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Master's Thesis

EFFECT OF PERMEABLE DOUBLE SKIN
FAÇADES ON VORTEX INDUCED
VIBRATIONS IN A HIGH-RISE
BUILDING

Student

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Abstract

Slender high-rise buildings are susceptible to vortex-induced vibrations (VIV), and permeable double-skin façades (PDSF) have been proposed as a passive means of mitigating them. This thesis examines the aerodynamic effect of such a façade on a rectangular prism of aspect ratio $B/D = 3.33$ — a transitional section whose wake alternates between leading-edge shedding and intermittent shear-layer reattachment. The flow is modelled with two-dimensional Unsteady Reynolds-Averaged Navier–Stokes (URANS) simulations using the k – ω SST closure in OpenFOAM, and the porous screen is represented by a Darcy–Forchheimer momentum sink characterised by a single pressure-loss coefficient k . The framework is validated against the canonical square and $B/D = 5$ prisms, and against wind-tunnel measurements of the same section: it reproduces the Strouhal number and wake topology accurately, while the absolute fluctuating forces retain the systematic two-dimensional bias — under-predicted mean drag and over-predicted lift fluctuations — expected from the neglect of spanwise decorrelation.

The response is analysed through global force statistics, surface-pressure distributions, force spectra, and proper orthogonal decomposition (POD) of the wake. Imposed cross-flow oscillations of the naked prism reproduce the sub-critical, lock-in, and super-critical regimes and link modal coherence to aerodynamic amplification. A sweep of the pressure-loss coefficient on the rigid porous configuration shows that increasing k displaces the effective separation contour from the inner sharp edges towards the outer screen: the Strouhal number falls from $St \approx 0.15$ (open, near-naked) towards $St \approx 0.08$ (resistive, near-solid), the fluctuating lift is progressively attenuated, and the leading wake mode loses spatial coherence. This behaviour maps onto an effective-elongation analogy, with k tuning the apparent slenderness of the prism, while a control-volume decomposition of the mean drag shows that the screen intercepts a growing share of the load and shields the inner structure. When motion is imposed on the porous configuration, lock-in is still established near resonance, but at reduced amplitude and spectral coherence. The porous layer, therefore, acts principally by weakening the intrinsic shear-layer instability and redistributing momentum, raising the threshold for spontaneous VIV onset rather than suppressing the synchronised state once it is established.

Keywords: Vortex-induced vibrations; Fluid–structure interaction; Rectangular cylinder; Permeable double-skin façade; Proper orthogonal decomposition; Darcy–Forchheimer model; URANS; Strouhal number; Lock-in; Aerodynamic mitigation.

Contents

Abstract	i
1 Introduction	1
1.1 Scope and Objectives of the Thesis	2
2 Literature Review	3
2.1 Vortex Shedding	3
2.1.1 Reynolds number dependency	3
2.1.1.1 Reynolds number	4
2.1.1.2 Separation	4
2.1.2 Shedding Frequency and Strouhal Number	6
2.1.3 Vortex Shedding on a Rectangular cylinder	7
2.1.3.1 Low aspect ratio	8
2.1.3.2 Intermediate aspect ratio	8
2.1.3.3 High aspect ratio	9
2.1.3.4 Strouhal number and wake width	10
2.2 Vortex-Induced Vibrations	10
2.2.1 Lock-In Phenomenon	11
2.2.1.1 Phase Synchronisation and Energy Transfer	12
2.2.1.2 Lift Force Amplification in VIV	13
2.2.2 Wake Deformation and Shedding Pattern Changes	13
2.2.2.1 Shear Layer Dynamics	13
2.2.2.2 Vortex Formation and Merging	15
2.2.2.3 Wake Width and Symmetry	15
2.2.2.4 Turbulence Characteristics During VIV	16
3 Methodology	17
3.1 Simulation Set-up	17
3.1.1 BlockMesh and Boundary Conditions	17
3.1.2 Solver and Turbulence Closure	18
3.1.3 Mesh Generation and Refinement	19
3.2 Grid Independence and Mesh Validation	19
3.2.1 Mesh resolution	20
3.2.2 Monitored non-dimensional parameters	20
3.2.2.1 Mean drag coefficient	20
3.2.2.2 Standard deviation of lift coefficient	20
3.2.2.3 Strouhal number	21
3.2.3 Grid convergence results	21
3.2.4 Selected mesh	21
3.3 Modelling the Permeable Double-Skin Façade	22
3.3.1 Reduced-Order Approach	22
3.3.2 Darcy–Forchheimer Formulation	23

3.3.3	Calibration and Validation of the Porous Model	24
3.3.4	Implementation in the Computational Domain	25
3.4	Post-Processing and Flow Analysis Tools	25
3.4.1	Proper Orthogonal Decomposition	25
3.4.1.1	Mathematical Formulation	26
3.5	Model Verification	29
3.5.1	Square Cylinder	29
3.5.1.1	Mean Drag Coefficient	29
3.5.1.2	Fluctuating Lift (Root-Mean-Square)	30
3.5.1.3	Vortex Shedding Frequency	30
3.5.1.4	Flow decomposition	30
3.5.1.5	Outcome	31
3.5.2	Rectangular Cylinder ($B/D = 5$)	31
3.5.2.1	Mean Drag Coefficient	32
3.5.2.2	Fluctuating Lift (Root-Mean-Square)	32
3.5.2.3	Vortex Shedding Frequency	32
3.5.2.4	Flow Decomposition	33
3.5.2.5	Outcome	33
3.5.3	Summary of Validation Results	33
4	Experimental Data	35
4.1	Experimental configurations and test conditions	35
4.2	Rigid-body aerodynamic response	35
4.2.1	Mean and fluctuating pressure distributions	36
4.2.2	Vortex shedding frequencies and Strouhal number	37
4.3	Aeroelastic response and VIV onset	37
4.3.1	Spectral organisation of aerodynamic forcing	38
4.4	Summary of experimental findings	38
5	Results	41
5.1	Effect of Aspect Ratio on the Aerodynamic Response of Rectangular Prisms	41
5.1.1	Variation of Global Aerodynamic Coefficients with Aspect Ratio	41
5.1.2	Comparison with Wind Tunnel Measurements	44
5.1.3	Spectral Characteristics of the Still Configuration	44
5.1.4	POD Analysis of the Still Configuration	45
5.1.4.1	POD Energy Distribution	45
5.1.4.2	Effect of Aspect Ratio on POD Spectral Content	45
5.1.4.3	POD Mode Shapes	47
5.1.5	Reynolds Number Dependency	48
5.2	Imposed Oscillations	49
5.2.1	Sub-Critical Forcing: $f = 0.75f_n$	50
5.2.1.1	Wake Topology	50
5.2.1.2	POD Energy Distribution	51
5.2.2	Lock-In Regime: $f \approx f_n$	52
5.2.3	Super-Critical Forcing: $f = 1.25f_n$	53
5.2.3.1	Wake Topology Transition	53
5.2.3.2	POD Energy Redistribution	54
5.2.4	Comparative Summary of Forcing Regimes	54
5.2.5	Frequency Content of POD Modes	55
5.2.5.1	Sub-Critical Forcing: $f = 0.75f_n$	55
5.2.5.2	Lock-In Regime: $f \approx f_n$	56
5.2.5.3	Super-Critical Forcing: $f = 1.25f_n$	56

5.2.6	Effect of Forcing Frequency on Aerodynamic Coefficients	57
5.2.6.1	Lift force spectrum	58
5.2.6.2	Coefficients of lift and drag	58
5.2.7	Modal–Force Coupling Interpretation	59
5.3	Porous Façade Configuration	59
5.3.1	Comparison with Experimental Data	60
5.3.2	Influence of the Pressure-Loss Coefficient k	61
5.3.2.1	Global Aerodynamic Parameters	61
5.3.2.2	Mean Pressure and Velocity Fields	62
5.3.2.3	Porosity as an Effective Elongation Ratio	66
5.3.2.4	Decomposition of the Mean Drag	70
5.3.2.5	Pressure Distributions Around the Perimeter	72
5.3.2.6	Force Spectra	74
5.3.2.7	POD Mode Shapes	75
5.3.2.8	POD Energy Distribution and Spectral Content	77
5.4	Imposed Oscillations on the Porous Configuration	78
5.4.1	Global Response and Force Spectra	79
5.4.2	Mean Gap-Flow Topology	80
5.4.3	Flow Structures	82
5.4.4	POD Energy Redistribution	83
5.4.5	Comparative Summary	84
6	Conclusions and Perspectives	87
6.1	Summary of Main Findings	87
6.2	Interpretation and Implications	89
6.3	Limitations and Future Work	90
	Bibliography	91
	List of Symbols	97
	List of Figures	101
	List of Tables	105

1 | Introduction

As urban populations surge and land availability diminishes, the vertical expansion of cities through high-rise buildings has become a defining feature of modern architecture. However, the increasing height and slenderness of these structures make them more susceptible to dynamic wind effects, particularly vortex-induced vibrations (VIV). VIV occurs due to alternating vortex shedding on either side of a building, resulting in oscillatory forces perpendicular to the wind direction. If not properly mitigated, these vibrations can compromise structural integrity, affect occupant comfort, and lead to long-term maintenance issues.



Figure 1.1: Isozaki tower in Milan's CityLife district.

Façade design has emerged as a key parameter not only in improving thermal and acoustic performance but also in influencing aerodynamic behaviour. The double skin façade (DSF) system, comprising two layers of façades separated by an air cavity, is widely adopted for its energy efficiency benefits, for example, in the Isozaki tower in Milan's CityLife district (Figure 1.1). A novel variation of this system—the permeable double skin façade (PDSF)—introduces strategically designed openings (Figure 1.2) that allow partial airflow through the cavity. This

permeability has the potential to disrupt vortex formation and alter pressure distributions around the building envelope.



Figure 1.2: Porous façade of the SDA Bocconi campus.

Limited research exists on the aerodynamic implications of porous double-skin façades. This work investigates how façade permeability influences vortex-induced vibrations of slender buildings.

1.1 Scope and Objectives of the Thesis

The purpose of this work is to provide a structured, quantitative assessment of the flow–structure interaction of a rectangular prism with aspect ratio $B/D = 3.33$, and to establish a consistent reference framework for evaluating the influence of a permeable external layer.

The study proceeds in two stages. The naked prism is first characterised in detail, both to confirm that the numerical framework reproduces the known aerodynamic behaviour and to identify the instability mechanisms that govern vortex shedding and lock-in — the synchronisation of vortex shedding with the structure’s own oscillation. The permeable façade is then introduced as a controlled modification of this baseline and analysed within the same framework, so that its effect on the shedding frequency, oscillation amplitude, and synchronisation range can be isolated by direct comparison.

The remainder of this thesis is organised as follows. Chapter 2 reviews the background on vortex shedding and vortex-induced vibrations. Chapter 3 presents the numerical methodology — the two-dimensional URANS setup, the Darcy–Forchheimer model of the permeable façade, and the proper orthogonal decomposition used to analyse the wake — together with its validation against the square and $B/D = 5$ reference prisms. Chapter 4 summarises the wind-tunnel campaign that provides the experimental reference data. Chapter 5 reports the results in four steps: the naked rigid prism and the effect of aspect ratio, the naked prism under imposed oscillation, the rigid porous configuration across a sweep of the pressure-loss coefficient k , and the porous prism under imposed oscillation. Chapter 6 draws the findings together and outlines future work.

2 | Literature Review

2.1 Vortex Shedding

The unsteady flow separation around bluff bodies gives rise to a phenomenon known as vortex shedding. When a fluid flows past an obstacle, the shear layers that separate from its surface can become unstable and roll up into alternating vortices downstream. This periodic detachment of vortices generates an oscillating lift force on the body, which, if coupled with a structural natural frequency, may lead to vortex-induced vibrations (VIV). The process is governed by the Reynolds number, geometry, and surface roughness, and it represents one of the most fundamental forms of fluid–structure interaction in wind engineering [1, 2]. Early analytical and experimental studies of these cable oscillations revealed that the alternating pressure distribution in the wake was caused by a periodic vortex street forming behind the body [3].

To understand and model this behaviour, researchers adopted the *circular cylinder* as a canonical geometry, since it reproduces the essential physics of vortex formation and wake instability in a simple, well-defined configuration. The circular cylinder has thus become the reference case for studying vortex shedding, providing the foundation for the analysis of more complex subsections, such as rectangular prisms and building cross-subsections [4, 5, 6, 7].

The characteristics of the flow pattern around a circular cylinder change markedly with the Reynolds number, resulting in distinct flow regimes ranging from steady laminar separation to fully turbulent vortex streets. To understand why the nature of the flow changes so drastically with the change in Reynolds number, it is useful to consider the governing Navier–Stokes equations.

2.1.1 Reynolds number dependency

For a compressible or incompressible Newtonian fluid (neglecting gravity), the dimensional Navier–Stokes equations can be written as

$$\begin{cases} \frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0, \\ \frac{\partial(\rho \mathbf{u})}{\partial t} + \nabla \cdot (\rho \mathbf{u} \otimes \mathbf{u}) = -\nabla p + \mu \nabla^2 \mathbf{u} + \rho \mathbf{f}, \end{cases} \quad (2.1.1)$$

where ρ is the density, $\mathbf{u}$ the velocity vector, p the pressure, μ the dynamic viscosity, and $\mathbf{f}$ an external body force [8].

2.1.1.1 Reynolds number

The Reynolds number Re appears as a dimensionless parameter and quantifies the ratio between inertial and viscous forces. The viscous term scales as $1/Re$, while the inertial and pressure-gradient terms are of order unity. When $Re \ll 1$, the viscous term dominates, and the momentum equation becomes effectively linear, leading to a steady, laminar flow. Conversely, when $Re \gg 1$, viscosity plays only a minor role and the non-linear convective term $\rho^*(\mathbf{u}^* \cdot \nabla^*)\mathbf{u}^*$ governs the dynamics, producing a complex, unsteady behaviour such as vortex shedding and turbulence [8]. This transition introduces bifurcations in the solution space and results in the appearance of periodic vortex shedding. And at sufficiently high Re , the onset of fully developed turbulence, as illustrated in Figure 2.1.

2.1.1.2 Separation

At sufficiently small Reynolds numbers (typically $Re \lesssim 5$), the fluid follows the curvature of the cylinder without separating from its surface. Example 1 in Figure 2.1 shows an attached flow.

Past this Reynolds number, separation at the rear of the cylinder begins to take place. The boundary layer detaches from the surface, and at the separation point, the local tangential flow velocity is zero. Downstream of this point, the fluid particles reverse their direction. This flow reversal starts to occur when the negative pressure gradient required to curve the flow around the cylinder becomes too large. Further downstream, the separated shear layers from both sides of the cylinder merge at the end of the recirculation region, forming the wake closure and creating pockets of circulating fluid trapped by the surrounding flow. From $Re = 4$ to $Re = 46$, the separation bubble grows in both length and width (Example 2 in Figure 2.1). The streamwise length of the separation bubble scales approximately linearly with Reynolds number. After $Re = 46$, these vortices begin to shed, forming a von Kármán vortex street (shown in examples 3 and 4 in Figure 2.1).

When fluid flows past a circular cylinder above a certain critical speed (characterised by a critical Reynolds number), the flow separates alternately from the two sides of the cylinder, creating a pattern of alternating vortices in its wake. This oscillating flow phenomenon is known as vortex shedding, and the repeating staggered array of vortices that it forms is called a Bénard–von Kármán vortex street. This transition occurs at a critical Reynolds number $Re_{cr} \approx 46$, where the steady symmetric recirculation behind the cylinder becomes unstable and starts to oscillate periodically [9, 10].

Above $Re \approx 46$, the two steady, symmetric vortices that form behind a cylinder at lower speeds become unstable and begin to shed periodically from the top and bottom in turns. Each shed vortex is carried downstream by the flow. The shed vortices arrange themselves in two staggered rows, creating low-pressure zones that alternate in the wake. The flow pattern remains coherent up to $Re \approx 189$, beyond which the shed vortices themselves become turbulent as three-dimensional instabilities develop in the wake [9, 10]. Classical linear stability analyses confirm that the alternating vortex configuration is the only stable mode of the wake, which explains why vortices do not shed symmetrically on both sides simultaneously [9].

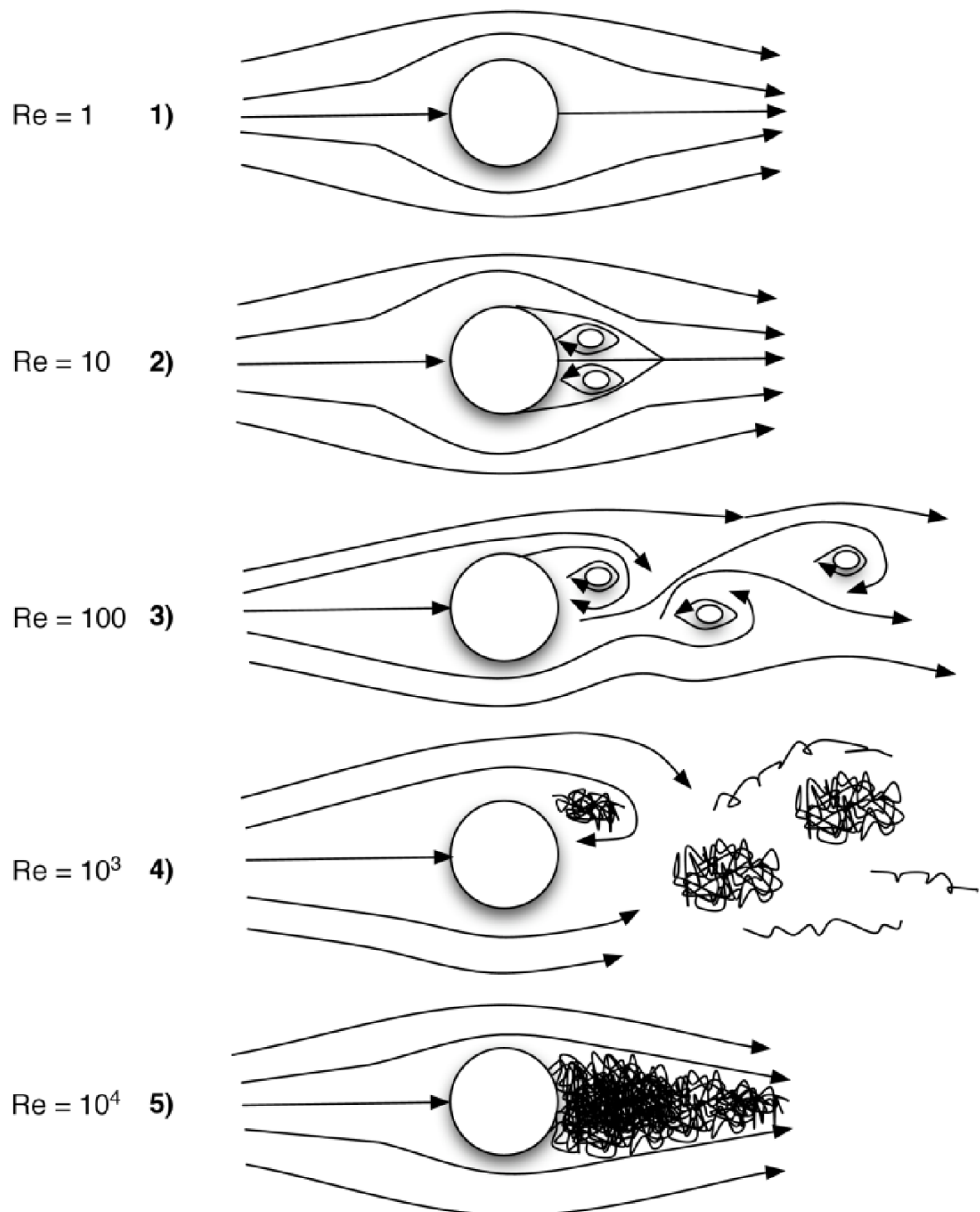


Figure 2.1: Flow around a cylinder at different Reynolds numbers [8].

2.1.2 Shedding Frequency and Strouhal Number

Vortex shedding is a self-sustained flow instability. Once it begins, the wake of the cylinder oscillates as a single, coherent structure. This behaviour can be described as a global mode, meaning that the entire near wake pulsates at one common frequency and spatial pattern [10]. Due to this coherence, the shedding frequency is well-defined and repeatable. The regularity of the process allows it to be characterised by the dimensionless Strouhal number,

$$St = \frac{fD}{U}, \quad (2.1.2)$$

where f is the vortex shedding frequency, D is the cylinder diameter, and U is the free-stream velocity [9, 7]. The Strouhal number is a fundamental parameter governing vortex shedding and is very robust for a circular cylinder in cross-flow.

Over a wide range of flow conditions, St remains nearly constant, indicating an almost linear relationship between shedding frequency and flow velocity. Across about four orders of magnitude in Reynolds number (from $Re \sim 10^2$ up to $\sim 10^5$), St for a smooth circular cylinder typically lies in an interval around 0.18–0.22, with a representative value $St \approx 0.20$ as can be seen in Figure 2.2. Meaning, the vortex shedding frequency is about one-fifth of U/D over a broad range of intermediate Re .

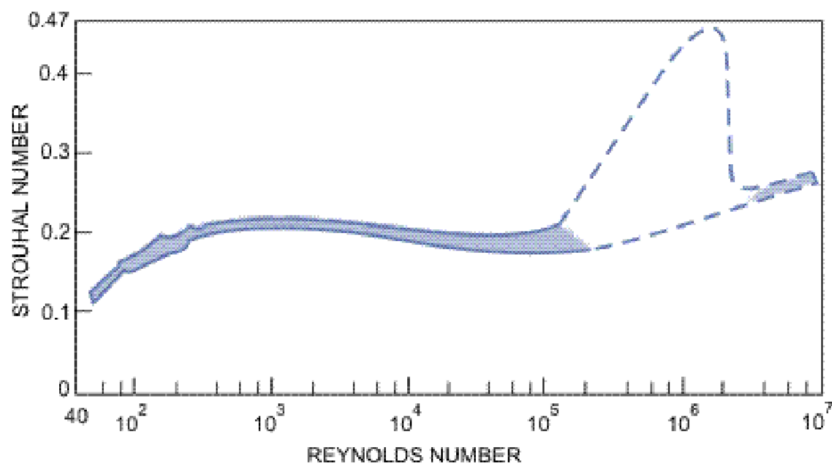


Figure 2.2: Strouhal number vs Reynolds number for flow behind a circular cylinder [11]

The slight dependence of St on Reynolds number reflects how the separated shear layers develop, become unstable, and roll up into vortices in the near wake.

In the laminar shedding regime at lower Re (e.g., $Re \approx 50$), enhanced viscous effects lead to wider wake spacing and a longer vortex formation region, resulting in somewhat lower values of St (about 0.13–0.17). As Re increases into the subcritical regime, the shear layers roll up more rapidly, and the wake structure stabilises, causing St to approach ~ 0.20 . Because the global shedding mechanism remains essentially unchanged once separation is fully established, the Reynolds-number dependence becomes weak.

For many engineering estimates in the range $100 < Re < 100,000$, it is common to take $St \approx 0.20$, allowing the shedding frequency to be predicted from

$$f \approx 0.20 \frac{U}{D}. \quad (2.1.3)$$

Outside the subcritical regime, or with significant alterations to the cylinder surface, or nearby flow interference, the Strouhal number can deviate from these values.

2.1.3 Vortex Shedding on a Rectangular cylinder

A rectangular cylinder (with width D in the cross-wind direction and length B in the flow direction) is a bluff body with sharp corners. Unlike a circular cylinder, a rectangular one forces flow separation to occur at the sharp leading edges for all Reynolds numbers of interest. The separated shear layers then either form vortices directly or interact with the body surfaces further downstream, depending on the cylinder's aspect ratio B/D . Therefore, the flow behaviour and the vortex shedding characteristics are determined by this aspect ratio. By varying B/D , the flow goes through several vortex shedding regimes.

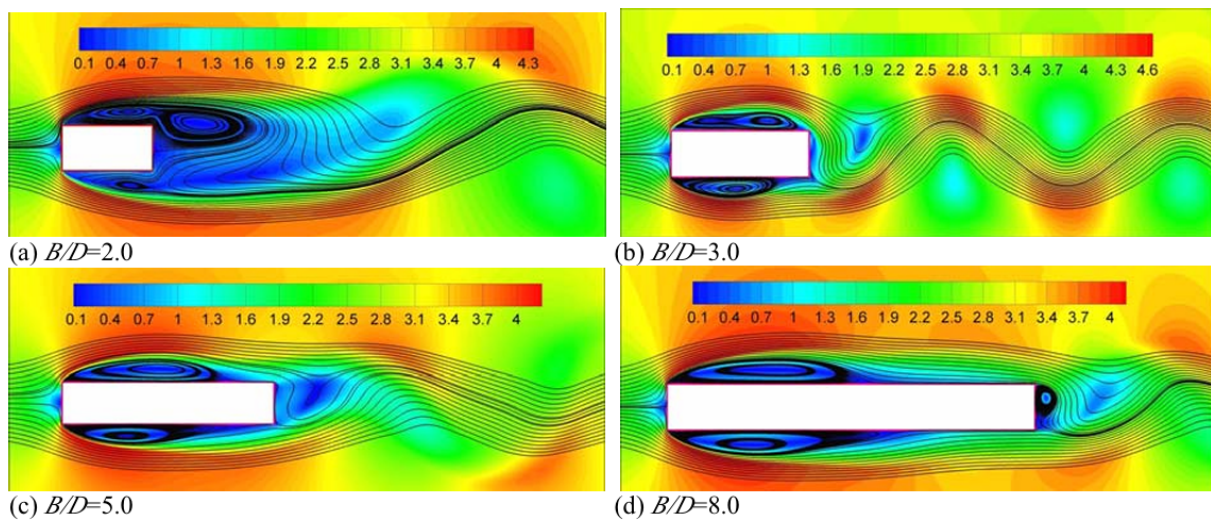


Figure 2.3: Illustration of shedding regimes for different aspect ratios of a square cylinder. Streamlines are shown in black, and the pressure contour is represented with the colour gradient [12].

The fundamental difference between a circular cylinder and a rectangular cylinder lies in where and how the boundary layer separates. The circular cylinder's smooth curvature leads to separation at an angle, whereas a rectangular subsection forces immediate separation at a sharp corner. A circular cylinder's shear layers initially form closer together, somewhat behind the cylinder's widest cross-section. On the other hand, a rectangular cylinder's shear layers start at the full width of the front face. For a short or square cylinder, those shear layers roll into vortices directly, resulting in a wide wake and low St . For a long cylinder, those shear layers reattach then separate again, effectively narrowing the wake at the point of vortex formation (the trailing edge) and thus increasing St . The circular cylinder lacks any such reattachment mechanism – its shear layers never reattach on the surface – so it cannot exhibit the multiple shedding regimes seen in rectangular bodies. The cylinder's shedding is always a single-mode Kármán street (until other three-dimensional instabilities or turbulence spectra come into play at very high Re), whereas a rectangular bluff body can transition from one shedding mode to another as B/D changes.

2.1.3.1 Low aspect ratio

A rectangular cylinder with low aspect ratio ($B/D \lesssim 2$) behaves as a classical bluff body characterised by large pressure drag and a broad wake generated by immediate separation at the sharp leading edges. Because the separation points are geometrically fixed by the corners and the stream-wise length is limited, the detached shear layers do not reattach to the side faces. Instead, they remain fully separated and roll up directly into large-scale vortices that are convected downstream, forming a relatively regular Kármán-type vortex street. In vortex-shedding classification, this regime corresponds primarily to Leading-Edge Vortex Shedding (LEVS), in which the dynamics are governed by the global instability of the separated shear layers rather than by shear-layer reattachment or side-face interaction [3, 13, 4].

