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A viable framework for wind load assessments with Large Eddy Simulations

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SUMMARY:
Large eddy simulations can provide very accurate predictions of the pressure exerted by the wind on a building. However, the assessment of transient flows using computational grids of high resolution is a computationally overwhelming task. Therefore, its use has been impracticable for most industrial applications, such as wind tunnel analysis. The recent technological developments along with alternative computational fluid dynamics paradigms might be able to change this scenario. Herein, we present results of high resolution LES using the lattice Boltzmann method. The LBM has a second-order accuracy of time and space and is highly localized. Hence the LBM has a very satisfactory precision and is extremely suitable for high performance GPU processing. Thereby engineering simulations can be performed overnight. The canonical case of a turbulent flow over a surface-mounted cube at Reynolds number 20,000 is assessed. Great performance and excellent agreement with experimental data for the pressure coefficient and its fluctuations are achieved.

Keywords: wind tunnel, lattice Boltzmann method, large eddy simulation

1. INTRODUCTION

The use of computational fluid dynamics (CFD) in wind engineering has had a noteworthy increase over the past few years. CFD is a well accepted engineering tool in applications such as wind farm layout optimization (Letzgus et al., 2022), pollutant dispersion (Pantusheva et al., 2022) and pedestrian comfort (Blocken et al., 2016). However, wind load assessments have requirements that are much more difficult to achieve with computation, and the current state of CFD has not been able to spread in this field.

Wind loading is essentially a transient problem with a wide range of frequencies that contribute to the measured pressures. The most popular CFD method for turbulence, which is the Reynolds-Averaged Navier-Stokes (RANS), is not able to capture the transient features of wind pressures in buildings. Hence, a considerable research effort has been directed towards the method of Large Eddy Simulation (LES). A great number of publications can be found with validations for high-rise buildings (Thordal et al., 2020; Xing et al., 2022), low-rise buildings (Aly and Gol-Zaroudi, 2020) and even solar panels (Aly and Whipple, 2021). Despite the excellent results in terms of precision, LES has a prohibitive computational cost. With the finite volume method, a single LES simulation for wind load assessment takes a few days to converge in a multi-CPU environment. For reference, a complete wind load assessment with LES (24 wind directions), would be more expensive than an experimental wind tunnel testing (Xing et al., 2022).

Many publications in computational wind engineering mention the lattice Boltzmann method (LBM) as a promising technique to achieve viable LES (Buffa et al., 2021; Han et al., 2020; Zhao et al., 2022). The expression "viable LES" in the present work means that a simulation can be properly executed overnight, in a hardware setup that can be found in any cloud computing provider. In this work, we describe a numerical method based in LBM-LES and its implementation for a GPU environment. This framework is able to solve wind loading problems overnight, with satisfactory precision levels. We present validation cases and a comparison with traditional LES solvers in terms of performance and viability.

2. SOLVER DESCRIPTION

The solver that we adopt is developed by Aerosim and speeds up high-performance computing (HPC) with GPUs by parallelizing operations of the code which are independent. The flow evolution is computed with LBM, which uses a different paradigm to solve the Navier-Stokes equations (NSE). The result is a numerical method that is highly localized and has a second-order accuracy of time and space.

In our current framework, the LBM is applied with the recursive regularized Bhatnagar Gross Krook (RR-BGK) collision operator (Mattila et al., 2017) and the Smagorinsky sub-grid LES model (Dong et al., 2008). We represent solid obstacles through Immersed Boundary Method (IBM) (Peskin, 2002), which allows a versatile delineation of geometries.

3. RESULTS

The turbulent flow over a surface-mounted cube is chosen as validation case since it is already well documented in the literature (Hölscher and Niemann, 1998; Lim et al., 2009; Richards et al., 2001). The Reynolds number is Re_h =20,000, the cube's height $h = 48$, and its position 270 units from inlet. The inlet boundary condition uses a precursor simulation, which changes its velocity linearly using data from a periodic turbulent flow simulation. Four towers of triangular transversal section are positioned at domain's entrance to increase the flow's turbulent intensity. The $192 \times 256 \times 960$ computational domain is illustrated in Figure 1:

