

LES of fluctuating wind pressure on a 3D square cylinder for PIV-based inflow turbulence

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ABSTRACT: We carried out LES of fluctuating wind pressure on a three-dimensional square cylinder for PIV-based inflow turbulence which is generated by using stereo PIV measurement data for inflow condition. PIV experiment was executed at low Reynolds number, so we try to produce the higher Reynolds number inflow turbulence using the low Reynolds number turbulence which was obtained on the basis of PIV measurement results. Also, using the obtained data at higher Reynolds number, we discuss the accuracy of prediction of wind loads on the cladding by comparison with wind tunnel experimental results.

KEYWORDS: LES, Wind Pressure, 3D Square Cylinder, Inflow Turbulence, PIV, Reynolds Number

1 INTRODUCTION

Wind loads acting on buildings immersed within a turbulent boundary layer are sensitively characterized by the approaching flow. In view of fluid dynamics, inflow wind fluctuations tend to affect the computed aerodynamic characteristics based on wake structures of an object, then their set-up should be concerned for CFD applications, since CFD has much flexibility for inflow generation. So, we proposed a new method for generating inflow turbulence where stereo PIV measurement results are directly used to impose the inflow boundary condition of LES (1). Namely we carried out LES of a turbulent boundary layer developed on a flat floor using stereo PIV measurement results at inflow and the generated PIV-based inflow turbulence was saved as the database after a full development. Also, this paper presents the computed results of the fluctuating wind pressure acting on rectangular cylinder obtained by LES under the condition of oncoming turbulence. But PIV experiment was executed at very low Reynolds number, so we try to make higher Reynolds number inflow turbulence modifying low-Reynolds-number turbulence provided by PIV measurement. It can be expected that this turbulent structures result in the accurate fluctuating components of physical quantities. Hence we aim at discussing the accuracy of prediction of wind loads on the cladding by comparison with wind tunnel experimental results.

2 LES FOR INFLOW GENERATION USING STEREO PIV MEASUREMENT DATA

PIV wind tunnel experiments were executed for a turbulent boundary layer developing on a flat plate using the wind tunnel of Building Research Institute. We measured the three-dimensional wind velocity of the turbulent boundary layer using a stereo PIV system assembled by SEIKA Corporation (Photo1 & Figure 1). The sampling frequency of the flow velocity images for the digital high-speed video camera was set to 1000Hz, and non-dimensionalized Nyquist frequency was equivalent to 3.57, and the Reynolds number Re_δ was equal to 8,400.

We used the image deformation correlation algorithm (sub-pixel image shifting) repeatedly five times for PIV images analysis to reduce noise elements in high frequency region. But a few noise

elements remain in high frequency region and sometimes very large spike-shaped peaks appear. So we corrected the PIV time histories by peak cutting and moving average. Figure 2 shows statistics of inflow velocity corrected PIV measurement data.

