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Spatio-temporal dynamics of extreme suction pressure events under the separation bubble of a 5:1 rectangular cylinder: effect of integral length scale

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Summary

Extreme suction events within the separation bubble on a 5:1 rectangular cylinder (BARC) are examined with emphasis on the role of the turbulence integral length scale relative to body depth, L_u^x/D. This study employs Large Eddy Simulation for three inflow conditions ($L_u^x/D = 2, 4, 8$) at constant turbulence intensity $I_u = 0.136$. Peak-suction events are identified using extreme-value statistics and used to trigger conditional sampling in space and time. The resulting ensemble fields reveal three distinct regimes of bubble dynamics: for small-scale inflow the peak coincides with the birth of a new leading-edge vortex as a large-scale structure convects the existing bubble downstream; for intermediate scales it is driven by impinging large eddies that compress the shear layer; for large scales the peak occurs during bubble growth under strong backflow. Conditional space–time POD recovers these mechanisms with a few energetic modes, providing a compact reduced-order description of extreme loads.

Keywords: *Separating-reattaching flows, Freestream turbulence, LES, peak pressures, conditional proper orthogonal decomposition*

1 INTRODUCTION

Accurate prediction of extreme wind loads on bluff bodies remains a central challenge in wind engineering, with direct implications for the design of tall buildings, bridges, and other structures exposed to atmospheric turbulence. Of particular concern are the intense suction pressures generated within the separation bubble at the sharp edges, where flow separation at leading edges creates highly unsteady, intermittent pressure fields. The benchmark aerodynamics of rectangular 5:1 cylinders (BARC) has emerged as a canonical configuration for studying these phenomena (Bruno et al., 2014), yet significant gaps persist in understanding how turbulence characteristics govern extreme loading events.

Early experimental work by Saathoff and Melbourne (1997) established that freestream turbulence (FST) amplifies peak suction loads relative to smooth-flow conditions. Their measurements revealed that FST-induced fluctuations in the separated shear layer drive intermittent reattachment events associated with extreme local pressures. However, the role of the relative integral length scale, L_u^x/D, has received comparatively less attention despite its importance in characterizing how the spatial coherence of the inflow turbulence interacts with the body-scale separation dynamics. Zhang et al. (2025) recently demonstrated that the spatio-temporal organization of separation bubble dynamics exhibits marked sensitivity to L_u^x, suggesting that length scale effects may play an important role for peak suctions under the bubble.

The present investigation addresses this gap by systematically examining extreme suction events for three large-scale inflows ($L_u^x/D \in \{2, 4, 8\}$) at fixed turbulence intensity ($I_u \approx 0.136$). High-resolution Large Eddy Simulation with controlled synthetic turbulence generation enables isolation of length-scale effects for peak events. We employ a multi-tiered diagnostic framework combining conditional sampling triggered by peak suction at statistically-identified peak pressure locations, Lagrangian Coherent Structure (LCS) analysis to reveal material transport barriers, and conditional space–time POD (CST-POD) for reduced-order characterization.

2 METHODS

2.1 Peak pressure calculation

Peak pressure values are determined using the statistical framework of Cook and Mayne (1980). The pressure time history is partitioned into sixteen equal segments, and the extreme suction of each segment is identified. These observed extremes are modeled using a Type I (Gumbel) distribution with parameters estimated using the Best Linear Unbiased Estimator (BLUE) method (Lieblein, 1974). The segment-based parameters are then scaled to represent the full-duration statistics, with the reported peak corresponding to the 80% probability of non-exceedance.

