

An efficient simulation of urban strong wind field during the typhoon process using the embedded LES model

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SUMMARY: (10 pt)

In order to predict the impact of a strong wind field on the target urban structures during the landfall of a real typhoon, an efficient numerical procedure is proposed to simulate the three-dimensional wind field within an urban area. Firstly, the typhoon track and intensity are reproduced by using the mesoscale Weather Research and Forecasting (WRF) model coupled with the urban canopy model (UCM), where the profiles of time-averaged wind speed and turbulence intensities within the target urban area are obtained. Secondly, the urban area is modelled in a micro-scale CFD model. The obtained wind profiles from WRF-UCM are used as the inflow turbulence condition to simulate the interaction between the strong wind field and urban buildings. To reduce the huge cost of using the LES in the large area simulation, a model combining the LES and the RANS, named Embedded Large-Eddy-Simulation (ELES) model is proposed and adopted to efficiently simulate the instantaneous aerodynamic results around target buildings. The application of the proposed ELES-based simulation procedure to the prediction of the urban strong wind field during a typhoon shows the high accuracy and efficiency of the proposed procedure after comparing the simulations with the in-situ measurement.

Keywords: Typhoon simulation, urban wind field, embedded LES

1. MOTIVATIONS

In recent decades, the Computational Fluid Dynamics (CFD) technique has become an important tool for the analysis of wind-related problems in urban areas. Among the CFD tools, the Large Eddy Simulation (LES) technique has become widely applied due to its ability to capture instantaneous results (Blocken and Stathopoulos, 2013; Nozu et al., 2008). However, when using LES in the prediction of the urban-scale wind field, the cost of simulation is always very high due to the required high grid resolution and the limited time step, which hinder its application in the engineering area. In general, it is of great significance if it can reduce the total cost of large-area LES while maintaining the accuracy of the simulated fluctuating results around buildings.

One important fact is that, for the wind engineering area, only the instantaneous results of one or several specific structures within an urban area will be concerned, and other surrounding buildings and structures, especially the general low-rise buildings with regular shapes always play the role of the "roughness blocks", whose instantaneous aerodynamic results are ignored even the related data has been obtained. Such fact makes it possible to only simulate the fluctuating results around target buildings by using the LES model while simulating the time-

average results around surrounding buildings by using the Reynolds-Averaged Navier Stokes (RANS) model whose cost is dramatically reduced due to its low requirement of the near-wall grid resolution compare with that of LES. In a word, this is an approach in which LES is applied in the regions that cover the target buildings only, while the RANS equations are employed elsewhere in the computational domain, and the fluid information will be transferred at the interfaces between LES and RANS domains to ensure the stability of calculation. Such a coupled model is so-called the Embedded LES (ELES) model whose high efficiency compared to the pure LES model has been approved by several applications (Jadidi et al., 2016; Masoumi-Verki et al., 2021). However, to the authors' understanding, no studies have clarified the performance of ELES in the simulation of a strong wind field within a real urban area.

In the present study, aiming at evaluating the ELES-based procedure for the simulation of an urban strong wind field, a new ELES model is adopted to simulate the wind field and the surface pressure of urban buildings during a real typhoon process. The inlet boundary conditions are obtained by using the WRF-UCM coupled model, and the simulated results are compared with the in-situ measurements to evaluate the accuracy of the proposed simulation procedure.

2. INTRODUCTION OF THE NEW ELES MODEL

The newly proposed ELES model is performed in the OpenFOAM toolbox. There are two main parts of the model, one is a multi-regional solver enabling the RANS and LES calculations to be carried out in user-defined regions, and another part is the boundary conditions allowing the transfer of field information between RANS and LES regions.

2.1. The multi-regional solver

The proposed ELES model divides the numerical domain into the separated RANS region and LES regions, which are loaded, initialized, and solved by the multi-regional solver. The concept of the ELES and the flow chart of the multi-regional solver are illustrated in Fig.1(a) and (b), respectively. The domain configurations such as the domain scales, mesh systems, numerical schemes, and turbulence models of each region can be independently defined, and the calculations are also independent between regions.

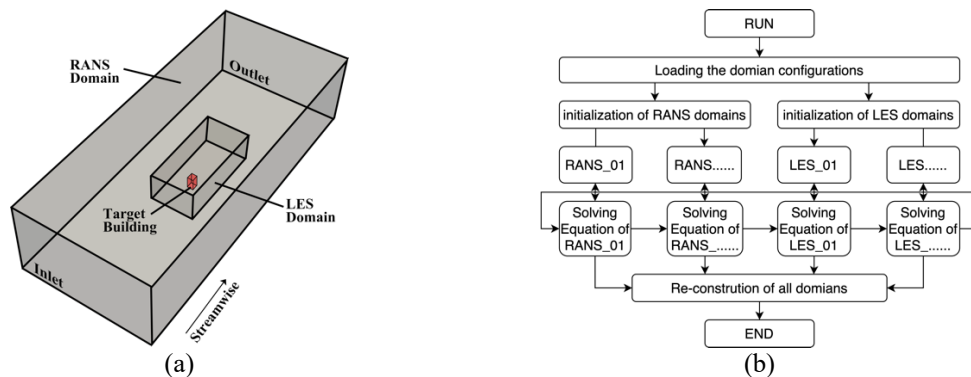


Figure 1. (a) the concept of the ELES model and (b) the flow chart of the proposed multi-regional solver.

2.2. Boundary conditions

Four groups of boundary conditions exist for the information transfer from the RANS region to

the LES region or from the LES region to the RANS region.