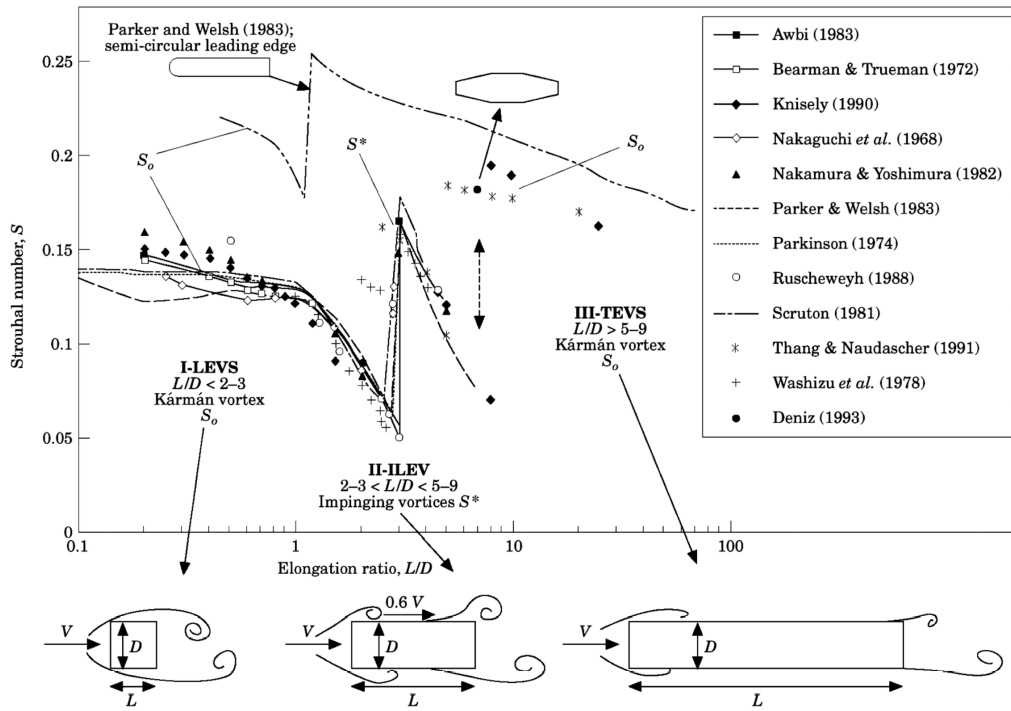


Figure 2.4: Vortex shedding frequency for rectangular cross-sections with different B/D ratios [14].

2.1.3.2 Intermediate aspect ratio

For intermediate aspect ratios ($2 \lesssim B/D \lesssim 3$), the flow transitions from classical Leading-Edge Vortex Shedding (LEVS) toward Impinging Leading-Edge Vortices (ILEV). In this regime, the shear layers separated at the front edges no longer roll up immediately into wake vortices. Instead, they intermittently reattach to the side surfaces or impinge near the trailing edges before rolling up into vortices further downstream. As a result, the vortex formation region is displaced further downstream, and the wake alternates between classical LEVS-type shedding and a reattachment-controlled ILEV mode.

A key experimental observation in this transitional range is a discontinuity or minimum in the Strouhal number. Okajima [3] reported that St reaches a local minimum around $B/D \approx 2$ (Figure 2.4). Physically, this can be interpreted through the increase in vortex formation length: as B/D increases from unity, the separated shear layers require a longer stream-wise development before rolling up into coherent vortices. The delayed roll-up increases the shedding period and

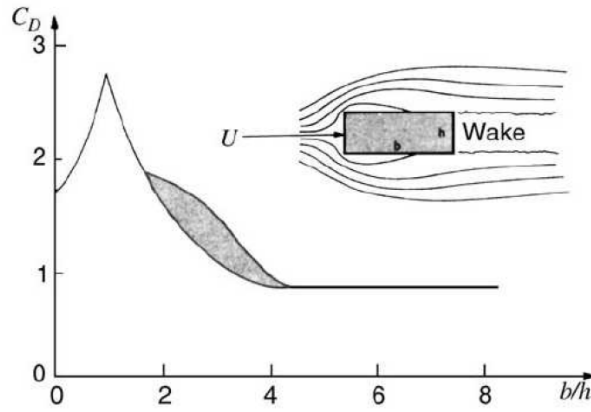


Figure 2.5: Drag coefficient versus elongation ratio B/D of a rectangular prism with sharp edges. [15]

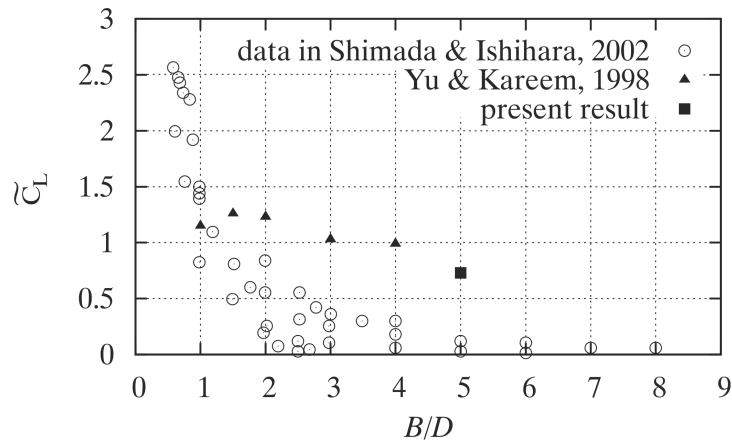


Figure 2.6: RMS Lift coefficient vs elongation ratio B/D of a rectangular prism with sharp edges. The present study indicates [16].

therefore reduces the shedding frequency f . Since $St = fD/U$, the longer formation time directly results in a lower Strouhal number. In this regime, vortices are shed more slowly because shear-layer reattachment and downstream development govern the instability process rather than immediate roll-up at the leading edges.

2.1.3.3 High aspect ratio

For sufficiently elongated rectangular cylinders ($B/D \gtrsim 3$), the shear layers separated at the sharp leading edges reattach in a time-averaged sense along the side surfaces before separating again near the trailing edges. Experimental investigations [3, 4] indicate that a stable reattachment bubble is established for $B/D \gtrsim 3.0$, marking the transition from impinging leading-edge vortex (ILEV) behaviour to Trailing-Edge Vortex Shedding (TEVS). In the TEVS regime, vortex roll-up is governed primarily by the instability of the trailing-edge shear layers rather than by leading-edge dynamics.

The quantitative signature of this transition is observed in the Strouhal number. After reaching a minimum around $B/D \approx 2.0$ ($St \approx 0.11$ – 0.13), the Strouhal number increases as B/D grows, attaining values of approximately $St \approx 0.16$ – 0.18 for $B/D = 3.0$ – 3.5 [3]. For $B/D \approx 3.3$, values around $St \approx 0.18$ – 0.19 are commonly reported, approaching those of a circular cylinder ($St \approx$

0.20). This increase reflects the downstream shift of vortex formation and the stabilisation of the reattachment process, which shortens the effective formation region relative to the transitional regime and produces a more regular shedding pattern.

As B/D increases further ($B/D \gtrsim 5-6$), the flow approaches an asymptotic TEVS state in which reattachment remains stable and the wake becomes narrower, more organised, and increasingly two-dimensional. In this regime, the Strouhal number becomes only weakly dependent on further increases in aspect ratio, typically remaining in the range 0.17–0.20 depending on Reynolds number and turbulence intensity [4, 6]. Although the body remains a bluff obstacle with fixed leading-edge separation, the presence of the stable reattachment bubble modifies the pressure distribution and generally reduces lift fluctuations compared to low- B/D configurations.

2.1.3.4 Strouhal number and wake width

Suppose we interpret the Strouhal formula $St = fD/U$ by using the effective transverse spacing between shear layers in the wake, in place of D . In that case, an intriguing observation is that all bluff bodies shed vortices at a similar non-dimensional rate. When using the distance between the two shear layers (which for a circular cylinder is on the order of the diameter, and for a rectangular cylinder might be the spacing of the reattached shear layers at the trailing edge), the Strouhal number tends to be roughly 0.2 universally [3].

This leads to the proposed universal Strouhal number of the von Kármán vortex street $St \approx 0.2$, when defined by using the appropriate wake width. That means the lower St observed for a square cylinder relative to a circular cylinder is because the square’s effective vortex formation width is larger than its front-face width. In contrast, an elongated rectangular cylinder that achieves trailing-edge shedding has an effective vortex formation width closer to the body width, resulting in a Strouhal number closer to 0.2. Thus, while geometry strongly influences the measured shedding frequency for a given reference length, the underlying non-dimensional shedding characteristics are similar across different bluff bodies when appropriately scaled.

2.2 Vortex-Induced Vibrations

Now let’s suppose the cylinder is elastically mounted in a mass-spring-damper system and free to move in the direction transverse to the flow. At low flow speeds, the structure remains nearly stationary. However, beyond a critical velocity, the oscillatory lift force injects energy into the structure’s motion, leading to self-excited oscillations. The equation of motion for the cylinder (modelled as a damped oscillator – Figure 2.7) is:

$$m\ddot{y} + c\dot{y} + k_s y = F_y(t) \quad (2.2.1)$$

where m is the mass, $c = 2m\zeta\omega_n$ is the damping coefficient, $k_s = m\omega_n^2$ is the spring stiffness, and $F_y(t)$ is the cross-flow lift force from vortex shedding. The lift force can be expressed in coefficient form as

$$F_y(y, \dot{y}, t) = \frac{1}{2}\rho U^2 DB C_L(y, \dot{y}, t), \quad (2.2.2)$$

where the dependence on the structural motion is contained in the unsteady lift coefficient C_L .

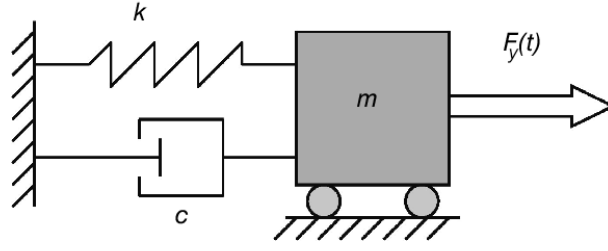


Figure 2.7: Schematic representation of the damped oscillator model.

In the VIV regime, C_L becomes state-dependent, as the body motion modifies the instantaneous angle of attack, relative velocity, and phase between lift and displacement [1, 9]. Consequently, the aerodynamic forcing depends on both the displacement and velocity of the cylinder.

For a cylinder of span D , the reduced velocity is defined as $U^* = \frac{U}{f_n D}$. As the flow speed increases, U^* enters a range in which the vortex shedding frequency $f_v = StU/D$ approaches the natural frequency f_n of the structure. When the ratio f_v/f_n comes within $0.8 \lesssim f_v/f_n \lesssim 1.2$ [1, 9], the lock-in phenomenon occurs. In this synchronisation regime, the shedding frequency locks onto the oscillation frequency of the cylinder. The structure and the flow now mutually interact, and the simple Strouhal relation no longer strictly holds within this range. Instead, the vortex shedding adjusts to the body motion such that $f_v \approx f_n$. This marks the onset of vortex-induced vibrations, as the system transitions from passive vortex shedding to a coupled vibration–shedding state [7].

2.2.1 Lock-In Phenomenon

During lock-in, the cylinder oscillates at roughly constant frequency (near f_n) over a band of flow velocities, instead of the frequency increasing with U . This can be seen as the plateau of the $f(U)$ curve in Figure 2.8.

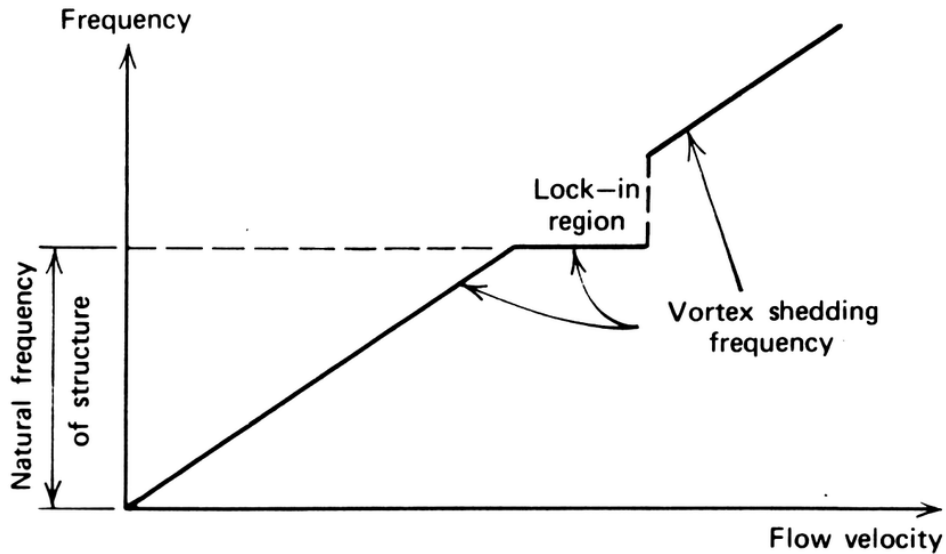


Figure 2.8: Dependence of frequency on flow velocity during lock-in [17].

This is also evidenced by a plateau or “bell-shaped” resonance-like response curve of amplitude versus reduced velocity. Tang et al. [7] report that a 4:1 rectangular cylinder exhibits a rapid rise in vibration amplitude within a certain reduced velocity range ($6.4 < U^* < 7.8$), followed by a saturation region ($7.8 < U^* < 9.1$), and finally a decline beyond $U^* > 9.1$ as synchronisation is lost (Figure 2.9). These regions correspond to the initial branch, upper branch, and desynchronisation regimes of VIV.

In the initial branch, oscillations build up rapidly as the vortex shedding frequency approaches the natural frequency of the structure. In the upper branch, oscillations persist at large amplitude over a finite velocity range. Beyond this range, the shedding frequency detunes from f_n , and the vibration amplitude diminishes.

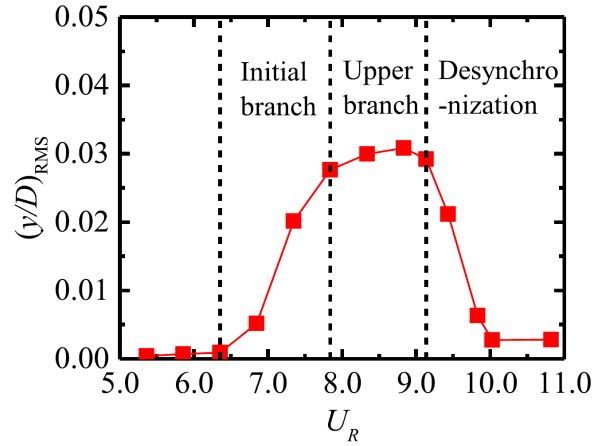


Figure 2.9: Dependence of VIV amplitude on reduced velocity for a 4:1 rectangular cylinder, adapted from Tang et al. [7]. In the original reference the reduced velocity is denoted U_R , which is equivalent to the present definition $U^* = U/(f_n D)$.

2.2.1.1 Phase Synchronisation and Energy Transfer

A crucial aspect of VIV lock-in is the phase relationship between the oscillating lift force and the cylinder’s motion. For the vibration to sustain, the fluid force must do positive work on the structure on average. This typically requires the lift force to be approximately in phase with the velocity of the body (90° out of phase with displacement). At the onset of lock-in, the phase between force and motion shifts into a range that feeds energy into the oscillation. Measurements often show a characteristic phase trend across the lock-in regime: as reduced velocity increases through the lock-in range, the phase of the force relative to the displacement changes smoothly from approximately 0° (in-phase) or small lag, through 90° near the peak response, towards 180° (out-of-phase) as the oscillation dies out.

In contrast, for a desynchronized case, the phase between any small motion and the fluid force tends to drift or be ineffective at feeding energy. For example, beyond the lock-in range (in the desynchronized regime), the vortex shedding slips out of phase with the structure’s movement, and the net energy transfer becomes negative (damping the motion). Catania et al. (2024) [2] observed that when their building model was outside of lock-in (either below or above the critical velocity), the coherence between force and motion signals dropped, and the relative phase was such that large oscillations could not be maintained.

2.2.1.2 Lift Force Amplification in VIV

A fixed cylinder sheds vortices with a certain base magnitude of fluctuating lift coefficient C_L . When the cylinder starts oscillating due to VIV, the vortex formation can strengthen the lift fluctuations. In the initial branch of VIV, as the oscillation amplitude grows, the fluctuating lift coefficient and its spatial correlation increase accordingly. Tang et al. [7] reported that for a 4:1 rectangular cylinder, the fluctuating lift coefficient C_L increased with vibration amplitude in the initial branch, and the correlation of pressure fluctuations along the span also rose.

Physically, once the body is moving, each shed vortex can exert force over a larger portion of the span in phase with the motion, resulting in a more coherent and stronger lift force. The mean pressure distribution is also altered: the time-averaged suction on the leading edges can increase when the structure oscillates, as the motion modulates the flow separation. This leads to a larger mean negative pressure on the side faces near the leading edge during VIV, representing a quasi-steady effect of the oscillation on the mean flow field.

During lock-in, the instantaneous lift force becomes state-dependent. This coupling can be expressed as

$$C_L(t) = C_L(y(t), \dot{y}(t), \ddot{y}(t); U^*), \quad (2.2.3)$$

where $y(t)$ is the cross-flow displacement. The non-linear dependence of C_L on $y(t)$ implies that the aerodynamic force adjusts dynamically with the motion. This state dependency leads to hysteresis in the force–displacement loop and a phase shift between force and motion, which determines whether the aerodynamic work input is positive or negative [1, 2]. When the lift is in phase with velocity, the flow injects energy into the structure, amplifying motion in the lock-in range.

2.2.2 Wake Deformation and Shedding Pattern Changes

The coupling of structural motion with the flow also causes deformation of the wake structure compared to the stationary vortex street. In stationary conditions, vortices are shed at regular intervals and convect downstream in two staggered rows, forming the classical 2S (two single vortices per cycle) Kármán street.

Under vortex-induced vibration (VIV), however, the instantaneous shedding pattern can change both topologically and dynamically. When the cylinder oscillates in the cross-flow direction, and lock-in occurs, the vortex shedding frequency synchronises with the structural natural frequency, altering the timing and location of vortex roll-up. As a result, different wake modes may appear depending on the reduced velocity and mass ratio [18].

These canonical shedding patterns were systematically classified by Williamson and Roshko [18] for oscillating bluff bodies and are illustrated schematically in Figure 2.10. In this notation, the first number indicates the number of vortex structures formed per oscillation cycle, while the letter describes whether they are single vortices (S), paired vortices (P), or structures with higher vortex count (C).

2.2.2.1 Shear Layer Dynamics

For a rectangular cylinder undergoing VIV, the behaviour of the leading-edge shear layer differs markedly from that of the stationary case. The oscillatory motion modifies both the instant-

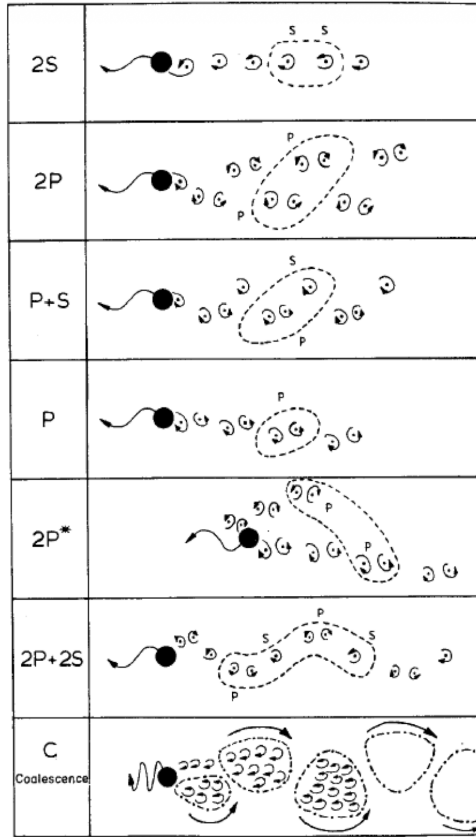


Figure 2.10: Canonical vortex shedding modes for oscillating bluff bodies, adapted from Williamson and Roshko [18].

neous separation point and the time-averaged reattachment location along the side face. As the vibration amplitude increases, the mean reattachment point moves upstream, indicating that the recirculation bubble on the side surface becomes shorter. This contraction of the separated region enhances the mean suction near the leading edge, consistent with the higher negative pressure observed during lock-in [7, 4].

Before resonance (in the initial branch), the reattachment point migrates slightly downstream with increasing amplitude, meaning that the shear layer remains attached longer before shedding a vortex. Tang [7] reported this behaviour for a 4:1 rectangular cylinder, where the instantaneous reattachment position shifted toward the trailing edge as the oscillation amplitude increased in the initial branch. This delay in detachment reflects a phase adjustment between the body motion and vortex formation.

In the upper branch, however, the shear layer no longer consistently reattaches. Large-eddy simulations and experimental observations by Tang [7] and Catania [2] show that the separated shear layer intermittently lifts off from the side face, forming a transient secondary vortex that interacts with the main wake. The resulting flow pattern transitions from a stable attached–reattached regime to one dominated by large-scale detachment and asymmetric vortex formation. This shift marks a fundamental change in the energy transfer mechanism: the loss of reattachment reduces side-face pressure recovery, while the alternating detached vortices reinforce cross-wind loading and sustain the large-amplitude oscillations characteristic of the upper branch.

2.2.2.2 Vortex Formation and Merging

When the cylinder oscillates, the vortices shed from the two sides no longer evolve independently as in the stationary case. The motion alters the phase and position of vortex release, which can cause the leading- and trailing-edge vortices to interact and merge before convecting downstream.

Large-eddy simulations of a 4:1 rectangular cylinder by Tang [7] confirmed that during the upper branch of VIV, the leading-edge shear layer rolls up into a coherent vortex that convects toward the trailing edge and combines with the opposite-side vortex at the instant of maximum displacement. The merged vortex pair then detaches as a single, large-scale structure. This process leads to a temporary suppression of new vortex formation near the surface and explains the drop in fluctuating lift observed in the upper branch.

A similar phenomenon was reported for elongated rectangular cylinders by Bruno [4], where instantaneous vorticity fields revealed that the two shear layers periodically interact and reconnect near the wake centreline, producing alternating asymmetric vortical structures. Experimental studies on high-rise building subsections have also observed comparable wake patterns [2], where vortex merging correlates with reduced shedding frequency and increased coherence along the span.

Zasso [1] linked these merging and splitting mechanisms to changes in the wake topology during lock-in, noting that the transition from a regular 2S (two single vortices) to a 2P (two paired vortices) shedding mode arises precisely when leading- and trailing-edge vortices coalesce. Such vortex fusion events therefore play a key role in defining the nonlinear fluid–structure interaction that sustains the large-amplitude, phase-locked oscillations of the upper VIV branch.

2.2.2.3 Wake Width and Symmetry

During vortex-induced vibration, the wake of an oscillating rectangular cylinder is commonly observed to become narrower and more symmetric than that of a stationary one at the same free-stream velocity. Large-eddy simulations and experiments show that, during lock-in, the instantaneous vortex shedding is constrained by the imposed body motion, resulting in vortices being shed closer to the wake centerline and with reduced lateral spreading. This narrowing of the wake has been reported for elongated rectangular cylinders in both numerical and experimental studies and is associated with the suppression of alternate large-scale wake deflections typical of the stationary case [7].

In free VIV, the structural motion actively enforces the temporal and spatial organisation of the shedding process. Measurements on tall prismatic models indicate that, during lock-in, the span-wise coherence of vortex shedding can approach unity, implying that vortices are shed nearly in phase along the entire height of the structure. In contrast, a stationary cylinder typically exhibits partial decorrelation along the span, with the wake divided into shedding cells of finite length. The transition from cellular shedding to highly coherent shedding during VIV has been documented through coherence analysis of pressure and velocity fluctuations for rectangular cylinders with aspect ratios in the range $3 < B/D < 5$ [4].

Overall, the wake of a VIV oscillator is dynamically reshaped by the two-way coupling between the flow and the structural motion. The classical staggered Kármán vortex street seen in a stationary flow may transition into a pattern locked to the oscillation cycle. The separated shear layers and vortices are no longer solely dictated by upstream flow parameters and body shape, but now also by the motion of the body itself. This two-way coupling leads to phenomena like

vortex merging, altered reattachment, and highly coherent wake structures that are not present for a fixed cylinder [7].

2.2.2.4 Turbulence Characteristics During VIV

The turbulence intensity in the wake can be defined as

$$I_u = \frac{\sqrt{u'^2}}{U}, \quad (2.2.4)$$

where u' denotes the fluctuating stream-wise velocity component and U is the free-stream velocity. This quantity represents the magnitude of velocity fluctuations relative to the mean flow.

In addition to fluctuation intensity, the turbulence length scale characterises the typical size of coherent eddies in the flow. In bluff-body wakes, this length scale is often of the order of the body depth D for stationary shedding. During vortex-induced vibration, however, the effective turbulence scale can change significantly.

In the initial branch of VIV, as oscillations build up, vortex shedding becomes more organised and phase-locked to the structural motion. The dominant wake structures grow in coherence and may extend over a larger portion of the span, effectively increasing the characteristic turbulence length scale. In the upper branch, large-scale vortex merging and synchronised shedding can produce even more spatially organised structures, reinforcing coherent lift fluctuations. Conversely, outside the lock-in regime, the vortex structures become less correlated along the span and break into smaller turbulent regions, reducing the effective coherence length.

Thus, the VIV response is closely linked to changes in both turbulence intensity and turbulence scale: strong, coherent large-scale structures promote sustained oscillations, whereas smaller-scale, less organised turbulence weakens the fluid–structure coupling.

3 | Methodology

The literature reviewed in the previous chapter established the physical mechanisms that any numerical investigation of vortex-induced vibrations must capture: the Reynolds-dependent transition of the wake, the aspect-ratio-dependent shedding regimes of rectangular prisms, the lock-in synchronisation mechanism and its dependence on mass-damping, and the role of phase relations and modal coherence in sustaining oscillations. These mechanisms define the set of indicators against which the numerical framework adopted in this thesis must be assessed. The present chapter introduces the URANS-based methodology used throughout the thesis, describes the reduced-order representation of the porous façade, presents the post-processing tools applied to the simulation data, and finally validates the framework against canonical bluff-body cases before its application to the configurations of interest.

3.1 Simulation Set-up

The computational domain, boundary conditions, and mesh refinement strategy are defined first. The mesh-independence study that ensures the predicted mean and unsteady aerodynamic quantities are not affected by spatial discretisation is presented in the subsequent section.

3.1.1 BlockMesh and Boundary Conditions

The numerical simulations were conducted using two-dimensional URANS in OpenFOAM. The computational domain was generated with **blockMesh** and extends sufficiently far from the body to minimise boundary effects on the wake development. In the stream-wise direction, the inlet and outlet are located at 7 and 20 building lengths from the model, respectively, while the lateral boundaries are positioned 10 building lengths from the cylinder centreline.

A uniform velocity profile was prescribed at the inlet using a fixed-value boundary condition, ensuring a steady and well-defined incoming flow. At the outlet, a zero-gradient condition was applied to the velocity field, allowing vortical structures to exit the domain without artificial reflection. The pressure field was specified using a zero-gradient condition at the inlet and a fixed reference value at the outlet, which provides a stable pressure recovery and ensures global mass conservation.

