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BCM-LES analysis of turbulent flows over and within actual urban canopy

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Abstract

This study discusses the analysis of turbulent flows over and within urban canopy by using BCM-LES technique. BCM is the building Cube Method which uses the very fine Cartesian grid with octree pattern. For the numerical model, the urban canopy has been constructed by the actual buildings in the city. This study recognizes the development of urban boundary layer over urban canopy and investigates the vertical wind profile. Also, this study examines the coherent structures of turbulence formed at the edge of urban canopy and clarifies the occurrence of wind gust at the specified part. Finally the data base of the turbulent boundary layer is explained.

Introduction

Turbulent structures over and within actual urban canopy relates closely to transportation of momentum between urban canopy and above area, and are researched in many previous studies. In Coceal [1], the unsteady turbulent structures above arrayed blocks are revealed, and the effect of layout and height of blocks on turbulent statistics is examined by Direct Numerical Simulation (DNS).

However, the actual urban areas have heterogeneity of an urban areas consisting of buildings of different shapes, sizes and layouts, and the effect of this heterogeneity on turbulent structures and statistics is rarely revealed.

On the other hand, recent techniques by computer fluid dynamics (CFD) has developed distinctly, and velocity and pressure field for actual urban area are computed by LES with unstructured grid (Nozu et.al; Yoshikawa et. al[2,3]) . However, in current stage of unstructured grid simulation, many modifications of CAD model and grid is required, and the performance of parallel calculation remains lower than that of the Cartesian grid system. In recent research, building cube method (BCM), which is based on the hierarchical-type Cartesian grid system, has been proposed for overcoming the problem of unstructured grid system. In BCM, it is not necessary to modify CAD data, and the performance of parallel computation is better than that of unstructured grid system.

This study applies BCM-LES to flow field for 25km x 12km area of central Tokyo for examining the turbulent structure above and within actual urban canopy. First, the development process of turbulent boundary layer is analyzed and the effect of blockage effect of urban roughness is examined. Then, focusing on the complicated geometry of urban surface, the characteristics of turbulence structures above and within actual urban canopy are analyzed. Finally, in order to evaluate the effect of these urban boundary layer on the wind load of each building in the future, database of turbulent boundary layer are obtained from 25km x 12km region computation.

Numerical Method for High-performance Computing

BCM uses the mesh system consisting of cubes and cells in the Cartesian grid. Each cube has 16 by 16 by 16 cells, and then the algorithm of computation is quite simple. As a result, the efficient solver on high performance computing is realized for parallel algorithm where the load balance is appropriately obtained at each core. For the wall inside the cell, the approach of direct forcing of IBM is incorporated in BCM. This method allows the appropriate mesh to be generated even for the dirty CAD data such as zero-thickness walls or three-dimensional complicated geometries without any manual repair of the geometry.

The BCM is a computational method to calculate the flow field using uniform Cartesian grids in the spatial domain. The space is discretized with cubic units called cubes. Cubes are regularly subdivided, and the smallest unit is called a cell. Figure 1 shows an example of cubes and cells. The algorithm of computation is quite simple, and it maintains the same number of elements (cells) within each cube. As such, the technique has high efficiency in large-scale parallel computation.

This study employs the incompressible Navier–Stokes equation with the IBM forcing term (Eq. (2)) and the continuity equation (Eq. (1)) as the governing equations:

$$\frac{\partial \bar{u}_i}{\partial x_i} = 0 \tag{2}$$

$$\frac{\partial \bar{u}_i}{\partial t} + \frac{\partial \bar{u}_i \bar{u}_j}{\partial x_j} = -\frac{1}{\rho}\frac{\partial \bar{p}}{\partial x_i} + \frac{\partial}{\partial x_j}\frac{1}{Re}\left(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i}\right) + \frac{\partial}{\partial x_j}\left(\overline{u_i u_j} - \bar{u}_i \bar{u}_j\right) \tag{2}$$

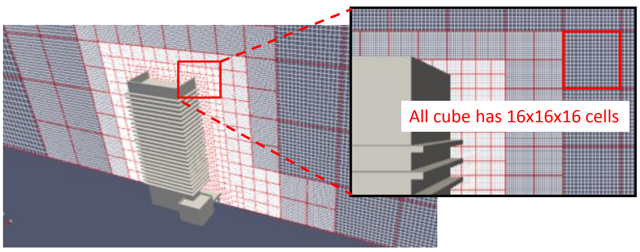

Figure 1. Building Cube Method (BCM):
Example of actual building case

To solve the advection term, the second-order central-difference scheme is used. To perform time integration, the second-order Crank-Nicolson scheme is used; the numerical algorithm is based on the MAC-styled fractional step approach using an intermediate velocity that is corrected with the pressure gradient obtained from the Poisson equation. The Poisson equation is solved using the red/black ordered successive over-relaxation method. All variables are defined at the cell center in the collocated grid. To keep the problem simple, a wall boundary represented by a stair shape is usually used. In this study, the IBM is used with a boundary condition that is defined by a ghost cell. The detailed method is described in Onishi's paper [4].

