Wind Engineering Joint Usage/Research Center
FY2021 Research Result Report

Research Field: Wind Hazard Mitigation, Wind-resistant construction field
Research Year: FY2021
Research Number: 21212003
Research Theme: Conditional space-time POD analyses of local severe suction on the side walls of a high-rise building based on TPU aerodynamic database

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Budget [FY2021]: 0 Yen

1. Research Aim

Evaluation of local peak pressure is critical in the wind-resistant design of cladding system in the façade of high-rise building considering the balance between safety and cost. The estimation of peak pressure is related to the space-time characteristics of local severe suction on the building walls. The strong suction events that are extremely localized in space might not be meaningful for cladding design, while events that extend over a larger region could play an important role.

The mechanism of the local severe suction which was observed in the vicinity of the lower windward corner of the side walls were investigated by experiments and numerical simulations (Okuda and Taniike 1993; Surry and Djakovich, 1995; Ono and Tamura 2013; Tambara et al. 2018; Cao et al. 2022). Despite great advancement about peak pressure, the aforementioned experimental studies did not provide the clear flow explanation for peak pressures, and the numerical studies did not provide the statistical characteristics of peak pressures. The space-time characteristics and mechanism of peak pressures of high-rise building are not fully understood.

Proper orthogonal decomposition (POD) is one of pioneering modal analysis methods, which has been applied in various fields. One drawback of standard POD method is that the inability of capturing localized and intermittent events. That is the reason why previous POD studies in wind pressures mainly cared about the mean or r.m.s pressures or integrated wind forces, with little focus on the localized negative peak pressures. Recent years witness an outpouring of newly proposed POD variants, including the method of conditional space-time POD (conPOD) (Schmidt and Schmid 2019). conPOD combined the idea of conditional averaging and the space-time POD with the aim of intermittent and rare events. The strength of conPOD is to provide the temporal evolution of specific rare events in a statistical manner.

The space-time characteristics of peak pressures need more in-depth clarification in a statistical manner, particularly in terms of the severe suction in the lower windward corner of the side wall and trailing-edge peak pressure. The novel POD variant, i.e., conPOD, is applied to investigate the average evolution of the extreme events on buildings in space and time. The generation mechanism of peak pressures and its relationship with the large-scale vortices around the building are explored.

2. Research Method

The experiments were conducted in a boundary layer wind tunnel in Tokyo Polytechnic University (TPU). The wind pressure was measured simultaneously at all pressure taps using a multi-channel simultaneous fluctuating pressure measurement system. The building model is shown in Fig. 1, which was immersed in a turbulent boundary layer. The profiles of two types of approaching flow are shown in Fig. 1(b), including time-averaged streamwise velocity ratio and turbulence intensity. The case of AR = 3, i.e., D=0.1 [m] and H=0.3 [m], is tested in this study. The angle of incidence of zero degrees is focused on. The vertical edges of the building are labelled at the bottom of the building in Fig. 1(a), including edge A, B, C, and D. The length factor and velocity factor between the scaled model and real world structure were assumed to be 1/400 and 1/4, respectively. The time series of C_p is publicly accessible in the website of http://wind.arch.t-kougei.ac.jp/system/eng/contents/code/tpu. The sampling frequency was 1000 [Hz]. The total duration of sampled C_p was approximately 32.8 [s], corresponding to approximately 60 [min] in full time scale. The spatial distribution of measurement probes is shown in Fig. 1(c). The resolution was generally 0.02 [m], while the nearest probe to the edge of the building was 0.01 [m]. In Fig. 1(c), two localized regions are indicated, including the lower windward corner of the side wall (marked by circle) and the region just upstream of the trailing edge (marked by triangle). They will be emphasized in the following sections.

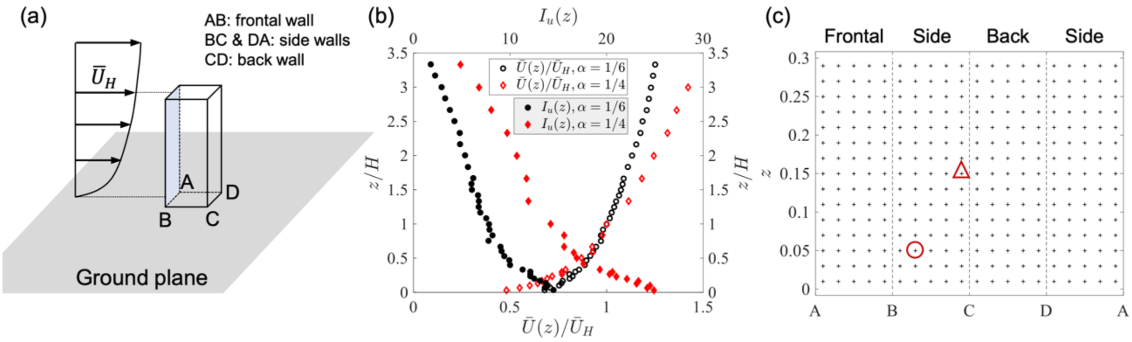

Fig. 1 (a) Building model; (b) profiles of time-averaged velocity and turbulence intensity of two types of approaching flow; (c) distributions of pressure taps on the building walls.