The cylinder surface was treated as a no-slip wall for the velocity field, while a zero-gradient condition was imposed on pressure. The lateral boundaries were modelled as symmetry planes, and the patches corresponding to the collapsed dimension were assigned empty boundary conditions, consistent with a standard two-dimensional formulation.

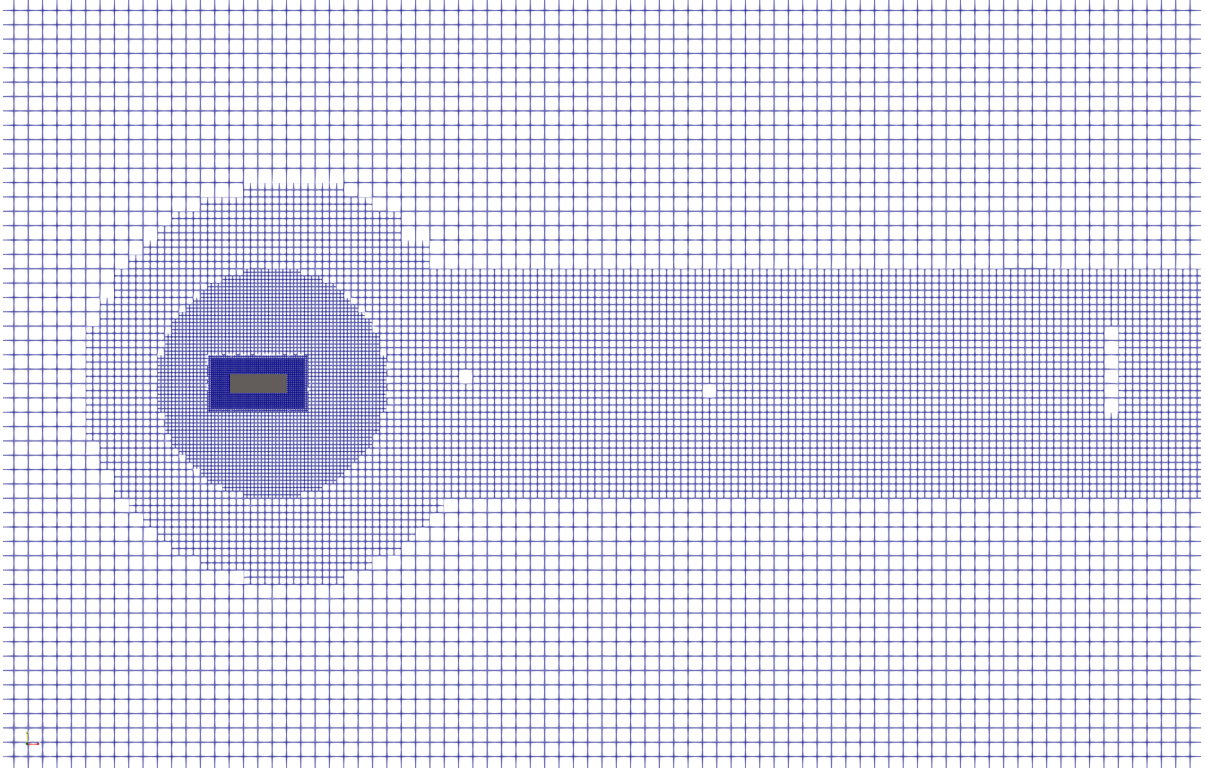


Figure 3.1: Computational mesh showing local refinement around the rectangular cylinder and in the wake region.

3.1.2 Solver and Turbulence Closure

The incompressible URANS equations were solved with the transient PIMPLE algorithm in OpenFOAM (`pimpleFoam`), using the consistent (SIMPLEC) formulation with five outer correctors, three pressure correctors, and one non-orthogonal corrector per time step. Turbulence was modelled with the k - ω SST closure of Menter, which blends a k - ω formulation near the wall with a k - ε behaviour in the free stream and is well suited to the adverse pressure gradients and separated shear layers that govern bluff-body wakes. The body surface was resolved with wall-adjacent cells at refinement level 5 (cell size $\approx 3 \times 10^{-3} B$), corresponding to $y^+ \approx 20$, so that the boundary layer is treated through the wall treatment of the SST closure rather than resolved to the viscous sublayer.

Time integration used a second-order implicit backward scheme, with the time step controlled adaptively to keep the maximum Courant number below $Co_{\max} = 0.5$. Momentum convection was discretised with a Courant-number-blended scheme, switching from a limited-linear discretisation (`limitedLinearV`) at low Courant number to a linear-upwind discretisation (`linearUpwindV`) above $Co = 0.05$ for stability, while the turbulence-transport equations used a limited linear scheme. Gradients were evaluated with a cell-limited least-squares scheme (cell-limited Gauss linear for the velocity gradient) and Laplacian terms with a Gauss linear scheme with limited non-orthogonal correction. Force coefficients, surface-pressure statistics, force spectra, and the POD snapshot ensemble were accumulated over ≈ 50 vortex-shedding cycles once the flow had reached a statistically stationary state, with the POD ensemble drawn from the final ≈ 27 cycles.

Within this closure, the two transport quantities — the turbulent kinetic energy and the specific dissipation rate — are written k_t and ω_t wherever they appear, to avoid confusion with the pressure-loss coefficient k and the angular frequency ω used elsewhere in this thesis.

3.1.3 Mesh Generation and Refinement

The computational mesh was generated using a structured background grid created with `blockMesh`, followed by local refinement using `snappyHexMesh`. The refinement strategy was designed to ensure adequate resolution of the flow features governing vortex shedding and unsteady aerodynamic loading, while maintaining a manageable overall cell count.

Two main refinement regions were introduced, as illustrated in Figure 3.1. The first refinement zone is located in the immediate vicinity of the rectangular cylinder and consists of multiple refinement steps. This near-body region ensures sufficient resolution of the separated shear layers forming at the sharp leading edges, which are responsible for generating alternating vortices. Accurate resolution in this area is essential for predicting both the amplitude of lift fluctuations and the correct vortex shedding frequency.

A second refinement region extends downstream of the cylinder into the wake. This wake refinement zone was introduced to capture the development, convection, and interaction of vortical structures over several characteristic lengths downstream of the body. The extent of the refined wake region was chosen to cover the area where coherent vortex shedding persists. It ensures reliable extraction of spectral quantities such as the Strouhal number and prevents excessive numerical dissipation of unsteady structures.

Outside these refinement zones, the mesh stays coarse toward the far-field boundaries. This reduces computational cost while preserving accuracy in the regions most relevant to vortex-induced vibration analysis. The refinement strategy remains identical across all mesh resolutions considered in the grid independence study, allowing the effects of mesh density to be assessed consistently.

3.2 Grid Independence and Mesh Validation

The grid-independence study was performed on the baseline configuration (rigid cylinder without façade) at the reference inflow conditions used throughout this thesis.

Numerical simulations of bluff-body aerodynamics are inherently dependent on the spatial discretisation of the computational domain. In our case, this dependency is particularly critical, as the correct prediction of vortex shedding and unsteady aerodynamic loads requires adequate resolution of the separated shear layers and near-wake region. A grid independence study was therefore carried out to ensure that the numerical results presented in this thesis are not affected by mesh-related numerical artefacts.

The validation focuses on three non-dimensional parameters that are directly relevant for vortex-induced vibration analysis:

- the mean drag coefficient $\overline{C_D}$,
- the standard deviation of the lift coefficient σ_{C_L} ,
- the Strouhal number St , derived from the dominant vortex shedding frequency.

These parameters were selected because they jointly describe the mean loading level, the intensity of unsteady cross-wind forcing, and the characteristic time scale of the wake through vortex shedding. They are therefore suitable indicators of whether the mesh resolves both mean and coherent unsteady structures relevant to VIV.

They are also commonly adopted in the literature as indicators of grid convergence for rectangular cylinders and building-like sections, as they jointly describe the mean loading, the intensity of unsteady transverse forces, and the characteristic wake dynamics [19].

3.2.1 Mesh resolution

Six different two-dimensional meshes were generated, all sharing the same computational domain, boundary conditions, and refinement strategy. The meshes differ only in spatial resolution, which was increased uniformly starting from the base *blockMesh* configuration. The total number of cells ranges from approximately 2.0×10^4 for the coarsest mesh to 2.5×10^5 for the finest mesh.

All meshes are one cell thick in the vertical direction, corresponding to a two-dimensional approximation of the flow. The relative distribution of cells between the near-body region, the separated shear layers, and the wake was preserved across all cases. This ensures that the observed variations in the monitored parameters can be attributed solely to grid resolution effects.

3.2.2 Monitored non-dimensional parameters

3.2.2.1 Mean drag coefficient

In the following, the characteristic length is taken as the cross-wind depth D of the section. Positive drag acts in the stream-wise direction and positive lift in the cross-wind direction.

The mean drag coefficient is defined as

$$\overline{C_D} = \frac{\overline{F_D}}{\frac{1}{2}\rho U^2 D}, \quad (3.2.1)$$

where $\overline{F_D}$ is the time-averaged drag force, ρ is the fluid density, U is the free-stream velocity, and D is the characteristic depth of the section.

The mean drag coefficient primarily depends on the time-averaged pressure distribution around the body and is therefore expected to converge more rapidly than unsteady quantities. Nevertheless, insufficient wake resolution may still lead to an underestimation of base pressure recovery and consequently affect $\overline{C_D}$.

3.2.2.2 Standard deviation of lift coefficient

The instantaneous lift coefficient is defined as

$$C_L(t) = \frac{F_L(t)}{\frac{1}{2}\rho U^2 D}, \quad (3.2.2)$$

where $F_L(t)$ is the instantaneous lift force acting on the body in the direction transverse to the incoming flow, ρ is the fluid density, U is the free-stream velocity, and D is the characteristic depth of the section.

The time-averaged lift coefficient is given by

$$\overline{C_L} = \frac{1}{T} \int_{t_0}^{t_0+T} C_L(t) dt, \quad (3.2.3)$$

where T denotes a sufficiently long time interval over which statistically stationary flow conditions are observed.

The standard deviation of the lift coefficient is defined as

$$\sigma_{C_L} = \sqrt{(C_L - \overline{C_L})^2}. \quad (3.2.4)$$

This parameter quantifies the intensity of unsteady transverse loading and is particularly sensitive to mesh resolution. Accurate prediction of σ_{C_L} requires sufficient resolution of the separated shear layers and vortex roll-up process. Coarse meshes tend to introduce excessive numerical dissipation, leading to a significant underprediction of lift fluctuations, as reported in previous studies of rectangular cylinders [19].

3.2.2.3 Strouhal number

The shedding frequency is extracted from the spectral analysis of the lift coefficient time history. For the coarsest meshes, a stable and periodic vortex shedding regime did not develop, preventing a reliable identification of the dominant frequency. Only meshes for which a clear spectral peak was observed were considered valid for the evaluation of the Strouhal number.

3.2.3 Grid convergence results

Figure 3.2 shows the effect of mesh resolution on the three monitored non-dimensional parameters.

For the coarsest two meshes, significant discrepancies are observed for all quantities. In particular, the vortex shedding process is either weak or irregular, resulting in unreliable estimates of both σ_{C_L} and St . As the mesh resolution increases, the mean drag coefficient rises and approaches an asymptotic value.

Beyond approximately 1.0×10^5 cells, variations in $\overline{C_D}$ become small, indicating that the mean flow field is sufficiently resolved. The convergence of the standard deviation of the lift coefficient is slower, reflecting its stronger dependence on accurately resolving unsteady wake structures. For meshes finer than approximately 1.5×10^5 cells, changes in σ_{C_L} become negligible.

A similar trend is observed for the Strouhal number. While coarse meshes underestimate the shedding frequency, the value of St stabilises as the grid is refined. The difference between the two finest meshes is below 1%, which is within the uncertainty typically reported for studies of bluff-body flows [19].

3.2.4 Selected mesh

Based on the combined convergence of the mean drag coefficient, the standard deviation of the lift coefficient, and the Strouhal number, the mesh with 1.25×10^5 cells was selected for all subsequent simulations.

This resolution ensures grid-independent predictions of both mean and unsteady aerodynamic quantities while maintaining a reasonable computational cost. The selected mesh is therefore

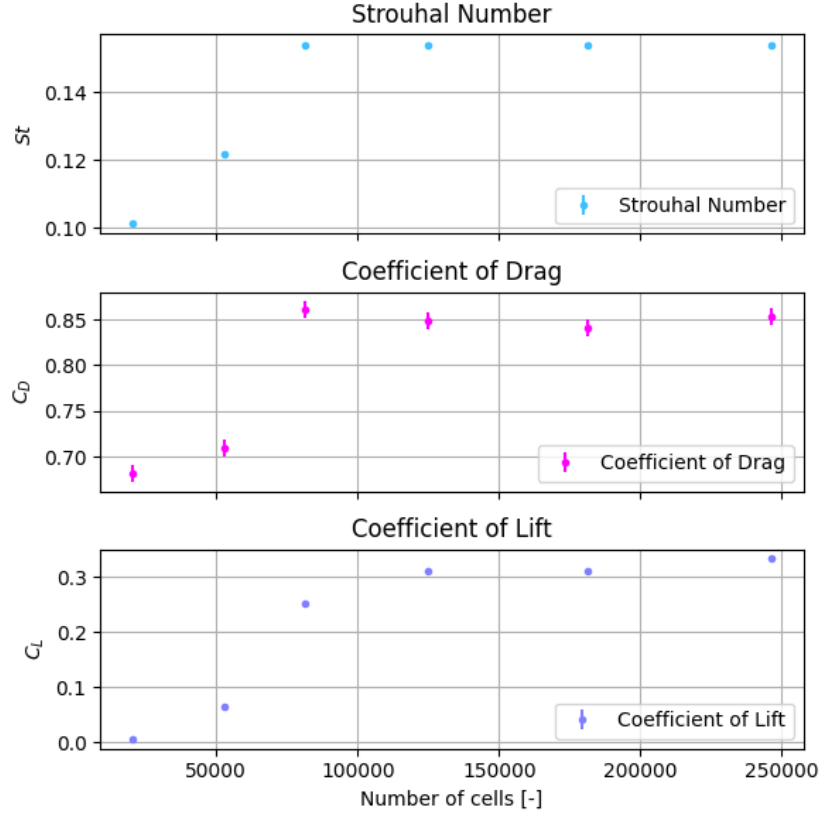


Figure 3.2: The effect of mesh coarseness on non-dimensional parameters.

considered suitable for the investigation of vortex-induced vibrations and for the analysis of façade effects presented in the following chapters.

With the discretisation of the bare-prism configuration now established, the methodology must be extended to account for the porous external layer that constitutes the second half of the thesis subject. The next section introduces the reduced-order model used to represent the porous façade within the same numerical framework.

3.3 Modelling the Permeable Double-Skin Façade

The numerical framework defined in the previous sections describes a single solid bluff body. The second half of the thesis subject, however, is the porous external layer that surrounds the inner prism in the permeable double-skin façade (PDSF) configuration. The present section introduces the reduced-order model used to represent this porous layer within the same URANS framework, so that the naked and porous configurations can be analysed and compared with the same numerical setup, the same mesh strategy, and the same post-processing tools.

3.3.1 Reduced-Order Approach

In a typical PDSF, the outer skin consists of perforated metal sheets whose pore size is of the order of a few millimetres, while the building cross-section is of the order of several metres. This four- to five-orders-of-magnitude separation between pore scale and global flow scale makes

a fully resolved geometric representation prohibitively expensive: a mesh capable of resolving every pore on a building-scale URANS simulation would require many orders of magnitude more cells than the present setup uses for the bluff-body wake alone.

For this reason, Pomaranzi et al. [20] proposed a reduced-order model (ROM) based on porous-media theory, in which the perforated sheet is replaced by a homogenised volumetric layer that reproduces the integrated aerodynamic resistance of the screen without resolving its detailed geometry. The approach has been validated against wind-tunnel measurements for the ENI head office in Milan and used in subsequent investigations of permeable double-skin façades [20, 2, 21]. It is adopted here without modification.

The porous façade is represented as a volumetric “porous slab” embedded in the computational domain, as illustrated in Figure 3.3. Within this slab, an additional momentum sink is introduced into the Navier–Stokes equations to reproduce the pressure drop that the perforated sheet would otherwise impose on the flow. The slab has a finite thickness matching the experimental setup and is positioned at a constant offset from the inner façade, reproducing the cavity geometry of the physical PDSF.

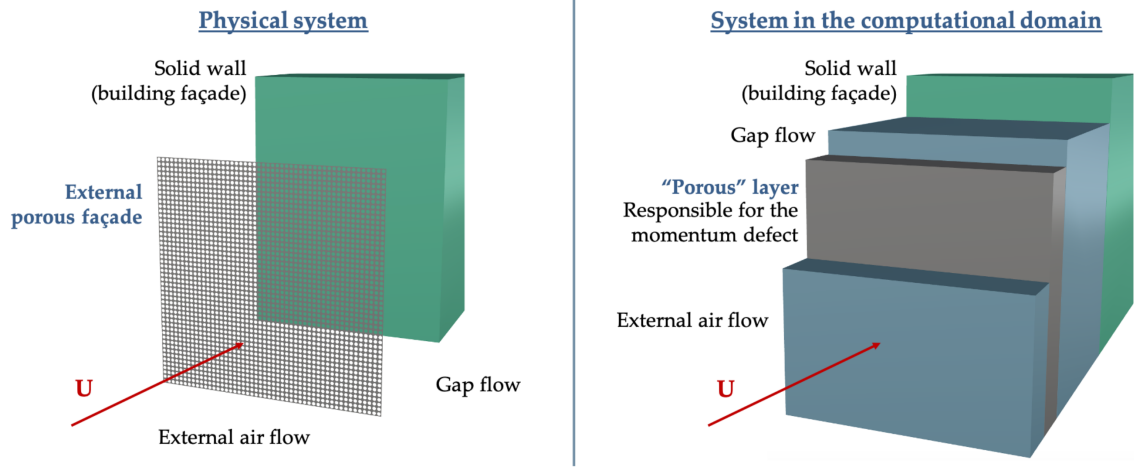


Figure 3.3: Schematic view of the reduced order modelling of the porous layer: comparison between the physical system (left) and the PDSF system in the computational domain (right). Reproduced from [20].

3.3.2 Darcy–Forchheimer Formulation

Under a steady-state assumption, the incompressible Navier–Stokes equations are modified by an additional volumetric source term inside the porous region [20]:

$$\rho(\mathbf{U} \cdot \nabla)\mathbf{U} - \mu\Delta\mathbf{U} + \nabla p = \mathbf{S}_m, \quad \nabla \cdot \mathbf{U} = 0, \quad (3.3.1)$$

where $\mathbf{S}_m$ is the additional momentum source term that accounts for the porous resistance. Outside the porous region $\mathbf{S}_m = \mathbf{0}$ and the equations reduce to the standard incompressible Navier–Stokes formulation used in the naked simulations.

The porous contribution is modelled using a Darcy–Forchheimer formulation,

$$\mathbf{S}_m = - \left(\mu\mathbf{D} + \frac{1}{2}\rho|\mathbf{U}|\mathbf{F} \right) \mathbf{U}, \quad (3.3.2)$$

where $\mathbf{D}$ is the viscous resistance tensor and $\mathbf{F}$ is the inertial resistance tensor. Physically, the first term describes a momentum sink that scales linearly with the local velocity (the Darcy contribution, dominant at low pore Reynolds numbers), while the second term scales with the square of the local velocity (the Forchheimer contribution, dominant at high pore Reynolds numbers). This decomposition follows the standard porous-media theory of Whitaker [22] and Nield and Bejan [23].

For the perforated metal sheets considered in the present configuration, the pore Reynolds number is sufficiently high that the inertial contribution dominates. Following Pomaranzi et al. [20], the Darcy term is therefore neglected and only the inertial component is retained.

Furthermore, since the perforated sheets primarily resist flow normal to their surface, the resistance tensor is reduced to a diagonal form with a single non-zero component aligned with the direction orthogonal to the façade:

$$\begin{bmatrix} S_{m,x} \\ S_{m,y} \\ S_{m,z} \end{bmatrix} = -\frac{1}{2}\rho|\mathbf{U}|k \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} U_x \\ U_y \\ U_z \end{bmatrix}, \quad (3.3.3)$$

where the scalar coefficient k is the inertial loss coefficient of the screen and quantifies the pressure drop across the façade for a given through-flow velocity. The orientation of the non-zero component is set per face so that the resistance always acts along the local normal to each side of the porous envelope.

This formulation assumes that tangential velocity components do not contribute significantly to the pressure loss and that flow deflection induced by the porous layer is negligible. Such an assumption is appropriate for thin perforated metal sheets with predominantly normal resistance [20].

3.3.3 Calibration and Validation of the Porous Model

The single parameter that fully characterises the porous layer in this formulation is the inertial loss coefficient k . In the experimental campaign of Catania et al. [2], k was measured directly in a separate wind-tunnel test, yielding $k = 1.8$ for the perforated metal sheet used in the rigid and aeroelastic PDSF model. This value is adopted as the reference porosity for the comparison with experimental data in Section 5.3.

The ability of the Darcy–Forchheimer ROM to reproduce the integrated aerodynamic behaviour of perforated screens, including the through-flow velocity across the slab and the cavity pressure distribution, has been validated in [20] against detailed wind-tunnel measurements on the ENI head office building. The same model has been used in subsequent studies of permeable double-skin façades at the same aspect ratio considered here, with good agreement against experimental Strouhal numbers and pressure fluctuations [2, 21]. The model is therefore considered an established representation of the porous layer for building-scale aerodynamic studies, and is used here as a fixed component of the methodology rather than as an object of further validation.

In the analyses of Section 5.3, the coefficient k is treated as a control parameter and varied systematically over more than two orders of magnitude. This sweep is not a parametric validation of the porous model itself, but rather a physical exploration of how varying degrees of porosity modify the intrinsic wake of the $B/D = 3.33$ prism, with $k = 1.8$ retained as the reference value matching the experimental configuration.

3.3.4 Implementation in the Computational Domain

Within the present URANS framework, the porous slab is implemented as a cell zone superimposed on the same base mesh used for the naked-prism simulations. The slab thickness, position, and standoff distance from the inner façade reproduce the geometric configuration of the experimental model [2]. Inside the cell zone, the momentum source term defined by Equations (3.3.1)–(3.3.3) is added to the momentum equation; elsewhere, the equations reduce to the standard formulation.

This implementation has three practical consequences that should be made explicit. First, the porous model adds no new mesh-resolution requirements beyond those of the naked simulations: the grid-independence study of Section 3.2 is therefore directly applicable. Second, the model does not introduce a sharp interface between the porous slab and the surrounding flow; pressure and velocity remain continuous across the boundary of the cell zone, with discontinuities only in their gradients due to the source term. Third, the formulation is local: the momentum sink depends only on the velocity at the cell where it is evaluated, so the slab automatically adapts to the instantaneous flow field, including unsteady and reversed flow conditions.

The reduced-order approach reproduces the global pressure drop and the resulting through-flow across the façade without resolving the pore-scale flow structures. This is sufficient for the building-scale analyses pursued in this thesis, where the quantities of interest — vortex shedding frequencies, integrated force coefficients, modal energy distributions — depend on the integrated aerodynamic effect of the screen rather than on the detailed jet structure emerging from individual perforations. The limitations of this approach, in particular the inability to capture pore-scale jets and the assumption of normal-only resistance, are revisited in Chapter 6.

3.4 Post-Processing and Flow Analysis Tools

With both the bluff-body discretisation and the porous-layer representation defined, a consistent post-processing framework is now introduced to analyse the resulting flow fields. The same tools are applied to every configuration considered in this thesis, so that the naked and porous cases, and the still and forced-oscillation cases, can be compared on the same footing.

In addition to the integrated force coefficients and spectral diagnostics already introduced in Section 3.2, the analysis relies on Proper Orthogonal Decomposition to identify the dominant coherent structures of the wake. The method is introduced below.

3.4.1 Proper Orthogonal Decomposition

Proper Orthogonal Decomposition (POD) is a widely used technique for extracting dominant coherent structures from high-dimensional fluid mechanics datasets. In the context of a rectangular-cylinder wake, POD enables the decomposition of unsteady flow fields—such as velocity, pressure, or vorticity—into a set of orthogonal spatial modes ranked by their energy content. This allows the identification of vortex-shedding structures and other large-scale features while filtering out noise and higher-frequency fluctuations.

The method originated in turbulence research through the work of Lumley and others, and was made computationally feasible for large-scale datasets by Sirovich’s *method of snapshots* [24]. A comprehensive theoretical foundation is provided in the review by Berkooz, Holmes, and Lumley

[25]. POD is now a standard tool in both experimental and computational fluid dynamics for flow analysis, reduced-order modelling, and control.

3.4.1.1 Mathematical Formulation

Snapshot Matrix and Mean Subtraction: Let's consider a set of N flow snapshots, each representing the flow field at time t_i . Each snapshot is discretised into a vector

$$\mathbf{q}_i \in \mathbb{R}^M, \quad (3.4.1)$$

where M is the total number of spatial degrees of freedom. These snapshots are assembled into the snapshot matrix

$$X = [\mathbf{q}_1 \ \mathbf{q}_2 \ \cdots \ \mathbf{q}_N] \in \mathbb{R}^{M \times N}. \quad (3.4.2)$$

To focus on the fluctuating part of the flow, we subtract the temporal mean,

$$\bar{\mathbf{q}} = \frac{1}{N} \sum_{i=1}^N \mathbf{q}_i. \quad (3.4.3)$$

yielding the mean-subtracted snapshot matrix

$$X' = X - \bar{\mathbf{q}} \mathbf{1}_N^T, \quad (3.4.4)$$

where $\mathbf{1}_N$ is a length- N vector of ones.

SVD and the Method of Snapshots: POD seeks orthonormal spatial modes $\phi_i(x)$ that optimally represent the fluctuation field in an energy sense. This corresponds to solving an eigenvalue problem for the spatial correlation operator, which is typically very large. Instead, Sirovich's method of snapshots reduces the computational cost by exploiting the fact that $N \ll M$ in most CFD applications.

We compute the singular value decomposition (SVD) of the centred snapshot matrix:

$$X' = U \Sigma V^T, \quad (3.4.5)$$

where

- $U \in \mathbb{R}^{M \times r}$ contains the spatial POD modes,
- $\Sigma = \text{diag}(\sigma_1, \sigma_2, \dots, \sigma_r)$ contains the singular values,
- $V \in \mathbb{R}^{N \times r}$ contains the temporal structures,
- $r = \text{rank}(X') \leq \min(M, N)$.

Modal Energy, Orthogonality, and Reconstruction: The singular values quantify the energy captured by each mode. The energy fraction associated with mode i is

$$E_i = \frac{\sigma_i^2}{\sum_{j=1}^r \sigma_j^2}, \quad (3.4.6)$$

with $\sum_i E_i = 1$.

The POD modes are orthonormal with respect to the discrete inner product defined over the computational domain,

$$\langle \phi_i, \phi_j \rangle = \sum_{k=1}^M \phi_i^{(k)} \phi_j^{(k)} w_k = \delta_{ij}, \quad (3.4.7)$$

where M is the number of spatial degrees of freedom, $\phi_i^{(k)}$ denotes the value of mode i at the k -th mesh cell, w_k is the corresponding cell volume, and δ_{ij} is the Kronecker delta function.

The fluctuation field can be reconstructed as

$$\mathbf{q}'(x, t) = \sum_{i=1}^r a_i(t) \phi_i(x), \quad (3.4.8)$$

where the temporal coefficients are given by

$$a_i(t_n) = \sigma_i V_{n,i}. \quad (3.4.9)$$

Truncating the expansion to the first R modes yields the best rank- R approximation of the data [25]. For a rectangular-cylinder wake, the first two modes typically capture the dominant coherent structures, which, in this case, are periodic vortex shedding.