Wide-area Computation of Flow Field in Urban Area of Tokyo

As an application of BCM to real urban area, wide-area computation was carried out to investigate the characteristics of the boundary layer developing over the urban area from the coastal area to the center of Tokyo by using the K-computer. This numerical model consists of the individual buildings and houses, so it means that the wind loading on each building can be estimated. In this area, development of the boundary layer will be influenced by buildings and ground surface undulation. For this computation, inflow turbulence generated by Lund's method[5] is connected to inlet plane. The power index profile of mean wind velocity is approximately 1/7, and the boundary layer thickness of inlet point is assumed to be δ=250m. The computational domain is 25kmx12km, including the main area of central Tokyo. The target wind direction SSE was the sea breeze of wind direction 157.5 degree. The minimum gird resolution was 6.28m around building surfaces and ground surfaces and the immersed boundary was utilized. Other calculation conditions are shown in Table 1.

Table 1. Calculation condition

Reynolds number	$U_\infty\delta/\nu$=247000 (U_∞≒1.5[m/s], δ=250[m],μ = 1.82*10^{-3} [Pa•s])
Resolution	$\Delta tU_\infty/\delta$=0.0015, 6.28m (Minimum)
SGS model	Dynamic Smagorinsky model
Damping function	Van Driest type
Time integration	2nd order Crank-Nicolson
Discritization scheme	2nd order Central
Boundary condition	Wall : Immersed boundary method Side,Top : Slip condition, Inlet : Turbulent boundary layer (α=1/7, δ=20[m], Re_τ=590) Outlet : Convective

Development of turbulent boundary layer in Tokyo area

Figure 3 shows the vertical profile of instantaneous velocity at the time of tU_∞/δ =20.25 and tU_∞/δ = 93.75. tU_∞/δ =20.25 is the time before arrival of inflow turbulence and tU_∞/δ =93.75 is after arrival of inflow turbulence. This development of the internal boundary layer is caused by the blocking effect of buildings located at the coastal area. The internal boundary layer gradually develops for the inland and the decrease of the mean wind velocity and the increase of the fluctuating wind velocity are emphasized.

Then, the turbulent boundary layer becomes thick by not only blocking effect of building but also turbulent structure which the inflow turbulence has. As a result of the development of turbulent boundary layer, the height of turbulent boundary layer becomes over 700m in the central Tokyo area, which is approximately 2 km away from coastal area. Also, high rise building which is much higher than surrounding buildings affects the vertical profile of mean velocity, the velocity deficit effect remains in the leeward point which is several times of building height away.