Schmidt and Schmid (2019) proposed the conditional space-time POD to the education of the average, intermittent or rare events. The extreme event is denoted by *H*. In discrete time and space, the eigenvalues and eigenvectors of the two-point space-time correlation tensor $\boldsymbol{P}$ are obtained from the decomposition:

$$\boldsymbol{P}\boldsymbol{P}^{T}\boldsymbol{\phi}_j = \lambda_j\boldsymbol{\phi}_j$$

where,

$$\boldsymbol{P} = \begin{bmatrix} \boldsymbol{p}\left(t_0^{(1)} - t^-\right) & \cdots & \boldsymbol{p}\left(t_0^{(N_{peak})} - t^-\right) \\ \vdots & \ddots & \vdots \\ \boldsymbol{p}\left(t_0^{(1)} + t^+\right) & \cdots & \boldsymbol{p}\left(t_0^{(N_{peak})} + t^+\right) \end{bmatrix}$$

represents the space-time matrix of realizations of events occurring at times $t_0^{(k)}$. The *k*th column of $\boldsymbol{P}$ hence contains the *k*th realization of even *H* evolving from time $t_0^{(k)} - t^-$ to $t_0^{(k)} + t^+$. The solved eigenvalues and eigenvectors are the modal energy and their corresponding space-time POD modes. In contrast with the classical POD method, the conditional space-time POD modes $\boldsymbol{\phi}(\boldsymbol{x}, t)$ are time-dependent and coherent in space and over the finite time duration in the temporal neighborhood of the extreme event *H*. The low-rank reconstruction of the conPOD method is similar as the standard POD method. According to the importance of conPOD modes, the first *r* order modes are selected to reconstruct the average evolution of the extreme event and remove the noise.

3. Research Result

3.1 conPOD analysis of local severe suction in lower windward corner of side walls

The extreme events of pressure in the lower windward corner of side walls are selected based on the time series of C_p, as shown in Fig. 2. Totally 26 segments of severe suction are extracted. The temporal evolution of the leading space-time conPOD mode of the local severe suction is shown in Fig. 3(a)-(b), where the white spheres are labelled to indicate the point of lower windward corner. Figure 3(a) covers the the whole duration from $t_{pk} - t^-$ to $t_{pk} + t^+$ with a time increment between sequential snapshots of Δt_1=0.025 [s], while Fig. 3(b) shows the close-up view around the peak instant with a smaller time increment of Δt_1=0.01 [s]. According to the pressure distribution in Fig. 3(a), the instant of $t_{pk} - 2\Delta t_1$ roughly represents the phase when the shear layer is close to the side wall DA, and the other shear layer is far from the side wall BC. The peak instant indicates that the shear layer is close to the side wall BC, and the other shear layer is far from the side wall DA. At the instant of $t_{pk} + 2\Delta t_1$, the flow phase recovers back to be the state that is similar to $t_{pk} - 2\Delta t_1$.

The previous studies by Okuda and Tannike (1993) and Ono and Tamura (2013) have related the local severe suction in the lower windward corner to the inverted conical vortex, which is accompanied with flow reattachment on the trailing part of the side wall. Following the general flow topology of surface-mounted square cylinder, we attempt to explain the flow features that induce the temporal evolution of the leading conPOD mode. In turn, the conPOD mode provides the statistical evidences for physical interpretation of local severe suction on the side walls. The instantaneous flow visualization is taken from Ono and Tamura (2013) and shown in Fig. 3(c), where the isosurface of instantaneous pressure was used to identify the vortices. The negative fluctuating pressure first occurs in the middle region of the side wall BC. The minimum negative pressure occurs in the middle-height region of the side wall at the instant of $t_{pk} - 2\Delta t_2$, which corresponds to roll up of the shear layer next to the side wall. At the same time, one can observe the positive fluctuating pressure near the trailing edge of the lower side wall, which implies the tendency of flow reattachment. During the period between $t_{pk} - 2\Delta t_2$ and t_{pk}, the positive fluctuating pressure near the trailing edge increases and reaches the maximum value at the instant of t_{pk}. Meanwhile, the negative fluctuating pressure zone that is first observed in the middle-height region transmits downward and approaches the ground plane. The negative fluctuating pressure reaches minimum at t_{pk}. According to Fig. 3(c), the shear-layer roll-up does not move downward to the ground plane like the tendency of negative fluctuating pressure that observed on the side wall. Instead, the shear-layer roll-up travels primarily downstream as observed in the duration from $t_{pk} - 2\Delta t_2$ to t_{pk}. Pressure of vortex in the lower-height region (separation bubble) becomes much lower at t_{pk} due to reverse flow from the reattachment line. At the instant of $t_{pk} + 2\Delta t_2$, the negative fluctuating pressure become very small, which is also reflected by the break-up of the separation bubble to smaller-scale vortices as shown in (c).

