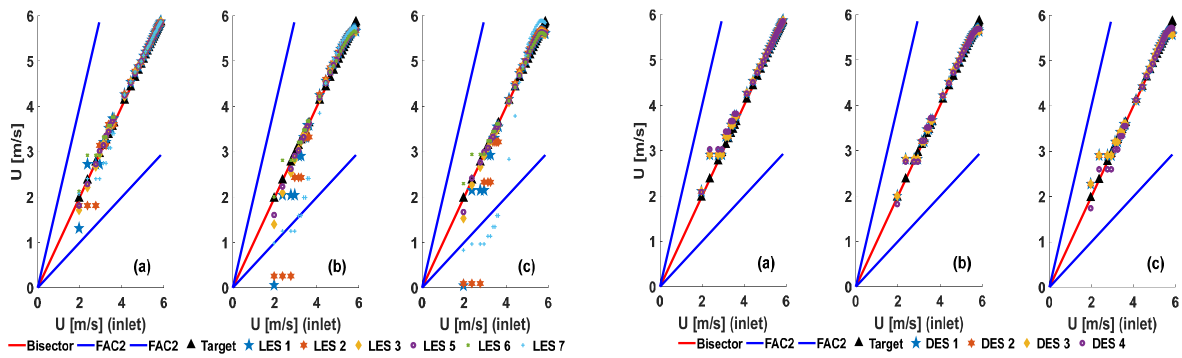


(a) (b)

Figure 1. (a) Computational domain, (b) Instantaneous velocity field at 132 seconds.

3. FINDINGS AND CONCLUSION

The comparative study reveals that LES (LES-7) with the one-equation eddy viscosity (SGS) model fails to offer adequate horizontal homogeneity. LES produces better homogeneity with the wall-adapting eddy viscosity (WALE) (LES-6) SGS model and the dynamic one-equation eddy viscosity (SGS) model (LES-3 and LES-5). However, the latter demands finer near-wall meshing to achieve the level of accuracy offered by the WALE SGS model with a relatively lower cell count. Figure 2 (a) demonstrates the superior performance of LES-3, LES-5, and LES-6 in maintaining the consistency of mean velocity profiles. WALE SGS model offers a reduction in computational time of 35% to 64% while comparing with the two cases of dynamic one-equation eddy viscosity dynamic model. Figure 1 (b) presents the turbulence observed in the instantaneous flow field at 132 seconds for the case LES-6.



(a) (b)

Figure 2. Scatter plots for comparison of mean velocities at locations A, C, and E; (a) LES cases, (b) DES cases

The scatter plots for the DES cases look much improved when compared with all the LES cases (Figure 2 (b)). The DES cases, with the Spalart-Allmaras (SA) URANS model, yield accuracy comparable to LES, with the WALE SGS model, and LES, with dynamic one-equation eddy viscosity SGS model within Y^+ of 130. DES cases are computationally faster (40%) than LES with a dynamic one-equation eddy viscosity model (Y^+=48); on the contrary, DES cases are time-consuming (40%) than LES, with the WALE SGS model, of almost identical accuracy. Therefore, it can be concluded that LES combined with the WALE SGS model, and DES, DDES, IDDES combined with the SA URANS model can model atmospheric boundary layer (ABL) flow with better accuracy consuming lower computational resources. The next phase of research will involve a similar study with the building inside and the influence of these models on surface pressure predictions.

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