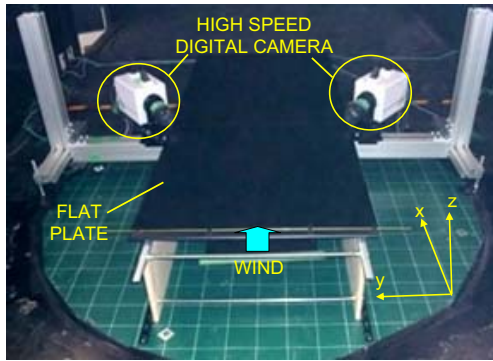


Photo 1 PIV measurement setup

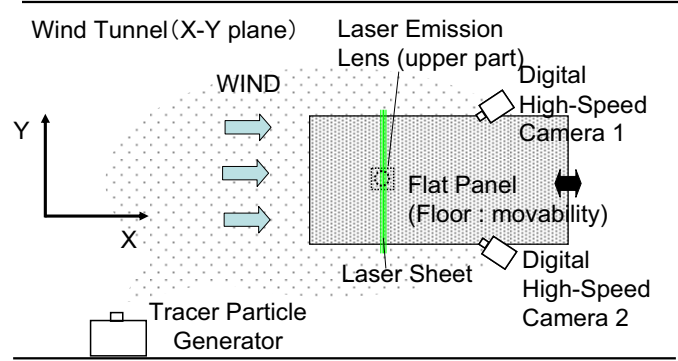


Figure 1 Outline of stereo PIV measurement

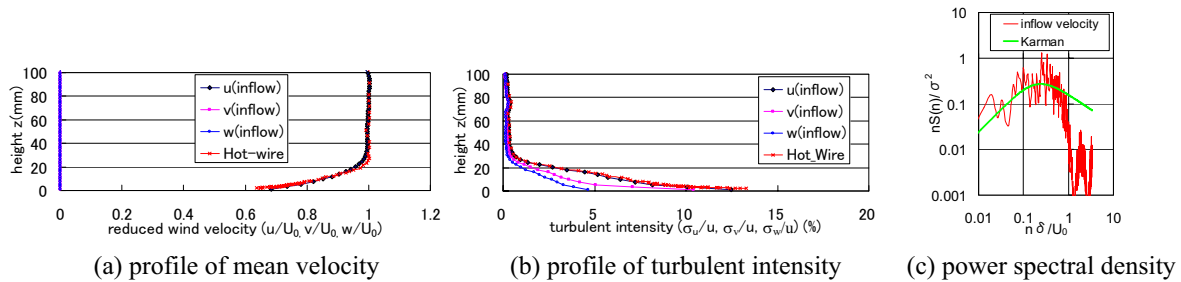


Figure 2 Statistics of inflow velocity based on PIV measurement data

LES computation using PIV-based inflow turbulence for inflow generation was carried out by OpenFOAM which has been widely circulated as an open-source code. The governing equations are given by the continuity and the incompressible Navier-Stokes (N-S) equations. This code uses the unstructured-grid based concept and the finite volume method for discretization of the governing equations. For the turbulence model of LES the standard Smagorinsky model is employed. The no-slip condition is used for the bottom boundary to this LES. This means the sufficiently fine mesh is required for near-wall region. The Reynolds number $Re_\delta (=U_0\delta/\nu, U_0$: wind velocity above turbulent boundary layer, δ : turbulent boundary layer thickness, ν : kinematic viscosity) is 8,400 and $Re_\tau (=u_\tau \delta / \nu, u_\tau$: friction velocity on floor) is about 360.

Fig.3 depicts the instantaneous velocity field as a result of LES computation. The wind velocity distribution has striped patterns with a long streamwise length near the floor. It can be thought that streak structures are surely formed immediately above the bottom surface. According to wind velocity contours in the vertical section, it is confirmed that velocity fluctuations given as inflow condition have convected smoothly downstream with drag effects by a bottom wall, and the turbulent boundary layer is appropriately developed with coherent structures such as bursting phenomena.

Fig.4 shows vertical profiles of mean wind velocity and turbulent intensity for u -component reduced by friction velocity u_τ . Both LES results correspond closely to experimental results by Degraaff and Eaton. Figure 5 shows the power spectral density of wind velocity of inflow data and the LES result with fully developed state near the wall ($z+=11$) and at the log-law region ($z+=130$). It is confirmed that turbulence structures near the wall are generated by appropriate

numerical method which can handle the grid size and the numerical dissipation. At the log-law region, spectral shapes of LES fit to the Karman type spectrum sufficiently.