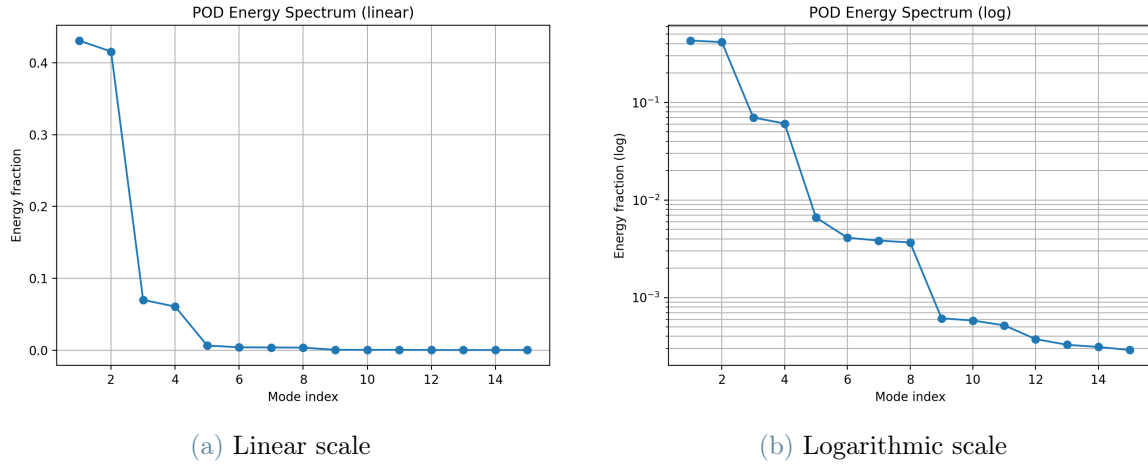


Figure 3.4: POD energy spectrum showing the energy fraction associated with each decomposed mode. The spectrum is reported on both linear and logarithmic scales to highlight the dominance of the leading modes and the rapid decay of energy in higher-order modes.

The distribution of modal energy was analysed to determine the number of POD modes required to represent the dominant wake dynamics. Figure 3.4 shows the energy fraction associated with each mode on both linear and logarithmic scales. The spectrum highlights the strong dominance of the leading modes: the first four modes capture the vast majority, about 98%, of the total fluctuating energy, while the remaining modes contribute only marginally. This indicates that higher-order modes are associated with weak, small-scale fluctuations.

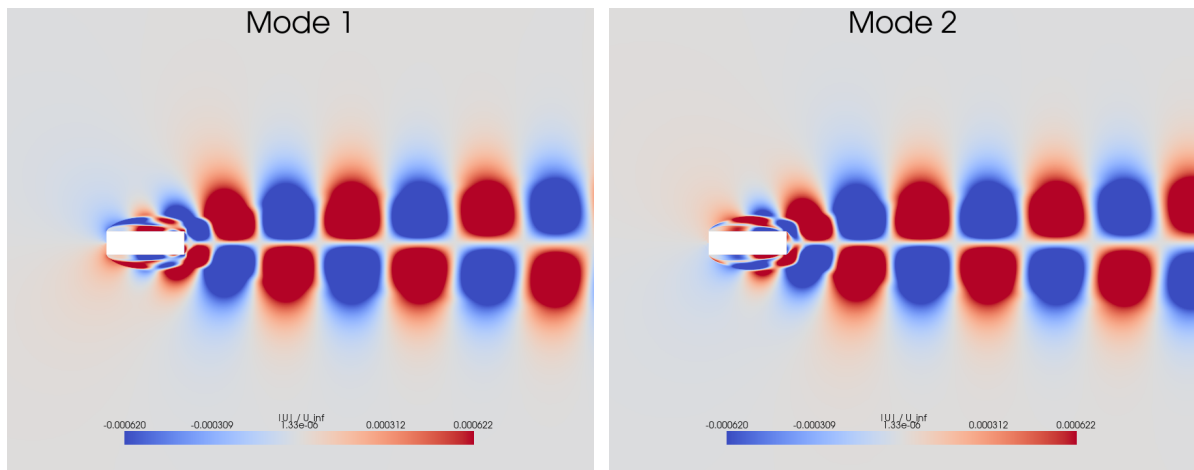
Based on this clear energetic separation, the focus of the subsequent analysis is on the first four POD modes, which are sufficient to capture the essential coherent dynamics of the rectangular-cylinder wake.

Rectangular-Cylinder Wake Flows: The leading modes often correspond to antisymmetric shedding structures, while subsequent modes may capture harmonic content, secondary instabilities, or shear-layer motions. This modal hierarchy provides a compact representation of the wake dynamics, forming a basis for low-dimensional modelling or flow control applications.

Throughout this thesis, the POD is computed on the fluctuating velocity field, and the mode shapes are visualised in terms of velocity magnitude. The contours shown, therefore, represent the spatial distribution of the velocity fluctuations carried by each mode; they are not vorticity fields, which would require the curl of the velocity vector. The compact, alternating high-magnitude regions can nonetheless be associated with the footprints of the shed vortices, and it is in this sense that the mode shapes relate to the vortical organisation of the wake.

Figure 3.5 illustrates the spatial structure of the first two POD modes. The two modes form a conjugate pair characterised by similar spatial distributions and a phase shift of approximately $\pi/2$, similar to sine and cosine components of a periodic signal. This pairing reflects the alternating nature of vortex shedding. Together, these modes represent the dominant antisymmetric shedding structure, with the temporal coefficients oscillating at the fundamental shedding frequency.

Numerous studies have applied POD to wake flows and similar unsteady configurations [26, 27, 28]. The decomposition clarifies the spatial organisation of vortices and the temporal characteristics of their oscillations.



(a) First POD mode, representing one phase of the antisymmetric vortex-shedding pattern. (b) Second POD mode, showing the same shedding structure with a phase shift of approximately $\pi/2$.

Figure 3.5: The first two POD modes for the rectangular-cylinder wake, highlighting the anti-symmetric vortex-shedding structure and phase-shifted modal pairing.

POD provides an optimal and physically interpretable decomposition of unsteady flow fields into orthogonal spatial modes and their associated temporal dynamics. For the rectangular-cylinder wake, POD isolates the dominant shedding structures and organises the flow dynamics into a hierarchy of energetic contributions. This enables both qualitative insights into wake physics and quantitative opportunities for reduced-order modelling and flow control.

The decomposition framework is applied to all simulation data presented in the following chapters. Before that, the complete numerical setup — mesh, porous model, and post-processing tools — is validated against canonical bluff-body cases.

3.5 Model Verification

The numerical framework defined in the previous sections is now validated against published data for two canonical bluff-body configurations: a square cylinder ($B/D = 1$) and an elongated rectangular cylinder ($B/D = 5$). These two cases are not chosen at random. They bracket the transitional aspect ratio $B/D = 3.33$ that is the subject of this thesis: the square cylinder corresponds to the fully separated, leading-edge-dominated regime, while the $B/D = 5$ case corresponds to the trailing-edge-dominated regime with stable shear-layer reattachment. Reproducing both endpoints with the same mesh and numerical setup demonstrates that the framework captures the two distinct flow physics that coexist intermittently in the configuration of interest.

The validation focuses on the same three diagnostics adopted throughout: the mean drag coefficient, the standard deviation of the lift coefficient, and the Strouhal number, complemented by the dominant POD modes. The validation of the porous model itself is discussed within Section 3.3.

3.5.1 Square Cylinder

The CFD simulation for a square cylinder ($B/D = 1$) at $Re = 73,659$ (air, URANS) produces the following aerodynamic parameters: a mean drag coefficient $C_D = 1.859$, a root-mean-square fluctuating lift coefficient $C'_L = 0.805$, and a non-dimensional vortex shedding frequency (Strouhal number) $St = 0.1176$. These values are obtained from the time-history of force coefficients and their frequency spectrum. The simulation was run for sufficient flow time to ensure well-converged statistics for mean and RMS values. Table 3.1 summarises the results alongside representative literature values for a square cylinder in a similar Reynolds number regime (10^4 – 10^5).

Quantity	Calculated	Literature Range	Sources
Mean drag coeff. C_D	1.859	2.0–2.2	Norberg [13], Shimada [29]
RMS lift coeff. C'_L	0.805	0.6–0.9 (scatter)	Norberg [13], Shimada [29]
Strouhal number St	0.1176	0.12–0.13	Norberg [13], Okajima [3]

Table 3.1: Comparison of present simulation results ($Re = 7.36 \times 10^4$, URANS, $B/D = 1$) with published data for square cylinders at $Re \sim 10^4$ – 10^5 .

3.5.1.1 Mean Drag Coefficient

The computed mean drag ($C_D \approx 1.86$) is on the lower end of the range reported in experiments. Past wind-tunnel studies on sharp-cornered square cylinders at high Reynolds number (fully turbulent regime) typically find C_D in the range of about 2.0–2.2 [13, 29]. For instance, Norberg’s measurements for a stationary square cylinder indicate a mean drag coefficient around 2.1 at $Re \sim 3 \times 10^4$ [13]. Similarly, CFD predictions validated by experiments (e.g., Shimada and Ishihara’s Reynolds-stress model results) show C_D values near 2.0 for $B/D = 1$ [29]. The URANS result (1.859) is therefore lower by roughly 10–15%. This under-prediction could stem from the turbulence modelling and two-dimensional assumption in URANS, which can somewhat attenuate pressure drag, or from moderate Reynolds number effects. Nonetheless, the result is of the correct order and reflects a fully separated flow, as expected for a bluff square prism. The agreement in C_D is acceptable for engineering purposes, given the known variability across different studies [4].

3.5.1.2 Fluctuating Lift (Root-Mean-Square)

The simulation predicts a relatively large fluctuating lift coefficient, $C'_L = 0.805$, indicating strong vortex shedding forces. Available experimental data for the rms lift on a stationary square cylinder are limited, but generally C'_L is on the order of 0.6–0.8 in the subcritical Reynolds number regime [13]. Norberg’s pressure measurements, for example, imply significant fluctuating side forces consistent with $C'_L \sim 0.7$ –0.8 [13]. The simulation result falls in this range, leaning toward the higher end. This level of lift fluctuation is reasonable: sharp-edged bodies produce vigorous vortex shedding, and measured lift spectra show a pronounced peak for square cylinders [3]. Some two-dimensional RANS/URANS studies tend to undervalue C'_L due to excessive artificial damping of unsteadiness [29]. The good agreement in C'_L lends confidence that the dominant unsteady wake mode (alternate vortex shedding) is well-resolved. Small discrepancies in the exact value can be attributed to experimental uncertainty and the sensitivity of C'_L to turbulence and span-wise effects (which a 2D simulation cannot replicate).

3.5.1.3 Vortex Shedding Frequency

The non-dimensional shedding frequency (Strouhal number) obtained from the simulation is $St = 0.1176$. This is in close agreement with classic experimental data: Okajima [3] reported $St \approx 0.13$ for a square cylinder in the Reynolds number range 10^4 – 2×10^4 . Numerous studies have found Strouhal numbers around 0.12–0.14 for Re up to 10^5 [3, 13]. This simulation’s value of 0.1176 is about 10% lower, but still within the expected range for a sharp-edged square prism. Such a discrepancy can arise from the two-dimensionality of the simulation and the turbulence model’s influence on the shear layer development. Importantly, the simulation exhibits stable single-frequency shedding, a characteristic of the subcritical regime. No spurious frequencies or mode-locking were observed. This similarity to the expected Strouhal number is a key validation point, as St is a sensitive indicator of the wake dynamics. The result confirms that the URANS approach captures the timing of vortex shedding with reasonable accuracy. In summary, the predicted $St \approx 0.118$ agrees well with established data (within experimental scatter).

3.5.1.4 Flow decomposition

The flow decomposition shows that the unsteady wake of the square cylinder is dominated by a single coherent shedding mechanism. The first two modes form a conjugate pair with nearly equal energy and antisymmetric spatial structure, characteristic of alternate vortex shedding. Mode 1, shown in Figure 3.6, clearly captures the large-scale organisation of the wake and represents one phase of the fundamental shedding cycle, while the second mode corresponds to the phase-shifted counterpart.

The temporal coefficients of the leading mode pair exhibit a well-defined single-frequency oscillation, yielding a Strouhal number consistent with that obtained from the force spectra. Higher-order modes contain substantially less energy and primarily describe secondary features and small-scale fluctuations.

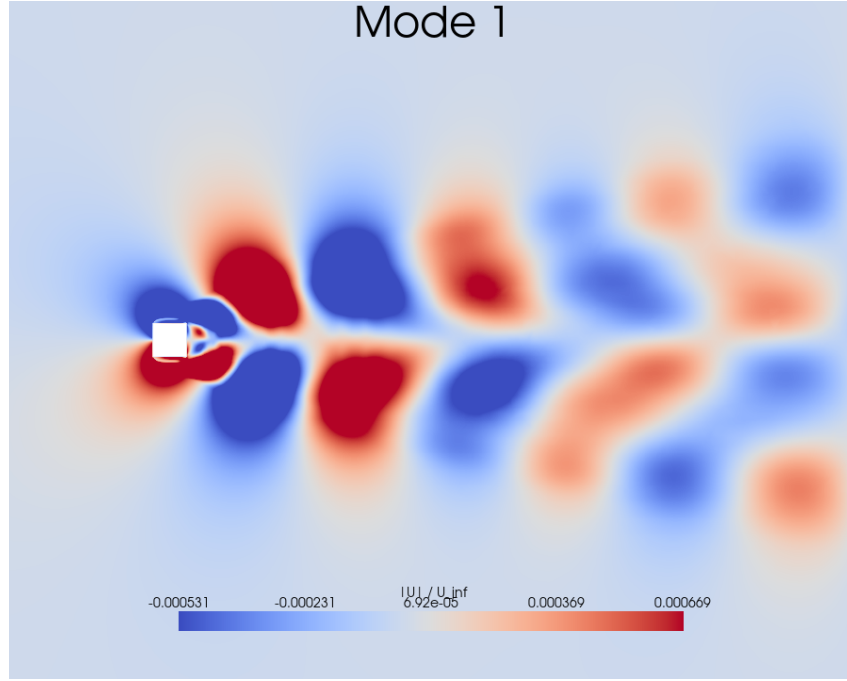


Figure 3.6: Mode one of the decomposed flow for the square cylinder at $Re = 7.36 \times 10^4$. With this method $St = 0.119$ for the first two modes.

3.5.1.5 Outcome

Overall, the results for the square cylinder compare favourably with literature values. The mean drag is slightly underestimated, but it follows the known trend. The fluctuating lift is of the correct magnitude, and the shedding frequency is very close to empirical benchmarks. The deviations can be explained by the modelling limitations of the two-dimensional URANS framework, consistent with similar trends reported in the literature [4]. Key aerodynamic coefficients (drag, lift fluctuations, shedding frequency) are within the range of well-established values [3, 13]. The model is therefore considered reliable for the fully separated, leading-edge-dominated regime that the square-cylinder case represents.

3.5.2 Rectangular Cylinder ($B/D = 5$)

The CFD simulation for a fixed rectangular cylinder with aspect ratio $B/D = 5$ at $Re = 7.4 \times 10^4$ (air, URANS) yields the following aerodynamic parameters: a mean drag coefficient $C_D = 0.65$, a standard deviation of the lift coefficient $C'_L = 0.23$, and a Strouhal number $St = 0.118$. These quantities are extracted from statistically converged force coefficient time histories and their frequency spectra, using the same post-processing methodology adopted for the square cylinder case.

Table 3.2 summarises the present results alongside representative literature values for elongated rectangular cylinders at comparable Reynolds numbers.

Quantity	Calculated	Literature Range	Sources
Mean drag coeff. C_D	0.65	0.6–0.9	Bruno [4], Shimada [29]
RMS lift coeff. C'_L	0.23	0.2–0.4	Bruno [4], Mannini [30]
Strouhal number St	0.118	0.11–0.13	Okajima [3], Bruno [4]

Table 3.2: Comparison of present simulation results ($Re = 7.4 \times 10^4$, URANS, $B/D = 5$) with published data for rectangular cylinders at $Re \sim 10^4$ – 10^5 .

3.5.2.1 Mean Drag Coefficient

The computed mean drag coefficient for the 5:1 rectangular cylinder is $C_D = 0.65$. Experimental and numerical studies on elongated rectangular cylinders report a relatively wide range of drag coefficients, typically between 0.6 and 0.9, depending on inflow conditions, turbulence level, and spanwise coherence [4].

The present value lies close to the lower bound of this range. This behaviour is consistent with previous URANS simulations, which tend to underpredict pressure drag for elongated sections due to enhanced numerical dissipation and reduced shear-layer unsteadiness. Similar trends were already observed in the square-cylinder validation and are therefore not unexpected.

3.5.2.2 Fluctuating Lift (Root-Mean-Square)

The standard deviation of the lift coefficient is $C'_L = 0.23$, indicating moderate cross-wind force fluctuations. Published data for stationary rectangular cylinders with $B/D \approx 5$ show significantly lower lift fluctuations than for square cylinders, typically in the range $C'_L \approx 0.2$ – 0.4 [4].

The reduced lift fluctuations are physically consistent with the partial reattachment of the separated shear layers along the side faces, which weakens the coherence of pressure oscillations compared to fully separated square-cylinder flow. The present result falls within the expected range.

3.5.2.3 Vortex Shedding Frequency

The dominant vortex shedding frequency extracted from the lift spectrum corresponds to a Strouhal number $St = 0.118$. Classical experimental studies and subsequent numerical investigations report Strouhal numbers in the range $St = 0.11$ – 0.13 for rectangular cylinders with $B/D = 5$ at Reynolds numbers of order 10^4 – 10^5 [3, 4].

The present value is in close agreement with these references. As for the square cylinder, the shedding process is characterised by a single dominant frequency, with no evidence of mode switching or spurious spectral content. This confirms that the URANS simulation captures the timing of the wake dynamics with satisfactory accuracy.

3.5.2.4 Flow Decomposition

Proper Orthogonal Decomposition of the near-wake velocity field shows that the unsteady flow is dominated by a single antisymmetric mode associated with alternate vortex shedding. The second POD mode, shown in Figure 3.7, exhibits a clear antisymmetric spatial structure with respect to the wake centreline and represents the primary coherent shedding mechanism.

Compared to the square cylinder, the modal energy is more strongly concentrated in the leading mode, indicating reduced complexity of the wake dynamics. Higher-order modes contain substantially less energy and correspond to secondary and small-scale fluctuations.

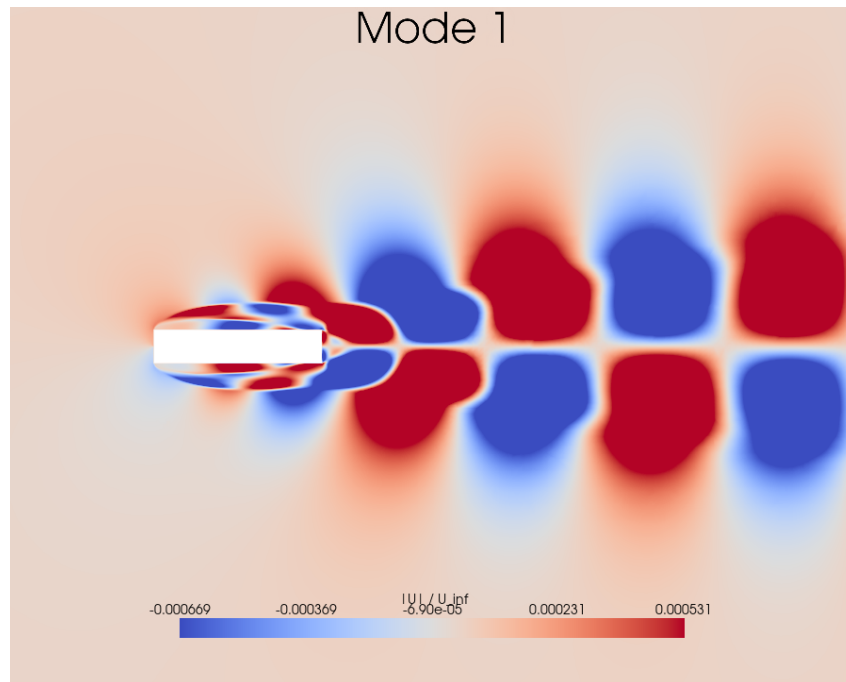


Figure 3.7: Second POD mode of the decomposed flow for the 5:1 rectangular cylinder at $Re = 7.4 \times 10^4$, showing the dominant antisymmetric vortex shedding structure.

3.5.2.5 Outcome

The numerical results obtained for the 5:1 rectangular cylinder compare favourably with published experimental and numerical data. The mean drag coefficient lies within the expected range, the fluctuating lift magnitude reflects the reduced cross-wind forcing characteristic of elongated sections, and the Strouhal number closely matches reference values.

3.5.3 Summary of Validation Results

Together, the square-cylinder and $B/D = 5$ rectangular-cylinder validations demonstrate that the numerical framework is able to reproduce both fully separated and partially reattached bluff-body flows with consistent accuracy, while sharing a single mesh strategy, turbulence model, and post-processing methodology. The validation also identifies a systematic tendency of the two-dimensional URANS framework to slightly underpredict mean drag, attributable to the absence of spanwise three-dimensional effects — a limitation that will be revisited when comparing CFD

predictions to wind-tunnel measurements in Chapter 5.

These two validation cases bracket the transitional aspect ratio $B/D = 3.33$ that is the subject of the rest of the thesis. The square-cylinder case validates the framework in the leading-edge-dominated regime, the $B/D = 5$ case validates it in the trailing-edge-dominated regime with stable reattachment, and the $B/D = 3.33$ configuration of interest is expected to exhibit intermittent reattachment between these two limits. The numerical framework is therefore considered ready for application to the configurations of interest in Chapters 4 and 5, including the porous-façade configurations introduced in Section 3.3.

4 | Experimental Data

This chapter presents the results of the wind-tunnel experiments conducted at the Politecnico di Milano wind tunnel. The experimental campaign investigates the aerodynamic and aeroelastic behaviour of a rectangular prism representative of a high-rise building, with particular focus on the effects of a permeable double-skin façade (PDSF) on vortex shedding (VS) and vortex-induced vibrations (VIV).

The results serve two purposes. They provide a physical interpretation of the flow mechanisms induced by façade porosity. And constitute the experimental reference for validation and comparison with the numerical simulations used in the thesis.

4.1 Experimental configurations and test conditions

Two façade configurations were investigated: a naked rectangular prism and the same prism equipped with a permeable double-skin façade. The reference geometry has an aspect ratio $B/D = 3.33$ and a height ratio $H/B = 2$, representative of a high-rise building cross-section.

In the porous configuration, a perforated metal shroud with a porosity of 55% was installed at a constant offset from the inner façade. The pressure loss coefficient of the porous layer was experimentally measured as $k = 1.8$, ensuring a well-defined and repeatable aerodynamic behaviour [21].

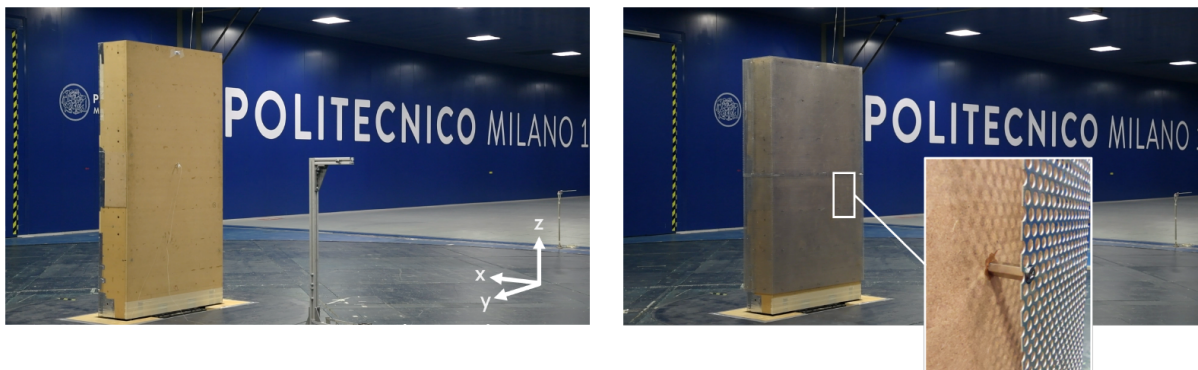


Figure 4.1: Model in the wind tunnel (naked and porous) [21].

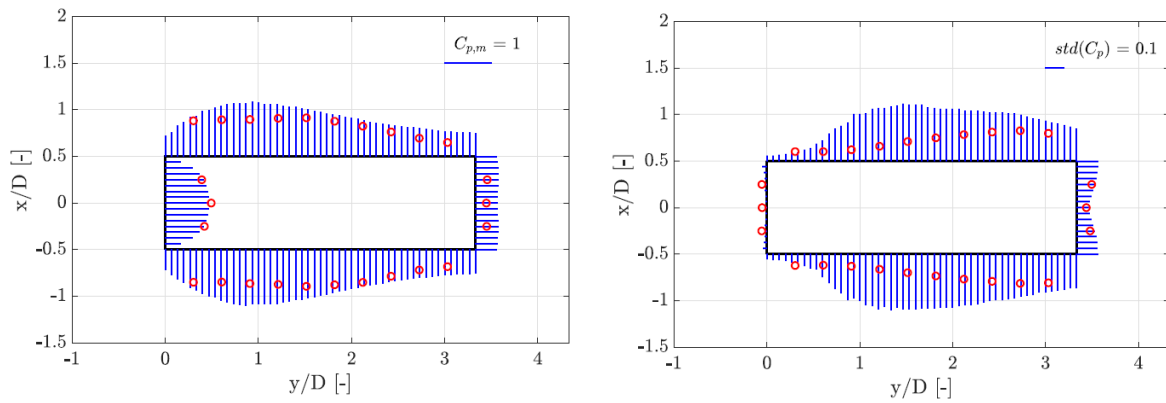
4.2 Rigid-body aerodynamic response

4.2.1 Mean and fluctuating pressure distributions

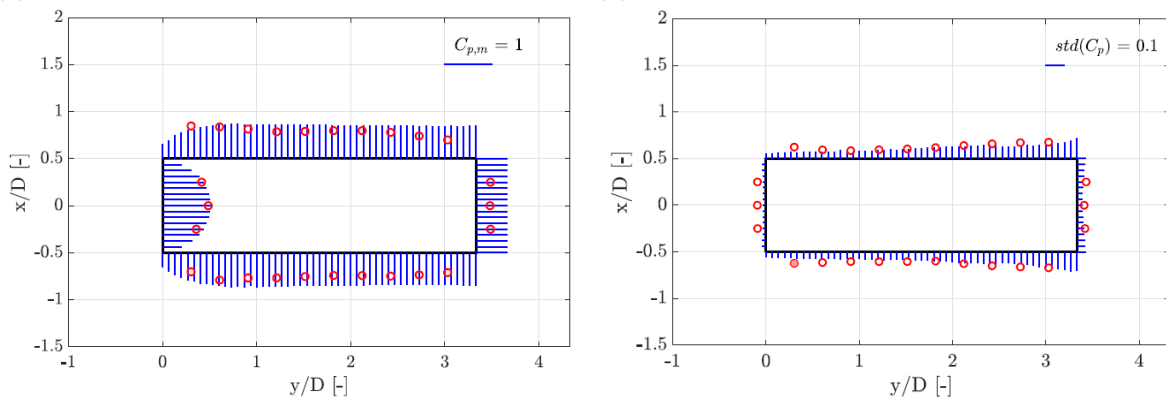
Rigid-model tests were performed to characterise the aerodynamic loading and vortex shedding behaviour in the absence of structural motion. Pressure measurements were obtained from taps distributed over eight vertical levels, allowing reconstruction of both local and global aerodynamic quantities.

