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Mean Reattachment Length of Roof-Separation Bubbles using Proper Orthogonal Decomposition

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SUMMARY:
Investigations of flow separation regions on the surface of three-dimensional bluff bodies in turbulent flows are important as they cause large aerodynamic loads. Separation bubbles can cause extreme pressure, making the roof components of low-rise buildings vulnerable. In this study, the Proper Orthogonal Decomposition (POD) of wind-induced roof pressure is used to determine the mean reattachment length of roof separation bubbles on a low-rise building model in turbulent flow. The mean reattachment length estimated from the POD first eigenmode is compared with the reattachment length obtained from an aerodynamic database. For the centerline of the roof, the mean reattachment length based on the POD is in good agreement with that using the aerodynamic database, with a difference of less than 5%. It is concluded that POD provides an efficient way to estimate the mean reattachment lengths of separation bubbles on low-rise buildings.

Keywords: mean reattachment length, separation bubble, three-dimensional bluff body, turbulent flow, Proper Orthogonal Decomposition

1. INTRODUCTION

Various methods have been applied to evaluate the reattachment lengths of roof separation bubbles through wind tunnel tests. Among them, the mean reattachment length evaluated using Particle Image Velocimetry (PIV) shows high accuracy (Fang and Tachie, 2019). However, estimating the mean reattachment length only with the measured pressure data without flow measurement has its limits. Recently, a methodology for estimating the mean reattachment length using a database of previously measured pressure coefficients and mean reattachment lengths has been proposed (Akon, 2017). However, this method has limitations in estimating the mean reattachment length for conditions with different building model geometries or flow characteristics that are not in the database.

POD can decompose physical fields based on the physical variables they represent. If the variables decomposed by the POD have physical meanings, separation and reattachment phenomena occurring on the roof can be identified using these variables. In this study, the eigenmode of the roof pressure is identified using the POD, and based on this, the mean reattachment length of roof separation bubbles is evaluated. Furthermore, the results of the POD are validated by comparing the mean reattachment length evaluated using the POD and the aerodynamic database.

2. THEORETICAL BACKGROUND OF THE POD

The objective of the POD is to identify a deterministic function ϕ that is the best correlated with all the elements of the ensemble of a physical field (Bienkiewicz et al., 1993). Given a random pressure $p(x,y,t)$, the function $\phi(x,y)$ can be obtained by the integral equation:

$$\int R_p(x,y,x',y')\phi(x',y')dx'dy' = \lambda\phi(x,y) \tag{1}$$

where

$$R_p(x,y,x',y') = \langle p(x,y,t)p(x',y',t)\rangle \tag{2}$$

is the space covariance of pressure and $p(x,y,t)$ is pressure fluctuation. The solution of Eq. (2) is a set of eigenvalues λ_i and eigenvectors $\phi_i(x,y)$, denoted hereafter as eigenmodes. The eigenmodes can be used as the base functions in a series expansion of the pressure:

$$p(\boldsymbol{x},t) = \sum_i q_i(t)\phi_i(x,y) \tag{3}$$

where the principal coordinates are

$$q_i(t) = \int p(x,y,t)\phi_i(x,y)dxdy. \tag{4}$$

3. WIND TUNNEL TEST FOR LOW-RISE BUILDING

Wind-induced roof pressure used in this study was obtained from a turbulent boundary layer modeled in the wind tunnel at MS Engineering Corp., located in Haman-gun, Korea. The experimental setup is illustrated in Figure 1.