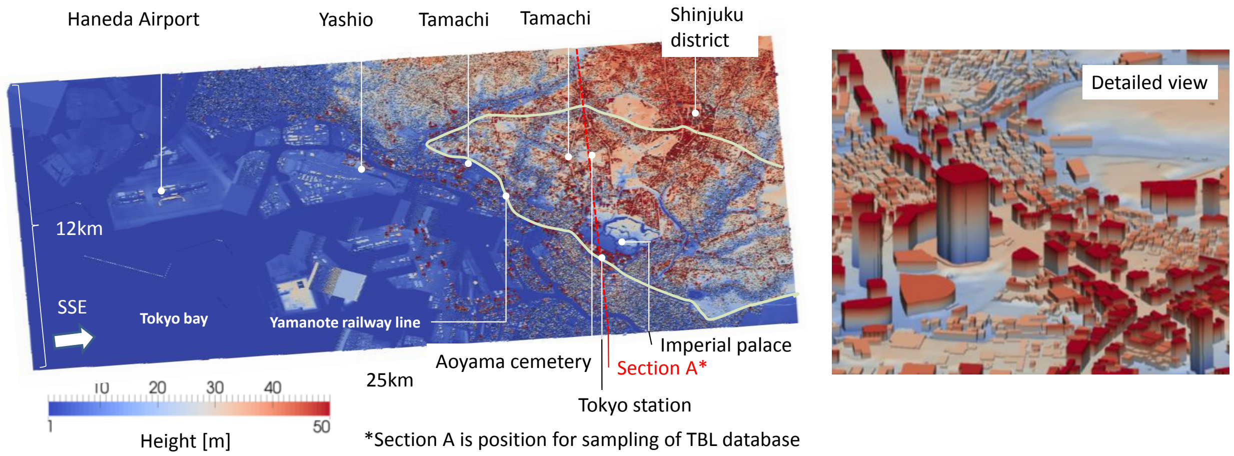

Figure 2. Calculation domain

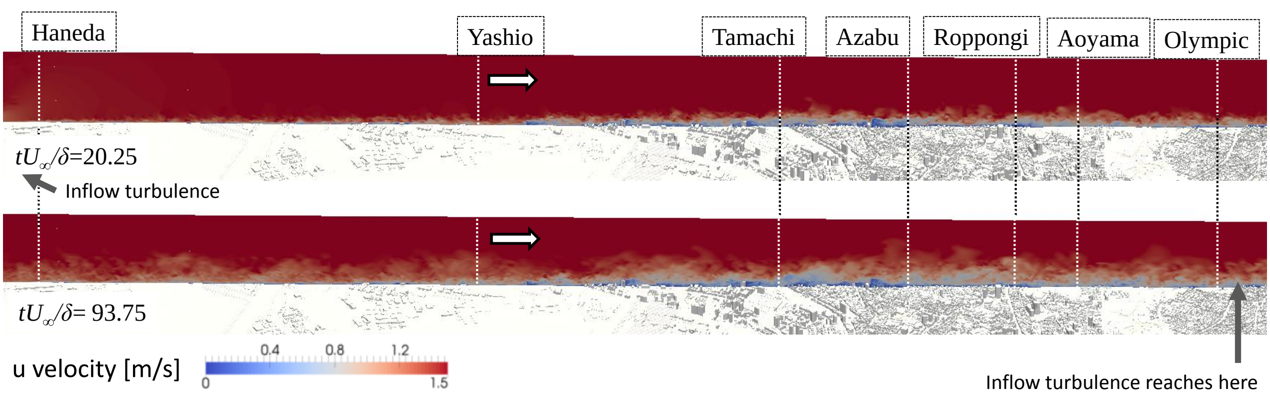

Figure 3. Effect of inflow turbulence on development of turbulent boundary layer

Turbulent Structure over and within Actual Urban Canopy

The effect of complicated geometry on the turbulence structure is analysed from 25x12km computation. Fig.4 shows the isosurface of Q criterion (Q=0.003, colored by vorticity x). In figure 4, coherent vortex structures whose radius has several meters appear 10-30m above region of low-rise urban blocks. It can be considered that these longitudinal vortices are generated as a result of the effect of low velocity coherent structures formed above the urban canopy. Also, vortex structures appear densely in the wake region of high-rise building. The scale of this vortex structure is a little larger than the vortex structures above the low-rise urban blocks.

For generation of coherent structure, the relation between coherent structures and low momentum region (LMR) has been discussed in previous researches (e.g. Adrian et. al [6]). Fig. 5 shows the isosurface of velocity u/u_{inf}=0.4 at the height of 50-100 m. However, the breadth of streak-like LMR, which seems to be determined by the length scale of high-rise buildings, is large compared with the scale of coherent structure above the low-rise urban blocks. Also, the streak-like structures is corresponding to vortex shedding of high-rise building, and flap from high-rise building to leeward area. In the actual urban area, there are several tall building which exceed the surrounding buildings. This standing-out building becomes the origin of the coherent low velocity region and forms the large streak structures. But this is a different coherent structures from the conventional one which is formed in a smooth-wall turbulent boundary layer.

Moreover, the spatially-vacant site also affects the turbulent structure on actual urban area. Fig. 6 shows vertical profile of velocity in spatially-vacant area. the mean velocity on spatially-vacant area increases at the height less than 70 m compared with the mean velocity on other points. This increase of velocity prevents the generation of LMR (fig.5), and generation of streamwise coherent structure seems to be suppressed (fig.4).

Database of the Turbulent Boundary Layer for Estimation of Wind Load

The spatial distribution of approaching flow is assumed to be uniform for spanwise direction in conventional way for estimation wind loading by wind tunnel experiment or CFD. However, the approaching flow with non-uniform characteristics, such as wake vortex from windward building, acts on the building.

This study make database of turbulent boundary layer (TBL) by extracting from the result of 25km x 12km region computation, and the spanwise distribution of turbulence statistics is analysed. The extraction location of TBL is shown in fig.2 (Section A). Fig. 7 shows the distribution of average and standard deviation of velocity on the extracted plane. The thickness of TBL is almost similar at point P1-P5, but the velocity profile is different at the height less than 500m. In Aoyama area (point P4), the mean velocity is larger than that at other points because of spatially-vacant site. Also in the area of point P2, the velocity is a little smaller than that at the point P4 because these areas are affected by wake turbulences of skyscraper area, which is located in 1-2 km windward area. At the points 1,3, the mean velocity becomes small and the turbulent intensity becomes high due to the wind ward buildings.

