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Loss of coherence in tandem building wakes under oblique wind

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SUMMARY:
Previous experiments on tandem buildings under oblique wind incidence have shown pronounced changes in wake structure, turbulence distribution, and pedestrian-level flow conditions. However, the mechanisms governing these changes remain unresolved. This study re-analyses time-resolved PIV data using Proper Orthogonal Decomposition (POD) and Oscillation Pattern Decomposition (OPD) to investigate the loss of coherence in tandem-building wakes under oblique inflow. The results show that increasing the angle of attack (AoA) redistributes energy from low-order to higher-order modes and induces a transition from coherent vortex shedding to broadband, weakly correlated dynamics. This transition is accompanied by reduced temporal periodicity and the disappearance of a dominant oscillatory mode. Coherence breakdown occurs earlier at the pedestrian level than at higher elevations, indicating strong vertical stratification driven by near-ground shear and confinement effects. These findings explain previously observed changes in turbulence intensity and ventilation in terms of wake destabilisation and coherence loss.

Keywords: tandem buildings, oblique wind, POD, wake coherence, urban aerodynamics

1. INTRODUCTION

Wind conditions at pedestrian level are of primary importance in urban environments, as they directly affect comfort, safety, and pollutant dispersion. In configurations involving multiple buildings, such as tandem arrangements, these conditions are strongly influenced by wake interference and gap-flow dynamics. The flow around tandem bluff bodies has been widely investigated in canonical configurations. Experimental studies by (Martinuzzi and Havel, 2000) demonstrated the existence of distinct wake interference regimes depending on spacing, while (Schewe, 2019) analysed the transition between flow states for tandem cylinders at different Reynolds numbers. These works provide fundamental insight into wake interaction mechanisms but are primarily limited to simplified geometries. For surface-mounted obstacles, near-ground flow is strongly influenced by three-dimensional effects such as horseshoe vortices and downwash. In urban contexts, these mechanisms become even more complex due to interactions among buildings and boundary-layer effects. Recent studies in urban aerodynamics emphasise the importance of accurately resolving pedestrian-level flow. For example, (Blocken, 2014) highlighted the sensitivity of pedestrian wind comfort to local flow acceleration and turbulence, while (Toparlar, 2015) demonstrated the need for validated models in complex urban environments. Despite these advances, the effect of oblique wind incidence on coherent wake structures in tandem-building configurations remains insufficiently understood, particularly from a dynamical perspective. The effect of oblique wind incidence on tandem configurations has only recently received attention. In particular, the experimental study by (Niegodajew et al., 2024) showed that increasing the angle of attack enhances flow penetration into the gap, redistributes turbulence kinetic energy, and significantly alters pedestrian-level wind conditions. However, this study relied primarily on time-averaged quantities and did not address the role of coherent structures. Modal decomposition techniques, such as Proper Orthogonal Decomposition (POD), have been successfully used to identify dominant flow structures and energy distribution in complex turbulent flows (Berkooz et al., 1993; Vitkovicova, 2020). These methods provide a natural framework for linking statistical flow properties with underlying dynamics. Despite their potential, the application of modal analysis to urban tandem-building flows under oblique wind conditions remains limited. In particular, the mechanisms responsible for the loss of coherence and the transition to broadband dynamics at the near-ground region have not been systematically investigated. The present study addresses this gap by focusing exclusively on the pedestrian-level flow and by applying Proper Orthogonal Decomposition (POD) and Oscillation Pattern Decomposition (OPD) to uncover the dynamical mechanisms governing wake destabilisation under oblique inflow conditions.

2. METHODS

The analysed configuration is shown in Fig. 1. The study is based on time-resolved PIV measurements of the flow around two square buildings of different heights arranged in tandem. The characteristic building width was denoted by D, while the streamwise spacing between the buildings was equal to $G = 1.5D$. The heights of the upstream and downstream buildings are denoted by H_1 and H_2, respectively. The incoming flow direction was defined by the angle of attack α, measured relative to the building alignment. The experiments were conducted at a Reynolds number of $Re \approx 1.7 \times 10^4$.

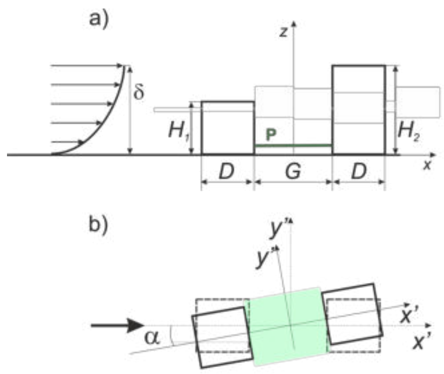

Figure 1. Schematic of the tandem-building configuration under oblique wind incidence together with the pedestrian-level measurement plane (P) and a photograph/schematic of the experimental PIV set-up. The incoming flow direction is defined by the angle of attack α, D denotes the characteristic building width, G is the spacing between buildings, and H_1, H_2 represent the building heights.

The analysis focuses on the pedestrian-level plane (P), located at $z \approx 0.08D$, which is sensitive to near-ground shear. Measurements were conducted for $\alpha = 0°–30°$. POD was used to quantify modal energy distribution and flow dimensionality, while OPD was applied to extract dominant oscillatory modes and assess temporal coherence. The experiments were conducted in a low-speed open-circuit wind tunnel using a time-resolved Particle Image Velocimetry (TR-PIV) system from Dantec Dynamics. The flow was illuminated by a double-pulsed Nd:YLF laser (527 nm), and images were acquired using a Phantom V611 high-speed camera (1280×800 px). Velocity fields were recorded at 100 Hz for 10 s, yielding 1000 instantaneous snapshots for each angle of attack. SAFEX particles ($\sim 1\,\mu$m) were used as tracers. The velocity fields were processed using cross-correlation algorithms and analysed with POD and OPD methods.