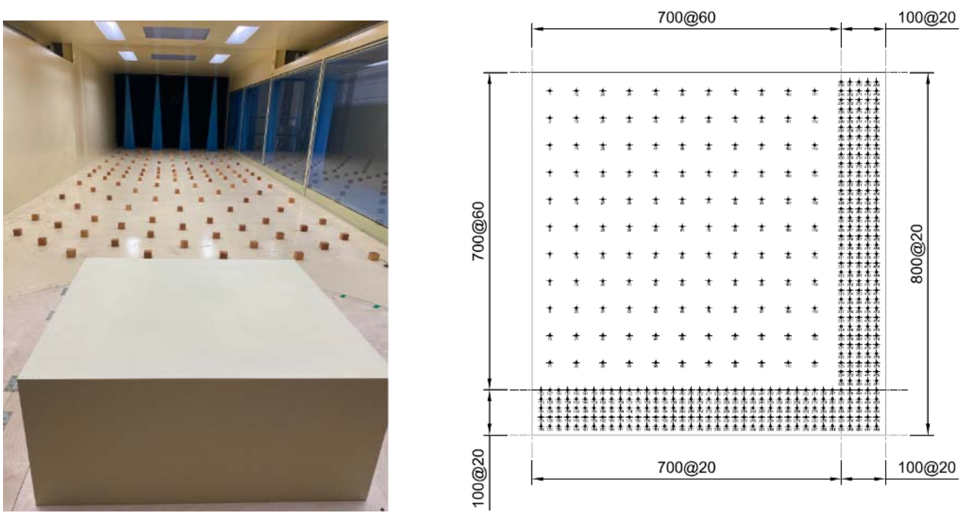

Figure 1. Low-rise building model and location of pressure taps on roof (unit: mm)

The dimensions of the building model used in this study were 400mm (height) x 800mm (length) x 800mm (width). The wind velocity and turbulence intensity values at the roof height of the building model were approximately 6.8 m/s and 13%, respectively. Roof point pressure was measured at 486 taps with the wind direction normal to the edge of the roof, as shown in Figure 1. The data was acquired using an electronically scanned pressure measurement system, with each record of pressure consisting of 16,384 data points per channel, sampled at 350 Hz.

4. TENTATIVE RESULTS

The roof pressure coefficients were analyzed using POD. The first eigenmode of POD is shown in Figure 2. The figure reveals that the eigenmode is split into a positive region marked in red and a negative region marked in blue. Considering the turbulent boundary layer characteristics of separated and reattaching flows over three-dimensional bluff bodies, it can be inferred that the red area represents the negative suction region inside the roof-separation bubble, while the blue area indicates the pressure region caused by the reattachment of the flow. From this observation, it is possible to identify the contour line with the eigenmode value of 0 between the two regions as the location at which flow separation and reattachment phenomena are distinguished. The distance from the leading edge to the contour line can be considered as the mean reattachment length X_r.

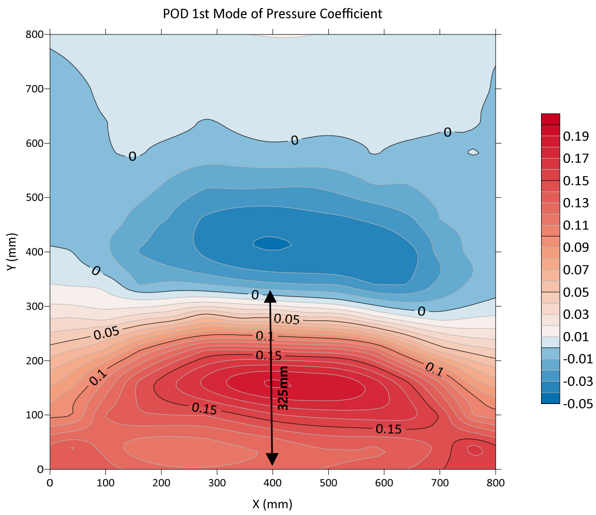

Figure 2. The POD first eigenmode of roof pressure coefficients (wind azimuth angle: 0°)

To validate the contour line of the mean reattachment identified through the POD analysis, the mean reattachment length of the roof centerline obtained based on the aerodynamic database was compared with that from the POD analysis. Akon (2017) found that when the mean pressure coefficient of the roof surface is normalized as shown in Eq. (5), the reduced pressure coefficient C^*_p at the location where mean reattachment occurs has a specific value depending on the level of turbulence intensity, as shown in Figure 3.

$$C^*_p = \frac{(C_{p\,mean} - C_{p\,min})}{(1 - C_{p\,min})} \tag{5}$$

Here, $C_{p\,mean}$ is the mean pressure coefficient, and $C_{p\,min}$ is the minimum value of the mean pressure coefficient on the surface under the separation bubble.