2.2 Conditional Space–Time POD

To isolate coherent spatio-temporal structures associated with intermittent extreme suction events, we employ Conditional Space–Time Proper Orthogonal Decomposition (CST-POD) introduced by Schmidt and Schmid (2019). This method extends the classical POD by incorporating a temporal evolution window conditioned on specific trigger events, H. Let $\boldsymbol{q}(\boldsymbol{x}, t)$ denote the vector of fluctuation quantities (e.g., pressure or velocity) defined on the spatial domain Ω and a finite time horizon $\mathcal{T} = [t_0 - T_-,\, t_0 + T_+]$ centered on a peak event at t_0. Following Schmidt and Schmid (2019), the weighted space–time inner product is given by:

$$\langle \boldsymbol{q}_1, \boldsymbol{q}_2 \rangle_{\Omega,\mathcal{T}} = \int_{\mathcal{T}} \int_{\Omega} \boldsymbol{q}_1^*(\boldsymbol{x}, t)\, \mathbf{W}(\boldsymbol{x})\, \boldsymbol{q}_2(\boldsymbol{x}, t)\, \mathrm{d}\Omega\, \mathrm{d}t, \tag{1}$$

where $\mathbf{W}(\boldsymbol{x})$ contains spatial quadrature weights and component scaling. The CST-POD modes, $\boldsymbol{\phi}_k(\boldsymbol{x}, t)$, are the optimal orthogonal basis functions that maximize the energy of the ensemble average conditioned on the occurrence of events H. This optimization yields a Fredholm eigenvalue problem of the second kind:

$$\int_{\mathcal{T}} \int_{\Omega} \mathbf{C}_H(\boldsymbol{x}, \boldsymbol{x}', t, t')\, \mathbf{W}(\boldsymbol{x}')\, \boldsymbol{\phi}_k(\boldsymbol{x}', t')\, \mathrm{d}\Omega'\, \mathrm{d}t' = \lambda_k\, \boldsymbol{\phi}_k(\boldsymbol{x}, t), \tag{2}$$

where λ_k represents the conditional energy captured by mode k. The kernel $\mathbf{C}_H$ is the conditional two-point space–time correlation tensor.

3 RESULTS

Statistical analysis reveals that while peak pressure magnitudes increase only modestly with the integral length scale, the underlying flow mechanisms exhibit fundamentally distinct topologies in the three inflow conditions.

For small scales ($L_u^x/D = 2$), peak suction at the statistical peak pressure location ($x/D \approx 0.2$) is driven by the formation of a compact leading-edge vortex (LEV). Concurrently, convection of a large-scale structure effectively separates this nascent LEV from the downstream extent of the existing bubble, which is swept away. This mechanism is consistent with the observations of Saathoff and Melbourne (1997). At intermediate scales ($L_u^x/D = 4$), extreme events arise from the direct interaction between larger inflow eddies and the separated shear layer. Conditional flow fields reveal compression of the separation bubble towards the body surface, with the peak occurring at $x/D \approx 0.19$ beneath a larger and more diffuse vortical structure. For large scales ($L_u^x/D = 8$), the mechanism shifts qualitatively: peaks are associated with sustained bubble expansion and intense backflow. The statistical peak pressure location migrates downstream to $x/D \approx -1.5$, and the peak pressure region broadens spatially. Analysis of the conditional separation bubble area $A(t)$ confirms that, unlike the small-scale case where the bubble contracts during peak events, the $L_u^x/D = 8$ configuration exhibits continued growth throughout the peak event.

The CST-POD analysis provides a compact description of these dynamics. In each case, the first CST-POD modes capture the dominant separation-bubble topology associated with the extreme event: a short bubble with a nascent LEV for $L_u^x/D = 2$; a compressed shear layer under an impinging eddy for $L_u^x/D = 4$; and an extended, high-backflow bubble for $L_u^x/D = 8$. Reconstructions using only three modes recover both the peak pressure magnitude and its streamwise attenuation, as well as the principal vortical features in the velocity field (Fig. 1). This demonstrates that, despite the strongly turbulent background, extreme suction events on the BARC configuration possess an intrinsically low-dimensional, scale-dependent structure.