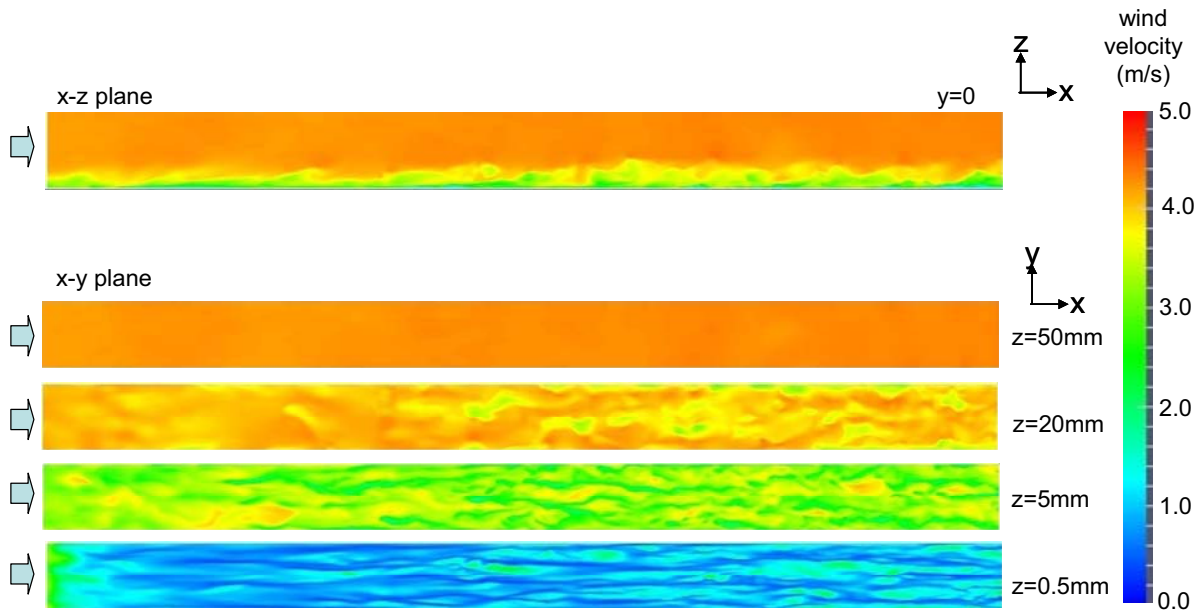
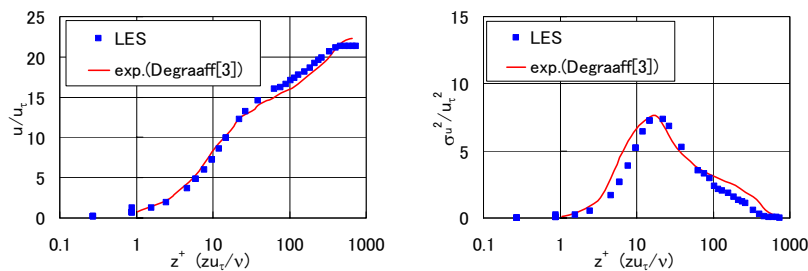


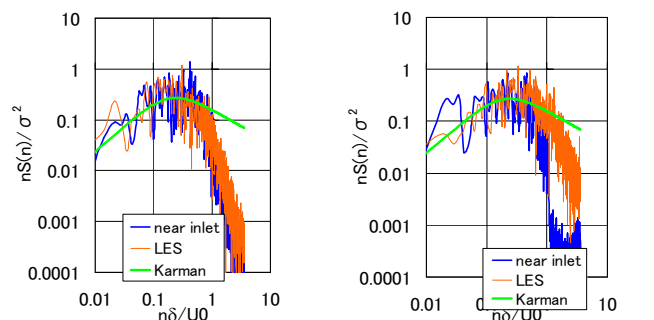
Figure 3 Instantaneous wind velocity distributions by LES for inflow generation



(a) mean wind velocity

(b) turbulent intensity

Figure4 Profiles of mean wind velocity and turbulent intensity reduced by friction velocity u_τ



(a) near wall ($z^+ = 10.8$)

(b) log-law region ($z^+ = 130$)

Figure5 Power spectral density of LES result

Inflow data for turbulent boundary layer simulation provided by the stereo PIV measurement has low-frequency fluctuations but no high-frequency fluctuations, and the accuracy level of PIV data near the wall is low by reflection of laser beam. In LES low-frequency fluctuations given by

PIV measurement data are maintained in whole computational domain. While, high-frequency fluctuations are generated by the energy cascade. Turbulence structures near the wall can be reproduced by high resolution in near-wall region under the usage of no-slip condition. Accordingly, the present proposed models using LES, the turbulent boundary layer can be reproduced by relatively short fetch.