Based on these results, the reduced pressure coefficient C^*_p at the location where mean reattachment occurred (X/X_r = 1) was found to be about 0.28 for 13% of the turbulence intensity of the roof height corresponding to present study.

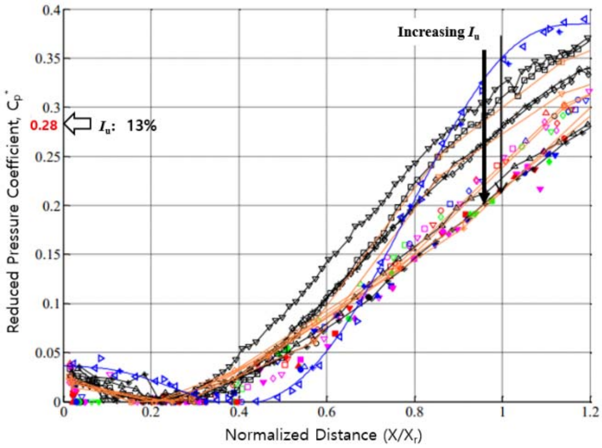

Figure 3. Distribution of reduced pressure coefficient under the separation bubble (Akon, 2017)

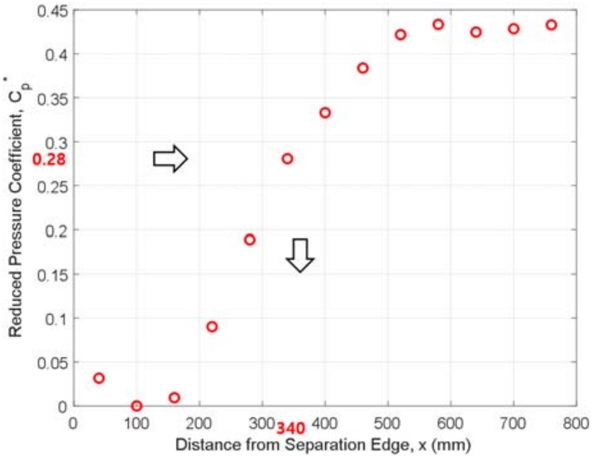

Figure 4. Distribution of reduced pressure coefficient under the separation bubble (present study)

Figure 4 shows the distribution of the reduced pressure coefficient using Eq. (5) along the roof centerline, with a value of 0.28 observed at 340 mm from the leading edge, corresponding to a mean reattachment length of 325 mm from Figure 2 with a 4.6% discrepancy. This comparison confirms the POD contour line of the first eigenmode value of 0 as the mean reattachment location.

5. CONCLUSIONS

This study used POD to determine the mean reattachment length of roof-separation bubbles on a low-rise building model. Comparing the results with an aerodynamic database shows that the distance from the leading edge to the first contour line where the POD first eigenmode value is 0 beyond the separation region identified by the POD corresponds to the mean reattachment length. Therefore, the POD method proposed in this study is useful for evaluating mean reattachment length using pressure data. The presentation will also address the effects of different turbulence intensity and wind direction on the mean reattachment length using the POD eigenmode.

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REFERENCES

Akon, F. A., 2017. Effects of turbulence on the separating-reattaching flow above surface-mounted, three-dimensional bluff bodies. Ph.D. Dissertation, Western University, London, Ontario, Canada.

Bienkiewicz, B., Ham, H. J., and Sun, Y., 1993. Proper orthogonal decomposition of roof pressure. Journal of Wind Engineering and Industrial Aerodynamics 50, 193-202.

Fang, X. and Tachie, M. F., 2019. Flows over surface-mounted bluff bodies with different spanwise widths submerged in a deep turbulent boundary layer. Journal of Fluid Mechanics 877, 717-758.