

LES of local severe suction on side face of a three-dimensional square cylinder

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ABSTRACT: The purpose of this paper is to investigate turbulence effects on characteristics of local severe suction on side face of a three-dimensional square cylinder by LES. The behavior of conical vortices associated with local suction at the angle of the attack $\theta=0^\circ$, and glancing angle are focused on. First, the computed results for distribution of the pressure coefficients are validated through comparison with the experimental data. Next, using the computed results, the effects of inflow turbulence on the high peak suction and flow characteristics are examined. As a result, high peak suction occurs associated with wake characteristics and flow reattachment characteristics affected by the large scale fluctuation of oncoming turbulence.

KEYWORDS: *LES, local severe suction, conical vortex, three-dimensional square cylinder*

1 INTRODUCTION

Recent advancements of computational techniques have made it possible to easily simulate the flow around a bluff body, and many investigations have been reported regarding applicability of computational models. Recently, in AIJ (Architectural Institute of Japan) CFD working group, around 10 members compute the flow around a three-dimensional square cylinder (breadth(B):depth(D):height(H)=1:1:3, 1:1:4) in boundary-layer turbulence by use of LES codes, such as commercial software, open source software and self-development software, and discuss adequate computational conditions and numerical formulations through the comparison with experimental data for the aerodynamic forces and the pressure coefficients.

On the other hand, the flow around a square cylinder is sensitively changed depending on angle of the attack. It is well known that local severe suction occurs in the flow separation regions of a three-dimensional square cylinder. Okuda et al.⁽¹⁾ showed from the results of wind tunnel experiments (wind pressure measurements and flow visualization) that the local severe suction near the leading edge were mainly caused by two types of conical vortices. One was an inverted conical vortex on the middle or lower side of the cylinder in the case where the wind perpendicularly attacked the front of the cylinder ($\theta=0^\circ$). This inverted conical vortex was nearly periodically formed associated with vortex shedding and causes a large fluctuation of the pressure near the bottom of the leading edge. The other was a standing conical vortex near the upper corner of the leading edge at the glancing angle ($\theta=13\sim15^\circ$) which leads to large level of the negative pressure. This vortex is hardly affected by vortex shedding in the wake. If the wind velocity did not change, the fluctuating suction was zero⁽¹⁾.

These experimental results by Okuda et al. ⁽¹⁾ clarified the flow mechanism of local negative suction on the surfaces of a three-dimensional square cylinder. However, the boundary-layer thickness is much lower than a cylinder height, so the oncoming flow is nearly smooth flow except the lower region of a square cylinder.

On the other hand, Surry et al. ⁽²⁾ investigated relationships of high peak suction with the characteristics of oncoming turbulence using the wind tunnel experiments. The results of pressure measurements on the side of the cylinder at angle of the attack $\theta=0^\circ$ reveal distinct periodicity associated with vortex shedding, as reported by Okuda et al ⁽¹⁾. Furthermore, the occurrence of peak event always coincides with the fluctuation induced by vortex shedding, an increase in turbulence intensity obscures the periodicity of vortex shedding, but peak relationship with remaining randomized vortex shedding appears to be maintained.

Okuda et al. ⁽³⁾ investigate characteristics of local negative suction from the results of the outdoor measurements. Above two types of the local severe suction are also recognized even in natural wind condition. However, the peak of the negative pressure becomes a sharp and peak values are much larger in natural wind condition compared with those of the wind tunnel experiments ⁽¹⁾.

Above studies ^{(1), (2), (3)} on characteristics of local suction near the leading edge have been investigated by utilizing the wind tunnel experiment. So, the data of pressure are easily obtained, but the information of flow structure could not be easily obtained. Namely, the flow mechanism causing local suction especially in boundary-layer turbulence has not reached completely understanding.

The authors of this paper computed the flow around of a low-rise structure (B: D: H=1:1:0.5) by utilizing the LES method ⁽⁴⁾. We used an over set grid in curvilinear coordinate system in order to sufficient grid resolution near the leading edge of the roof of the cylinder, and then showed that the computed results showed very good agreement with the experimental data. Also, based on the computed results, the flow mechanism causing the local suction on the roof in uniform and boundary-layer turbulence flows is clarified ⁽⁵⁾.

