Towards practical use of LES in wind engineering

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ABSTRACT: In order to numerically simulate unsteady flow phenomena, LES or DNS technique should be used. Especially LES is appropriate for application in the wind engineering problem, because the requirement of computational power and memories is reasonable. The present study discusses the applicability of LES to several issues such as practical use for wind-resistant design, wind velocity affected by the terrain or the ground surface condition, turbulence structures and atmospheric diffusion in the urban area. Comparison with full-scale measurement data is important for all cases to clarify the effectiveness of LES.

KEYWORDS: LES, inflow turbulence, full-scale measurement, bluff body aerodynamics, wind in cities, ground surface condition, terrain effect, atmospheric environment

1 INTRODUCTION

LES (Large Eddy Simulation) technique recently has become a powerful tool for turbulent flow analysis in the field of computational wind engineering as well as computational fluid dynamics. As its reason, the following issues can be provided.

1) Inflow turbulence which is an essential characteristic of natural wind can be generated for numerical simulation of the bluff-body flows.
2) Sophisticated sub-grid scale turbulence model is developed for the unsteady separated flows with vortex shedding around a bluff body.
3) Numerical discretization without accuracy loss is possible for representing complicated geometry.

As a result of development for a numerical modeling, LES can predict the wind flows around a building and a structure under the conditions very close to the actual state. Therefore the practical use of LES even in the field of wind engineering becomes almost possible now. Here we discusses the applicability of LES to several issues such as practical use for wind-resistant design, wind velocity affected by the terrain or the ground surface roughness, turbulence structures inside or over urban canopies and atmospheric dispersion of mass and heat in the urban area. Based on the examples shown in the following sessions, a current state or a future possibility of practical use of LES in the wind engineering is examined. Especially, in order to independently estimate the accuracy, or reproducibility of wind-related natural phenomena, to the numerical example obtained by LES, comparison with full-scale measurement, rather than wind tunnel test, is performed for all cases as much as possible.

2 AIJ ACTIVITIES IN RELATION TO LES FOR WIND-RESISTANT DESIGN

2.1 Wind loading estimation

Architectural Institute of Japan (AIJ), by establishing the working group, has investigated the applicability of CFD technique to the wind-resistant design of actual buildings and struc-
Consequently the current state of predictive accuracy by the numerical model has been clarified and also, the guide for the appropriate numerical model and method was provided. Here the activities of AIJ are shown concerning estimation for performance and limitation of various types of numerical modeling in the computational wind engineering. AIJ deals with a low-rise (1:1:0.5) and a high-rise (1:1:4) buildings. Both of RANS simulation and LES are carried out for aerodynamics of these building models. The computed wind force and pressure for these simple configurations are validated by comparison with the experimental data[3]. Also AIJ provides the wind loading on these buildings predicted by RANS and LES.

2.2 Generation of inflow turbulence for LES

In many cases of LES applied to the wind engineering problems, the generation of inflow turbulence, which is time sequential data with physically-corrected spatial structures, is a very important issue. Lund et al.[4] proposed the technique of inflow generation, where various development ratios of boundary-layer parameters such as a depth or the friction velocity etc. are estimated using the computed result just obtained sequentially. The velocity profile at the inflow boundary is reset based on the law of the wall or defect law on the spatially developing process of the boundary layer on a smooth surface. Kataoka et.al.[5] proposed a simplified version to Lund’s method, where the development of the boundary layer thickness is neglected and the mean velocity profile is fixed at inflow. While, Nozawa and Tamura[6],[7] extended Lund’s method to a rough-wall boundary layer flow, where they use the roughness arrangement and the experimental formula to predict the development over rough surface. As a different type of method, inflow turbulence is generated by statistical method, which is mainly employed for the homogeneous turbulence in two-dimensional problem. All above processes giving the inflow condition allow the simulation of spatially developing neutral turbulent boundary layer with a small computational domain.

Recently thermally stratified effect can be considered for above type of boundary-layer simulation[8],[9]. For unstably stratified boundary layer, in the driver region velocity fluctuation is generated by using the quasi-periodic boundary condition for rough wall, while temperature is treated as a passive scalar. The generated inflow data for temperature as well as velocities are introduced into the main computational domain, where physical quantities are solved taking into consideration buoyancy effects. For the stable boundary layer, the generated inflow data of velocities at the recycle station are introduced into the main computational region. But for the temperature data, the assumed profile is imposed at inflow boundary of the main region and the temperature starts to be solved taking into consideration buoyancy effects. Because fluctuation of the passive scalar is too large and not appropriate for inflow condition of stable turbulent boundary layer.