3 GENERATION METHOD OF HIGH-REYNOLDS INFLOW TURBULENCE

It is expected to acquire wind loads on structures by calculating flow field around bluff bodies with inflow turbulence which simulates the boundary-layer type of flow structures in wind engineering. We aim at creating the database of inflow turbulence for LES calculation based on the PIV measurement data. However, the Reynolds number and the boundary layer thickness obtained in PIV wind tunnel experiment are restrictive, so some problems occur in similarity to calculation for actual wind loads evaluation. Here, we propose a method generating inflow turbulence at higher Reynolds number. We have verified the validity of this method by LES using the inflow turbulence with the low Reynolds number developed on the flat plate shown in chapter 2, and discuss the enhanced applicability of inflow turbulence database based on PIV measurement results.

The Reynolds number Re_δ (defined by boundary layer thickness δ) of the PIV based inflow turbulence presented in the preceding chapter is about 8400, while the Reynolds number Re (defined by the width of 3D-cylinder) is about 2000. Here, in realizing the computation of the flow field around a three dimensional square cylinder at the same order of Re as the wind tunnel experiment, we try to set about 5 times Re as the order exceeding 10000. For this, the kinematic molecular viscosity is changed to $1/5$ on calculation.

In the process of the rescaling by Lund et al.(2), a boundary layer is generally divided into two domains, one is an inner region where the law of the wall can be realized, the other is outer region where the velocity defect law can be realized. Basically using this concept, the conversion from low to higher Reynolds number flow for inflow turbulence is also enforced to each region.

In the inner region the law of the wall can be realized, and the mean velocity profile collapses the logarithmic distribution to z^+ non-dimensionalized by the friction velocity u_τ and the kinematic viscosity ν shown in Fig.4. Since Re is converted into 5 times higher by $1/5 \nu$, also as a result of larger u_τ , the vertical size of the inner region estimated on the basis of z^+ is reduced to less than $1/5$ on dimensionalized scale (Fig. 6). In the outer region, the boundary layer thickness is the same for both the Reynolds number flows, inflow turbulence fluctuations are corresponding to each other at same height. However, since the wind velocity at the top of the inner region is specified, the velocity at upper location in outer region should be shifted following the inner value, so that this method assumes to have an average wind velocity profile according to the power law on the flat plate with $\alpha=0.15$. The outline of the procedure of changing the Reynolds number of the inflow turbulence is shown in Fig. 6. The profile of mean wind velocity with z^+ is shown in Fig. 7.

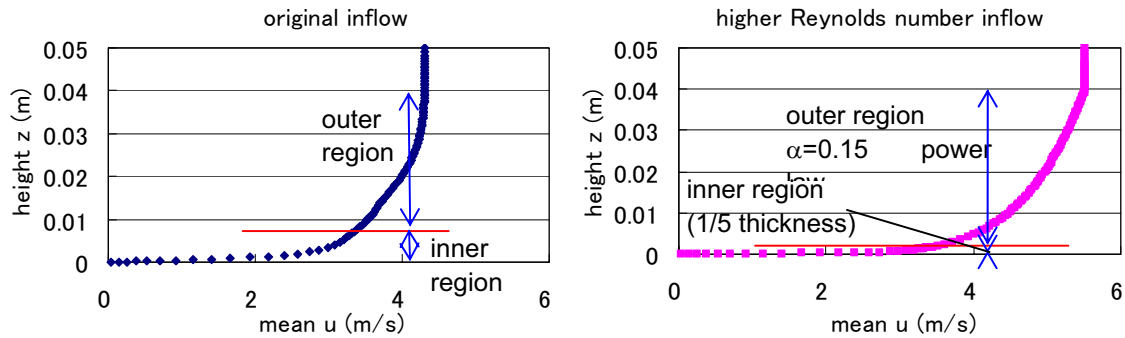


Figure 6 Outline of the procedure of changing the Reynolds number of the inflow turbulence