In this research, the LES method ⁽⁴⁾ using sufficient grid resolution is applied to the flow around a square cylinder (B: D: H=1:1:4) in boundary-layer turbulence at angles $\theta=0^\circ, 15^\circ$ of the attack, and unsteady characteristics of conical vortex are investigated. First the present LES model is validated for prediction of the pressure characteristics on a square cylinder through comparison with the experimental data ⁽⁶⁾. Next, the relationships between high peak suction and unsteady motions of two types of conical vortices such as an inverted conical vortex and a standing conical vortex in boundary layer turbulence are investigated by computed data.

2 PROBLEM FORMULATION

The governing equations are given by the incompressible Navier-Stokes and the continuity equations. To advance the solutions of velocities and pressure in time, a fractional step method is employed. The time integral of the momentum equation is hybrid, that is to say, the Crank-Nicolson scheme is applied to the viscous terms and the explicit third-order Runge-Kutta method is used for convective terms. Spatial derivatives of variables are treated as second-order central difference. Convective terms are approximated using the higher-order interpolation method. We use the dynamic-mixed model. To avoid the numerical instability, the very small numerical dissipation is added to the convective terms. The details of the present numerical formulation can be referred in (Ono&Tamura, 2002⁽⁴⁾).

3 COMPUTATIONAL MODEL

As a computational model, we deal with a three-dimensional square cylinder (Breadth: Depth: Height=1:1:4). An overset grid is used to get sufficient resolution near the cylinder. Figure 1 shows computational grid system which consists of three grids (Grid1; 155X160X80, Grid2; 201X66X100, Grid3; 40X40X65). Wind angles of the attack are set to 0 and 15° as shown in Figure 2. The convective condition is imposed at downstream boundary. No-slip condition is used at the cylinder surface. Smallest grid size is $0.1/(Re)^{0.5}$ ($Re=U_H B/\nu$; U_H : is oncoming velocity at the height of the cylinder, ν is the kinematic viscosity). The Reynolds number (Re) is equal to 36,000.

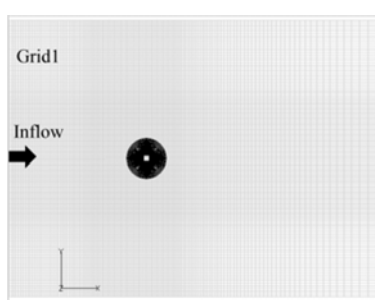


Figure 1 Computational grid system

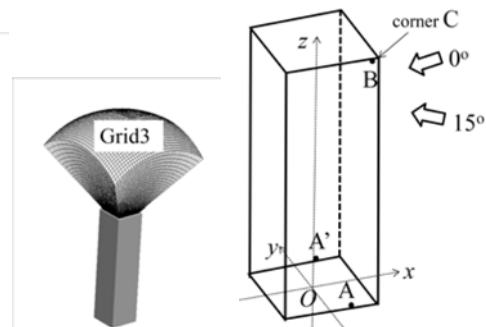
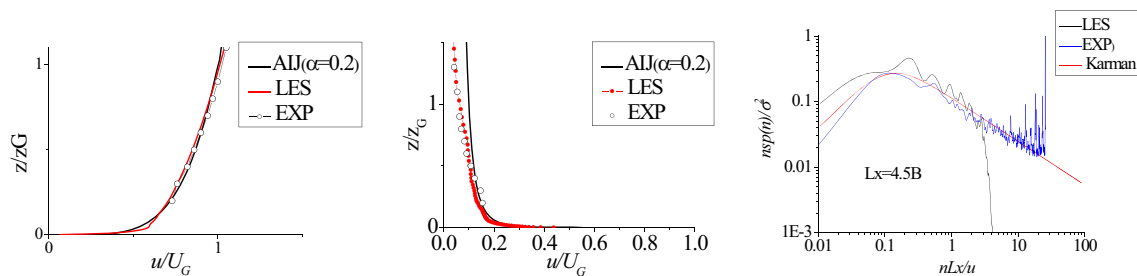


