Volume 6 Issue 1 (2018) 28-30 ISSN 2347 - 3258
International Journal of Advance Research and Innovation

Synthetic Inflow Boundary Condition based on Digital Filtering with Different Length Scales

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Article Info
Article history:
Received 02 January 2018
Received in revised form 20February 2018
Accepted 28 February 2018
Available online 15 March 2018

Keywords
LES, Synthetic inflow, Correlation, Length scale

Abstract
Large Eddy Simulation (LES), which has recently been developed and used for turbulent flow analysis, can be applied for a variety of area. In particular, in order to achieve a faster performance, an artificial generation of inflow turbulent flow would be necessary to make the faster convergence as well as to maintain the real turbulent flow in the calculation domain. In this study, the synthetic inflow generator has been developed based on spatial and temporal correlation functions, which have a form similar to an exponential function. This inflow data obtained by the synthetic inflow generator imposed into the inlet condition of LES simulation on a channel with smooth wall. In the result, fully developed turbulent boundary layer was successfully generated in the computational domain. In addition, the variation of various length scales was taken into account to observe the effect of the inflow length scales. The results in the variation of integral length scale shows that larger length scale in inlet section has faster rate of recovery in wall shear stress, which has an implication that in order to develop the boundary layer faster, a larger length scale of inlet section would be necessary to achieve the fully developed turbulent boundary layer.

1. Introduction

Modelling the turbulent boundary layer in the numerical simulation is important as it is a precondition for modeling the flow around bluff bodies such as building and structures. [1] It is used to estimate wind loads on structural models, to predict wind velocities around new developments, and to investigate the dispersal of airborne pollutants. In modeling the flow around structures and buildings, it is usually necessary to consider the length scale as the relatively larger scale than that obtained in a naturally grown boundary layer, because a more rapid decrease of the turbulence parameters with height than is shown in the atmosphere.

In order to generate the turbulent boundary layer, the most direct method would be to simulate a laminar inflow and allow it to develop spatially over a suitably long domain, i.e. over a hundred times the thickness of the eventual boundary layer depth of interest. However, even this 'simple' method would present difficulties associated with, amongst other things, ensuring the correct surface condition, such as length scale. It would in any case be extremely expensive computationally. Alternatively, a time-evolving LES or direct numerical simulation (DNS) with a periodic [2-5] inlet-outlet boundary condition can be used to generate appropriate turbulent flow. These simulations generate a realistic turbulent flow field. However, it is also expensive and has limitations, being applicable for example to simple geometries only. It is difficult to see how such a method could be used for a genuine urban-type situation.

Synthetic turbulence generation is of particular interest when only limited turbulence statistics data are available for the procedure. Hanna et al. [6] generated one-dimensional time series of inflow data based on an exponential correlation function to simulate flows over an array of cubes using LES. The time series were tailored to provide the required time scale and turbulence intensities and the subsequent LES was able to reproduce the main characteristics of the measurements. The merit of the method is its very high efficiency, but because no spatial correlation was imposed at inlet its accuracy is seriously limited. Because of the features of atmospheric boundary layer flows as inflow condition, one of the representative papers would be the work of Xie & Castro. [7] They implemented the urban boundary layer flows, which is high Reynolds number, fully developed turbulence and driven by weather scale motions. They used a digital-filter based method, which allows spatially varying turbulence scales on non-uniform grids to be imposed at the inlet.

In this study, the synthetic inflow generator has been developed based on spatial and temporal correlation functions, which have a form similar to an exponential function. Since the filtering process is made by this correlation function, it firstly was processed to get filtered data by having a convolution of filter coefficients with a set of two-dimensional random data. After filtering process, the spatial and temporal correlated data can be obtained in the inlet domain. With the virtue of this technique, the integral length scale obtained by integrating the correlation function can be easily given for spanwise and wall-normal direction (i.e., vertical) component, separately. In order to validate the turbulent boundary layer profiles in the channel domain from the synthetic inflow generator, the paper compares those results with the existing data which was similarly obtained in the calculated and measured domain.

In addition, in order to observe the effect of the inflow length scales which is imposed at inlet section, the variation of various length scales was taken into account.

2. Numerical method

2.1 Governing equation

The governing equation used in this study is the filtered Navier-Stokes equation and the discretization method is the finite volume method. The Smagorinsky model was used as a subgrid-scale model. The Smagorinsky constant was 0.065.

