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High frequency recovering technique of turbulent inflow for LES of urban wind

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1. Introduction

In evaluation of unsteady heat and pollutant diffusion, or wind resistance design of buildings and structures in cities, large eddy simulation (LES) is one of the best appropriate numerical techniques for prediction of the wind flow and transport phenomena. Especially it is important to capture the near-ground flow field within the urban canopy layers. Wind engineering researchers carried out a few cases of LES for wind flows over actual urban districts and obtained the unsteady flows affected by the surrounding buildings and adjacent ground shapes. However, in order to reproduce the flow field in the urban canopy, not only the local effect by surrounding detailed geometry but also the long-ranged effect based on the developing atmospheric boundary layer should be considered.

Hybrid simulation of meteorological model and LES is one of the appropriate methods to reveal the effect of a wide range of meteorological phenomena on the near-ground flow field. However, meteorological model usually carries out the numerical simulation by the coarser spatial resolution compared with LES, and the sufficient fluctuation cannot be obtained due to numerically stable scheme for turbulent flows. In order to connect the results by the meteorological model to the flow fields in the LES calculation domain, we have to show the methodology to add high frequency fluctuation to the computed results with low frequency fluctuation.

Some researchers proposed the methods to generate the fluctuating part for urban wind of LES. Xie (2008) and Kondo (2012) proposed the method generating fluctuation statistically with corresponding to the specified turbulent statistics. However, strictly speaking, the artificially-generated fluctuation in these methods doesn’t satisfy the continuity and the momentum equations. On the other hand, in order to make the fluctuations with satisfying the governing equations, the methods to generate and amplify the fluctuation parts by using driver region have been also proposed. Nakayama (2012) proposed the method using driver region where the deviation from the averaged values can be estimated. However, it remains difficult to add appropriate-scale high frequency fluctuation to flow field fluctuating with low frequency because the deviation has no physical structures.

This study assumes the flow field with low frequency fluctuations (e.g. meteorological model results), which cannot contain the high frequency fluctuation by the coarse spatial resolution, as a kind of spatial filtered inflow (This study calls this kind of flow field as "Spatially-filtered inflow".) Therefore, this study focuses on a driver region calculation with spatial filtering technique, which is able to physically decompose the computed wind velocity to the scale of spatial filtered inflow and residual fluctuation appropriately. Then, the present method to add appropriate-scale high frequency fluctuation to spatial filtered inflow is proposed.

Finally, the proposed method is validated by a priori test using the spatially-filtered turbulent boundary layer as a spatially-filtered inflow. In the spatially-filtered turbulent boundary layer, the high frequency component of wind velocity fluctuation is decayed. In the test calculation, it is confirmed whether the high frequency fluctuation recovers in the developing process of the driver region by comparing with the original turbulent boundary layer before a filter operation imposed.

2. Proposal of high frequency recovering technique of turbulent inflow using rescaling and spatial filtering technique

In order to effectively obtain the sufficient developed flow field with high-frequency wind fluctuation, this study presents the method using driver region calculation with spatial-filtering and rescaling technique. Fig.1 shows the outline of the presented method.

First, the wind fluctuation is amplified in the driver region, and time series data of the amplified fluctuation are extracted at the recycling plane. Then, the spatial filtering technique decomposes the extracted wind velocity to spatially-filtered component $\overline{U}_i$ and residual component u'_i, which is fluctuating with high frequency (Eq.2). In this study, by adjusting the scale of spatial-filtering, it is possible to obtain the high frequency fluctuation with appropriate scale to the spatially-filtered inflow. Also, the each decomposed component satisfies the continuity condition because the spatially-filtered component of velocity satisfies the continuity equation.

Then, the high-frequency fluctuation obtained by spatially-filtering technique is rescaled in order to adjust the fluctuation from the velocity scale at recycling plane to that at inlet plane. The rescaling process is carried out based on Lund's method, and only residual component is rescaled. In the inner layer, where the vertical profile of wind velocity follows the law of the wall, $(u'_i)_{recy}^{inner}$ is converted to the velocity scale at the inlet point by the coordinate conversion of wall unit and the multiplication of friction velocity ratio of inlet station to recycle station (Eq.3). On the other hand, in the outer layer, where the vertical profile of wind velocity follows the velocity deficit law, $(u'_i)_{recy}^{outer}$ is converted to the velocity scale at the inlet point by boundary layer thickness and the ratio of friction velocity of inlet station to recycle station (Eq.4). The rescaled residual components u'_i in the inner and outer layer are composed by the weighting function (η) and the composed residual components is added to the spatially-filtered inflow with low frequency fluctuation. The resulting velocity is reintroduced to the inlet surface.