For the naked configuration, the mean pressure coefficient exhibits the typical distribution associated with sharp-edged rectangular cylinders, as seen in Figure 4.2a, with strong suction on the lateral faces and a pronounced pressure deficit on the leeward side. The standard deviation of the pressure coefficient highlights intense fluctuations near the leading edges, associated with shear-layer separation (Figure 4.2b).

The introduction of the porous façade leads to a substantial modification of the pressure field. Both the mean and fluctuating pressure coefficients on the inner façade become more uniform along the height (Figure 4.2c), with a reduction of up to 40% in pressure fluctuations (Figure 4.2d). This homogenisation effect is attributed to the filtering action of the porous layer, which weakens the shear-layer roll-up and confines the flow in the cavity region [21].



(a) Naked configuration, mean pressure coefficient. (b) Naked conf., pressure coefficient, std. deviation.



(c) Porous configuration, mean pressure coefficient. (d) Porous conf., pressure coefficient std. deviation.

Figure 4.2: Floor 5, $U = 4$ m/s. Red dots: experimental results, blue bars: CFD results of their experiment. Mean and RMS pressure coefficients (naked vs porous) [21].

4.2.2 Vortex shedding frequencies and Strouhal number

The vortex shedding dynamics were analysed through spectral analysis of the cross-wind force reconstructed from pressure measurements. For the naked configuration, two dominant Strouhal number branches are observed.

A low-frequency branch at $St \approx 0.03$ is associated with fully detached shear layers, while a higher-frequency branch at $St \approx 0.14$ (Figure 4.3a) corresponds to reattached shear-layer shedding. This dual behaviour happens rectangular cylinders in the critical aspect ratio range $2.5 < B/D < 3.5$, where separated-flow and reattachment modes coexist.

In the porous configuration, the dominant shedding frequency shifts towards lower values, with a primary peak at $St \approx 0.055$ (Figure 4.3b). This shift indicates that the porous envelope introduces an additional separation point at the windward edge of the shroud, producing wider wake structures and modifying the coherence of vortex formation [21].

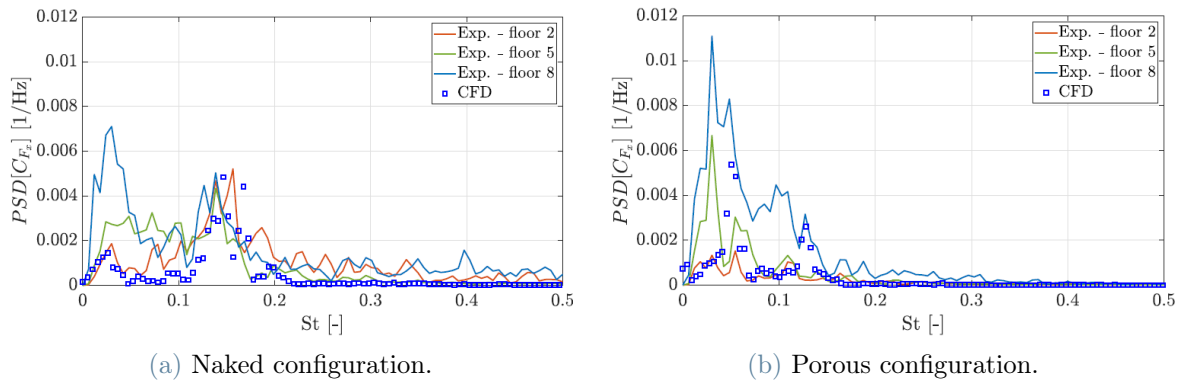


Figure 4.3: Comparison between the power spectral density of the force coefficients measured at floors 2,5,8 (coloured lines) and the one calculated from the CFD simulation (blue squares) at $U = 4$ m/s. Power spectral density of force coefficients. [21]

4.3 Aeroelastic response and VIV onset

Aeroelastic tests were conducted by mounting the model on an elastic base, allowing cross-wind oscillations. Three types of initial conditions were examined: build-up tests starting from rest, progressive-regime tests obtained by gradually increasing wind speed, and externally perturbed tests initiated by an imposed displacement.

For the naked configuration, classical VIV behaviour is observed, with a bell-shaped response of oscillation amplitude as a function of reduced velocity and clear lock-in between the vortex shedding frequency and the structural natural frequency.

In the porous configuration, the onset of VIV is strongly dependent on initial conditions. Under build-up conditions, oscillations remain suppressed, indicating that the porous façade disrupts the early force coherence required for lock-in. However, when the system is externally perturbed, force synchronisation is restored, and VIV develops with amplitudes comparable to the naked case.

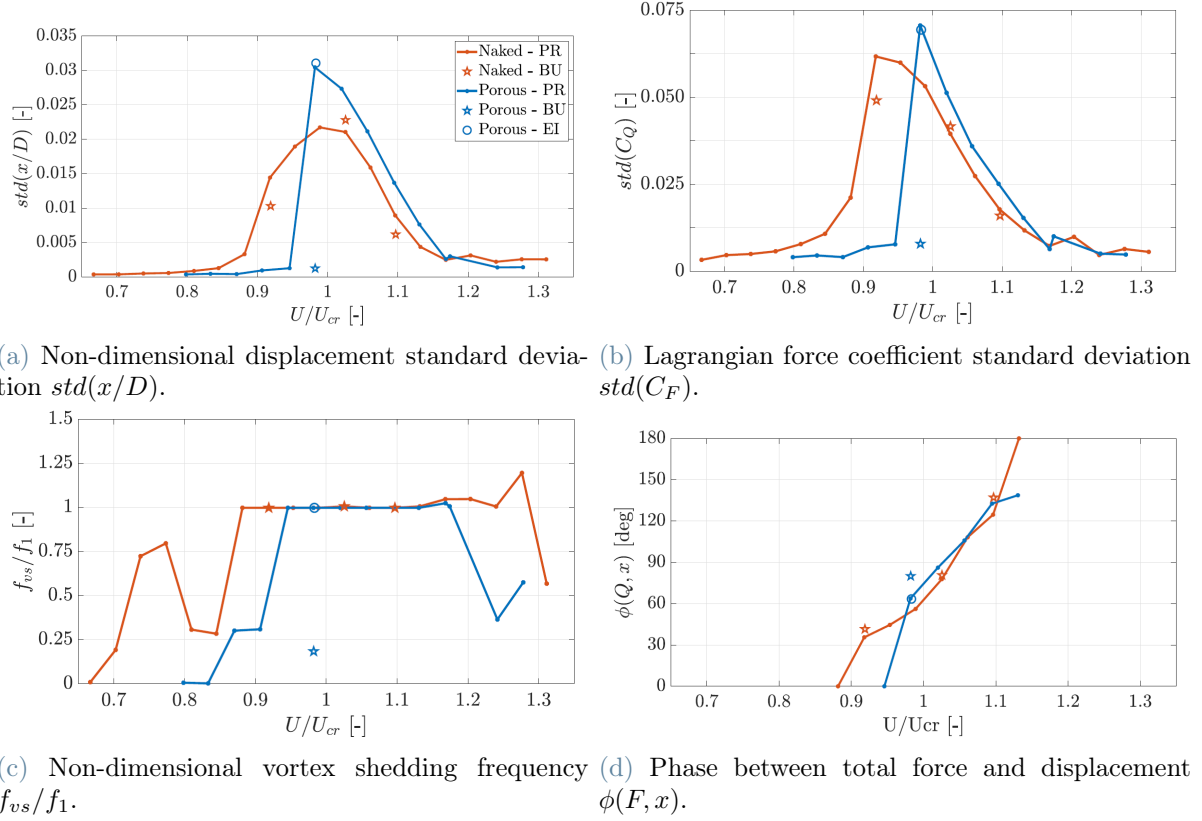


Figure 4.4: [21].

4.3.1 Spectral organisation of aerodynamic forcing

Figure 4.5 reports the power spectral density of the Lagrangian aerodynamic force evaluated at different floors during aeroelastic tests of the porous configuration. The spectra are dominated by a low-frequency component associated with the porosity-induced shedding mechanism, corresponding to the Strouhal number identified in the rigid-body tests ($St \approx 0.055$). This contribution is consistently observed along the height, indicating a coherent forcing mechanism introduced by the porous façade.

The spectral peak associated with motion-induced vortex shedding, occurring near the structural natural frequency, is weak or absent under build-up conditions. This demonstrates that, although unsteady aerodynamic forcing is present, the spanwise coherence required for lock-in is not established in the early stages of motion. Consequently, the aerodynamic forces do not provide sustained positive work to the structure, and self-excited oscillations remain suppressed [21].

4.4 Summary of experimental findings

The wind tunnel experiments show that permeable double-skin façades significantly modify the aerodynamic forcing and aeroelastic response of rectangular prisms. In rigid conditions, the porous envelope alters flow separation, reduces pressure fluctuations on the inner façade, and shifts the dominant vortex shedding towards lower Strouhal numbers.

Under aeroelastic conditions, porosity changes the spectral organisation and spatial coherence of the aerodynamic forces. A porosity-induced low-frequency component dominates the force spec-

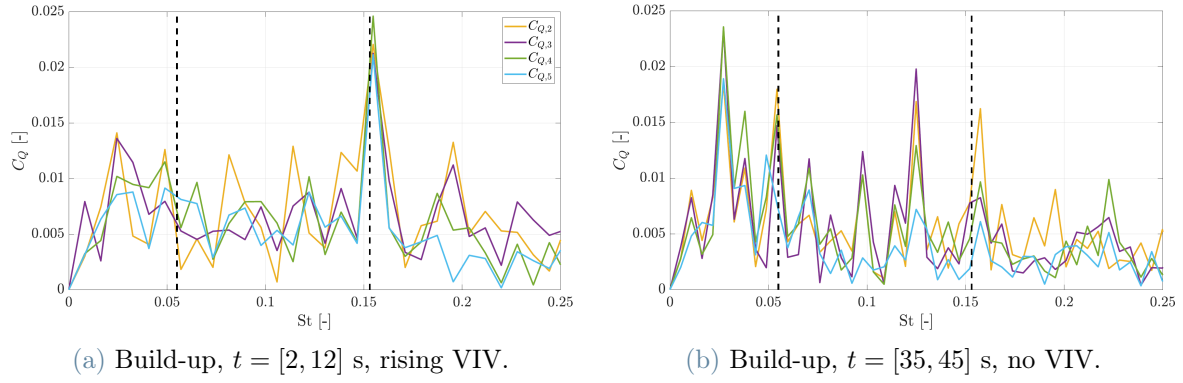


Figure 4.5: Porous configuration, $U/U_{cr} = 1.02$. Spectra of Lagrangian force components of floors 2,3,4,5. The vertical dotted black lines highlight the St number associated with porosity and motion-induced Vortex Shedding [21].

tra and remains coherent along the height, while motion-induced vortex shedding is suppressed under build-up conditions due to insufficient force synchronisation. As a result, the onset of lock-in is delayed, and self-excited oscillations are inhibited.

The experimental results provide a consistent reference for the numerical analyses presented in the following chapters, where CFD is used to reproduce the observed spectral features and to quantify the role of façade porosity in controlling vortex shedding and VIV.

Source	Configuration	B/D	$C_{D,m}$	$\text{std}(C_D)$	$\text{std}(C_L)$	St
Present study	Naked (Exp.)	3.33	1.10 ± 0.01	0.079 ± 0.049	0.25 ± 0.05	0.138 ± 0.016
Present study	Porous (Exp.)	3.33	1.12 ± 0.01	0.058 ± 0.036	0.17 ± 0.04	0.038 ± 0.020
Shimada & Ishihara (2002)	Naked (RANS)	3.5	1.23	–	≈ 0.4	0.140–0.155
Sohankar (2008)	Naked (LES)	3.5	1.20	0.02–0.10	≈ 0.5	0.150
Yu & Kareem (1998)	Naked (LES)	4.0	≈ 1.35	–	≈ 1.0	≈ 0.155
Alvarez et al. (2019)	Naked (LES)	4.0	1.03–1.14	0.04–0.10	0.31–0.90	0.131–0.142
Wang et al. (2024)	Naked (LES)	4.0	1.07	0.05	0.53	0.137

Table 4.1: Comparison between experimental aerodynamic quantities measured on a section of the rectangular cylinder and reference data from the literature. Statistics are obtained from rigid-model tests at $U = [3, 4, 5, 6, 8]$ m/s. For the experimental results, only floors 3–5 are considered [21].

5 | Results

5.1 Effect of Aspect Ratio on the Aerodynamic Response of Rectangular Prisms

The influence of the cross-sectional aspect ratio B/D on the aerodynamic response is analysed using numerical simulations for representative configurations ranging from square to elongated rectangular prisms.

Particular attention is given to the $B/D = 3.33$ case, which represents an intermediate configuration between square and elongated geometries and is therefore especially sensitive to shear-layer reattachment and wake instabilities.

This analysis provides a baseline reference for the subsequent investigation of porous configurations, allowing the effects of geometric modifications to be clearly distinguished from those induced by permeability.

5.1.1 Variation of Global Aerodynamic Coefficients with Aspect Ratio

The aerodynamic behaviour of rectangular prisms is strongly governed by the evolution of the separated shear layers as the aspect ratio increases. Depending on the elongation ratio, the wake transitions from a fully separated Kármán-vortex regime to configurations characterised by intermittent or persistent shear-layer reattachment [3, 13, 31].

Figure 5.1 compares the Strouhal numbers obtained in the present CFD simulations with the classical experimental classification proposed by Deniz and Staubli [31]. The red markers indicate the configurations investigated in the present work.

For lower aspect ratios ($B/D \lesssim 2$), the wake is dominated by leading-edge vortex shedding without flow reattachment. In this regime, the Strouhal number decreases progressively with increasing aspect ratio due to the elongation of the recirculation region behind the prism.

As the aspect ratio increases further, the separated shear layers begin to interact with the side surfaces of the prism. The present $B/D = 3.33$ configuration lies inside this transitional regime, where intermittent reattachment occurs, and both leading-edge and trailing-edge mechanisms contribute to vortex formation.

For elongated prisms ($B/D \gtrsim 5$), the flow becomes increasingly governed by impinging shear-layer dynamics and trailing-edge vortex shedding, producing a more stable wake structure and lower force fluctuations.

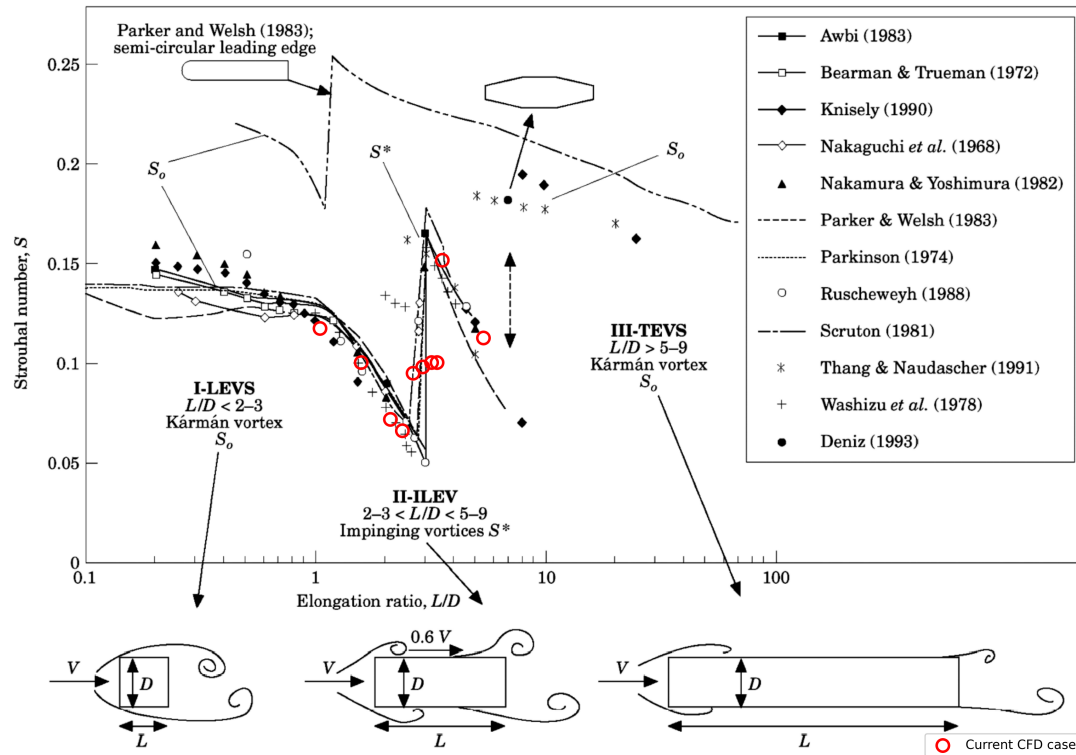


Figure 5.1: Overlay of the present CFD cases on the Strouhal-number classification for rectangular prisms adapted from Deniz and Staubli [31]. The red markers indicate the configurations investigated in the present work.

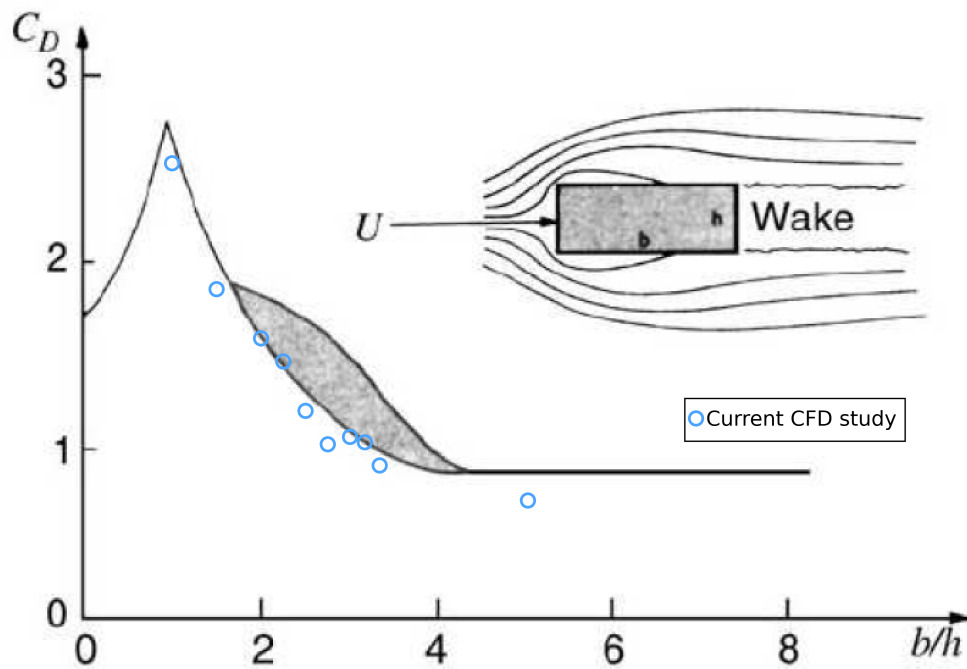


Figure 5.2: Overlay of the present CFD drag coefficients on classical drag-coefficient trends for rectangular prisms. The blue markers indicate the configurations investigated in the present work.

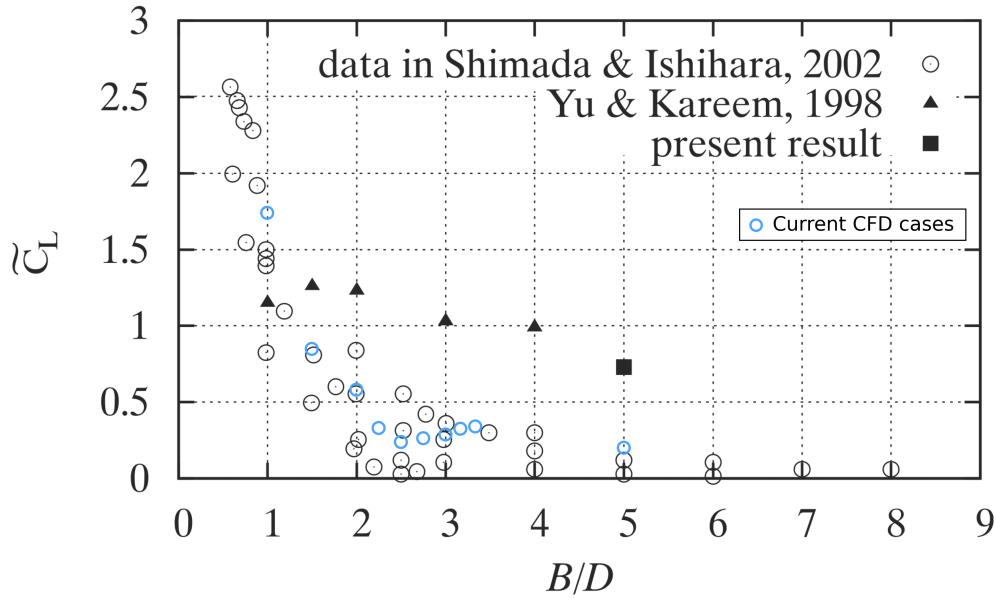


Figure 5.3: Overlay of the present CFD RMS lift coefficients on classical fluctuating lift-coefficient trends for rectangular prisms [16]. The blue markers indicate the configurations investigated in the present work.

The evolution of the drag coefficient with increasing aspect ratio is similarly governed by changes in separation and reattachment behaviour. Figure 5.2 compares the drag coefficients obtained in the present simulations with the classical drag-coefficient trends for rectangular prisms.

The results show the expected reduction in drag with increasing elongation ratio, associated with progressive narrowing of the wake and partial reattachment of the separated shear layers.

Compared to the square prism, the $B/D = 3.33$ case exhibits both reduced drag and reduced cross-wind force fluctuations together with a higher Strouhal number, indicating partial loss of wake coherence associated with intermittent shear-layer reattachment.

Conversely, the elongated prism exhibits the lowest lift fluctuations and a stabilised shedding process governed by persistent reattachment and trailing-edge dominated vortex formation.

These observations are fully consistent with the classical aspect-ratio-dependent flow regimes reported in literature [3, 13, 4, 7].

The evolution of the RMS lift coefficient is shown in Figure 5.3. The reference data show that lift fluctuations generally decrease as the aspect ratio increases. Nearly square sections exhibit large cross-wind force fluctuations because the separated shear layers roll directly into the wake, while more elongated sections promote side-face interaction and partial reattachment, reducing wake coherence.

The present CFD results follow the same overall trend. The square-prism cases show the largest RMS lift coefficients, whereas the elongated configurations exhibit lower values. The $B/D = 3.33$ cases lie in an intermediate range, consistent with a transitional regime characterised by intermittent shear-layer reattachment.

CFD values generally stay within the experimental envelope, but trend toward the higher end for $B/D \approx 3$ –5. This is expected because the present two-dimensional simulations preserve stronger vortex-shedding coherence than three-dimensional wind-tunnel flows, where spanwise

decorrelation, end effects, and incoming turbulence reduce the correlated lift fluctuations.

5.1.2 Comparison with Wind Tunnel Measurements

Table 5.1 compares the global aerodynamic coefficients obtained from CFD with wind tunnel measurements for the rigid naked configuration.

The numerical simulations reproduce the experimental Strouhal number with good accuracy and correctly capture the reduction in fluctuating lift relative to the square prism.

Configuration	B/D	$C_{D,m}$	C'_L	St
Square prism (CFD)	1.0	1.85–1.90	0.80–0.82	0.117–0.120
Rectangular prism (CFD)	3.33	0.85–0.90	0.65–0.70	0.150–0.155
Rectangular prism (Exp.)	3.33	1.10–1.15	0.25–0.30	0.135–0.145
Rectangular prism (CFD)	5.0	0.65–0.70	0.38–0.42	0.115–0.120

Table 5.1: Comparison of global aerodynamic parameters for fixed rectangular prisms without porous cladding.

Differences in absolute force levels are attributed primarily to three-dimensional effects and incoming-flow turbulence present in the experiments but not represented in the two-dimensional numerical framework.

5.1.3 Spectral Characteristics of the Still Configuration

The spectral content of the aerodynamic forces provides additional insight into wake coherence and vortex-shedding mechanisms.

For the $B/D = 3.33$ prism, the dominant shedding frequency remains clearly identifiable, but the spectral energy is distributed over a wider band compared to the elongated configuration.

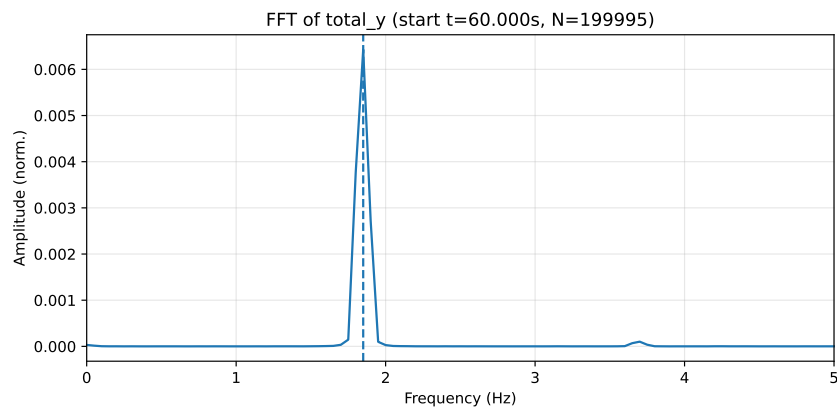


Figure 5.4: Spectral content of the aerodynamic forces in the cross-flow direction.

The broader spectral distribution confirms the transitional nature of the wake, where intermittent reattachment produces reduced temporal coherence compared to fully separated or fully

reattached regimes.

5.1.4 POD Analysis of the Still Configuration

5.1.4.1 POD Energy Distribution

The POD energy spectrum indicates that the majority of the fluctuating kinetic energy is captured by the first two modes.

For the $B/D = 3.33$ prism, the energy fraction captured by the leading modes is comparable to experimental observations, but the spectrum decays more slowly than in the $B/D = 5$ case.

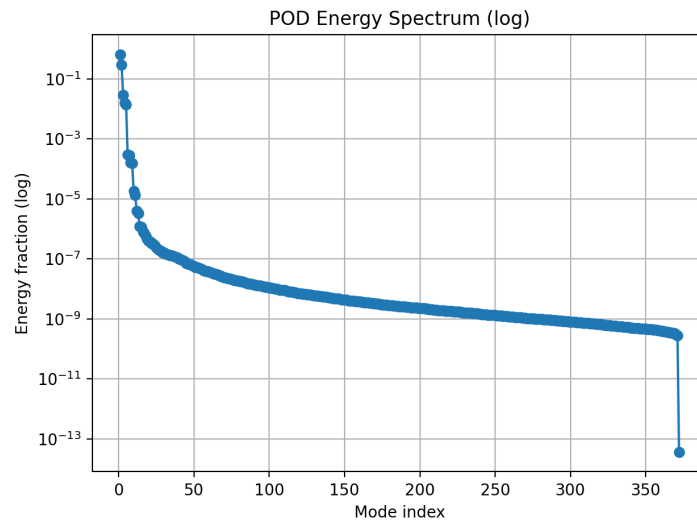


Figure 5.5: Energy spectrum of the POD modes for the $B/D = 3.33$ prism.

This behaviour confirms the intermediate nature of the wake, which is neither dominated by a single coherent shedding mode nor fully stabilised by persistent reattachment.