Figure 2 Angle of the attack

Inflow turbulence is generated using the simplified method of the quasi-periodic condition proposed by Kataoka et al. ⁽⁷⁾, and then developed over the upwind fetch with the surface roughness. Figure 2(a), (b) show the comparison of computed results for profiles of time-averaged velocity and turbulent intensity with the experimental data. The present computations show good agreement with the experimental results. The computed power spectrum distribution is also presented in Figure 2(c). It can be confirmed that the computed result agrees with the experimental data and the Karman-type spectrum. The computed turbulent scale by fitting to the Karman-type spectrum (Figure 3 (3)) is 4.5 B.



(1) Profile of mean velocity (2) Profile of fluctuating velocity (3) Power spectrum distribution

Figure 3 Comparison of computed inflow turbulence with experimental data

4 VALIDATION OF COMPUTATIONAL MODEL

Figure 4 (1), (2) show the comparison of the computed results with the experiments for the mean pressure distributions and the RMS value of the fluctuating pressure coefficients on a square cylinder. Concerning the mean pressure distributions, the present computations show good agreement with the experiments ⁽⁶⁾, though the computed stagnation points tend to be located upper than those in the experiments. This discrepancy must be due to the difference of vertical resolutions of the sampling points used for the visualization.

In the cases of $\theta=0^\circ$, large values of the fluctuating pressure coefficients are recognized near the bottom of the leading edges (A, A'). Furthermore, concerning the mean pressure distributions at the glancing angle, the local suction occurs near the upper corner of leading edge (B). Namely, local suction at $\theta=0^\circ$ and the glancing angle which are observed in the experiments in smooth flow ⁽¹⁾ are recognized even in boundary-layer turbulence.