As explained above, the presented method adds the appropriate range of high frequency fluctuation to spatially-filtered inflow with low frequency fluctuation. Also, the fluctuation added at the inlet plane satisfies the continuity equation.

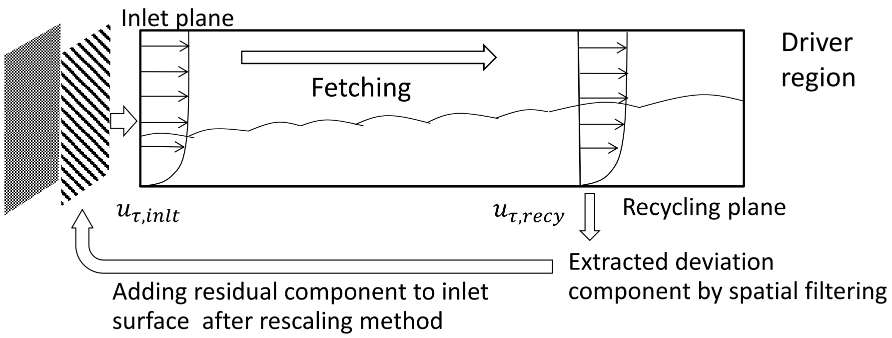


Fig.1. Driver region calculation for adding high-frequency fluctuation to spatially-filtered inflow

$$(u_i)_{inlt} = (U_{i0}) + \left[(u'_i)_{inlt}^{inner}\right]\left[1 - W(\eta_{inlt})\right] + \left[(u'_i)_{inlt}^{outer}\right]\left[W(\eta_{inlt})\right] \qquad (1)$$

$$u'_i(x,y,z,t) = u_i(x,y,z,t) - \overline{U}_i(x,y,z,t) \qquad (2)$$

$$(u'_i)_{inlt}^{inner} = \gamma(u'_i)_{recy}(y_{inlt}^{+}, z, t) \qquad (3)$$

$$(u'_i)_{inlt}^{outer} = \gamma(u'_i)_{recy}(\eta_{inlt}, z, t) \qquad (4)$$

$$W(\eta) = \frac{1}{2}\left\{1 + tanh\left[\frac{\alpha(\eta-b)}{(1-2b)\eta+b}\right]/\tanh(\alpha)\right\} \qquad (5)$$

where (U_{i0}) is time series of spatially-filtered inflow, u_i is velocity, u'_i is residual component of velocity, $\overline{U}_i$ is spatially-filtered component of velocity, γ is friction velocity ratio of the inlet station to the recycle station, y^+ ($= u_\tau y/\nu$) is the coordinate by wall unit, η is the coordinate normalized by the thickness of boundary layer, W is Weighting function (based on Lund's method). The subscripts mean that inlt is inlet station, recy is recycle station, inner is inner region and outer is outer region. The constants are given as α=4 and b=0.2.

3. Test calculation: a priori test using the spatially-filtered turbulent boundary layer (Re_τ=3300)

3.1 Numerical conditions

The proposed method is validated by a test calculation using a spatial-filtered turbulent boundary layer as a spatially-filtered inflow. In the test calculation, it is confirmed whether the high frequency fluctuation recovers in the driver region by comparing with the data of the original turbulent boundary layer.

The governing equations are given by the spatially-filtered forms of the continuity and the Navier-Stokes equations. For the subgrid scale turbulence model, the standard Smagorinsky model (Smagorinsky, 1963) is employed. The Smagorinsky constant is 0.1. Also, van Driest type of damping function is introduced near the wall.