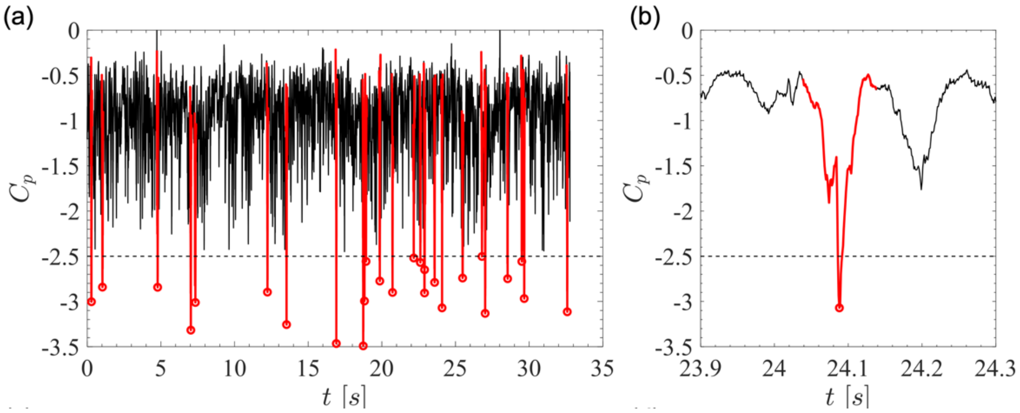

Fig. 2 (a) Selection of local severe suction in the lower windward corner of the side wall, as indicated by red lines in the time series of pressure coefficients. **(b)** Close-up of local severe suction.

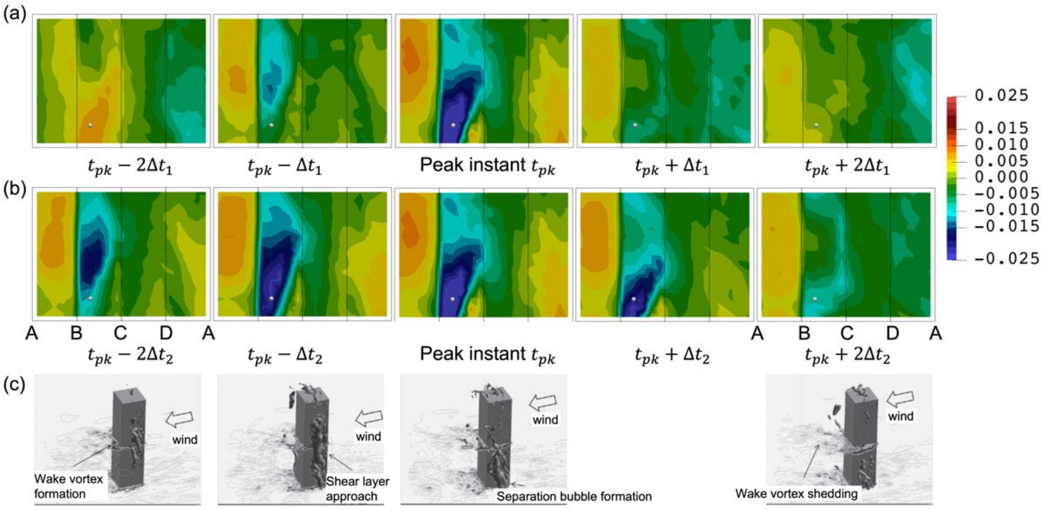

Fig. 3 (a)-(b) Temporal evolution of the leading conditional POD mode of local severe suction, where the upper row is in a large time interval of Δt_1=0.025 [s] and the lower row is in a small time interval of Δt_2=0.01 [s]. The white sphere on the side wall BC indicates the reference location for selecting the peak events. **(c)** Isosurface of instantaneous pressure (Ono and Tamura, 2013).