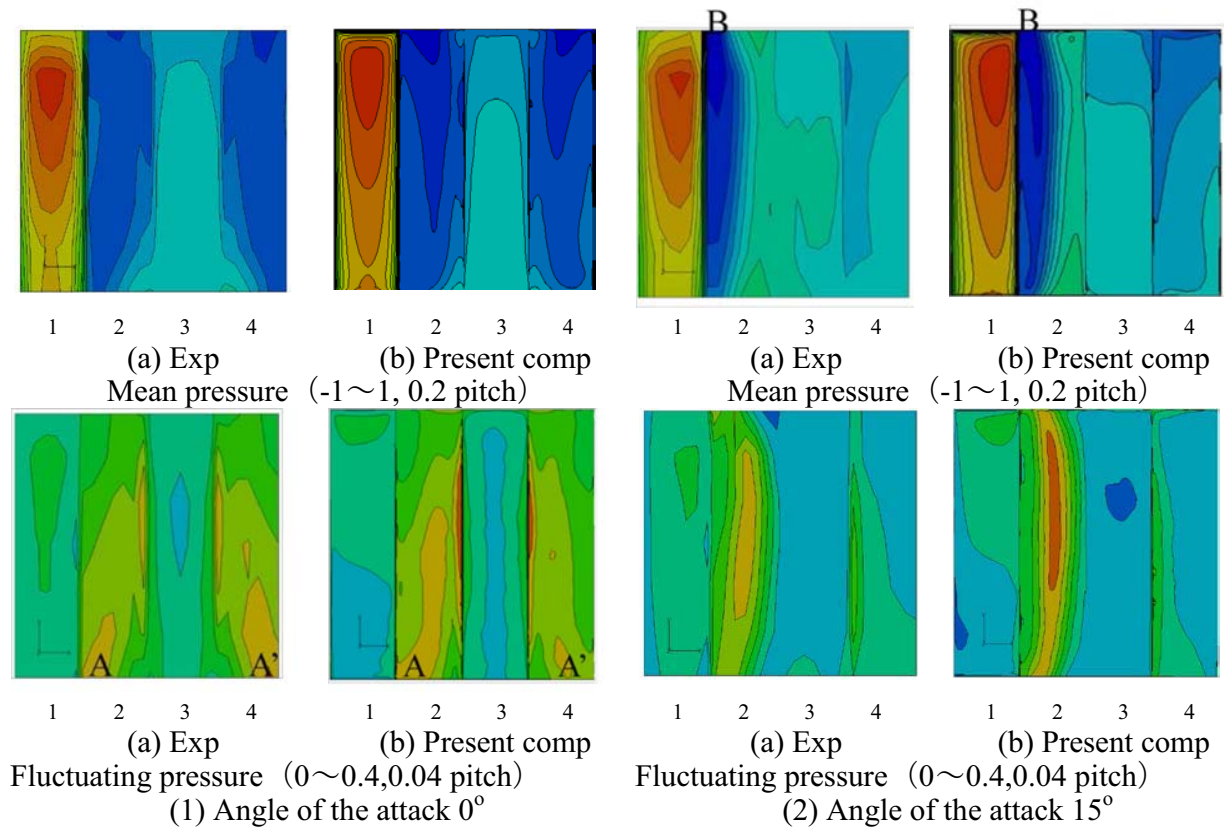
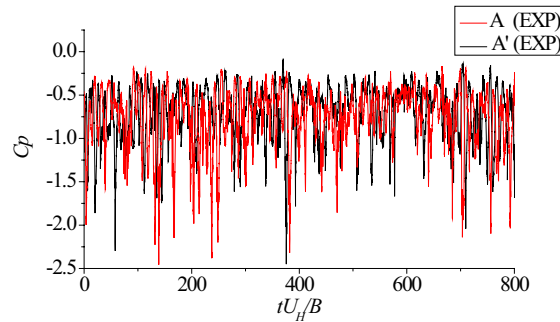
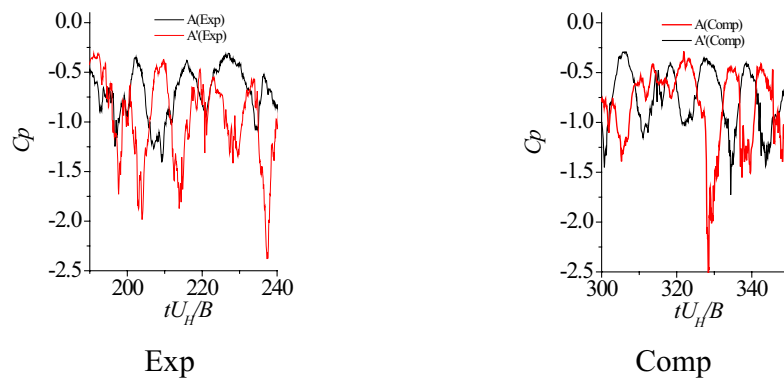


Figure 4 Distributions of mean and fluctuating pressure coefficients on square cylinder



(1) Experimental data (800 dimensionless times)



(2) 50 dimensionless times

Figure 5 Time histories of the pressure coefficients of A and A' ($\theta=0^\circ$)

5 STUDY OF RELATIONSHIP OF FLOW STRUCTURE AND LARGE SUCTION

5.1 Large suction near the bottom of leading edge at angle of the attack $\theta=0^\circ$

Figure 5 (1),(2) show experimental results⁽⁶⁾ for time histories of pressure coefficients at the points A, A' (shown in Figure 2) near lower corner of the leading edge at $\theta=0^\circ$. In Figure 5(1), pulse-like peaks are randomly observed in the pressure fluctuations. On the other hand, looking at time histories in about 50 dimensionless time in details (Figure 5(2)), the levels of the negative pressures of A, A' change in turn periodically, though the peak values are randomly changed. These characteristics of peak suction show the same tendencies as the experiments by Surry et al.⁽²⁾.

