論文の内容の要旨

論文題目　Analysis of turbulent structures around building via spectral proper orthogonal decomposition and its applications to outdoor wind environment
（SPODによる建物周りの乱流構造解析及び屋外風環境分析への応用）

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Understanding the main turbulent structures is of vital importance for pedestrian-level wind or outdoor air ventilation control. However, the turbulence still has not been fully understood in physics, and continuing inability to understand the turbulence limits reliable predictions and further technological advancement. Modal analysis methods are the potential solutions, and the technique called spectral proper orthogonal decomposition (SPOD) is one of them. SPOD is a decomposition method combining the spatial decomposition of proper orthogonal decomposition (POD) and temporal analysis of Fourier series.

This study pioneers the applications of SPOD in wind environment fields. The applications in the following two classical cases were introduced: the flow field around single square-section building model and the two-dimensional street canyon flow. The effectivity of SPOD in identification of characteristic flow structures was well proved, even for the cases with very high Reynolds numbers. In addition, mathematical tools for evaluating the pedestrian-level wind environment and outdoor air exchanging are also developed in this study.

First, SPOD analysis was performed on the flow field around a square-section building model calculated by large-eddy simulation (LES) to identify the three-dimensional main flow features within the sampling field. The identified features, including the low-frequency modes related to the

fluctuation of the incoming flow, primary wake vortex shedding (Kármán-type vortex shedding), tip and base vortices, and primary side vortex shedding (flow separation), were extracted from the single case at once. The primary frequency and the intensity of these features were revealed by studying the typical SPOD modes and estimating the energy percentage. In addition, the local-space SPOD spectrum was also defined to analyse the composition of the kinetic energy within some local parts of the sampling domain.

The identified flow features and their details are summarised as follows: first, two energetic modes at low frequency were chosen as the typical modes to depict the symmetric and antisymmetric fluctuations around the building. They were found to be directly related to the inflow fluctuation by the local-space SPOD spectrum. The primary wake vortex shedding was depicted using a complex mode at the Strouhal frequency, which exhibited periodic vortex shedding. The tip and base vortex pair on one side of the building appeared in one SPOD mode, which indicated their correlation. The mode also showed an arch structure by which the tip and base vortices were connected. The same structure was found on the roof of the building illustrated by another mode, which showed the other kind of development of the tip vortices. The primary side vortex shedding caused by the strong shear force and separation appeared on both the roof and sides of the building. However, the vortices at different heights on the sides were not synchronised. Finally, the local-space SPOD spectrum precisely showed the different compositions of the fluctuation patterns on the front, side, and back of the prism. In general, the SPOD spectrum provided a comprehensive view of the turbulent structures in this flow field, which was an integration of all the above flow features. Unlike previous studies, where different flow features were studied by different physical quantities, this study revealed the primary frequency and intensity for all features, using a single mathematical process.

Subsequently, the target was focused on the pedestrian-level wind of the same case. The SPOD results for two simulation cases were compared, where the only difference was the existence of fluctuation at the inflow boundary, to show how the inflow fluctuation influenced the turbulent structures around the building. The results showed that the input of the inflow fluctuation on the inlet boundary had a significant influence on the turbulent structures at a low frequency because the modes and energy significantly differed. In both cases, the strongest modes corresponded to the Kármán-type vortex shedding, while the frequency was slightly larger when no fluctuation was input at the inflow boundary. The difference in the shapes of the Kármán-type vortex shedding was considered related to the difference in the mean velocity and TKE fields of the two cases. At a high frequency, flow separation phenomenon occurred on both sides of the building. In the case where no fluctuation was input at the inflow boundary, this phenomenon exhibited a peak on the distribution of energy, while it was not quite significant in the other case. A method was developed to decompose the TKE at a certain point and display the extent to which the fluctuating wind speed at the point is influenced by each mode. This is considered useful in the finding the main reason of large fluctuation and improvement of pedestrian-level wind.

In the other application, the SPOD technique was applied to decompose the velocity field of a two-dimensional street canyon. The SPOD modes, depicting the large-scale coherent structures and Kelvin–Helmholtz instabilities, were well extracted and visualised. The SPOD modes depicted the Kelvin–Helmholtz instabilities as a series of vortices, which are generated at the roof level, and enter the canyon following the principal recirculation, while the fluctuation caused by the external large-scale coherent structures directly strengthens or weakens the principal recirculation. In addition, the ejection events and pollutant removal were quantitatively analysed using the newly defined SPOD co-spectra to understand their relationships with the turbulent fluctuation patterns. The results showed that both Kelvin–Helmholtz instabilities and large-scale coherent structures can cause ejection and sweep events at the roof level, thus contributing to pollutant removal. However, the former contributed to stronger ejection and sweep events with stronger vertical components. The Kelvin–Helmholtz instabilities accounted for a small percentage of TKE, but they contributed most to the vertical turbulent mass flux at the roof level. In contrast, the large-scale coherent structures occupied a large proportion of the TKE, while they contributed less towards vertical turbulent mass flux. The intermittent concentration fluctuation fit better with the time scale of the Kelvin–Helmholtz instabilities.

The spanwise performance and nonlinear interactions of the turbulent structures were investigated by modifying the original SPOD to the one combining two-dimensional Fourier transform (2DFT). The SPOD co-spectrum defined in our previous study was also modified to a 2DFT version. As the result, the modes extracted by SPOD with 2DFT showed clearer shapes of turbulent structures than the previous study because of the increasing of the flow realisations. These turbulent structures were depicted by periodic fluctuation patterns detected along both time and spanwise direction with specific frequencies and wavenumbers. The nondimensional time scales were found approximately 4–5 times of the nondimensional spanwise length scales for both large- and small-scale structures, although the mechanism of these structures differ. This can be explained by the self-similarity of the high-Reynolds-number turbulence, i.e., a constant aspect ratio of the length scale is maintained. The SPOD co-spectra showed that the sweep and ejection events at the roof level mainly occurred at the spanwise nondimensional wavenumber of 1–4 and frequency of 0.2–0.8. This range coincided with that of the small-scale structures caused by the Kelvin–Helmholtz instabilities at the roof level. The same range wavenumber and frequency were found for pollutant removal. Although the large-scale structures contributed less to the pollutant removal than the small-scale structures, they still had a good chance to enhance the pollutant removal indirectly by amplifying the small-scale structures. The amplitude of the small-scale structures showed a weak but nonnegligible correlation with the state of the large-scale structures. The joint probability distribution indicated that the high- and low-momentum fluids passing through the canyon were related to the amplifying and suppressing of the small-scale structures. This phenomenon appeared stochastically along both the time and spanwise direction.

In summary, as SPOD has shown its effectivity and efficiently in turbulent structure analysis for high-Reynolds-number turbulence, it has the potential to become another useful tool for further research or design in the field of wind environment. Techniques developed in this study are also considered of great application value in broad application prospects.