To investigate the dynamical characteristics of the flow topology, additional measurements were performed at 2000 Hz over 2 s.

3. RESULTS

The results are presented in terms of modal energy distribution and temporal coherence at the pedestrian level. The present study extends the previous research presented in Niegodajew et al., 2024, which investigated the effect of the angle of attack on the flow around two non-identical-height square buildings in a tandem arrangement.

3.1. Modal Energy Redistribution

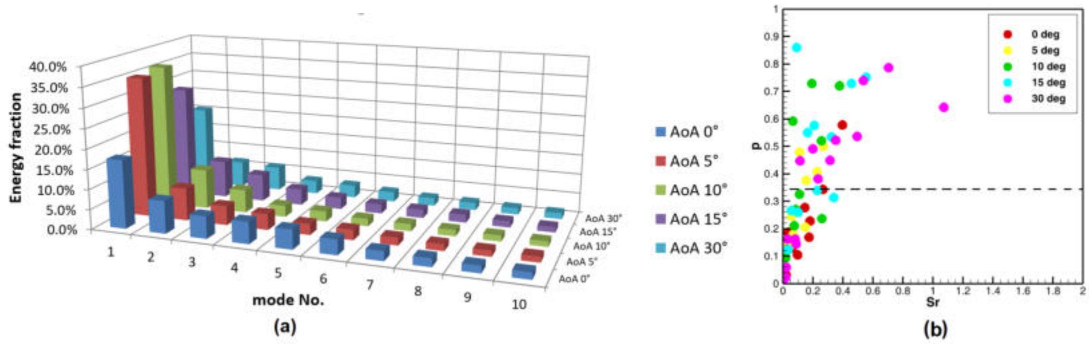

Figure 2. (a) Cumulative POD energy at pedestrian level P. (b) OPD spectrum in the periodicity–Strouhal plane at pedestrian level P.

As shown in Fig. 2(a), the cumulative POD energy at the pedestrian level exhibits a strong dependence on the angle of attack. At $\alpha = 0°$, a substantial portion of the energy is captured by the first few modes, indicating a low-dimensional and highly coherent flow regime associated with organised vortex shedding. As AoA increases, the energy distribution shifts away from modal dominance, requiring a larger number of modes to represent the flow dynamics. This behaviour reflects a redistribution of energy toward higher-order modes and the gradual loss of dominance of large-scale coherent structures. Consequently, the flow transitions from an organised regime to a broadband multi-scale regime. This is consistent with canonical wake studies, where increasing flow complexity reduces modal dominance (Berkooz et al., 1993; Vitkovicova, 2020).

3.2. Loss of Coherence

The evolution of temporal coherence at the pedestrian level is illustrated in Fig. 2(b), which presents the OPD spectrum in the periodicity–Strouhal (P–Sr) plane. At $\alpha = 0°$, the dominant modes exhibit high periodicity, indicating sustained and coherent vortex shedding with a well-defined oscillatory structure. As the angle of attack increases, a systematic shift toward lower periodicity values is observed. This trend indicates a progressive reduction in temporal coherence and the emergence of multiple competing modes. The flow dynamics become increasingly fragmented, with no single mode dominating the oscillatory behaviour. At higher AoA, the modal distribution becomes scattered and concentrated in the low-periodicity region, indicating a broadband regime characterised by short-lived and weakly correlated structures. These results demonstrate that oblique wind incidence disrupts coherent vortex shedding, leading to fundamentally different wake dynamics in the near-ground region. Such a transition from periodic to broadband dynamics has been reported in bluff-body wakes under perturbed or asymmetric inflow conditions, where coherent vortex shedding is progressively disrupted (Schewe, 2019).

3.3. Vertical Dependence

Although the present analysis focuses on the pedestrian level, the observed transition is inherently height-dependent. Comparison with previous measurements at higher elevations suggests that the loss of coherence occurs earlier near the ground than at higher elevations, indicating strong vertical stratification of the wake dynamics. This behaviour is attributed to enhanced shear, confinement effects, and intensified interactions between the boundary layer and wake structures. A similar height-dependent behaviour has been noted in wall-mounted obstacle flows, where near-ground regions exhibit stronger shear and earlier breakdown of organised structures (Castro and Robins, 1977).

4. DISCUSSION

The results provide a dynamical interpretation of previously observed changes in turbulence and ventilation. Increasing AoA destabilises the wake, leading to modal fragmentation and broadband dynamics. The disappearance of a dominant shedding frequency is directly linked to modal energy redistribution and loss of coherence identified by POD and OPD. The earlier onset of this transition at the pedestrian level highlights the role of near-ground shear. These findings extend (Niegodajew et al., 2024) by providing a modal interpretation of wake destabilisation.

5. CONCLUSIONS

This study demonstrates that oblique wind incidence induces a systematic loss of coherence in tandem-building wakes. Increasing the angle of attack drives a transition from coherent vortex shedding to broadband, multi-scale dynamics. This transition is governed by modal energy redistribution accompanied by a progressive reduction in temporal coherence. Furthermore, the breakdown of coherence occurs earlier at the pedestrian level, indicating a strong vertical stratification of the wake. These results highlight the importance of explicitly accounting for oblique wind directions in urban wind engineering, particularly in assessing pedestrian-level flow conditions.

ACKNOWLEDGEMENTS

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