Then, Fig. 8 shows TBL database for estimating wind load of buildings in Tokyo station area. The distribution of power spectrum density at the point at the height of 43m is also shown in fig. 8. In the power spectrum density, large value is obtained

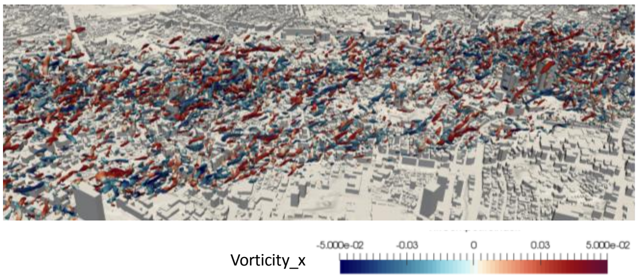

Figure. 4. Turbulent structure above urban canopy layer (Q=0.003, colored by vorticity x)

Figure. 5 Visualization of isosurface of velocity

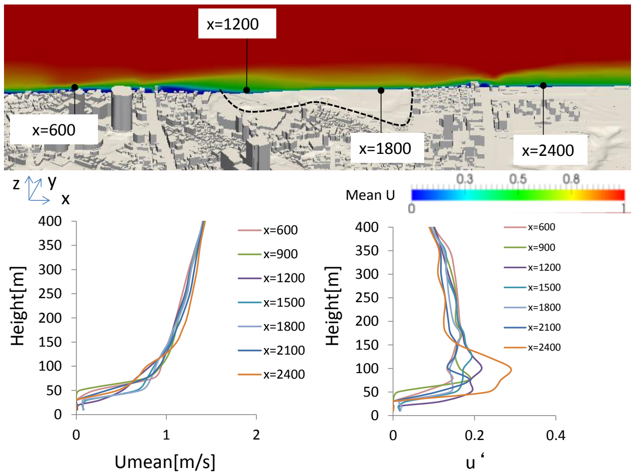

Figure. 6. Vertical profile of velocity in spatially-vacant area

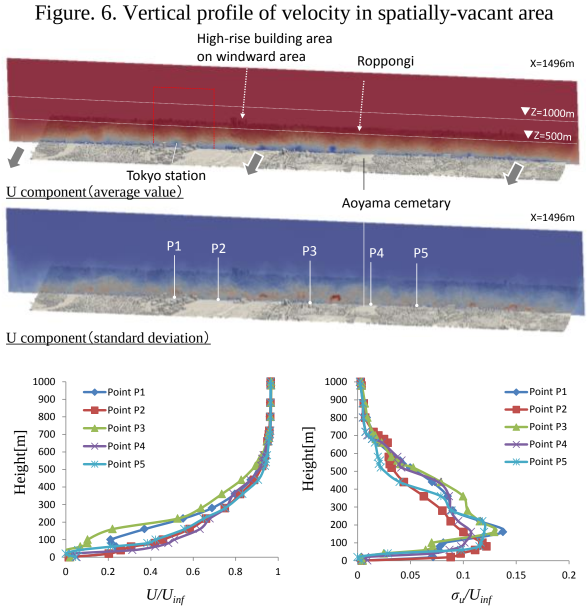

Figure 7 turbulent statistics of spanwise plane

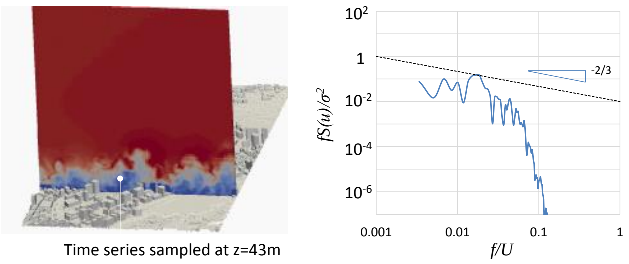

Figure 8 database of the turbulent boundary layer and power spectrum

also in low frequency region because the TBL is generated after over 10 km fetch. At the conference, power spectrum density in more broad frequency region will be shown.

Conclusions

This study analyse the turbulence structure over and within urban canopy by BCM-LES of 25x12km region in Tokyo central area and the following results are conducted.

First, the development process of turbulent boundary layer (TBL) is analysed, and the thickness of TBL becomes over 700m by introducing inflow turbulence.

Next, the effect of this heterogeneity on turbulent structures and statistics is examined from 25x 12km computation. As a result, the coherent structure is confirmed above low-rise urban blocks. However, the structure of low momentum region is considerably larger than the coherent structure and it seem to be determined by the length scale of high-rise building in low-rise urban blocks. Also, in the spatially vacant area, the increase of velocity prevents the generation of coherent structure.

Finally, database of turbulent boundary layer (TBL) is constructed from the result of 25km x 12km region computation, and the effect of roughness and windward building is examined from the spanwise distribution of turbulence statistics.

Acknowledgments

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