Figure 6 (1)-(4) show the iso-surface ($p = -1.45$) of pressure and the contours of the vorticities at the section of $z/B=2, 0.01$ before and after the high peak suction occurs at the point A. In (1) $tU_H/B=326.3$, the vortex begins to be formed in the wake region of the cylinder. After that, the separated shear layer approaches closely to the side surfaces of the cylinder and the negative pressure region is recognized in wide range near side face (2). In (3) where the high peak suction occurs, the shear layer reattaches to the side surface and the separation bubble is formed near the bottom of the leading edge. In (4), wake vortex sheds downstream, the level of the negative pressure is recovered. Therefore, based on instantaneous flow characteristics, it can be presumed that the behavior of the wake vortices result in the reattachment of the separated shear layer near the bottom of the leading edge, and the strong curvature of the separation bubble leads to the high peak suction.

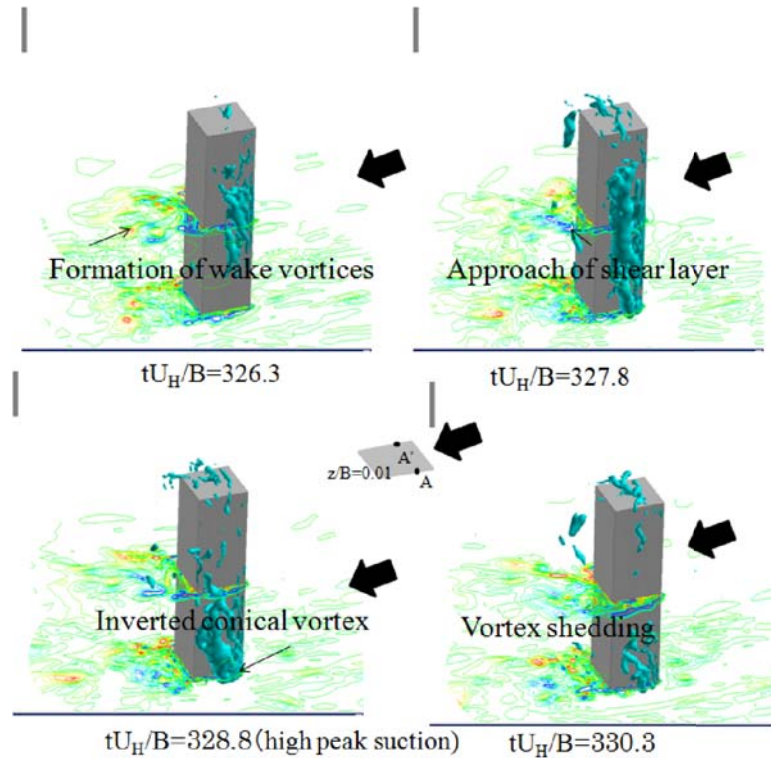


Figure 6 Iso-surface of instantaneous pressure and vorticities contours
($p=1.45$, $\theta=0^\circ$)

Figure 7 (1),(2) show the iso-surface ($p=-0.75$) of the conditional pressure. Conditional sampling manner indicates two types of averaged data. One is the averaged data when the peak values ($C_{p_{peak}}$) of the pressure coefficients of point A are large than -1.5 and smaller than -1.0. The other is averaged data when $C_{p_{peak}}$ are smaller than -2.3.

In the case (1) ($-1.5 < C_{p_{peak}} < -1.0$), the iso-surface is depicted near the side of the cylinder. However, it is not recognized in wake region because the levels of the negative pressure are not so high. On the other hand, in case (2) ($C_{p_{peak}} < -2.3$), the iso-surface is depicted not only near the side surface but also near the base of the cylinder. Figure 8 (1), (2) show the contours of conditional vorticities at the section of $z/B=0.01$. The strong circulation of the separation bubble is recognized in the case (2) ($C_{p_{peak}} < -2.3$).

Therefore, high peak suction occurs, when periodic vortices are strongly formed near the base of the cylinder and the early reattachment of the separated shear layer near the bottom of the leading edge is caused.

Figure 9 shows the time histories of the pressure coefficient at the point A and the fluctuating velocities at the three points (T0, T1, T2) in the upwind region. It can be seen that the velocities at all points largely increase and its state continues before the high peak suction occurs. It can be presumed that this process of change in velocities causes the wake vortices to be strongly formed, and then results in the large peak suction near the bottom corner of the leading edge of the cylinder.

