

# Vortex Shedding of Square and Rectangular Cylinders in Accelerating and Decelerating Flow Conditions

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## Summary

This study presents a detailed numerical investigation of the aerodynamic behaviour of square and rectangular cylinders subjected to Gaussian-type accelerating and decelerating inflow conditions. The analysis covers chord-to-depth ratios from 1 to 5 and Reynolds numbers in the range  $Re = 17200\text{--}65360$ . Across all geometries, vortex shedding does not follow the instantaneous Reynolds number but organizes into distinct, constant-frequency time cells separated by abrupt transitions in the lateral flow and wake dynamics. These time cells, first identified for square cylinders in Lunghi et al. (2024), also appear in elongated rectangular sections (Morello et al., 2025). The combined analysis of aerodynamic forces, Strouhal number evolution, and instantaneous flow fields provides a perspective on how bluff bodies with different chord-to-depth ratios respond to non-stationary inflow conditions.

**Keywords:** *accelerating and decelerating inflow, square and rectangular cylinders, LES simulations, time-frequency analysis*

## 1 INTRODUCTION

The aerodynamic response of civil structures is commonly assessed within the quasi-steady framework introduced by Davenport (1961), which assumes that aerodynamic forces adjust instantaneously to changes in wind velocity. This approximation is well supported for synoptic winds and for canonical bluff bodies tested under steady inflow, including square and rectangular cylinders across a range of chord-to-depth ratios (see, e.g., Bearman and Obasaju, 1982). However, non-synoptic winds—such as downbursts, gust fronts, and thunderstorm outflows—exhibit strong temporal gradients that may invalidate the quasi-steady assumption. Their short duration and limited spatial extent hinder full-scale measurements, while transient inflow can significantly alter separation, recirculation, and vortex-shedding processes. Consequently, several recent studies have examined whether loads and shedding frequencies obtained under stationary inflow remain applicable during acceleration or deceleration (Yang and Mason, 2019). Wind-tunnel experiments by Brusco et al. (2022) analyzed Gaussian-type acceleration on a square cylinder over  $Re = 17200\text{--}65360$ , revealing that vortex shedding evolves through distinct constant-frequency time windows separated by abrupt transitions. Brusco et al. (2024) further showed that these transitions coincide with sharp variations in drag and lift fluctuations.

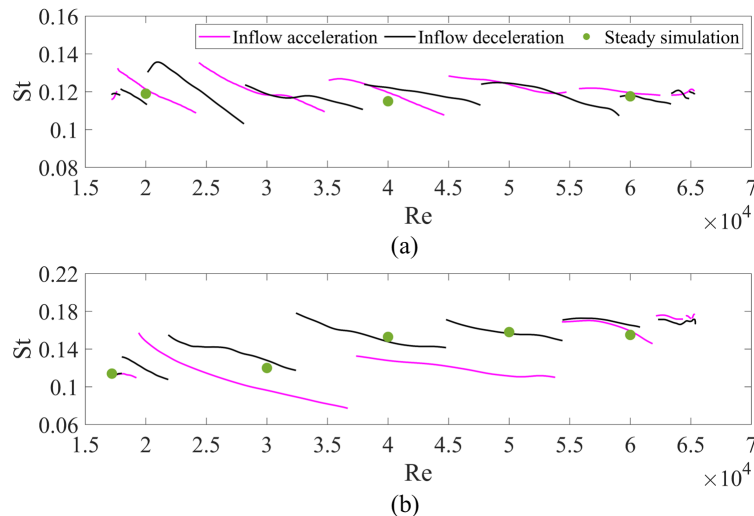
Herein, we present the results of Large Eddy Simulations (LES) carried out in Lunghi et al. (2024) for the same experimental setup as in Brusco et al. (2022). The simulations corroborate the wind-tunnel findings and provide additional insight into the flow features within and among the constant-frequency time windows. In Morello et al. (2025), Gaussian-type acceleration was also investigated for rectangular cylinders with chord-to-depth ratios of 3:1 and 5:1, where constant-frequency windows were again observed despite the more complex flow topologies. The effect of the acceleration severity was addressed. Finally, we computationally examine square and rectangular cylinders with chord-to-depth ratios from 1 to 5 under decelerating flow conditions. Particular attention is devoted to assessing the reliability of steady-inflow predictions in structural design and