2.3 Turbulence effects on bluff body aerodynamics

Thus far several researchers have investigated the aeroelastic instability of prismatic structures on the basis of the numerical results by large eddy simulation for turbulent flows around a square and a rectangular cylinders. From the wind engineering point of view, the turbulence effect on unstable oscillations should be clarified. Turbulence of the oncoming flows changes sensitively the behavior of separated shear layers and the vortex formation around a prism, so we need to investigate details of the flow structures under unstable oscillations, as well as the aeroelastic characteristics of a prism. By using inflow homogeneous turbulence generated by the statistical method, we can carry out LES for aerodynamics of prisms in turbulent flows. The turbulence effects on aerodynamic and aeroelastic characteristics of a prism was clarified[10].
It is well known that a square or a streamwise-elongated rectangular cylinder has a possibility for onset of unstable oscillation called galloping at the reduced velocity basically higher than the resonant velocity. On the other hand, in the case of a short rectangular cylinder, a different type of unstable oscillation is observed. High-speed galloping occurs due to the negative damping force generated by the after body effect and its physical mechanism has been almost understood. However concerning the unstable oscillation for a short rectangular cylinder, which is generally called low-speed galloping, there remain many unsolved problems. We do not know how this instability stems from, so its physical mechanism has not been clearly understood. Especially turbulent effects on low-speed galloping have not been studied so much. Tamura et al. [11] describes aerodynamic and aeroelastic characteristics of a rectangular cylinder with small side ratio for smooth and turbulent inflow conditions, and clarifies their physical meanings by using LES results.

3 WIND FLOW VELOCITY AFFECTED BY TERRAIN

3.1 Wind flow a hill with sinusoidal curve

LES was carried out to investigate the turbulent boundary-layer type of flows over a hill-shaped model with a steep or a relatively moderate slope at moderately high Reynolds numbers [12]. Here, the surface condition of a hill is strongly focused on, such as roughness effects as well as curvature effects. For the Sub-grid Scale (SGS) modeling of LES, both of the dynamic Smagorinsky model and the dynamic mixed model are used. It is well known that the separated shear layers behavior and the vortex motions are sensitively affected by the oncoming turbulence, such that the separated shear layer comes close to the ground surface, or the size of a separation region becomes small. Based on unsteady phenomena of the wake flows over a smooth and a rough 2D hill-shaped obstacle, roughness effects on the flow patterns and the turbulence structures distorted by the hill are clarified. Also, the applicability of DSM and DMM are discussed, especially focusing on the recirculation region behind a steep hill. The performance of the eddy viscosity and the scale similarity models is clarified from the basic concept of their modeling process.

3.2 Ground surface modeling for vegetation

This example of LES brings into focus modeling of grasses and trees on the ground surface [13]. In order to model the vegetation effects for LES, we employ the feedback forcing method proposed by Goldstein et al. (1993). In this model, the equation of motion for trees or grasses are coupled with the Navier-Stokes equation, so turbulence in the vegetation canopy can be numerically expressed. Both the computed results over the hill with and without vegetation are in good agreement with the previous experimental data for a rough and a smooth hill. Also, the effects of vegetation on turbulence statistics, including the coherent structures above the vegetation, are clarified. Especially the turbulence statistics inside the vegetation canopy are shown.

3.3 Actual complicated terrain and comparison with the full-scale measurement data

The purpose of this research is to establish the safety of the flight around the heliport to be located on a cliff top at northern area of Aogashima Island [14]. Because the heliport is surrounded by steep geographical features, there is a possibility that strong wind gust or large wind fluctuation have an impact on the flight. Previously, to obtain observational data of local wind field around the heliport, flight test was conducted using the research helicopter. The results of LES are compared with the measurement data obtained by research helicopter to validate numerical
simulation. As a result, LES well has reproduced separation and reattachment of the unsteady wind field over the complicated terrain of Aogashima Island. Also, it is shown that LES can provide instantaneous flow field and be used to identify the location and the condition in which high turbulence is likely to occur. Details of the wind velocity and the turbulence structures are clarified locally around the heliport as well as in the overall region of the island wake.

4 WIND IN CITIES

4.1 Design wind velocity profile over various rough surfaces

This research example performs the estimation by LES on the vertical profiles of wind velocity in the urban area[15]. The accuracy of GIS (Geographic Information System) data is recently improved, so it is expected that we can utilize these data for the estimation of the wind profile over the complicated surface roughness in the urban area. Raupach proposed the relation between the roughness length normalized by the roughness height and the roughness density for uniform rough surface where the boundary layer thickness is estimated to be sufficiently larger than the roughness height by experiment. However actual urban area does not have a thick boundary layer compared to the building height because there are usually several tall buildings. This research aims at finding the universal relation between the parameters of wind profile and surface roughness in the cases of cities. LES is carried out for the wind flow over the model of various actual urban models and the vertical design wind velocity profile is provided based on the computed results by LES.