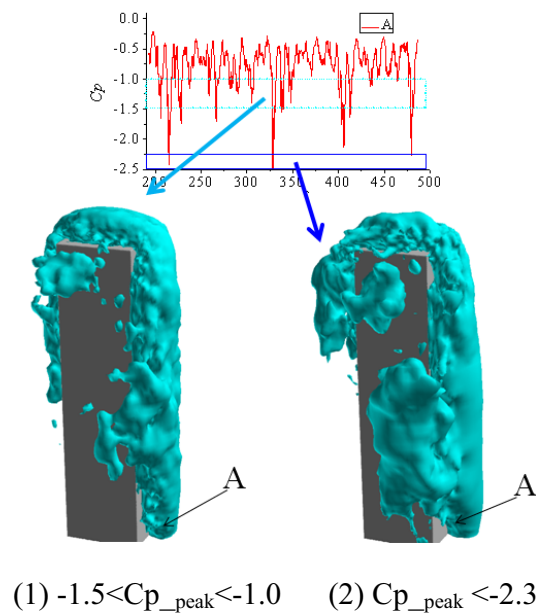


Figure 7 Iso-surface of conditional pressure ($\theta=0^\circ$)
(C_{p_peak} is the peak values of negative pressure)

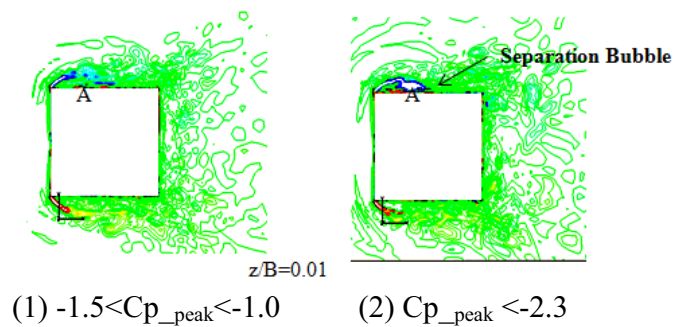


Figure 8 Conditional vortices contours ($\theta=0^\circ$)

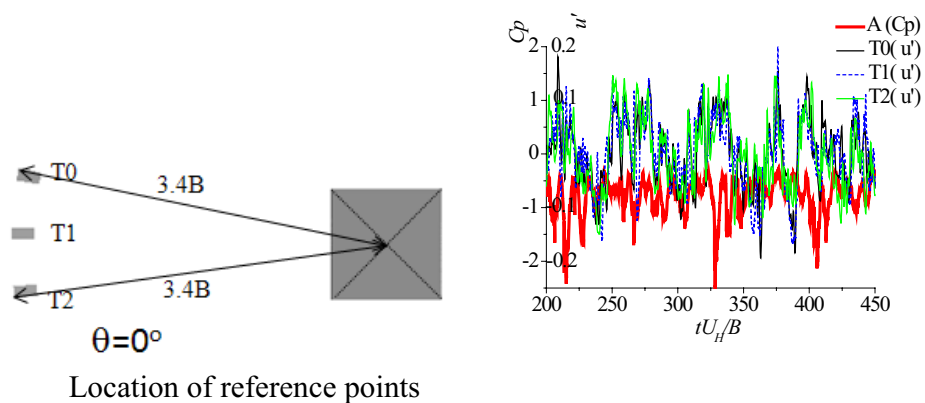


Figure 9 Time histories of the pressure coefficients at A
and velocity at T0,T1,T2 ($\theta=0^\circ$)

5.2 Large suction near the upper corner of leading edge at glancing angle

Figure 10 (1), (2) show the time histories of the pressure coefficients at the point B (shown in Figure 2) near the upper corner of the leading edge at the glancing angle ($\theta=15^\circ$). The pulse-like peaks are intermittently recognized in the temporally sequential data for both of the present computation and the experiments⁽⁶⁾. These kinds of peaks had not been observed in the experiments in smooth flow⁽¹⁾. In the case of smooth flow⁽¹⁾, a standing vortex is formed near the upper corner of the leading edge and leads to stationary local suction.