5.1.4.2 Effect of Aspect Ratio on POD Spectral Content

Figures 5.6a–5.6d compare the power spectral density of the temporal coefficients associated with the first four POD modes.

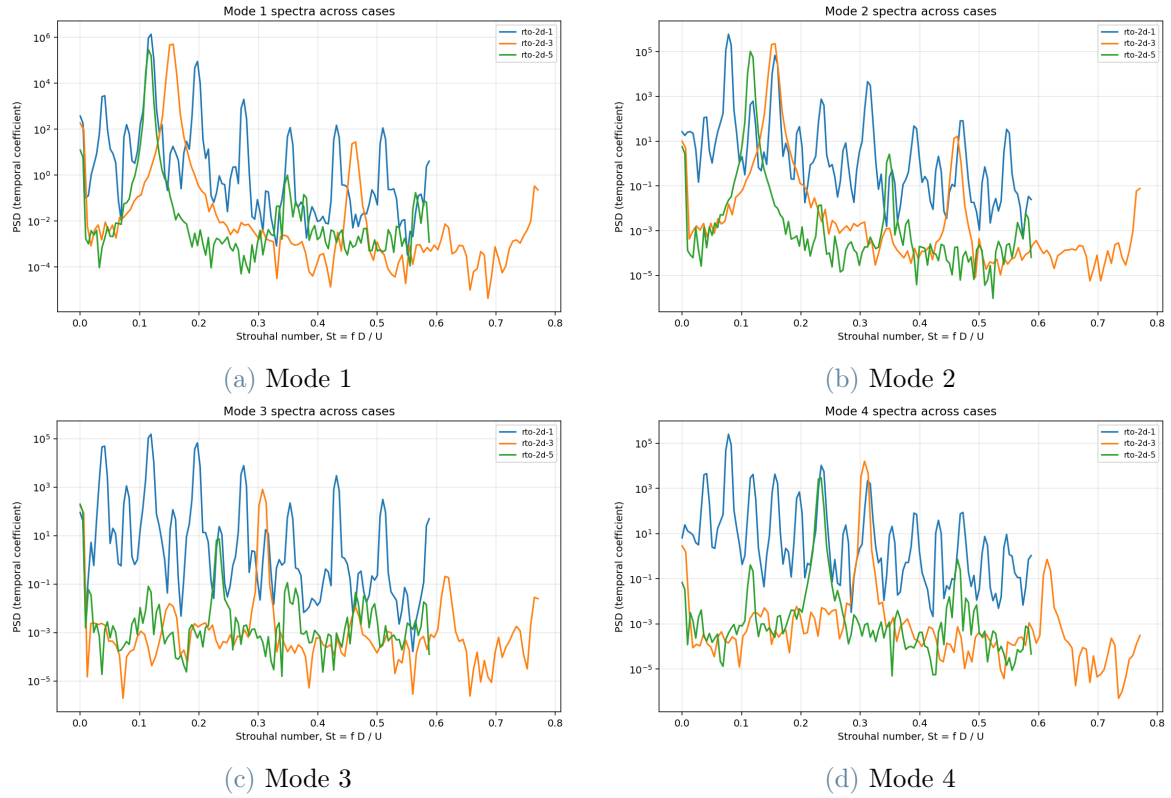


Figure 5.6: Power spectral density of the temporal coefficients associated with the first four POD modes for the investigated aspect ratios.

For the square prism, the leading POD modes exhibit sharp spectral peaks at the shedding frequency and its harmonics, indicating a highly coherent vortex street.

In contrast, the elongated prisms display broader spectral peaks and increased broadband content, reflecting reduced temporal coherence and enhanced modal interaction.

This behaviour is particularly pronounced in the $B/D = 3.33$ case, confirming its transitional aerodynamic nature.

5.1.4.3 POD Mode Shapes

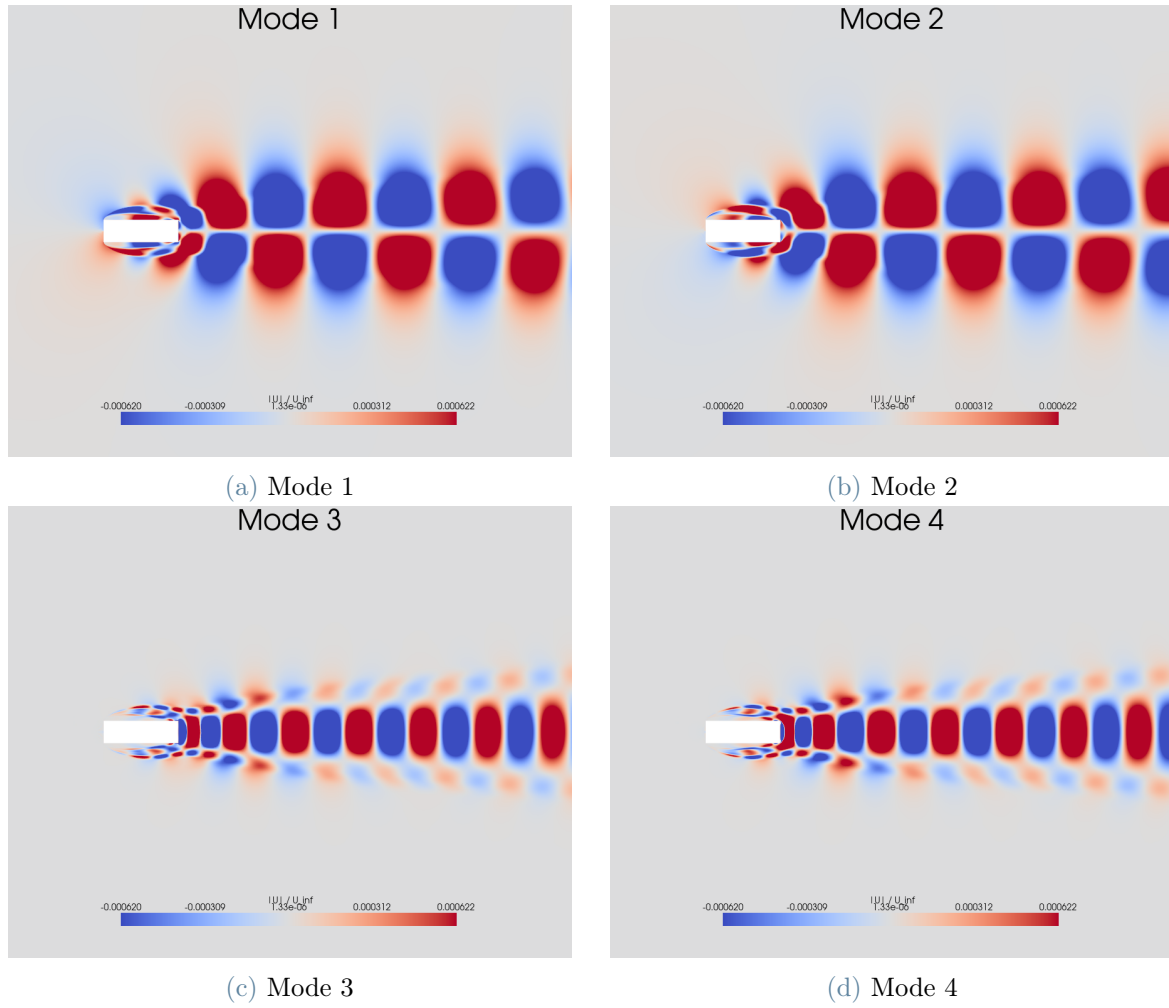


Figure 5.7: Spatial distribution of the first four POD modes for the $B/D = 3.33$ prism.

The POD mode shapes exhibit characteristics similar to those observed in the validation cases corresponding to the square and elongated prisms. However, the wake generated by the $B/D = 3.33$ prism is noticeably narrower and displays intermittent flow reattachment along the side faces.

For the square prism, no reattachment occurs and the separated shear layers develop directly into the wake. In contrast, elongated prisms exhibit shear layers that partially reattach before separating again downstream.

For the $B/D = 5$ configuration, reattachment is persistent and stable, whereas for the $B/D = 3.33$ prism the reattachment process occurs intermittently. This behaviour can be observed by comparing Figures 5.7b and 5.7c, which form a POD mode pair representing alternating reattachment and non-reattachment states.

5.1.5 Reynolds Number Dependency

The same configuration was simulated at multiple wind-speed values within the investigated Reynolds-number range.

Figure 5.8 compares the global aerodynamic indicators obtained for the different Reynolds numbers. The Strouhal number, mean drag coefficient C_D , and standard deviation of lift $\sigma(C_L)$ remain at comparable levels for all cases considered.

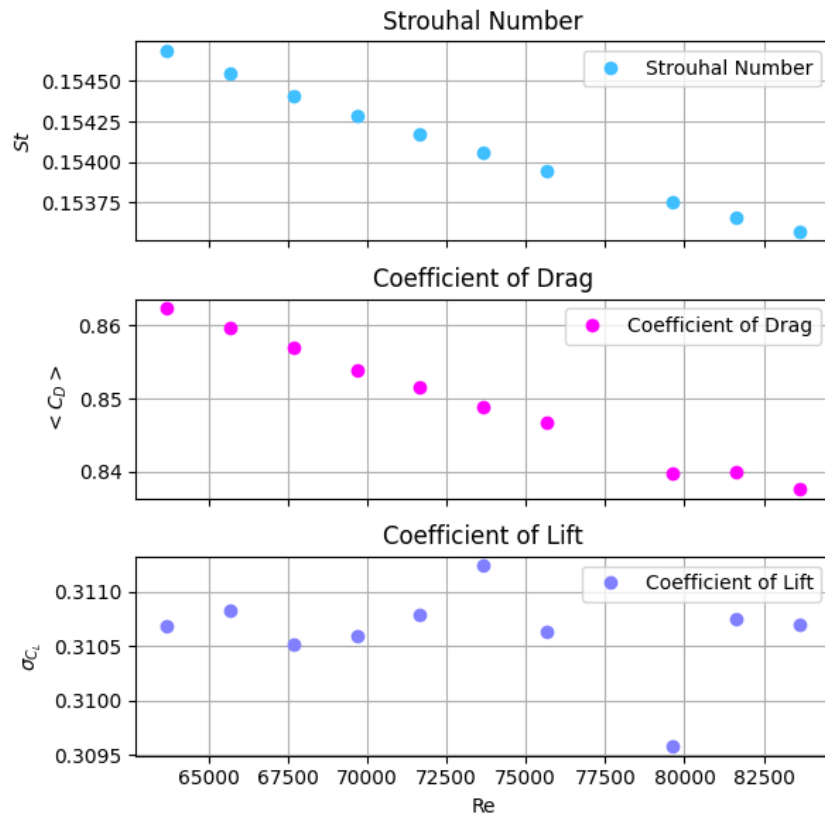


Figure 5.8: Comparison of global aerodynamic parameters as a function of Reynolds number.

The modal content obtained from the POD analysis exhibits the same robustness. As shown in Figure 5.9, the power spectral density of the first POD mode overlaps almost perfectly between the different Reynolds-number cases.

The dominant peak corresponding to the vortex shedding frequency remains unchanged, while the secondary peaks preserve both their position and relative magnitude.

This confirms that the coherent shedding dynamics and energetic hierarchy of the wake structures are preserved across the investigated Reynolds-number range. The aerodynamic response of the prism is therefore largely independent of the precise Reynolds number within the present numerical framework.

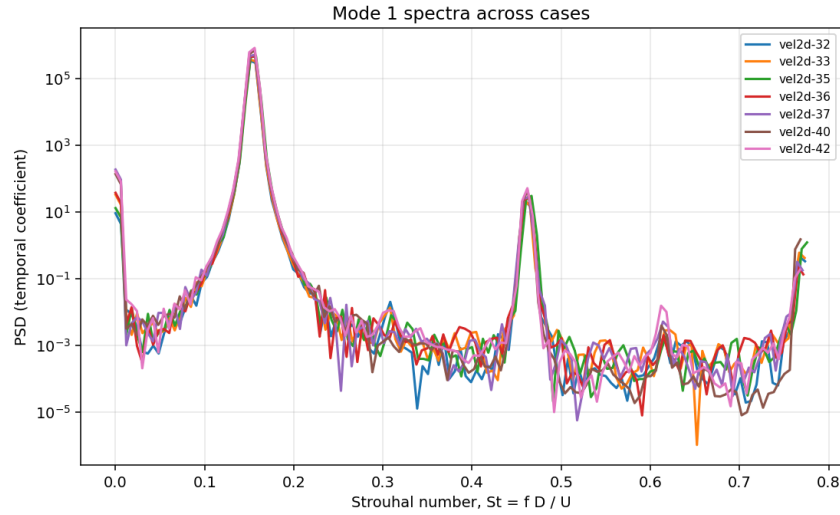


Figure 5.9: Comparison of the temporal POD coefficients for different Reynolds numbers.

5.2 Imposed Oscillations

This chapter investigates the wake dynamics of the bare rectangular subsection subjected to imposed sinusoidal oscillations at and around the natural vortex shedding frequency f_n . The objective is to interpret the flow structures using Proper Orthogonal Decomposition (POD) and to identify how the dominant modes evolve across sub-critical, lock-in, and super-critical forcing regimes.

Previous chapters established the lock-in characteristics and force responses of the system. Here, the focus shifts to the spatial structure and energetic hierarchy of the wake. POD is employed to decompose the URANS flow field into orthogonal modes ranked by kinetic energy content. This methodology has been widely used to characterise oscillating cylinder wakes and identify coherent shedding structures [32, 33].

The classification of vortex shedding modes follows the framework introduced by Williamson and Roshko [18], who identified distinct wake patterns such as 2S (two single vortices per cycle), 2P (two vortex pairs per cycle), and P+S modes in oscillating bluff bodies. This classification provides a consistent reference for interpreting the wake transitions observed in the present simulations and is visualised in Figure 2.10

The simulations were conducted with forcing frequencies ranging between $0.5f_n$ and $2f_n$, with particular attention given to two forcing conditions:

- Sub-critical forcing: $f = 0.75f_n$
- Super-critical forcing: $f = 1.25f_n$

The results are compared qualitatively with the findings of Parasuram and Sinha [32], who applied POD to an oscillating circular cylinder and documented transitions between 2S and more complex shedding modes.

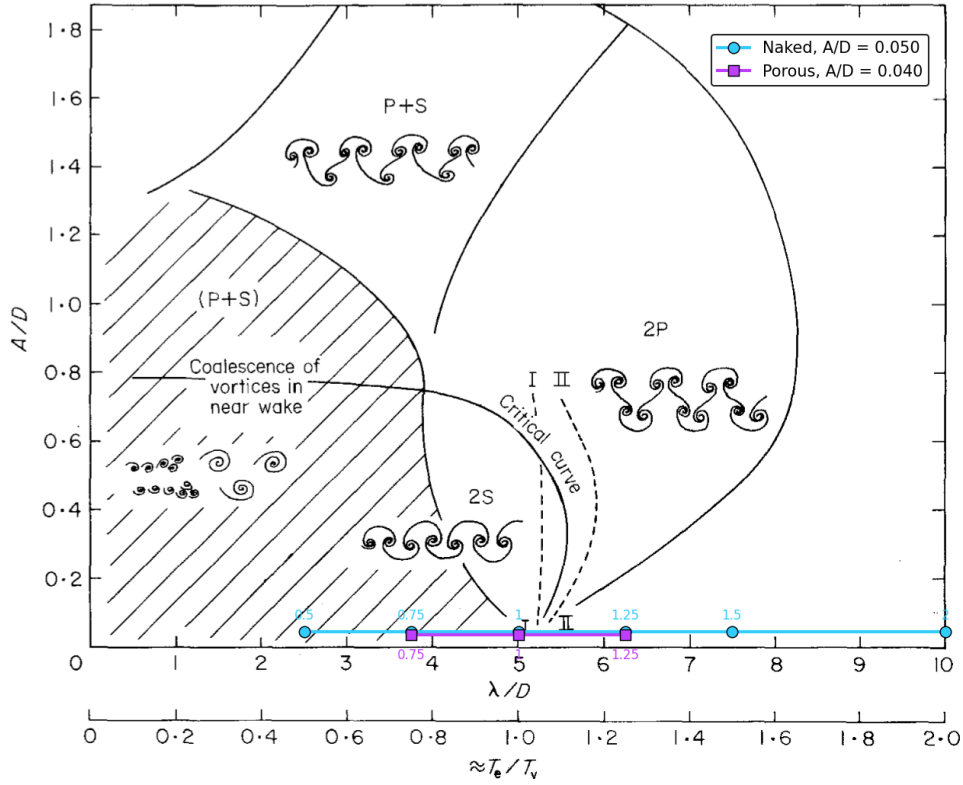


Figure 5.10: Regime map for flow past oscillating cylinder, adapted from Williamson and Roshko [18]. Both porous and naked cases from this researches experiments have been added to the plot.

5.2.1 Sub-Critical Forcing: $f = 0.75f_n$

5.2.1.1 Wake Topology

At $f = 0.75f_n$, the imposed motion is slower than the natural vortex formation process. The wake retains the classical anti-symmetric Kármán vortex street, characterised by alternating shedding from the upper and lower shear layers. With coupled antisymmetric modes.

The shedding remains periodic and coherent. According to the terminology of Williamson and Roshko [18], the wake corresponds to a 2S mode, in which two single vortices are shed per oscillation cycle in an alternating fashion.

This behaviour is consistent with observations for off-resonant oscillations reported in [32], where the natural shedding mode remains dominant when the forcing frequency is sufficiently separated from f_n .

This structure aligns with the dominant POD modes identified in oscillating cylinder studies under non-lock-in conditions [32]. The wake dynamics remain essentially one-dimensional in modal space.

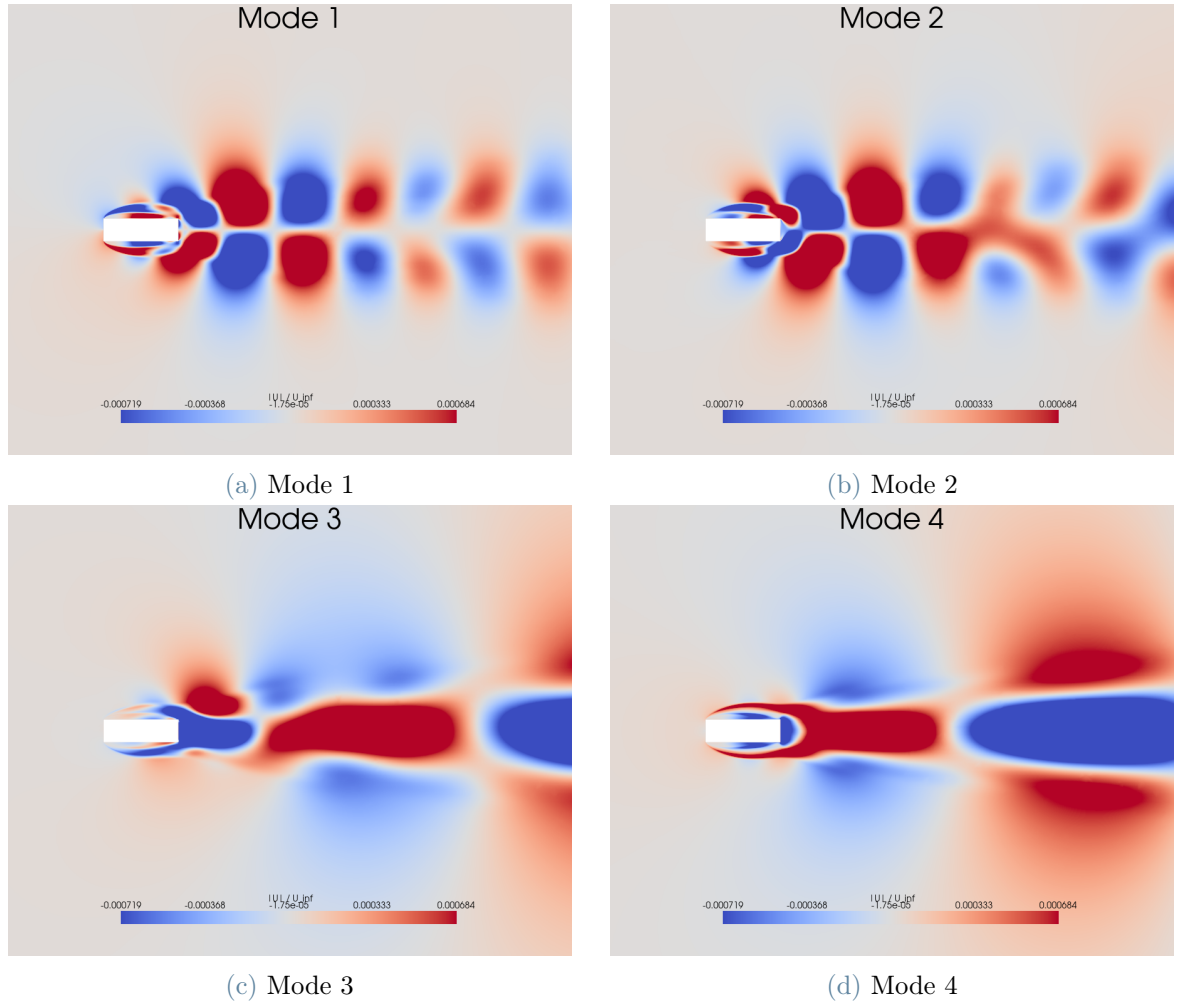


Figure 5.11: POD modes for sub-critical forcing ($f = 0.75f_n$) showing classical alternating 2S vortex shedding.

5.2.1.2 POD Energy Distribution

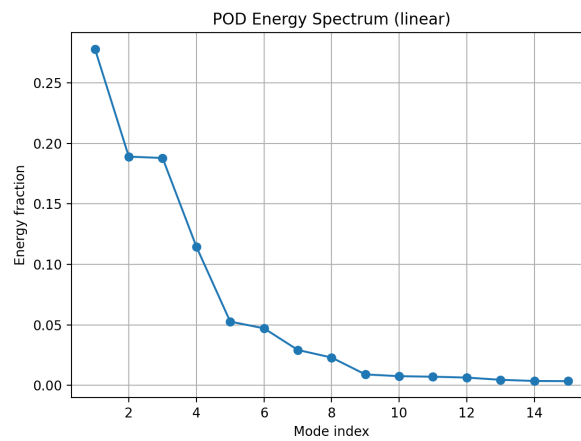


Figure 5.12: POD energy spectrum for $f = 0.75f_n$.

The POD analysis reveals strong energy concentration in the first four modes. Modes 1 and 3 form a conjugate pair representing the alternating vortex shedding.

While modes 2 and 4 represent the conjugate pair of movement in the wake caused by the periodic forcing.

This strong modal dominance is characteristic of periodic 2S shedding regimes described in oscillating bluff-body studies [18].

5.2.2 Lock-In Regime: $f \approx f_n$

At $f \approx f_n$, synchronisation between motion and shedding occurs. The wake becomes highly coherent and organised (Figure 5.13).

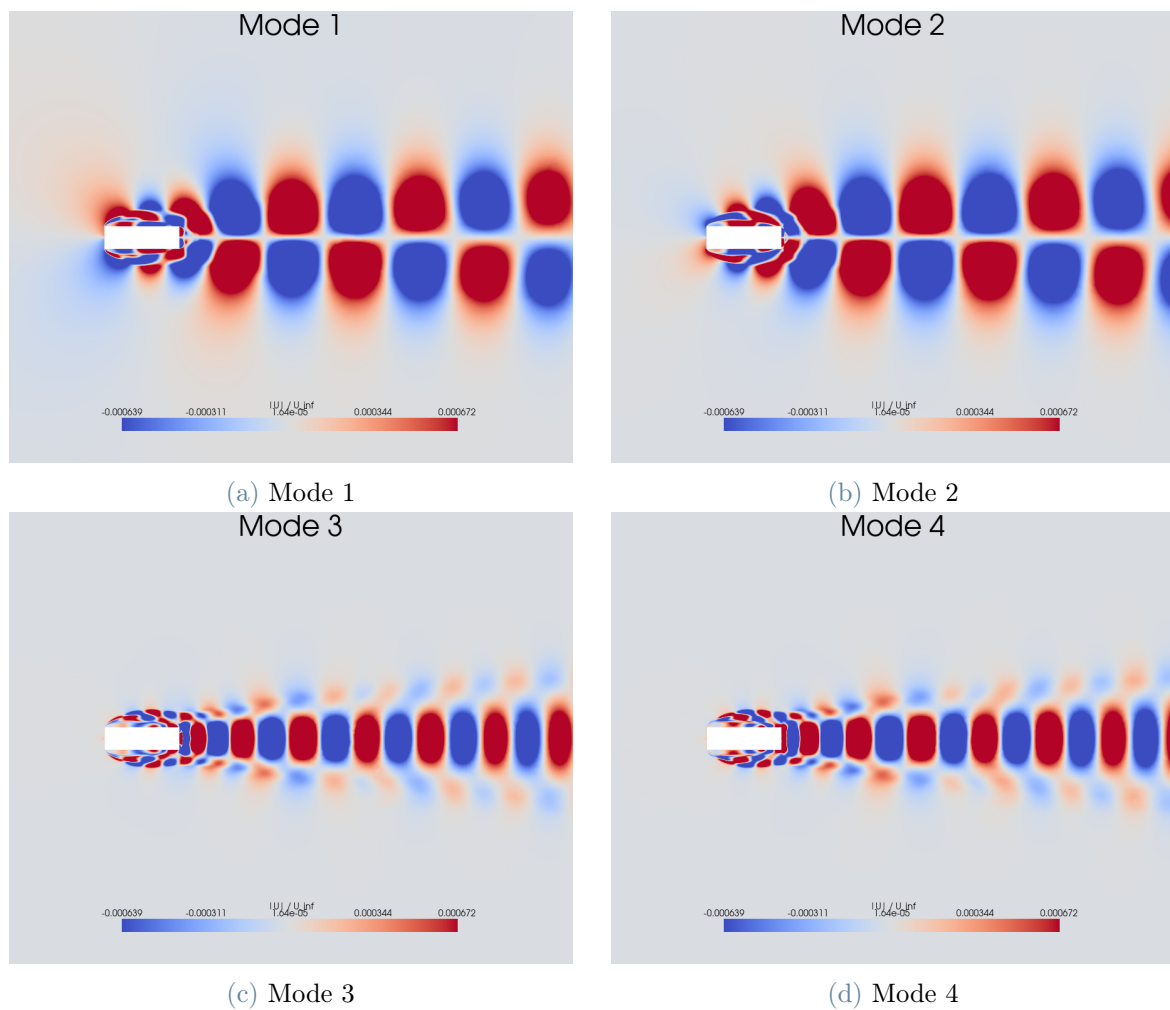


Figure 5.13: POD modes for Lock-In Regime forcing ($f \approx f_n$)

In this regime, the shedding frequency locks to the imposed oscillation frequency. While the dominant pattern remains fundamentally 2S, the vortex formation process becomes phase-locked to the motion, leading to enhanced regularity and sometimes harmonic content.

Williamson and Roshko [18] showed that oscillating bodies may exhibit transitions to P+S or 2P modes within synchronisation windows depending on forcing amplitude. In the present case,

however, the wake remains predominantly synchronised 2S, with limited higher-mode activity.

The POD energy remains concentrated in the first two modes, though higher modes may capture harmonic contributions associated with strengthened vortex interactions.

5.2.3 Super-Critical Forcing: $f = 1.25f_n$

5.2.3.1 Wake Topology Transition

At $f = 1.25f_n$, the imposed motion is faster than the natural vortex formation process. The wake no longer maintains a purely alternating structure.