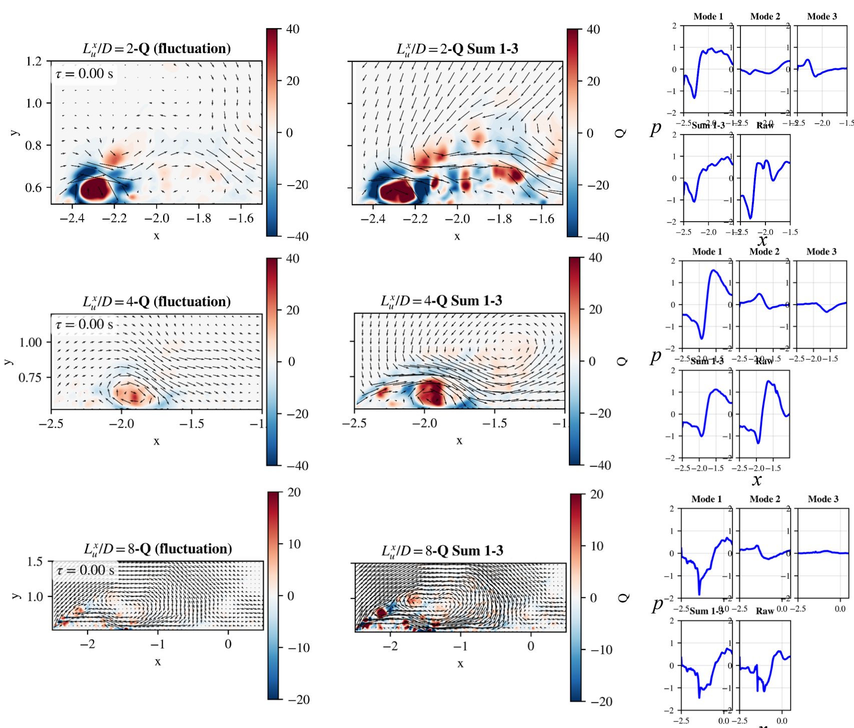

Figure 1: Comparison of Q-criterion and pressure fields for the fluctuating flow and CST-POD reconstructions. The first column shows the instantaneous Q-criterion at the peak event for each inflow condition (from top to bottom: $L_u^x/D = 2, 4, 8$). The second column presents the Q-criterion computed from the flow fields reconstructed using the first three CST-POD modes. The third column reports the corresponding pressure fields: individual contributions of the first three modes, their superposed reconstruction, and the original fluctuating pressure field associated with the peak event. Note that the spatial coordinates x and y are normalized by the section depth D, with the leading edge located at $x/D = -2.5$. The y axis label p of the third column denotes the non-dimensional pressure coefficient.

4 CONCLUSIONS

This study characterized the spatio-temporal flow structure during extreme suction events on a 5:1 rectangular cylinder (BARC) using high-resolution LES with varying integral length scales ($L_u^x/D \in \{2, 4, 8\}$) at fixed turbulence intensity ($I_u \approx 0.136$). By integrating statistical analysis with conditional sampling and conditional space–time POD (CST-POD), we identified distinct flow topologies governing peak loads. Additional LCS analysis that corroborates these findings will be presented in the presentation.

Three distinct regimes of bubble dynamics were identified. For small-scale inflow, extreme suction coincides with the birth of a new leading-edge vortex. For intermediate scales, peaks are primarily generated by large incoming eddies that impinge on and compress the separated shear layer, triggering partial bubble truncation. For large scales, the most severe suctions occur during sustained bubble growth under strong backflow, with a large vortex filling the separation region before eventual shedding. Across all regimes, the formation of a leading-edge vortex is a robust local signature of intense suction near the leading edge, even though the global pressure minimum may occur further downstream for large L_u^x/D. The application of CST-POD (Schmidt and Schmid, 2019) reveals that the leading conditional modes effectively reconstruct the space–time evolution of these rare events. This confirms that extreme suction phenomena admit a compact reduced-order representation despite their stochastic nature. These findings advance the understanding of peak-event flow physics while also informing practical concerns. Specifically, approaches such as partial turbulence simulation (PTS), which replicate only the small-scale portion of the turbulence spectrum during experiments, will be challenged to reproduce the scale-dependent peak-event flow topologies identified here. Further investigation is needed to evaluate the quantitative implications for peak-load prediction when the inflow integral scale differs from that in the target environment.

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