In order to investigate relationship between the occurrence of high peak suction and the behavior of a standing vortex in boundary-layer turbulence, the iso-surface ($p=-1.2$) of the pressure around the cylinder before and after the high peak suction occurs are shown in Figure 11 (1)-(4). In (1) $tU_H/B=168.8$, the flow separates from the leading edge of the cylinder and the regions of negative pressure are recognized near the side of the cylinder. On the other hand, in (2) $tU_H/B=170.2$, the conical vortex begins to be formed near the upper leading corner. In (3) $tU_H/B=171.3$ where high peak suction occurs, the conical vortex is clearly recognized. After that, negative pressure is recovered when the conical vortex becomes unclear.

This conical vortex is similar to a standing vortex in smooth flow⁽¹⁾. However, this vortex does not always exist in boundary-layer turbulence. The conical vortex is intermittently recognized at the moment high peak suction occurs. Also, the level of peak suction induced by the conical vortex is much larger than that by a standing vortex⁽¹⁾.

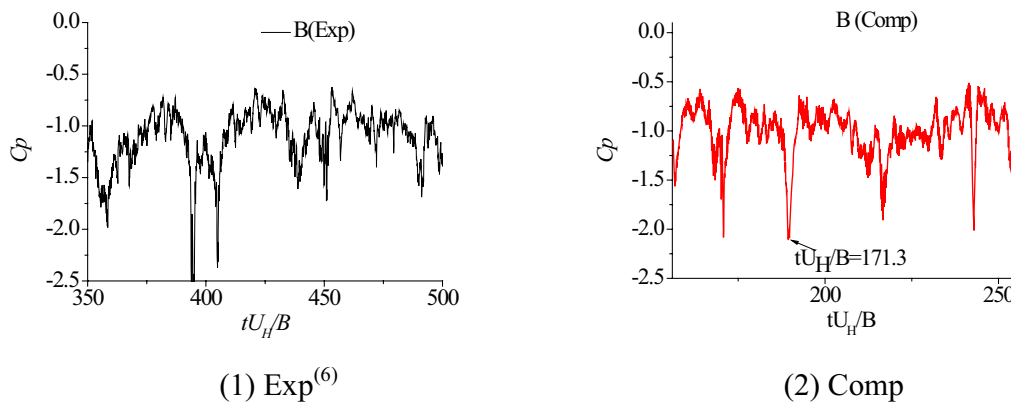


Figure 10 Time histories of the pressure coefficients of B ($\theta=15^\circ$)

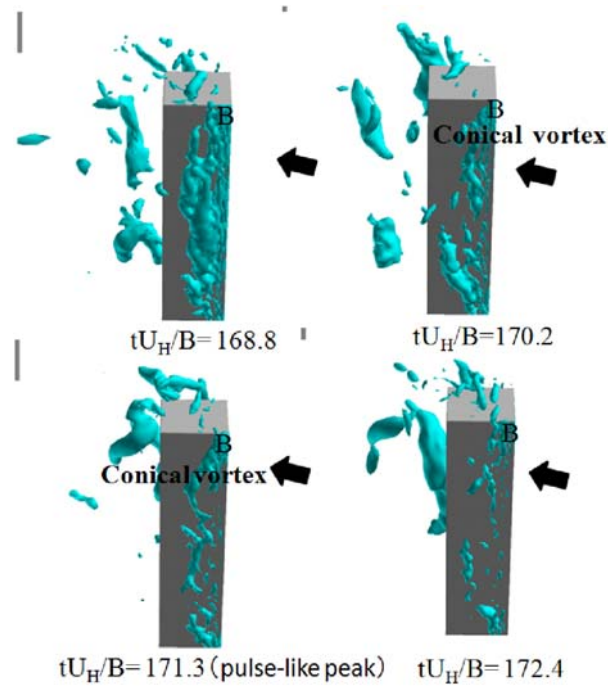
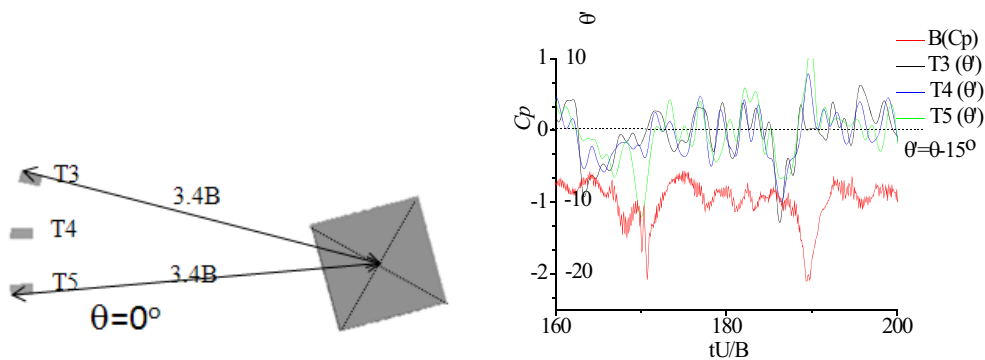