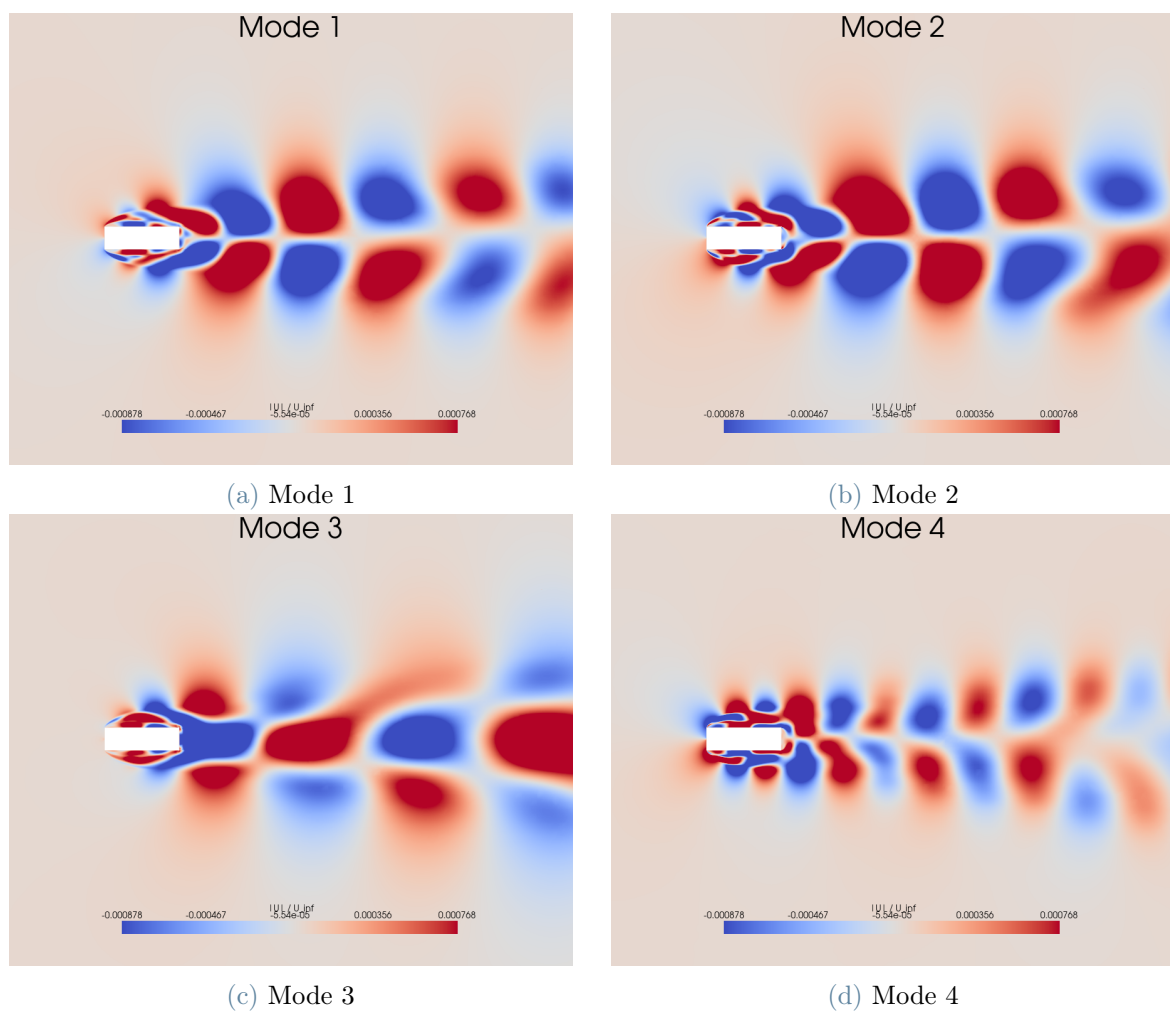


Figure 5.14: POD modes for super-critical forcing ($f = 1.25f_n$) showing mixed mode vortex shedding.

Modes 1 and 2 still contain elements of the alternating shedding pattern. However, the vortices exhibit a more diagonal shape. That suggests simultaneous or paired vortex formation consistent with transitional P+S behaviour and therefore transitioning from a coherent 2S wake to a mixed-mode regime as described in [18].

The following features are observed:

- Irregular vortex spacing
- Occasional paired shedding events
- Skewed vortex shape

5.2.3.2 POD Energy Redistribution

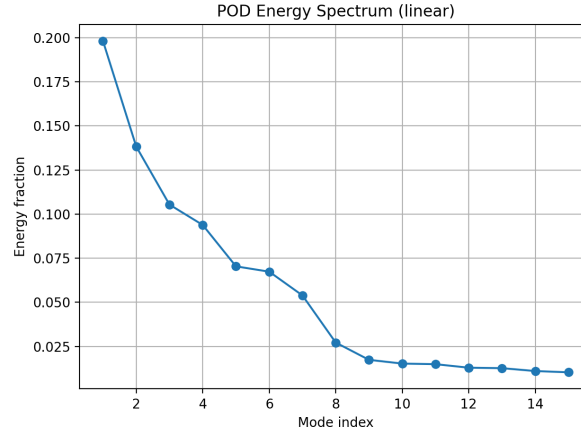


Figure 5.15: POD energy spectrum for $f = 1.25f_n$.

Unlike in the lock-in and sub-critical cases, energy is more evenly distributed across several modes. The first mode pair no longer dominates the flow energetics. Higher modes contain significant energy, indicating multi-scale and multi-frequency contributions.

This flattening of the POD energy spectrum reflects the reduced coherence of the wake and the presence of competing shedding structures.

5.2.4 Comparative Summary of Forcing Regimes

	Sub-Critical	Lock-In	Super-Critical
Wake Symmetry	Anti-symmetric	Phase-locked	Mixed / Irregular
Shedding Mode	2S	Synchronised 2S	2S + P+S / 2P
POD Energy Concentration	High (Modes 1-2)	High + harmonic	Distributed
Coherence Level	Strong	Very strong	Reduced

Table 5.2: Wake characteristics across forcing regimes.

The imposed-motion simulations reveal a modal transition as the forcing frequency crosses the natural shedding frequency. Below f_n , the wake remains dominated by the classical alternating instability. At resonance, synchronisation enhances coherence. Above f_n , the wake loses modal dominance and exhibits a more mixed shedding behaviour.

These findings are consistent with wake mode transitions documented for oscillating cylinders [18, 32]. The modal redistribution observed here confirms that the wake dynamics become progressively higher-dimensional as synchronisation is lost. This has implications for energy

transfer mechanisms and aerodynamic damping, which are governed by the phase relationship between dominant modes and structural motion.

The POD analysis demonstrates that:

- Sub-critical forcing preserves the classical 2S shedding structure.
- Lock-in produces highly coherent, energy-dominant modal behaviour.
- Super-critical forcing leads to mixed-mode shedding and distributed modal energy.

The transition from modal dominance to modal dispersion provides a quantitative measure of wake destabilisation. These results establish a reference baseline for assessing how flow modifications, such as porous treatments, can alter coherent structure formation and VIV response.

5.2.5 Frequency Content of POD Modes

While the spatial POD modes describe the topology of the wake, their power spectral density (PSD) reveals the dominant frequencies governing the flow dynamics.

5.2.5.1 Sub-Critical Forcing: $f = 0.75f_n$

In the sub-critical case, the PSD of the dominant POD modes shows clear and isolated peaks at the natural shedding frequency f_n and the frequency of imposed motion f .

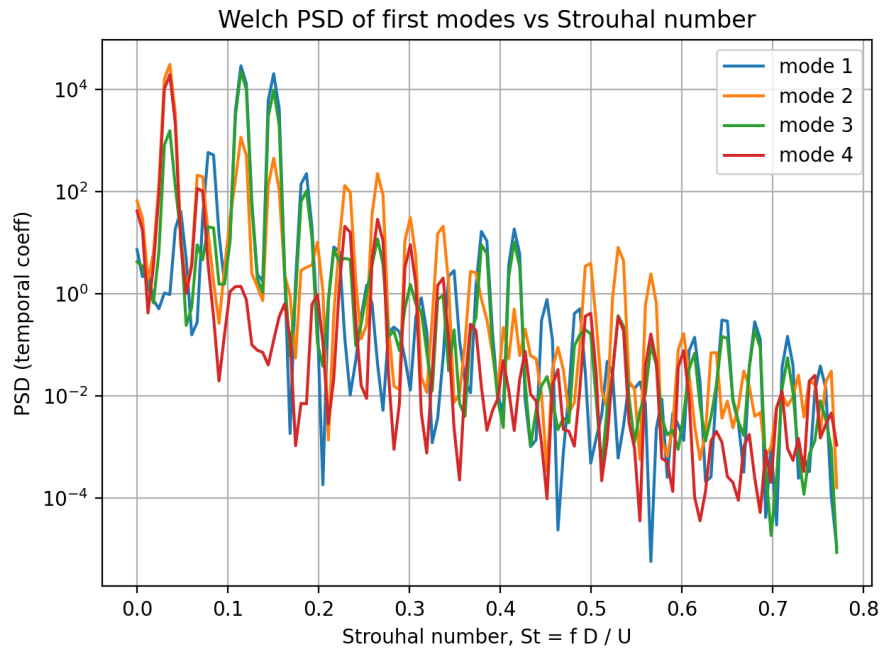


Figure 5.16: Power spectral density of the first POD modes for $f = 0.75f_n$.

The following behaviour is observed:

- Modes 1 and 3 (mode 2 a bit lower) exhibit a dominant peak at f_n .
- The imposed forcing frequency does not dominate the modal response.
- Higher modes contain only minor secondary contributions.

This confirms that the wake oscillates primarily at its natural instability frequency. Such behaviour corresponds to a stable 2S shedding regime outside synchronisation. The forcing frequency acts as a perturbation but does not modify the fundamental shedding mechanism.

5.2.5.2 Lock-In Regime: $f \approx f_n$

In the lock-in regime, the PSD of the POD modes changes significantly. The modes look very clean with obviously visible peaks and their higher harmonics.

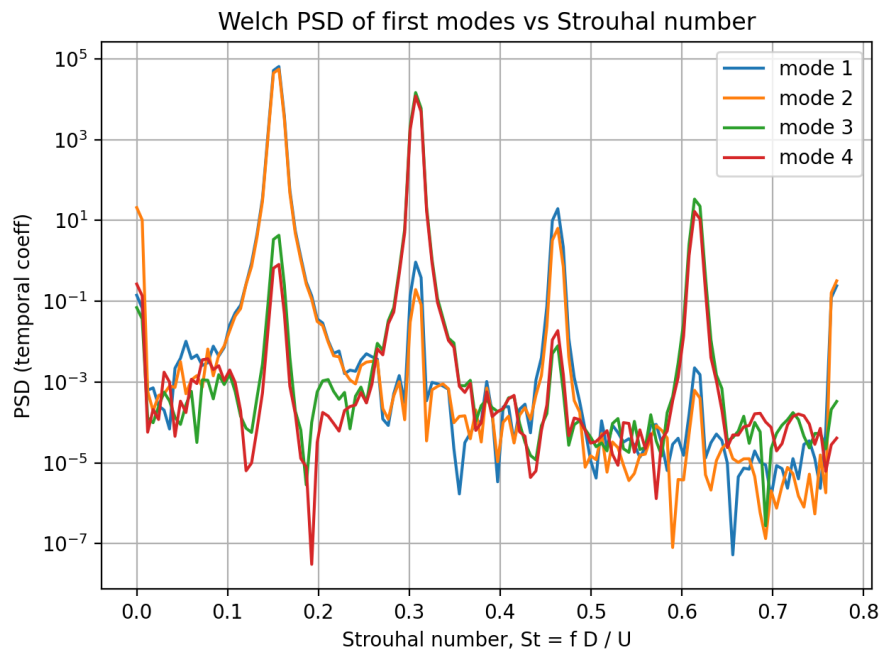


Figure 5.17: Power spectral density of POD modes at lock-in ($f \approx f_n$).

The dominant spectral peak aligns with the imposed forcing frequency. Since $f \approx f_n$, the natural and imposed frequencies coincide, leading to frequency synchronisation.

This behaviour reflects classical lock-in described in [18], where the vortex shedding frequency locks to the oscillation frequency within a defined parameter window.

5.2.5.3 Super-Critical Forcing: $f = 1.25f_n$

For super-critical forcing, the PSD of the POD modes shows two less significant peaks with no visible peaks at higher frequencies.

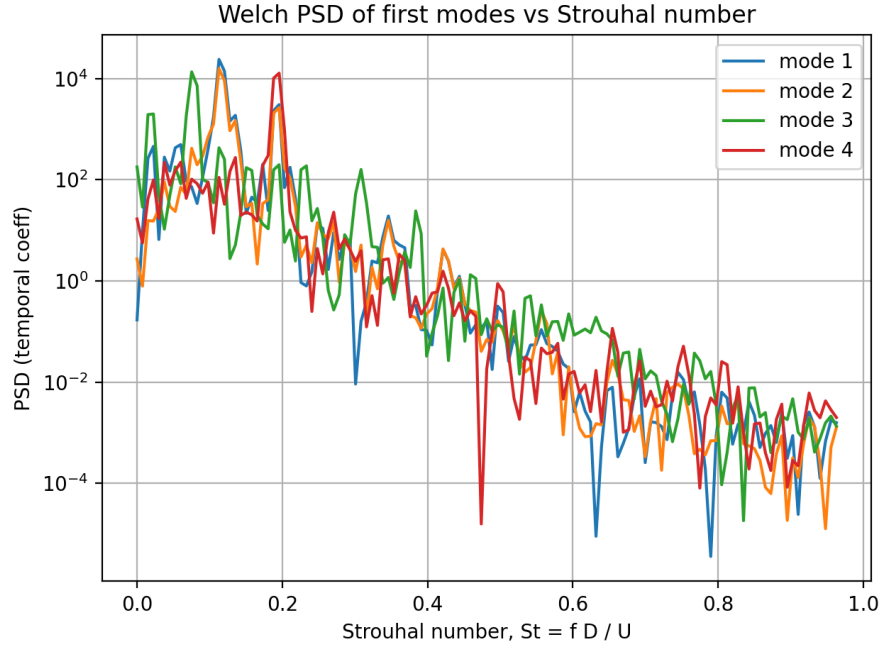


Figure 5.18: Power spectral density of POD modes for $f = 1.25f_n$.

The spectrum reveals:

- A peak at the forcing frequency.
- A secondary peak near the natural shedding frequency.
- Broadened spectral content.

This dual-frequency behaviour confirms incomplete synchronisation. The wake attempts to oscillate at both the imposed frequency and its intrinsic instability frequency. Such competition between modes suggests a transitional regime identified in oscillating bluff-body studies [18, 32].

The broader distribution of spectral energy corresponds directly to the more evenly distributed POD energy observed previously in Figure 5.15.

5.2.6 Effect of Forcing Frequency on Aerodynamic Coefficients

The flow regime changes observed in POD analysis directly influence the aerodynamic force response.

5.2.6.1 Lift force spectrum

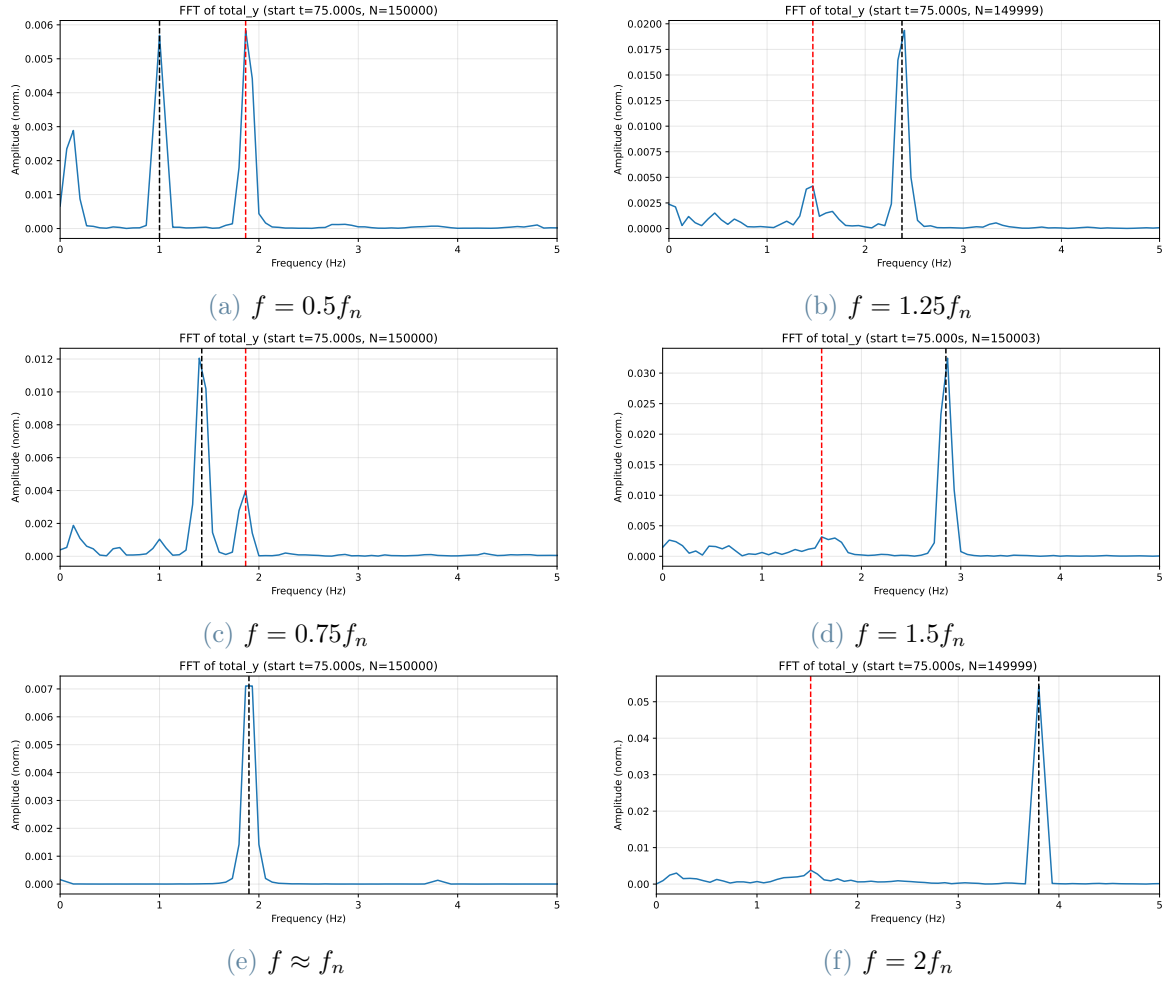


Figure 5.19: Spectrum of lift force at various forcing frequencies f .

The lift response in Figure 5.19 shows clear dependence on forcing regime:

- Sub-critical case: dual peaks at f and f_n .
- Lock-in case: peak shifts to imposed frequency.
- Super-critical case: dominant peak at f and another lower and wider peak at f_n . The broader peak reflects reduced modal coherence.

5.2.6.2 Coefficients of lift and drag

The drag and lift coefficient diagrams in Figure 5.20 further highlight regime transitions.

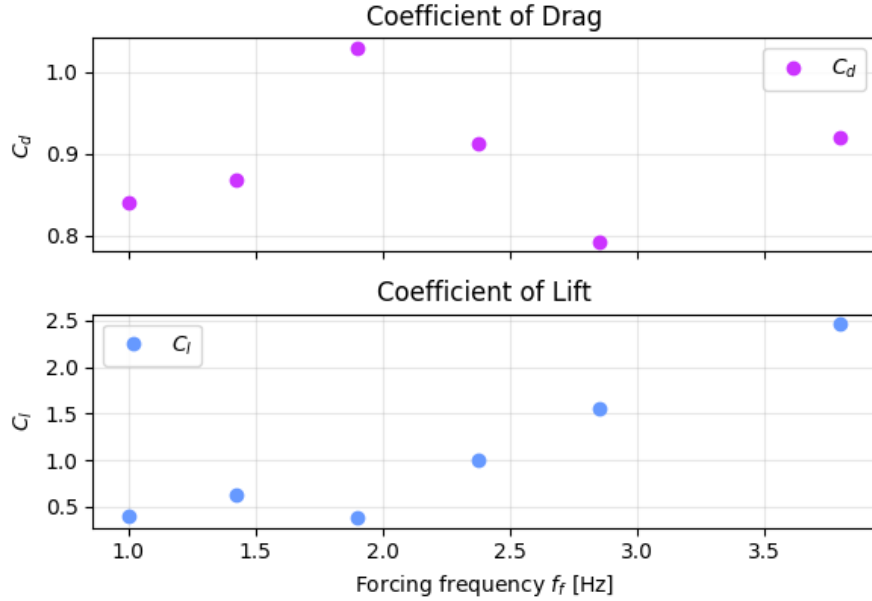


Figure 5.20: Comparison of drag and lift coefficients across forcing regimes.

The drag coefficient peaks at the lock-in frequency and is lower in both sub- and super-critical regimes. The lift coefficient stays steady until starting to linearly grow after entering the super-critical forcing.

5.2.7 Modal–Force Coupling Interpretation

The combined POD and force analyses reveal a direct relationship between modal coherence and aerodynamic amplification. When POD energy is concentrated in a single conjugate pair (2S regime), the lift response is narrow-band and predictable. During lock-in, modal dominance increases and lift amplitude reaches a maximum. When modal energy spreads across multiple modes (super-critical forcing), the lift spectrum broadens, and peak amplitude decreases.

5.3 Porous Façade Configuration

The naked-prism analyses of Sections 5.1 and 5.2 established two reference frameworks: a stationary baseline characterising the intrinsic wake of the $B/D = 3.33$ prism, and an imposed-motion characterisation identifying the modal and spectral signatures of the lock-in transition. With these two references in place, the porous double-skin façade is now introduced as a controlled modification of the external flow field, following the experimental setup of Catania et al. [2].

The objective of this section is twofold: to isolate the aerodynamic effect of the porous layer in stationary conditions, and to determine whether the synchronisation mechanism identified for the naked prism is preserved, modified, or suppressed when the intrinsic shedding is weakened by the porous screen.

The analysis proceeds in two stages. First, the influence of the pressure-loss coefficient k is examined at a fixed Reynolds number on the rigid configuration, to characterise how the porous

screen modifies the stationary wake. Second, sinusoidal oscillations are imposed on a representative porous case at forcing frequencies that span the sub-critical, near-resonant, and super-critical regimes, to assess the interaction between porous-modified vortex shedding and motion-induced synchronisation.

The same diagnostic tools used in the previous sections are applied throughout: global aerodynamic coefficients, force spectra, surface pressure distributions, dominant POD modes, and POD energy distributions. This consistency allows the role of the porous layer to be cleanly isolated from the role of imposed motion.

5.3.1 Comparison with Experimental Data

Before discussing the parametric sweep, the numerical framework applied to the porous configuration is benchmarked against the wind-tunnel data reported in Chapter 4. The comparison uses the experimentally calibrated pressure-loss coefficient $k = 1.8$, which matches the perforated metal shroud of [2], and the same free-stream velocity range as the experimental campaign. The diagnostics adopted are the three quantities shared by the experiment and the CFD: the mean drag coefficient $\overline{C_D}$, the standard deviation of the lift coefficient σ_{C_L} , and the dominant Strouhal number St .

Table 5.3: Comparison of porous-configuration aerodynamic quantities between present CFD ($k = 1.8$, rigid model) and the wind-tunnel measurements of Chapter 4. The experimental Strouhal number range encompasses both the single-velocity peak and the multi-velocity statistic of Table 4.1.

Quantity	CFD ($k = 1.8$)	Experiment	Relative deviation
$\overline{C_D}$ on inner prism	1.02	1.12 ± 0.01	−8.9%
σ_{C_L}	0.21	0.17 ± 0.04	+24%
St (dominant peak)	0.144	0.038–0.055	see text

The mean drag and lift-fluctuation magnitudes agree with the experiment within the scatter typically expected for a two-dimensional URANS simulation of a sharp-edged bluff body. The $\overline{C_D}$ underprediction of approximately 9% is consistent with the systematic 10–15% drag underestimation already observed in the validation cases of Section 3.5, and is attributable to the absence of spanwise three-dimensional effects in the present formulation, as discussed in Section 3.5.3. The overestimation of σ_{C_L} by approximately 24% reflects the same mechanism in the opposite direction: in two dimensions, vortex shedding is perfectly correlated along the (collapsed) span, whereas in the experiment, the spanwise decorrelation of pressure fluctuations reduces the integrated fluctuating force. This is a known limitation of 2D URANS for slender prisms [4, 34] and affects naked and porous configurations alike.

The dominant Strouhal number, however, exhibits a substantial discrepancy that warrants a separate discussion. The CFD predicts $St_{\text{CFD}} = 0.144$, whereas the experiment identifies a primary peak at $St_{\text{exp}} \approx 0.038\text{--}0.055$, depending on whether the multi-velocity or single-velocity statistic is considered. The disagreement is not a quantitative error of $\sim 60\%$ on a single quantity but rather a qualitative one: the CFD captures the higher-frequency shedding branch associated with the inner prism, while the experimental dominant peak corresponds to the lower-frequency branch associated with the outer porous envelope, as identified in Figure 4.3b. The lower branch is not visible in the CFD dataset as it is a limitation of URANS:

- In the experiment (Figure 4.3b), the low-frequency peak at $St \approx 0.038\text{--}0.055$ is energetically dominant, while a secondary, weaker peak near $St \approx 0.14$ is visible on the upper floors.
- In the CFD (Figure 5.30c), the spectrum at $k = 1.8$ exhibits a dominant peak at $St \approx 0.144$.

For the present work, this discrepancy implies that the absolute Strouhal numbers reported in Section 5.3.2 should be interpreted as the inner-prism branch only, and that quantitative comparison with the experimental dominant peak is not meaningful without a three-dimensional formulation. The qualitative trends with k — the monotonic attenuation of σ_{CL} , the redistribution of POD energy, and the emergence of dual-peak spectra at intermediate k — are robust to this limitation, since they reflect the modification of the shear-layer instability mechanism by the porous layer rather than the specific frequency at which that instability operates.

5.3.2 Influence of the Pressure-Loss Coefficient k

In this first stage, the prism remains fixed, and the pressure-loss coefficient k of the external screen is varied systematically. The parameter k controls the inertial resistance of the porous layer through the Darcy–Forchheimer momentum sink introduced in Section 3.3, so that increasing k raises the pressure drop across the screen and strengthens its shielding effect, while decreasing k progressively approaches the naked configuration [22, 23].

Five representative values are considered, spanning more than two orders of magnitude in resistance: $k = 0.05$, $k = 1.8$ (matching the experimental value of Catania et al. [2]), $k = 3.1$, and $k = 10$, together with additional intermediate cases used in the parameter sweep of Figure 5.21. The choice of $k = 1.8$ as the reference configuration for the imposed-oscillation study of Section 5.4 reflects the experimentally calibrated value of the PDSF screen.

5.3.2.1 Global Aerodynamic Parameters

The three global parameters considered throughout this work — the mean drag coefficient, the standard deviation of the lift coefficient, and the Strouhal number — are reported as a function of k in Figure 5.21, using the same graphical format adopted in Sections 5.1 and 5.2.

Three trends emerge consistently. The standard deviation of the lift coefficient is attenuated monotonically as k increases, dropping by approximately an order of magnitude between the most open case ($k \lesssim 0.2$, which recovers the naked prism) and the most resistive case ($k = 10$). This indicates a progressive reduction in the coherence of the alternating shear-layer roll-up as the screen is made more resistive.