2.2.1. Velocity boundary condition

For the velocity transferred from LES to RANS, the fluctuating velocity is firstly time-averaged and then specified as the inflow condition of the RANS region, as shown in Eq. (1). While for the velocity transferred from RANS to LES, the inlet turbulence field is synthesized at the inlet patch of LES region based on the mean velocity and the kinetic energy by using a newly proposed technique named the Iterating-Reshaping based Consistent Discrete Random Flow Generation (Zhang et al., 2022), as shown in Eq. (2) and (3). Detailed information of the parameters in Eq. (3) is given in the reference.

$$u_i(x_j, t)^{RANS} = \overline{u_i(x_j, t)^{LES}} \quad (1)$$

$$u_i(x_j, t)^{LES} = u_i(x_j, t)^{RANS} + u_i'(x_j, t)^{SYN} \quad (2)$$

$$u_i'(x_j, t)^{SYN} = \sum_{m=1}^M \sum_{n=1}^N (p_i^{m,n} \cos(k_j^{m,n} \tilde{x}_j^m + 2\pi f_{m,n} t) + q_i^{m,n} \sin(k_j^{m,n} \tilde{x}_j^m + 2\pi f_{m,n} t)) \quad (3)$$

2.2.2. Pressure boundary condition

The pressure at the interfaces between the RANS region and the LES region is forced to the same value to ensure the stability of the simulation, as shown in Eq. (4).

$$p(x_j, t)^{RANS} = p(x_j, t)^{LES} \quad (4)$$

2.2.3. Other boundary conditions

The kinetic energy k and the dissipation rate ε should be estimated when transferring from LES to RANS, and the equations are shown in Eq. (5) and (6).

$$k(x_j, t)^{RANS} = \frac{1}{2} (\overline{u'(x_j, t)^2} + \overline{v'(x_j, t)^2} + \overline{w'(x_j, t)^2})^{LES} \quad (5)$$

$$\varepsilon(x_j, t)^{RANS} = 2\nu \overline{(S_{ij} \cdot S_{ij})}^{LES} \quad (6)$$

3. SIMULATION PROCEDURE AND EXPECTED RESULTS

3.1. Typhoon simulation

To obtain the mean velocity and the turbulence intensity profiles within an urban area as the inlet boundary conditions of the ELES model, a mesoscale WRF-UCM coupled simulation of a typhoon process is first carried out.

3.2. ELES of the empty atmospheric boundary layer

The proposed ELES model is validated by generating a turbulent atmospheric boundary layer (ABL) without urban structures. The obtained wind profiles from WRF-UCM are used as the inflow condition. A user-defined LES region is totally immersed in the outer RANS region, and the simulated instantaneous and time-averaged wind fields are shown in Fig. 2(a) and (b).

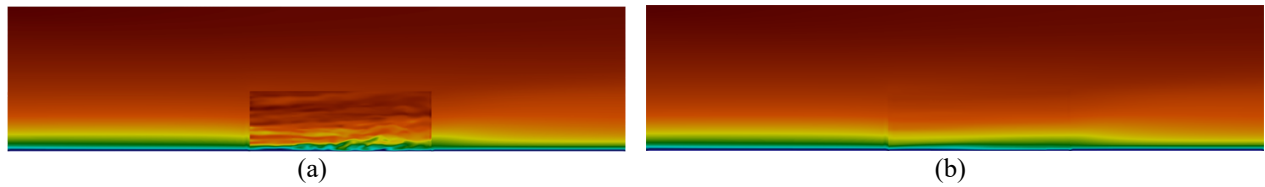


Figure 2. The ELES results of the (a) instantaneous and (b) time-averaged wind fields of an empty ABL.

3.3. ELES of the real urban wind field

In this section, the three-dimensional wind field within a real urban area is simulated using the ELES model. The target urban building is immersed in an LES domain while the RANS model is adopted for other urban areas. Some wind field results are shown in Fig. 3. The time-averaged and fluctuating wind speed as well as the distributions of surface pressure of the target building are compared with the in-situ measurements to evaluate the applicability of adopting the ELES model to urban strong wind field simulation.

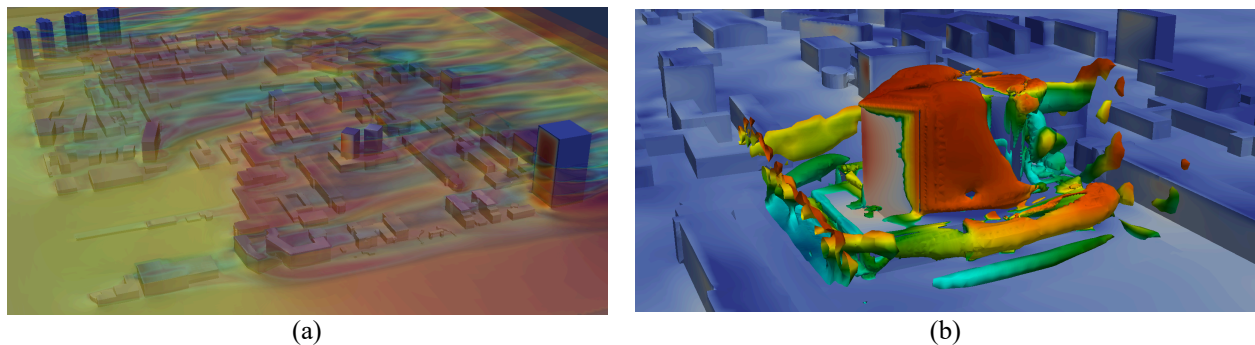


Figure 3. The ELES results of the (a) instantaneous urban wind field and (b) the topology of vorticities around an isolated building in terms of Q-criterion

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