3.2 conPOD analysis of local severe suction upstream of trailing edges

Figure 4(a) shows the fluctuating pressures of the first conPOD mode in the middle-height cross-section, when focusing on the local severe suction upstream of trailing edge. Figure 4(b) shows the reconstructed pressure based on the mean and first conPOD mode. The majority of pressure coefficient on the side wall BC decreases within the duration from $t_{pk} - 2\Delta t_2$ to $t_{pk} - \Delta t_2$ which actually corresponds to the approach of shear layer to the side wall BC. From $t_{pk} - 2\Delta t_2$ to $t_{pk} + 2\Delta t_2$, the windward portion of side-wall pressure increases gradually, which indicates the departure of shear layer away from the side wall BC. Within the same duration, the pressure on wall DA decreases, implying the fact of the wall DA becomes nearer the shear layer on this cylinder side. Generally speaking, the phase of anti-symmetric vortex shedding within the duration from $t_{pk} - 2\Delta t_2$ to $t_{pk} + 2\Delta t_2$ is that the shear layer moves away from the wall BC and the shear layer on the other side approaches to the wall DA. The fluctuating pressure in the localized region upstream of the trailing edge C witnesses a different tendency from the large-scale anti-symmetric vortex shedding. Trailing-edge peak pressure occurs when the shear layer on the same side of the trailing edge moves away from the vicinity of the side wall, approximately before the symmetric state of two shear layers on both sides of the cylinder. The duration from $t_{pk} - 2\Delta t_2$ to $t_{pk} + 2\Delta t_2$ witnesses an action duration of trailing-edge negative pressure when the reconstructed $C_p \leq 1.0$. It means that the action duration of trailing-edge peak pressure is approximately 0.04 [s], which is 0.36 of the period of vortex shedding. The fundamental mechanism of trailing-edge severe suction on high-rise building is similar to that of infinite-length square cylinder.

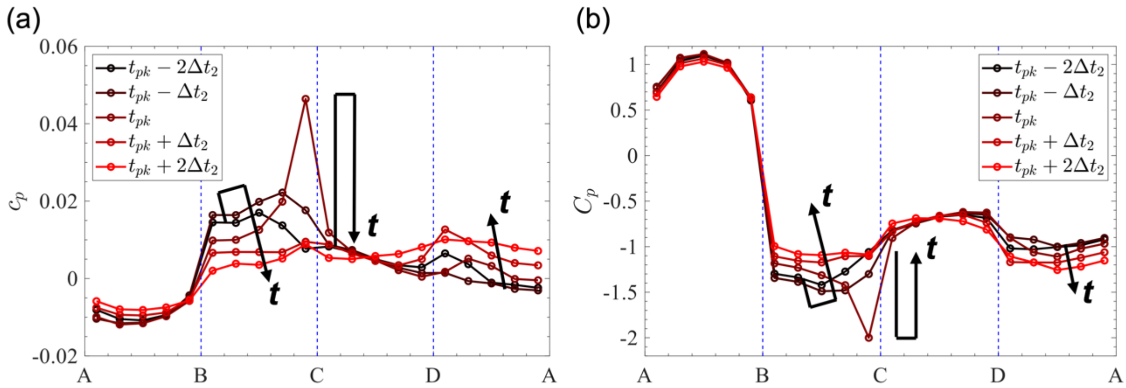

Fig. 4 (a) Fluctuating pressures of the first conPOD mode in the middle-height cross-section; **(b)** reconstructed pressure based on the mean and first conPOD mode. The duration between $t_{pk} - 2\Delta t_2$ and $t_{pk} + 2\Delta t_2$ is approximately 0.36 of the period of Kármán vortex shedding.

References:

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4. Published Paper etc.

[Underline the representative researcher and collaborate researchers]

[Published papers]

Cao, Y., Liu, X., Zhou, D., Ren, H., 2022. Investigation of local severe suction on the side walls of a high-rise building by standard, spectral and conditional POD. Building and Environment, 217, 109047.

[Presentations at academic societies]

No

[Published books]
No

[Other]
Intellectual property rights, Homepage etc.
No

5. Research Group

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6. Abstract (half page)

Research Theme: Conditional space-time POD analyses of local severe suction on the side walls of a high-rise building based on TPU aerodynamic database
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Summary・Figures
This study analyzed the characteristics and mechanism of wind peak pressures on building models by conditional space-time POD (conPOD) method, with a focus on two regions of the lower windward corner of the side wall and the localized region upstream of the trailing edges. The building model has the aspect ratio of 3. conPOD is demonstrated to be a powerful tool to study the average evolution of peak pressures, regardless of infinite-length square cylinder or surface-mounted building model. In terms of evolution process of peak pressure in the lower windward corner of the side wall, the minimum pressure is accompanied by high fluctuating positive pressure in the trailing portion of the lower side wall. It indicates the roll-up of shear layer and formation of separation bubble next to the lower side wall. The negative peak pressure in the middle-height region immediately upstream of the trailing edge is found to share the same mechanism as that of an infinite-length square cylinder. It is induced by small trailing-edge vortex, which has great concentrated vorticity. The understanding of the characteristics and mechanism of wind peak pressures may be helpful for the design of measurement points in the experiments.