In order to confirm that this inflow turbulence generated for higher Reynolds number flow is adapted to the whole computational domain, we executed LES of turbulent boundary layer using this inflow turbulence for inflow condition. Computation outline is the same as that of the preceding chapter, the mesh resolution in the vertical direction is made for the first mesh point to be set to $z^+ < 1$ near the wall and the mesh resolution in the spanwise direction is twice finer than the former case.

Figure 8 shows the profiles of mean wind velocity and the standard deviation reduced by friction velocity u_τ . In buffer layer, The computed wind velocity shows smaller values. It is considered that this phenomenon is caused by the discontinuity of fluctuation component of inflow at the connecting point between the inner and the outer regions, in spite of connecting mean component of inflow smoothly. Figure 9 shows the instantaneous flow field of LES at the higher Reynolds number. In inner region, the distribution of 1/5 height of higher Reynolds number flow (fig. 9 $z=0.1\text{mm}$) is similar to that of low Reynolds number flow (Fig. 3 $z=0.5\text{mm}$). In outer region, the distribution of each flow at the same height (Fig. 3 and Fig. 9 $z=20\text{mm}$) is well alike. This means that it is rational to divide into two regions at inner and outer sides to generate the higher Reynolds number inflow turbulence.

Since it is mostly in agreement to inflow above log-law region, we carry out LES of flow field around a 3 dimensional square cylinder using this computed result as inflow turbulence.

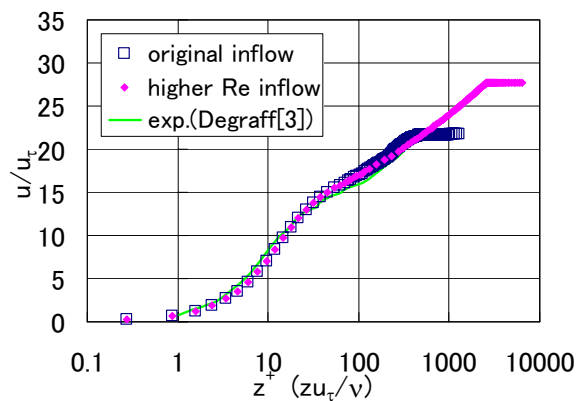


Figure 7 Profiles of mean wind velocity with high Reynolds number reduced by friction velocity u_τ

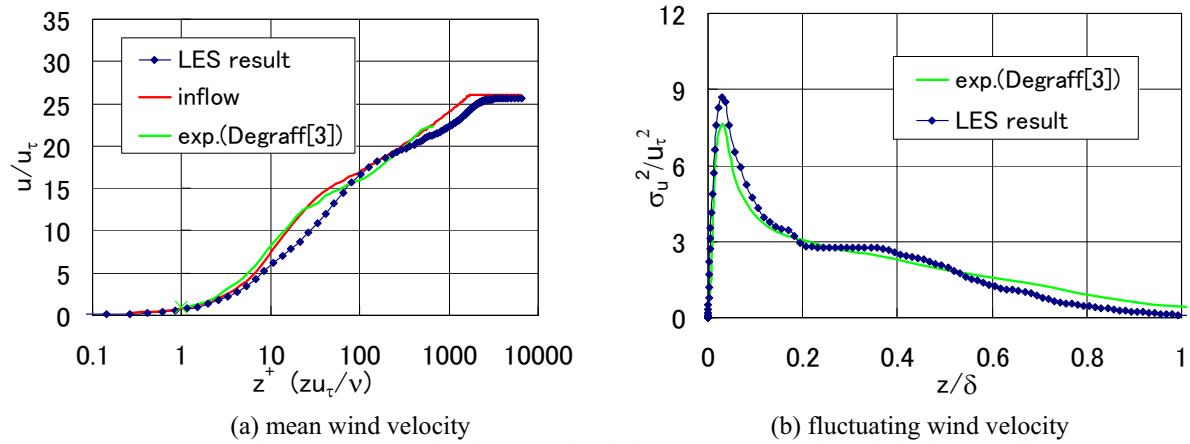


Figure 8 Profiles of mean wind velocity and turbulence of LES result with high Reynolds number