$$\frac{\partial \bar{u}_i}{\partial x_i} = 0 \qquad (6)$$

$$\frac{\partial \bar{u}_i}{\partial t} + \frac{\partial \bar{u}_i \bar{u}_j}{\partial x_j} = -\frac{1}{\rho}\frac{\partial \bar{p}}{\partial x_i} + \frac{\partial}{\partial x_j}\frac{1}{\mathrm{Re}}\left(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i}\right) + \frac{\partial}{\partial x_j}\left(\overline{u_i u_j} - \bar{u}_i \bar{u}_j\right) \qquad (7)$$

where ui,p,v. and ρ stand for the wind velocity vector, pressure, molecular kinematic viscosity and density. The detailed Numerical condition is shown in Table. 1. In this study, spatially-filtered turbulent boundary layer (TBL) is introduced to inlet boundary surface with rescaled velocity fluctuations. The data of spatially-filtered TBL is obtained by imposing the 4th order Gaussian filtering technique to the computed data for TBL at Reτ=3300. In order to assume the spatially-filtered TBL as computed results with coarse spatial resolution, the TBL results at 4368 points (Time series of wind velocity, vertical direction: 168 points, spanwise direction: 26 points) are sampled and spatially-filtered in the spanwise direction. The spatial filtering length is about 0.01δ.The differentials of velocity are approximated by the central difference method (5 point stencil, 4th order accuracy). Interpolation method is employed.

Similarly, the spatial filtering technique is also applied to the computed data on the recycling plane in the driver region. The type of spatial-filtering is 4th order Gaussian filter. The size of spatial filtering is the same as that used for the spatially-filtered inflow (0.01δ).

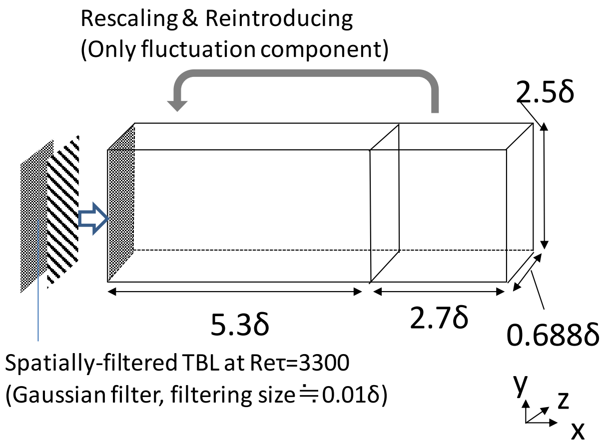
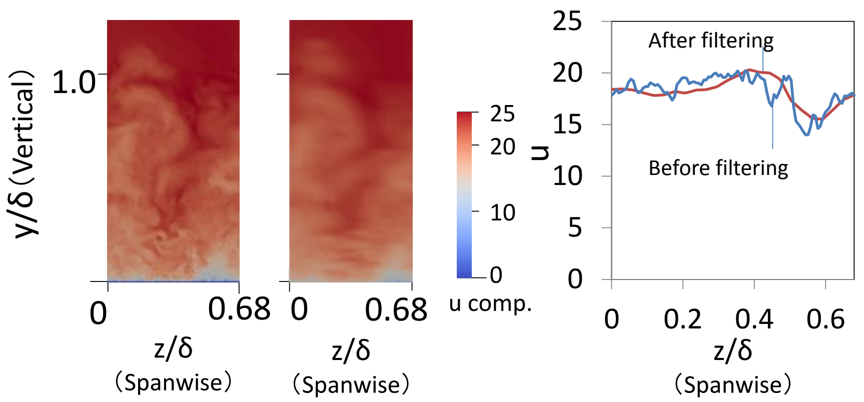


Fig.2. Domain of test calculation

Table.1 Numerical condition

Turbulence model	Smagrinsky model (Cs=0.1)
Dumping function	Van Driest type
Spatial discretization	4th order central difference
Time marching	Adams-Bashforth
Pressure solver	SOR
Domain size (X,Y,Z)	(8δ,2.5δ,0.68δ)
Grid number (N_X,N_Y,N_Z)	(600,250,100)
Spatial resolution (dx^+,dy^+,dz^+)	(44,1-54,22)
Time resolution	⊿t=0.000025
Reynolds number	Reτ=3300



(a)Before filtering (b)After filtering (c)Horizontal profile of u component (y=0.1δ)

Fig.3. Inflow condition: Spatially-filtered turbulent boundary layer (Re τ =3300)

3.2 Computed results

Fig.4 shows the adding process of high-frequency fluctuation extracted from the computed results. The u velocity distribution of spatially-filtered component, which is obtained by the spatial filtering at the rescaling point, has the similar structure as the spatially-filtered inflow. Then, the high-frequency fluctuation can be added to the spatially-filtered inflow, because of the appropriate fluctuation for inflow.