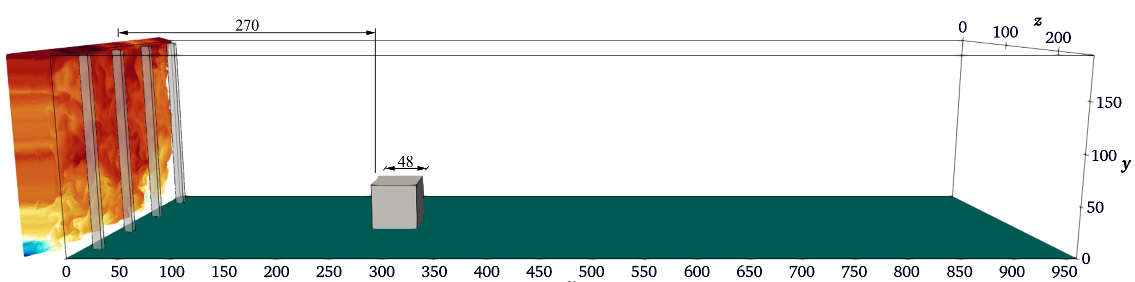
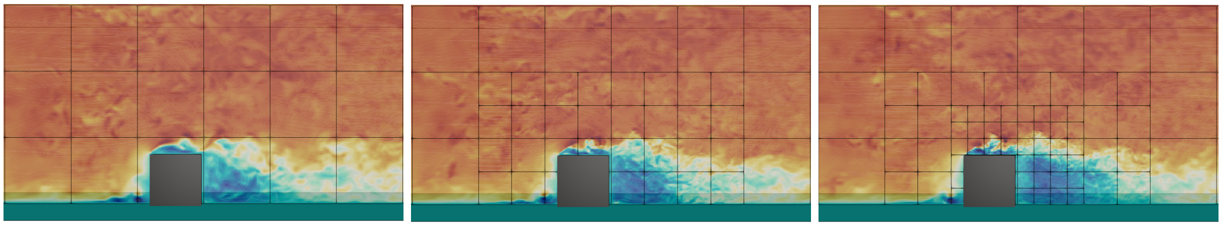


Figure 1. Computational domain setup, a precursor simulation of a atmospheric turbulent flow is fixed at inlet, wall at bottom, and free slip at laterals, and Neumann at outlet. The pressure gradient is zero between inlet and outlet.

Three resolutions were simulated using a multigrid approach, as illustrated in Figure 2. The time elapsed is measured with convective time-scale (CTS=h/U_h), where U_h is the velocity at height h



(a) S1 - 49,432,500 nodes **(b)** S2 - 84,584,500 nodes **(c)** S3 - 137,312,500 nodes

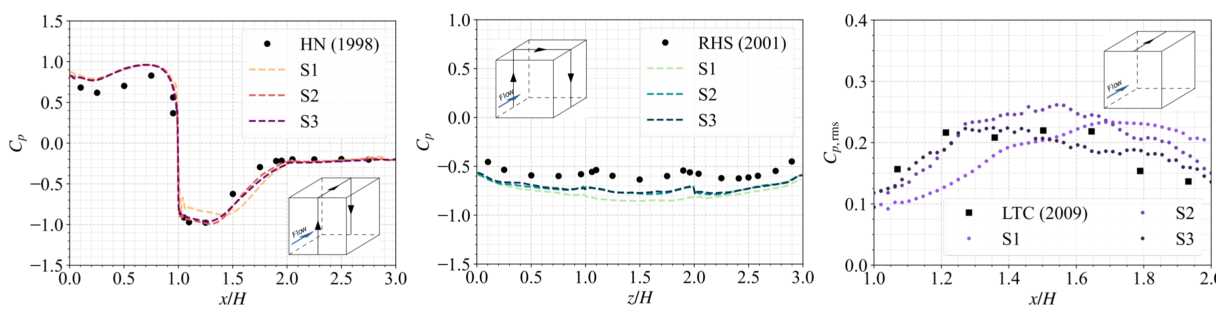
Figure 2. Instantaneous velocity profile for each resolution at $t = 360$CTS.

The flow was assumed as statistically developed after 100CTS. Statistic values were calculated for a 260CTS time interval. The requirements of each simulation are presented in Table 1.

Table 1. General requirements of each simulation. A single Tesla A100 GPU was used for each case.

Simulation	$\Delta x/h$	360CTS(s)	Time steps	GPU Memory usage (GB)
S1	1/48	22,101.35	360,000	12.37
S2	1/96	45,467.01	720,000	19.76
S3	1/192	119,072.64	1,440,000	30.86

In Figure 3, we present results of the average pressure coefficient C_p, and the root mean squared pressure coefficient $C_{p,\text{rms}}$. An excellent agreement against wind tunnel data from HN (Hölscher and Niemann, 1998), RHS (Richards et al., 2001), and LTC (Lim et al., 2009) was achieved.



(a) Longitudinal direction **(b)** Transversal direction **(c)** $C_{p,\text{rms}}$ at the top

Figure 3. Plots of C_p and $C_{p,\text{rms}}$ for different directions against experimental data.

In Table 2, we show a comparison between the LBM and a conventional Finite Volume Method (FVM) solver. The LBM works with isotropic grids and require more elements.

Table 2. Performance comparison of present solver against conventional FVM solver.

Solver	Hardware	Δx	Δt(CTS)	Grid elements	Time-step/s	360CTS(h)
LBM Solver	Tesla A100 GPU	1/64	1/1,422	56,300,000	17.76	8.00
FVM Solver	Intel Xeon Ice Lake CPU	1/64	1/64	20,000,000	0.059	108.47

4. CONCLUSIONS

We presented results of a LES framework which is able to perform engineering-level simulations overnight. In other words, statistical convergence in a 10^8 grid can be achieved in a few hours, in contrast to a few days that would be necessary to solve the same problem with a FVM solver. In the full paper, we will benchmark wind loading cases in low- and high-rise buildings.

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