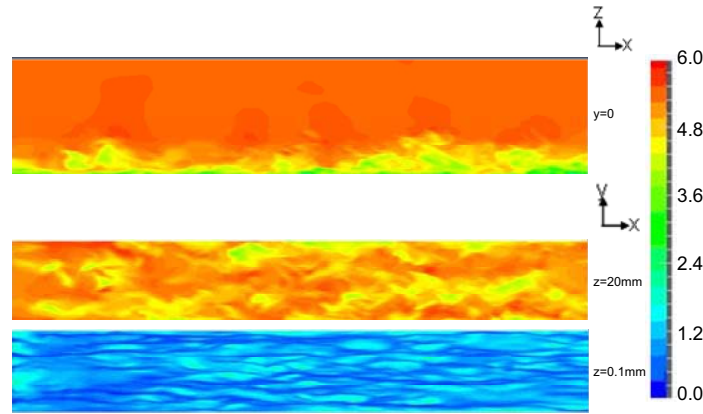


Figure 9 Instantaneous wind velocity distribution by LES for higher Reynolds number flow

4 LES AROUND 3D SQUARE CYLINDER FOR PIV-BASED INFLOW

LES of flow field around a 3-dimensional square cylinder is carried out using inflow turbulence generated in the preceding chapter. Figure10 shows the outline of mesh generation for this computation. The resolution around the square cylinder is raised using refinement mesh function equipped in OpenFOAM four times. Whenever it uses refinement function, the mesh resolution in the three directions becomes twice respectively. Therefore, the resolution of domain 5 is 16 times that of the outer domain 1. One side of the square cylinder is divided into 120 meshes.

Figure 11 shows the instantaneous flow field of the computed result. Figure 12 shows the mean and fluctuating pressure coefficients compared with the experimental result at several heights.

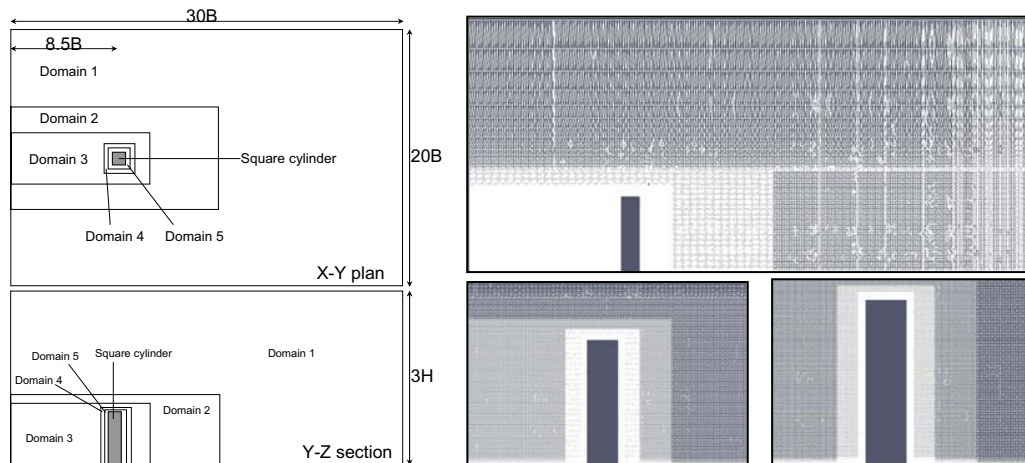


Figure 10 Outline of mesh generation by refinement function and meshes around a square cylinder