2.2 Synthetic inflow method

The instantaneous value of the velocity u_i may written as

$$u_i = \bar{u}_i + a_{ij}\boldsymbol{\psi}_j \tag{1}$$

where $\bar{u}_i$ is mean, a_{ij} is amplitude tensor[8] and $\boldsymbol{\psi}_j$ is unscaled fluctuation ($\bar{\boldsymbol{\psi}}_j = 0$, $\overline{\boldsymbol{\psi}_j\boldsymbol{\psi}_j} = 1$). The correlations in most turbulent shear flow have similar features, whereas it

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has an advantage of the correlation function that the correlation function approximates to the form of exponential function[7].

$$\psi_m = \sum_{j=-N}^{N} b_j r_{m+j} \qquad (2)$$

$$b_j = \tilde{b_j} \Big/ \left(\sum_{l=-N}^{N} \tilde{b}_l^2 \right)^{1/2}, \text{where } \tilde{b_j} = \exp\left(-\frac{\pi |l|}{n}\right) \qquad (3)$$

$$\psi_{m,l} = \sum_{j=-N}^{N} \sum_{k=-N}^{N} b_j\, b_k r_{m+j,l+k} \qquad (4)$$

$$\boldsymbol{\psi}_i(t+\Delta t, y, z) = \boldsymbol{\psi}_i(t,y,z)\, exp\left(-\frac{\pi \Delta t}{2T}\right) + \psi_i(t,y,z)\left[1 - exp\left(-\frac{\pi \Delta t}{T}\right)\right]^{0.5} \qquad (5)$$

where b_j is filter coefficient, r_m is random sequence, N is related with length scale.Eq(3) is two dimensional form of ψ_m. The fluctuation $\boldsymbol{\psi}_i(t+\Delta t, y, z)_i$ of the next time step can be calculated using Eq. (5) using the fluctuation $\psi_i(t,y,z)$ at the previous time step. T is a lagrangian time scale.

3. Channel flow

3.1 Boundary condition

The Reynolds number is derived as Re_τ = 150 with the friction velocity (u_τ) and the half height (d) of the channel. Figure 1 shows the schematics of computational channel domain. The boundary conditions are a no-slip condition on the top and bottom with $y^+ < 1$, a periodic boundary condition on the lateral direction, and a zero gradient condition on the outlet. The synthetic turbulence obtained by the synthetic inflow generation model was interpolated into the inlet plane.

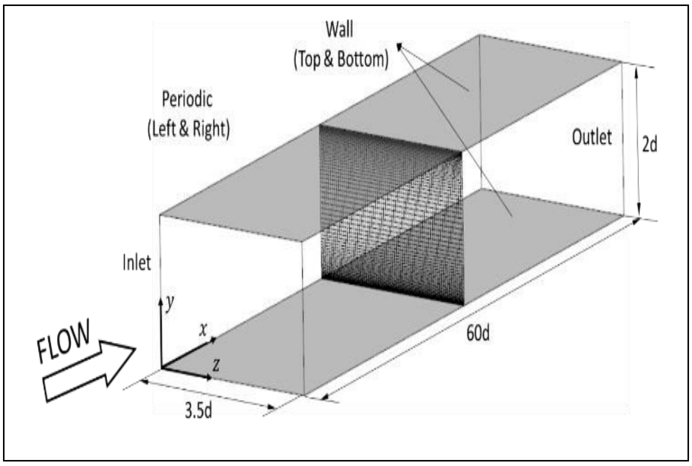

Fig. 1 Schematics of computational channel domain

Figure 2 shows the length scale obtained from the DNS database[9] and the simplified length scale applied to the synthetic inflow generation. Figure 2(a) shows the streamwise direction length scale, L_x, distribution along the wall-normal direction. Figure 2(b) shows the length scale for y- and z-direction.

In order to observe the effect of the inflow length scales which is imposed at inlet section, the considered length scales are shown in Table 1.