### 3 RESULTS AND DISCUSSION

Across all geometries examined, the flow subjected to Gaussian-type accelerating and decelerating inflow does not adjust continuously to the instantaneous Reynolds number. Instead, vortex shedding organises into distinct constant-frequency time cells (or time windows), separated by abrupt discontinuities in the shedding mechanism. After each transition, shedding reappears at a different frequency, indicating that non-stationary inflow fundamentally alters the temporal structure of the wake. For the 1:1 and 2:1 cylinders, each time window is characterised by a nearly constant cell-averaged Strouhal number. In particular, for the square cylinder the Strouhal number varies within the same range during both acceleration and deceleration, oscillating around  $St \approx 0.12$ , which is the value observed under steady inflow. However, the corresponding time windows do not overlap, highlighting the intrinsic hysteresis of the transient response (see Fig. 2a).

On the other hand, the 5:1 cylinder exhibits the strongest sensitivity to unsteady inflow. Here, the cell-averaged Strouhal number is directly related to changes in the mean recirculation region along the lateral side: a longer recirculation region results in lower shedding frequencies. Moreover, the range of Strouhal-number variation differs significantly between acceleration and deceleration. During acceleration, pronounced deviations from the steady-flow prediction emerge near the acceleration peak ( $Re \approx 45000$ ), whereas the decelerating-flow results remain much closer to their stationary-inflow counterparts (see Fig. 2b). Rectangular cylinders with chord-to-depth ratios equal to 3 and 4 show the same sequence of constant-frequency windows, but with smaller variations between cells compared to the 5:1 case. This reduced sensitivity is linked to their flow topology: the separated shear layers tend to reattach close to the rear edges, forming a mean recirculation region that does not change across different time windows. These findings indicate that steady-inflow predictions remain reasonably reliable for square and moderately elongated cylinders (up to 4:1), since the deviations induced by acceleration and deceleration considered in the present study remain relatively small. In contrast, for highly elongated sections such as the 5:1 cylinder, steady-flow estimates fail to capture the characteristic frequencies observed during acceleration.



**Figure 2:** Comparison of the evolution of the vortex-shedding Strouhal number as a function of the Reynolds number between the two unsteady inflow conditions and the reference data obtained from steady-flow simulations: (a) square cylinder, (b) 5:1 rectangular cylinder.

## 4 CONCLUSIONS

This study examined the unsteady aerodynamics of square and rectangular cylinders subjected to Gaussian-type accelerating and decelerating inflow conditions, suggesting that non-synoptic wind conditions must be explicitly considered when evaluating aerodynamic loads for structural design. In particular, the simulations reveal that vortex shedding does not evolve continuously with the instantaneous Reynolds number; instead, it reorganises into distinct constant-frequency time cells separated by abrupt transitions in wake dynamics. This behaviour is observed across all geometries but becomes increasingly significant for elongated cylinders. For square and rectangular cylinders up to 4:1, the cell-averaged Strouhal numbers remain close to those obtained under steady inflow, indicating that stationary-flow estimates provide a reasonable approximation of the unsteady shedding behavior. In contrast, the 5:1 configuration shows marked deviations during acceleration, driven by transient modifications of the recirculation region and wake width, leading to shedding frequencies that cannot be inferred from steady-state data alone. Overall, the emergence of constant-frequency time windows appears to be a robust feature of transient vortex shedding, yet its aerodynamic implications depend strongly on chord-to-depth ratio and on whether the inflow is accelerating or decelerating.

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