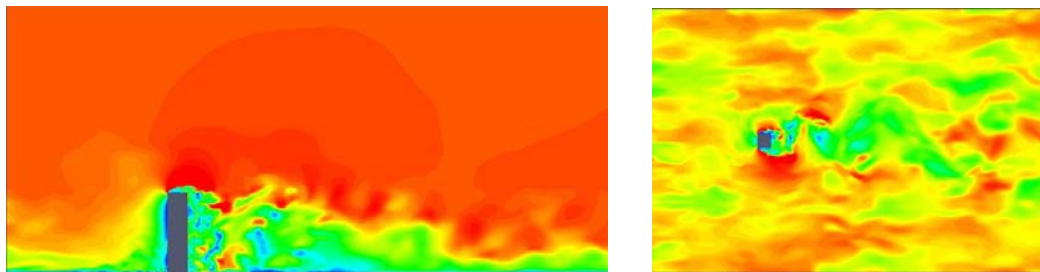


Figure 11 Instantaneous wind velocity distribution around a 3D square cylinder

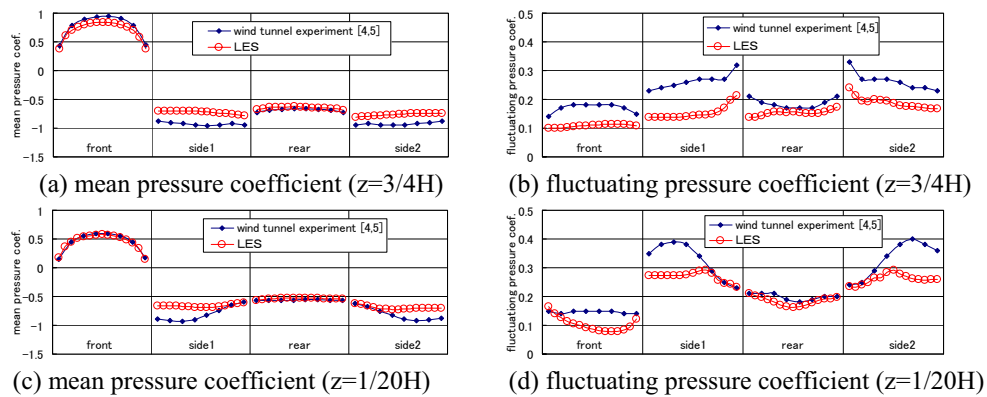


Figure 12 Pressure coefficients on a 3D square cylinder

Height at $z=3/4H$ is located near the stagnation point, and height of $z=1/20H$ is near the floor. Mean pressures of front and rear surfaces correspond with those of experiment. Mean pressure on side wall is different from that of experiment. Especially, it differs near the frontal location. Fluctuating pressure coefficient of front surface is different from the experimental result. At side surface, although fluctuating pressure coefficient value is different from the experimental result, it is qualitatively similar. At rear surface, fluctuating pressure coefficient is corresponding with experimental result. In this LES, since the height of the square cylinder to boundary layer thickness is higher as compared with the experiment, it can be considered that turbulent intensity in the upper part of a square cylinder is small. As a result, the fluctuating pressure coefficients are not in agreement with experimental data.

5 CONCLUSIONS

We executed LES of flow field around a 3-dimensional square cylinder to estimate pressures on the surfaces using PIV based inflow turbulence for inflow condition. To compare LES results with experiment results, we tried to reproduce higher Reynolds number inflow turbulence modifying low-Reynolds-number turbulence provided by PIV measurement. In this paper, we proposed the method of generating inflow turbulence at higher Reynolds number, using the concept that the boundary-layer type of turbulent structures are divided into an inner and outer regions. In order to use this method, it is a future problem to maintain a continuity of turbulent structures at the connecting position. The LES results for wind pressure on the square cylinder using PIV based inflow turbulence was qualitatively in agreement with experimental data.

6 REFERENCES

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