4.2 LES versus RANS for turbulent flows in urban canopies

For wind in cities, there remains a discussion which numerical model is employed, RANS or LES. Figure 1 shows velocity contours computed by RANS and LES in the Shinjuku area[16]. Completely inside the urban canopy close to the ground, LES depicts the instantaneous complicated structures between the building blocks. But due to isotropic tendency of turbulence structures in the canopy, the time-averaged contours of LES results are reasonably in agreement with the RANS results. At the higher level crossing tall buildings, the wakes obtained by RANS and LES are not necessarily consistent with each other. In the present result, the building wake of RANS results becomes wider due to larger turbulence viscosity, compared to the case of LES case. LES still maintains the applicability to the wind flow among the densely-arrayed tall buildings where the vortex shedding and the interaction of separated shear layers from tall buildings generate unsteady flow patterns strongly.

5 ATMOSPHERIC ENVIRONMENTS

5.1 Dispersion of hazardous gasses in urban area

Next example[17] is LES applied to the problem of atmospheric dispersion of hazardous gasses inside urban area for oncoming turbulence, where the estimation of concentration fluctuation is very important. This numerical model has been already validated in comparison with the previous field experimental results for plume dispersion through regular arrays of roughness blocks. The characteristics of flow and plume dispersion are investigated in detail for actual urban area. The occurrence of peak-to-r.m.s. concentrations based on various kinds of surface roughness is examined for safety analysis. Obtained results show that the patterns of spatial distribution of mean concentration in actual urban area is very different from those in regular arrays of roughness blocks. Also, fluctuating concentrations in actual urban area have special
features, for example along the main street or inside the dense buildings, which can not be explained by the physical mechanism of the dispersion process obtained in regular arrays of roughness blocks.

5.2 Urban heat island and local-scaled atmospheric circulation

For the mitigation of heat island effects on coastal cities, it is sometimes expected that the sea breeze come into the inland area of a city, where its cold air mingles with the hotter air over and inside the urban canopies. In the downtown of Tokyo, there exists a coastline at the southeast boundary. But recently several very tall buildings have been constructed at Shiodome near this coast line between the center of Tokyo and the Tokyo bay. We are concerned about that these tall buildings block a passage of sea breeze into the downtown of Tokyo. So, the LES computation is carried out for wind flows over actual roughened ground surface in Tokyo area[18]. For the horizontal inflow boundary condition of the computational domain at the Shiodome area of 1 km by 1.5 km, turbulent flow data such as wind velocity or temperature are imposed by taking into consideration existence of the sea upstream. According to the previous study, the field measurement around the Shiodome area showed that the extreme reduction of wind velocity behind a group of tall buildings. LES results for turbulent flows in the roughness layer over a city also illustrate that the flow velocity extremely decreased behind the building blocks. Accordingly we can easily imagine the occurrence of the environmental degradation for the thermal condition due to densely arrayed tall buildings. Also, in the urban canopy, the very special aspect can be found, such as the steady patterns of a path with strong wind in the wake of a group of tall building. By the passive scalar (temperature) analysis from the heat sources on the surface of the building blocks, it can be recognized that the heat has been convected and diffused largely far away at a higher position. While below the buildings, passive scalar is not transported so much by the effect of the blocking sea breeze. Also it can be seen that a passive scalar has stagnated in the building group because the cavity region is formed among dense buildings.

6 COMBINED METHOD WITH MESO-SCALE METEOROLOGICAL MODEL

Final example[19] investigates the microscale structure and variability of severe winds in an urban canopy by conducting the coupled simulation of LES and mesoscale meteorological model (MM5). The analysis is focused on actual urban canopy in downtown of Tokyo during a period of explosive cyclogenesis. Wind fields with urban scale are simulated with MM5, while turbulent flow fields inside the urban canopy are computed by LES that incorporates explicitly the effects of actual shape for buildings and structures. Generally, by LES we cannot obtain the absolute values for wind flow, only relative value to the reference wind can be estimated. So, combining the results by MM5, we have estimated the wind velocity value and compared with observational data. Also, the LES/MM5 combined analysis can exhibit details of local gust wind and sudden changes of canopy winds. This study suggests that the combined method is a powerful tool for predicting of a severe wind disaster in the urban area.

7 CONCLUDING REMARKS

Many examples of LES in wind engineering are shown in order to understand the current state and the future possibility of the practical use of LES model. In wind engineering field, there remain many problems where the peak-type of values should be predicted, such as the estimation of wind loading on buildings and structures, the gust evaluation around tall buildings and the prediction of concentration fluctuation in the dispersion process of hazardous gasses etc. LES
certainly comes close to accurately provide the predictive values. Next step is to directly compare the data obtained from full-scale measurement in order to establish the numerical model, which can provide useful data for wind engineering problem, as an independent and powerful tool. Cost for computation is not serious, probably reduction of CPU price and innovative development of parallel algorithm and its user-friendly usage solve this problem. Consensus and advancement of incentives and motivation for using a numerical model in the wind engineering field are much more important.

8 REFERENCES

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Figure 1 Velocity contours computed by RANS and LES in the Shinjuku area.
( wind direction: south, roughness category: IV )