Figure 3(a) shows the change of the wall shear stress of Case01, Fig. 3(b) shows the distribution of Reynolds stresses at each position of x/d of the Case01. The wall shear stress decreases near the inlet region of the channel and slowly recovered in the streamwise direction, resulting in a constant value from the region where x/d is more than 40. If the domain size is set to less than x/d=40, the desired result cannot be obtained. When the domain size was originally set to be $x/d = 12$ along the streamwise direction, the wall shear stress (i.e., a dashed line in Fig. 4.2(a)) was continuously reduced until it reached the outlet without any recovery.

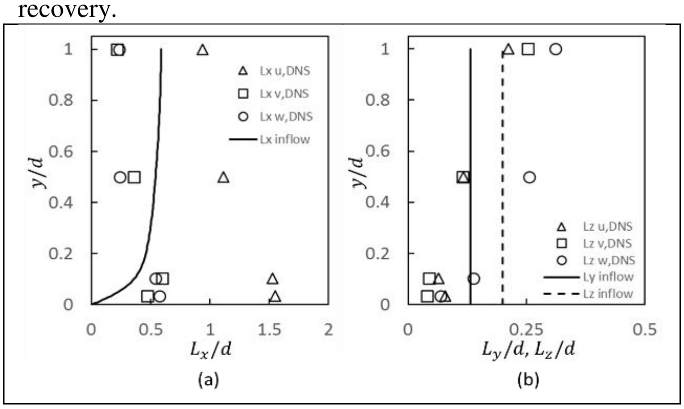

Fig. 2 Profiles of integral length scales in the inlet L_z^*

Table 1. Length scales

Name	y/d <0.1	0.1< y/d <0.2	y/d > 0.2
Case01	$1L_z^*$	$1L_z^*$	$1L_z^*$
Case01	0, random	0, random	0, random
Case03	$0.15L_z^*$	$0.15\mathrm{Lz}_*$	$0.5L_z^*$
Case04	$0.3L_z^*$	$0.3L_z^*$	$1L_z^*$
Case05	$0.5L_z^*$	$0.5L_z^*$	$1.5L_z^*$
Case06	$0.3L_z^*$	$1L_z^*$	$1L_z^*$
Case07	$2L_z^*$	$2L_z^*$	$2L_z^*$
Case08	$3L_z^*$	$3Lz_*$	$3Lz_*$

3.2 Results

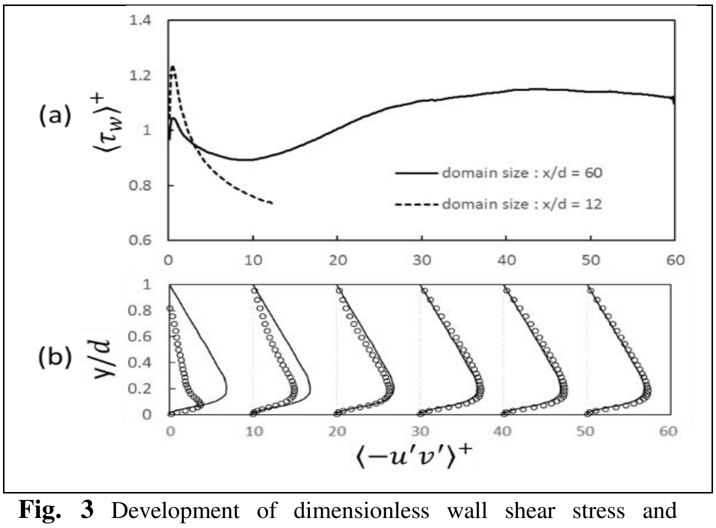

Fig. 3 Development of dimensionless wall shear stress and Reynolds stress of Case01

Figure 4 shows the distribution of wall shear stress for 8 cases with different length scales. It can be seen that the change in the length scale applied to the entrance has a significant effect on the recovery of wall shear stress. Figure 4(a) shows the $\langle \tau_w \rangle^+$ distribution for cases with lower length scale than Case01, and Fig. 4(b) shows the $\langle \tau_w \rangle^+$ for cases with higher length scale than Case01. From Case02 to Case05, wall shear stress $\langle \tau_w \rangle^+$ was not stabilized in whole channel domain. It means that a longer domain size is required to obtain fully developed turbulence. Case01 and Case06 had the almost similar wall shear stress profiles. Case07 and Case08 show that the rate of change of $\langle\tau_w\rangle^+$ converges to zero at x/d of 25 which is 17% upstream of Case01. Case08 has a higher length scale than Case07, but the distance required to recover the $\langle\tau_w\rangle^+$ is almost same.