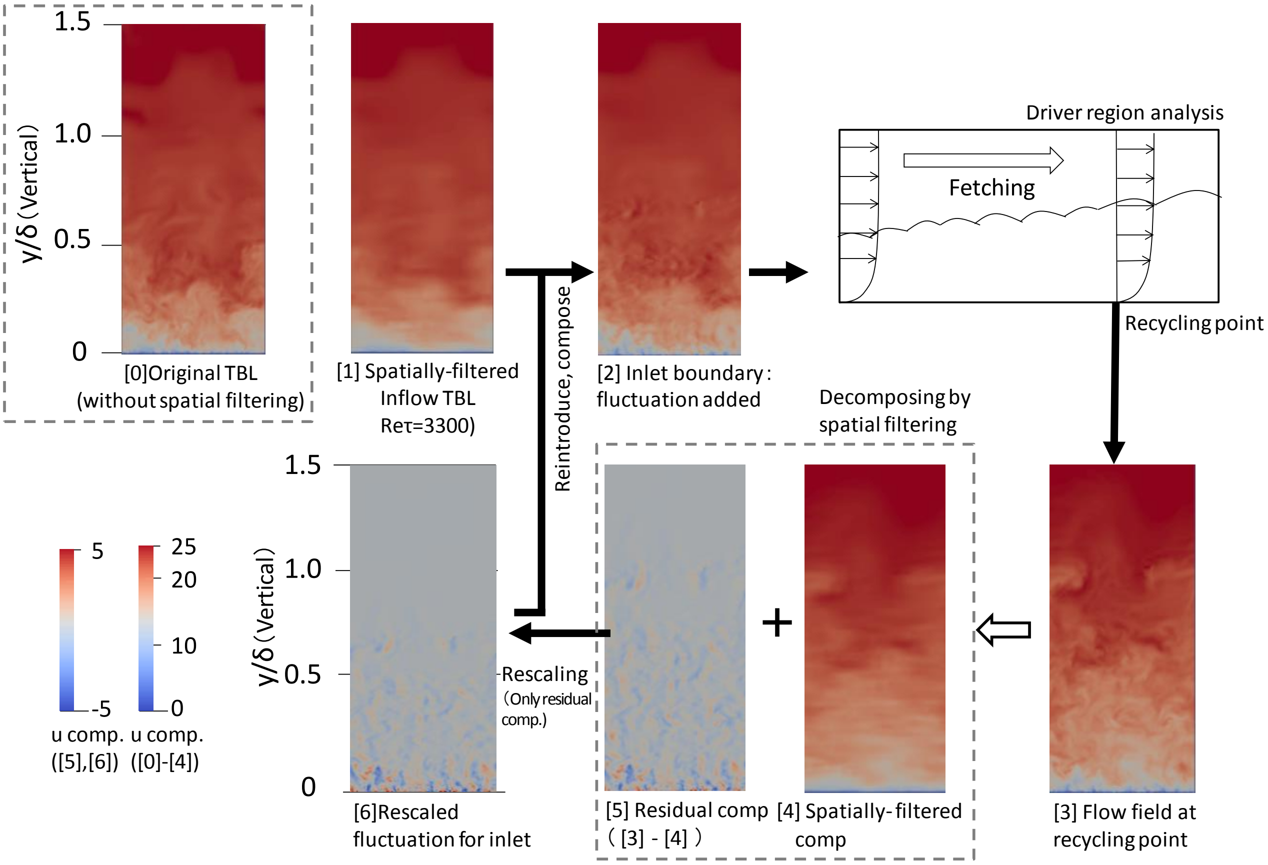


Fig.4. Adding process of high frequency fluctuation in the computed result

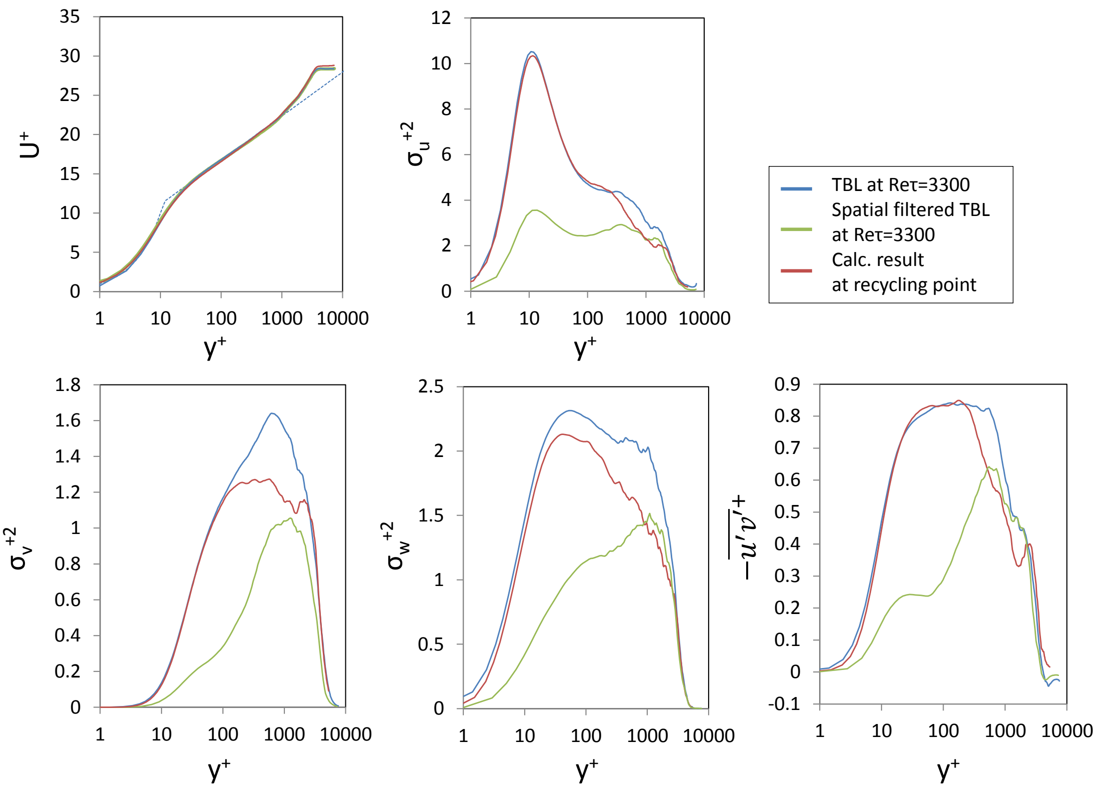


Fig.5. Computed results of turbulent statistics: Does the high frequency fluctuation recover?

Fig.5 shows the vertical profile of mean velocity and turbulent intensity. This study compares the calculation result at recycling point, the spatial-filtered TBL(Reτ=3300), and the original TBL (Reτ=3300) before spatial –filtering. The u mean velocity consists of three profiles and all profiles follow the logarithmic law. Next, This study focusses on the vertical profile of turbulent intensity of u. In the spatially-filtered TBL, the spatial filtering decreases the turbulent intensity by 65 %. In the calculation result at recycling point, the turbulent intensity almost recovers to the level of original TBL before spatial filtering. But, difference between the computed results and the original TBL data remains around y^+=1000. The turbulent intensity of v, w also shows the similar tendency. As a result of these differences, the vertical profile of Reynolds stress u'v' in the computed result shows the 22% difference compared with the original TBL data but the similar result to the original TBL data is obtained.

4. Conclusion

This study presented the calculation method to add the high frequency fluctuation appropriately to the spatial filtered inflow, focusing on the following points.

- Driver region calculation for generating the high frequency fluctuation with satisfying the continuity equation.
- Spatial filtering technique to decompose the calculated wind velocity to the scale of spatially-filtered inflow and residual fluctuation appropriately
- Rescaling techniques for adding appropriate range of fluctuation to spatially-filtered inlet flow

Then, in order to validate the presented method, a test calculation using spatially-filtered turbulent boundary layer was implemented. As a result, the high frequency fluctuation, which was decayed by spatial filtering, recovered by the present method. It was confirmed that the turbulent intensities of u, v, w in the test calculation results reproduced those in the original turbulent boundary layer within 10% difference in the region of $y^+>3000$ and $y^+<100$.

As next steps, in order to improve the accuracy of the presented method, other filtering schemes will be introduced to the present method and the obtained results will be compared with the present test calculation results. Then, the present method willemploy the computed results of WRF (Weather Research and Forecasting Model), or WRF-LES, and it will be confirmed whether the high frequency fluctuation for LES of urban wind is added.

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