Figure 11 Iso-surface of instantaneous pressure ($p=1.2$)



Location of reference points

Figure 12 Time histories of the pressure coefficients at A

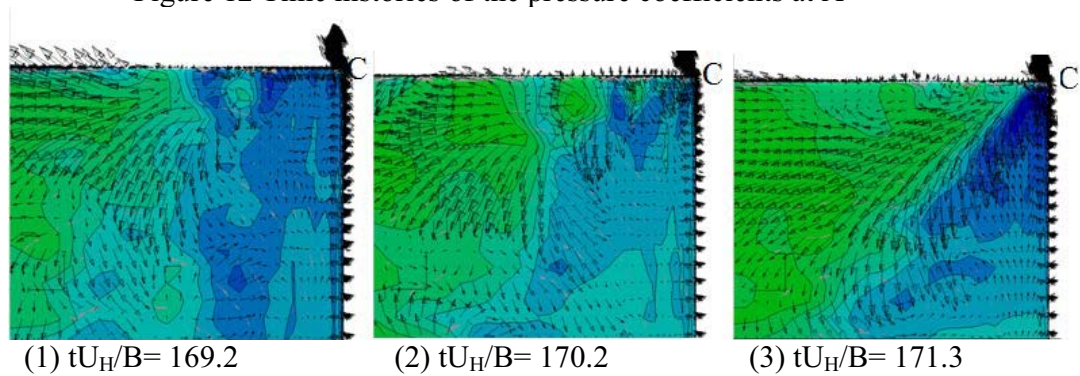


Figure 13 Time series of velocity vectors and pressure distributions

Figure 12 shows the time histories of pressure coefficients at the point B and the fluctuating angle of the attack at the three points (T3, T4, T5) in the upwind region. It can be found that the angles of the attack of all points show a decrease (the angles of the attack changes in anticlockwise direction) before peak suction occurs. After that, peak suction is recognized when the angle of the attack gradually increases.

Figure 13 shows the time series of the velocity vectors and the pressure distributions on the plane close to the side surface. A decrease of the angle of the attack causes the reattachment points to move downstream (the green domain showing a pressure recovery region moves downstream). On the other hand, reattachment points tend to approach closely to the upper corner (C) (the green domain approaches C), as angle of the attack begins to increase. The occurrence of the strong circulation of the conical vortex associated with this change in angle of the attack leads to high peak suction near the upper corner of the leading edge.

6 CONCLUSION

Unsteady characteristics of the conical vortices near the bottom of leading edge at $\theta=0^\circ$ and near the upper corner of the leading edge at the glancing angle are studied by LES analysis. It is made sure that the present LES model can simulate the pressure characteristics on the square cylinder through comparison with the experimental data. As a result of study of computed flow structure, it can be presumed that the large scale fluctuation of oncoming flow plays an essential role for vortex structures close to a square cylinder. It introduces a conical vortex generation and its concentration near the leading edge, and results in high peak suction

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