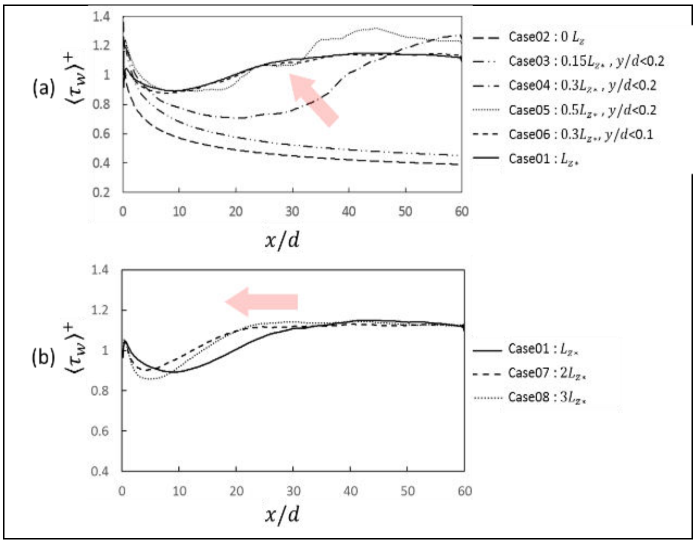

Fig. 4 Statistics of turbulence at inlet and x/d =50

Figure 5 compares the second moments of synthetic turbulence imposed at the inlet and the turbulence obtained from Case01, Case06, Case07, Case08 at the x/d = 50. The turbulence statistics at the inlet and at the x/d = 50 show similar distributions. The difference between the turbulent boundary layers at the input and at the x/d of 50 is considered to be caused by the lower resolution of LES than DNS.

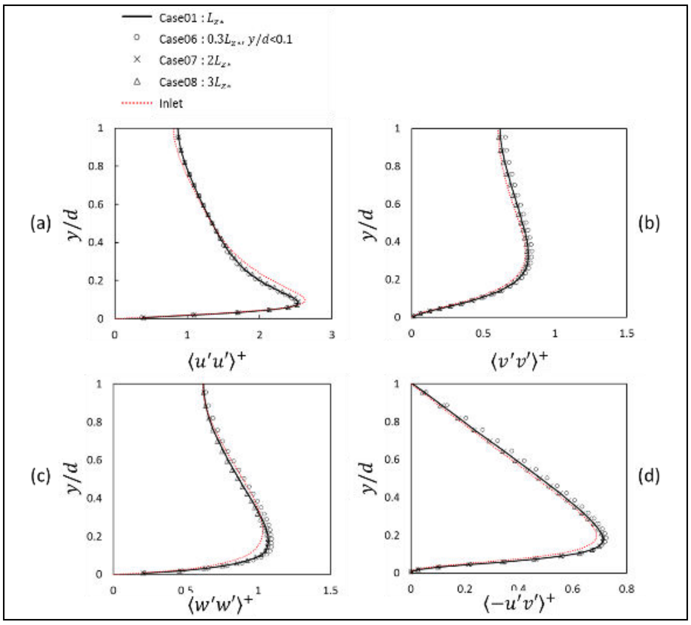

Fig. 5 Mean and second moments distribution along wall-normal direction at x/d=50

4. Conclusion

In this study, turbulent boundary layer was successfully simulated in the channel domain using LES with inflow data obtatineed by the synthetic inflow generator.

Larger length scale in inlet section has faster rate of recovery in wall shear stress, which has an implication that in order to develop the boundary layer faster, a larger length scale of inlet section would be necessary to achieve the fully developed turbulent boundary layer.

Regardless of the inlet length scales, the fully developed turbulent boundary layer on downstream region had alomost similar statistics.

Acknowledgment

This work was supported by "Human Resources Program in Energy Technology" of the Korea Institute of Energy Technology Evaluation and Planning (KETEP), granted financial resource from the Ministry of Trade, Industry & Energy, Republic of Korea (No. 20164030201230). In addition, this work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIP) (No. 2016R1A2B1013820). This research was also supported by the Fire Fighting Safety & 119 Rescue Technology Research and Development Program funded by the Ministry of Public Safety and Security (MPSS-2015-79)

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