The mean drag coefficient on the inner prism decreases overall as k increases: it remains of order unity at low and moderate resistance ($C_D \approx 1.0$ for $k \lesssim 1.8$) and then falls sharply as the screen is made more resistive, reaching $C_D \approx 0.2$ at $k = 10$. This reflects the progressive shielding of the inner prism by the resistive screen, which intercepts an increasing share of the freestream momentum, together with the partial pressure equalisation across the porous envelope reported in similar configurations [35, 36]. The load partitioning behind this trend is quantified in Section 5.3.2.4.

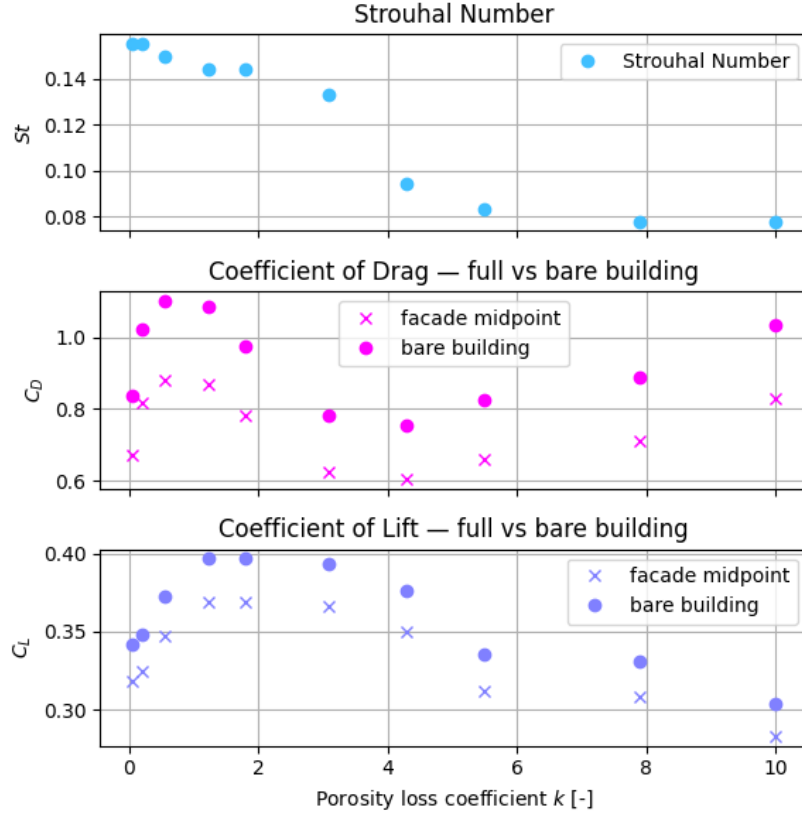


Figure 5.21: Global aerodynamic parameters as a function of k for the rigid porous configuration.

The Strouhal number shifts towards lower values as the pressure-loss coefficient increases, from $St \approx 0.15$ at $k = 0.05$ (open screen, near-naked prism) to $St \approx 0.08$ at $k = 10$ (resistive, near-solid screen). This shift confirms that the effective separation contour is progressively governed by the outer porous layer rather than by the inner sharp edges of the prism, in agreement with the experimental observations for permeable double-skin façades of comparable aspect ratio [2, 21].

The mean pressure coefficients on the four faces of the prism (Figure 5.22) display the same monotonic structure. At $k = 0.05$, the front-face $\overline{C_p}$ retains its near-stagnation value (rising towards the unity limit) and the side and rear faces exhibit pronounced suction, as expected for a naked-like configuration. As k increases, the front-face stagnation weakens and the side-face suction becomes milder and more uniform, indicating that the outer screen is taking over the role of separation surface and that the inner cavity settles to a near-uniform low pressure.

5.3.2.2 Mean Pressure and Velocity Fields

The integrated face coefficients of Figure 5.22 and the global trends of Figure 5.21 can be traced to their spatial origin in the time-averaged fields. Figures 5.23 and 5.24 report, respectively, the mean pressure coefficient $\overline{C_p}$ and the mean streamwise velocity $\overline{U_x}/U_\infty$ for six representative values of k , both in a near-body view and in a zoomed view of the cavity above the prism roof (the *gap* view). Together they provide the field-level mechanism behind the trends discussed in Section 5.3.2.1 and formalised in Sections 5.3.2.3 and 5.3.2.4.

The mean pressure field (Figure 5.23) makes the migration of the separation surface explicit.

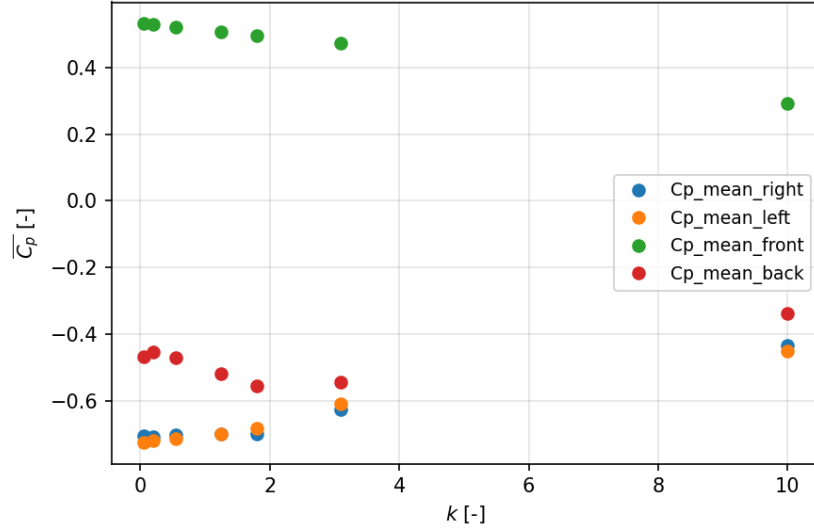


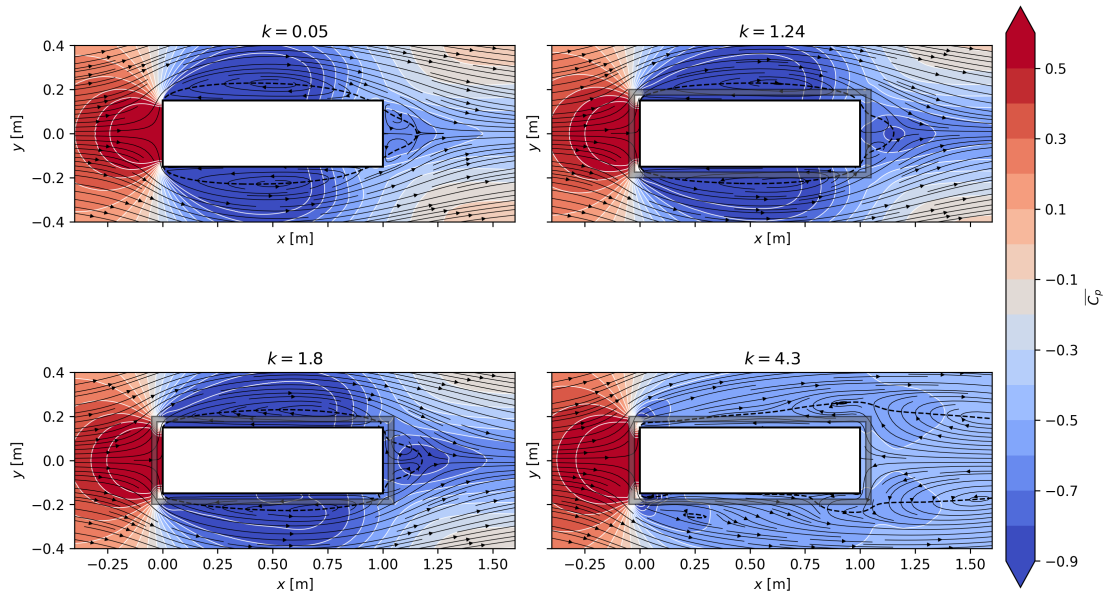
Figure 5.22: Mean pressure coefficient on the four faces of the inner prism as a function of k .

At the lowest resistance, $k = 0.05$, the open screen leaves the inner prism exposed: a compact, intense stagnation core sits on the front face and concentrated suction develops along the leading edges of the side faces, reproducing the pressure signature of the naked $B/D = 3.33$ prism of Section 5.1. As k increases, the front-face stagnation weakens and the suction enveloping the prism becomes progressively milder and more uniform, until at $k = 4.3$ the inner prism sits in a near-homogeneous low-pressure field. The gap view shows the counterpart inside the cavity: the strong, structured suction that follows the naked shear layer at low k gives way to a spatially uniform, weak suction at high k . This is the field manifestation of the cavity pressure equalisation invoked in Sections 5.3.2.1 and 5.3.2.4.

The mean streamwise velocity field (Figure 5.24) resolves the wake topology underlying the Strouhal trend. The signed component is plotted, so that the zero contour $\bar{U}_x = 0$ delimits the mean recirculation region and reverse flow appears in blue. At $k = 0.05$, the leading-edge separation produces thin reverse-flow layers along the side faces and a compact closed recirculation that reattaches a short distance behind the rear face — the narrow, rapidly recovering wake characteristic of the naked prism. As k increases, the near wake immediately behind the prism becomes progressively quiescent while the recirculation region migrates downstream and broadens; at $k = 4.3$ the reverse-flow lobe is displaced well into the wake and spreads in the cross-flow direction, indicating a markedly wider and longer mean wake. The gap view tells the complementary story above the roof: the strong roof-mounted recirculation bubble present at low k collapses into a near-stagnant cavity flow at high k , as the resistive screen intercepts the incoming momentum and shields the inner surface.

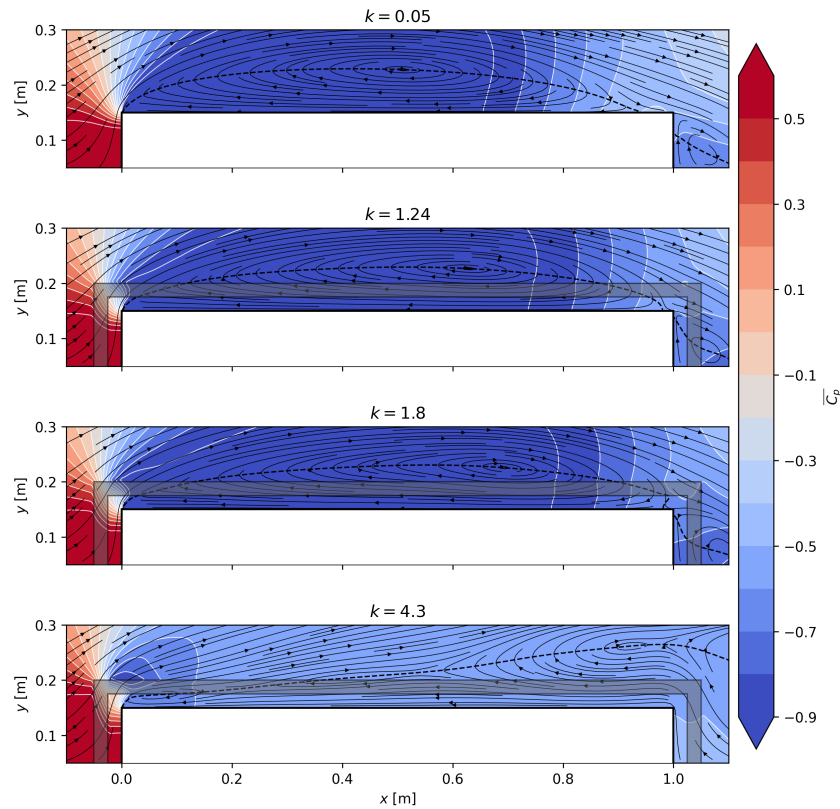
Read together, the two fields supply the spatial evidence for the interpretation developed in the remainder of this section. The downstream migration and broadening of the mean recirculation as k increases is the kinematic origin of the outward displacement of the effective separation contour, and therefore of the reduction in Strouhal number that Section 5.3.2.3 casts as a decrease in effective elongation: a wider, longer wake corresponds to a lower shedding frequency, exactly as a reduction in geometric aspect ratio would produce. The progressive stagnation of the cavity flow and the homogenisation of the inner-prism pressure are, in turn, the field-level expression of the momentum redistribution quantified in Section 5.3.2.4, in which the porous envelope intercepts an increasing share of the load as the screen is made more resistive while the inner prism is increasingly shielded.

Comparison of C_p Mean (near view)



(a) Near-body view.

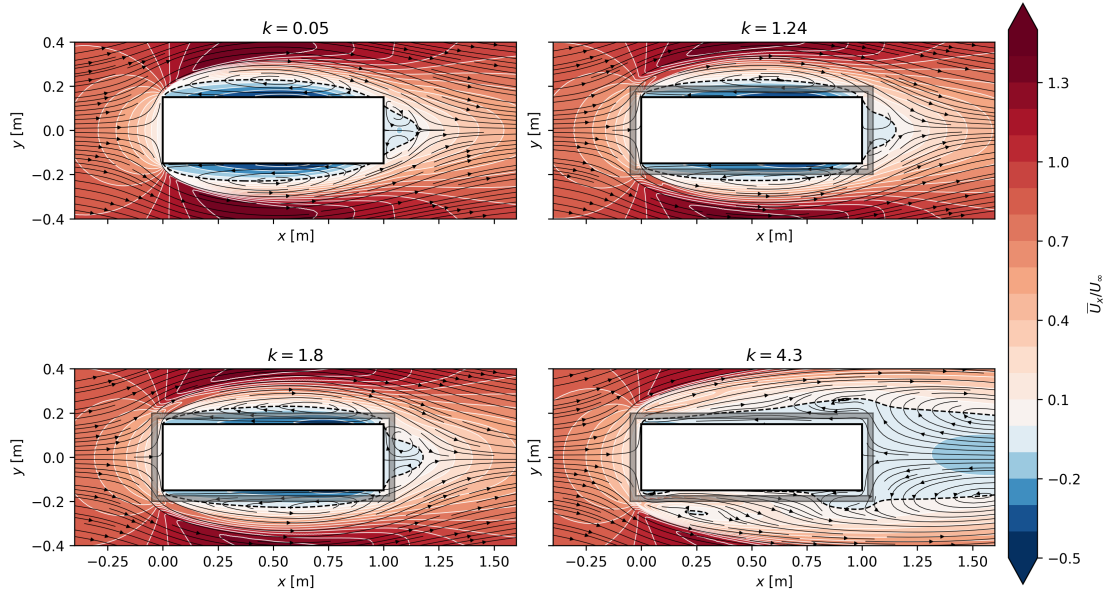
Comparison of C_p Mean (gap view)



(b) Gap (cavity) view above the prism roof.

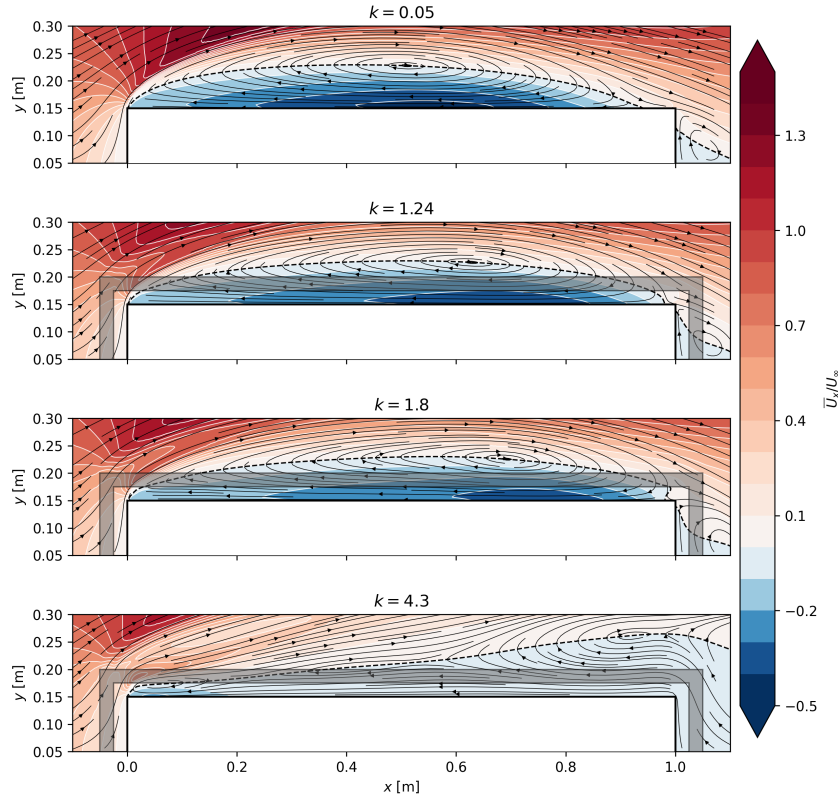
Figure 5.23: Mean pressure coefficient field $\overline{C_p}$ for the rigid porous configuration. The inner prism is masked in white.

Comparison of $\bar{U}_x$ Mean (near view)



(a) Near-body view.

Comparison of $\bar{U}_x$ Mean (gap view)



(b) Gap (cavity) view above the prism roof.

Figure 5.24: Mean streamwise velocity field $\bar{U}_x/U_\infty$ for the rigid porous configuration. The signed component is shown so that the $\bar{U}_x = 0$ contour bounds the mean recirculation region; blue denotes reverse flow. The inner prism is masked in white.

The k -sweep of Figures 5.23 and 5.24 isolates the monotonic trend across the full resistance range. It is useful to complement it with a direct, side-by-side contrast between the two reference states that bracket the present study: the open-screen limit $k = 0.05$, which recovers the naked $B/D = 3.33$ prism, and the experimentally calibrated screen $k = 1.8$ of Catania et al. [2] benchmarked in Section 5.3.1. Figures 5.25 and 5.26 present this comparison for $\overline{C}_p$ and $\overline{U}_x/U_\infty$, respectively. Exploiting the statistical symmetry of the mean field about the wake centreline at zero incidence, each panel maps the naked configuration onto the upper half-plane and the porous configuration onto the lower half-plane, with the inner prism (masked in white) straddling the centreline; the grey frame on the porous side marks the porous screen, drawn 2.5 cm off the prism wall and 2.5 cm thick. Both a full-wake and a near-body view are shown.

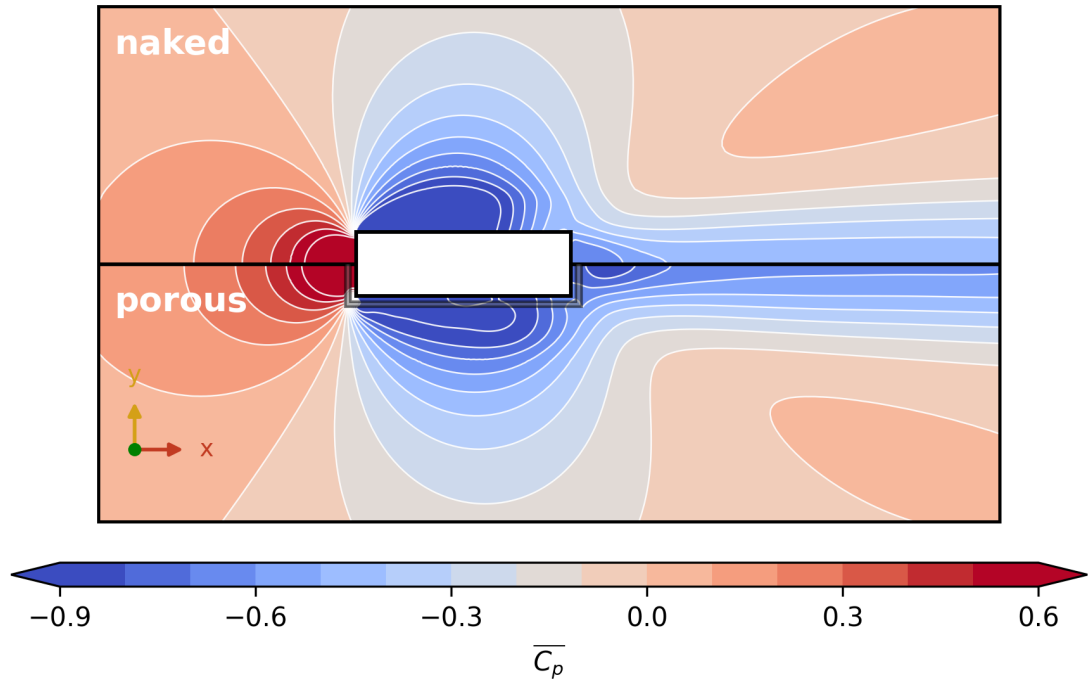
In the pressure field (Figure 5.25) the two states remain qualitatively close at this intermediate resistance, consistent with the still order-unity inner-prism drag at $k = 1.8$ in Figure 5.21. Both halves retain the compact front-face stagnation core and the concentrated leading-edge suction characteristic of the naked prism. The signature of the screen is nonetheless legible in the near-body view: on the porous half the suction no longer hugs the prism walls but is drawn out towards the outer frame, and the rear-face pressure recovery is displaced downstream. This is the incipient form of the migration of the separation surface from the inner sharp edges onto the porous envelope that becomes dominant at higher k (Section 5.3.2.3). The full-wake view shows the corresponding mild elongation of the downstream low-pressure region on the porous side relative to the naked baseline.

The streamwise-velocity field (Figure 5.26) makes the kinematic counterpart explicit. In the near-body view, the naked half exhibits the thin reverse-flow layers along the side faces and the compact, rapidly reattaching recirculation of the bare prism. On the porous half, the low-momentum (blue) region is detached from the wall and redistributed along the screen, and the near-wake velocity deficit is visibly broader and longer: the early stage of the downstream migration and cross-flow broadening of the mean recirculation that, by $k = 4.3$, displaces the reverse-flow lobe well into the wake. The full-wake view confirms that even at the experimentally calibrated resistance, the porous envelope already yields a measurably wider and slower mean wake than the naked prism, in line with the reduction in shedding frequency and the decrease in effective elongation discussed in Section 5.3.2.3.

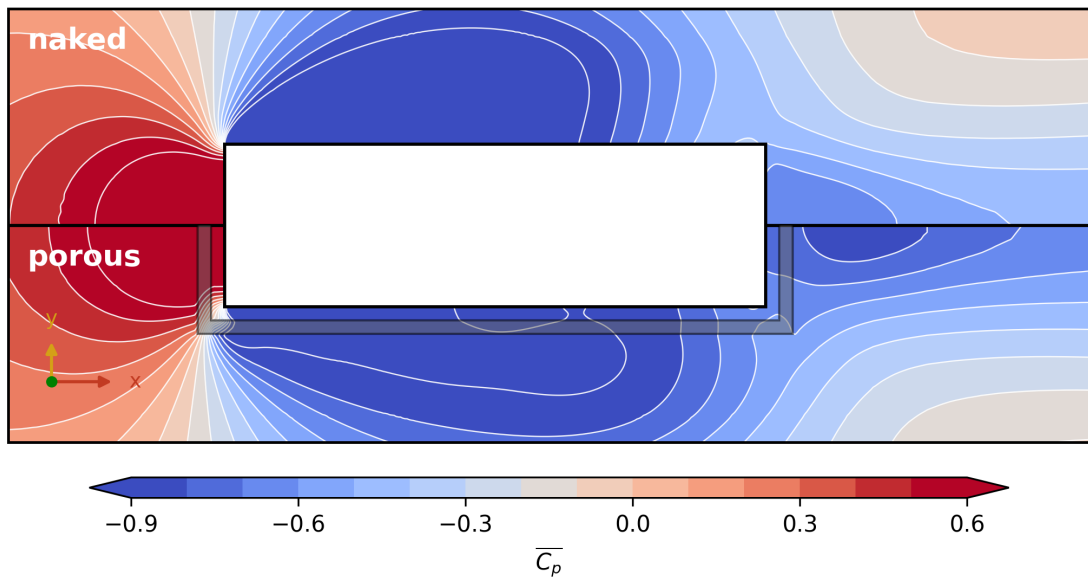
5.3.2.3 Porosity as an Effective Elongation Ratio

The trends reported above can be read in a second, complementary way. Section 5.1 showed that, for the naked prism, the global coefficients vary systematically with the elongation ratio B/D as the wake passes from a fully separated to a reattaching regime. The porous screen produces a qualitatively similar reorganisation of the separation contour without altering the geometry of the inner prism: as the pressure-loss coefficient k increases, the effective separation surface migrates from the inner sharp edges towards the outer envelope, and the inner cavity equalises to a near-uniform low pressure. The aerodynamic body *seen* by the free-stream is therefore neither the bare $B/D = 3.33$ prism nor a longer solid block, but an intermediate configuration whose apparent slenderness is set by k .

This suggests interpreting k as an *effective elongation ratio*. The two limits make the mapping explicit. As $k \rightarrow 0$, the screen becomes effectively transparent, imposes no momentum penalty, and the ensemble recovers the intrinsic wake of the naked $B/D = 3.33$ prism. Conversely, the most resistive case ($k = 10$) approaches a near-solid outer skin: the stand-off cavity is added to the stream-wise footprint of the obstacle, the separation point is fixed at the leading edge of the screen, and the body behaves as if its frontal aspect ratio had been reduced towards $B/D \approx 3.0$,

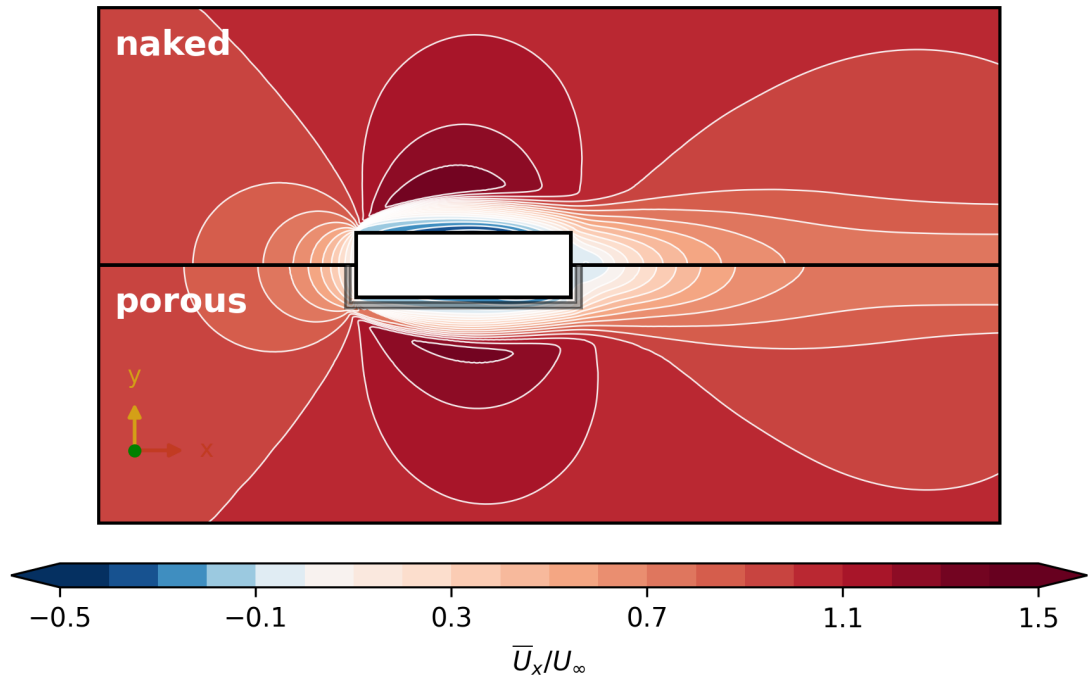


(a) Full-wake view.

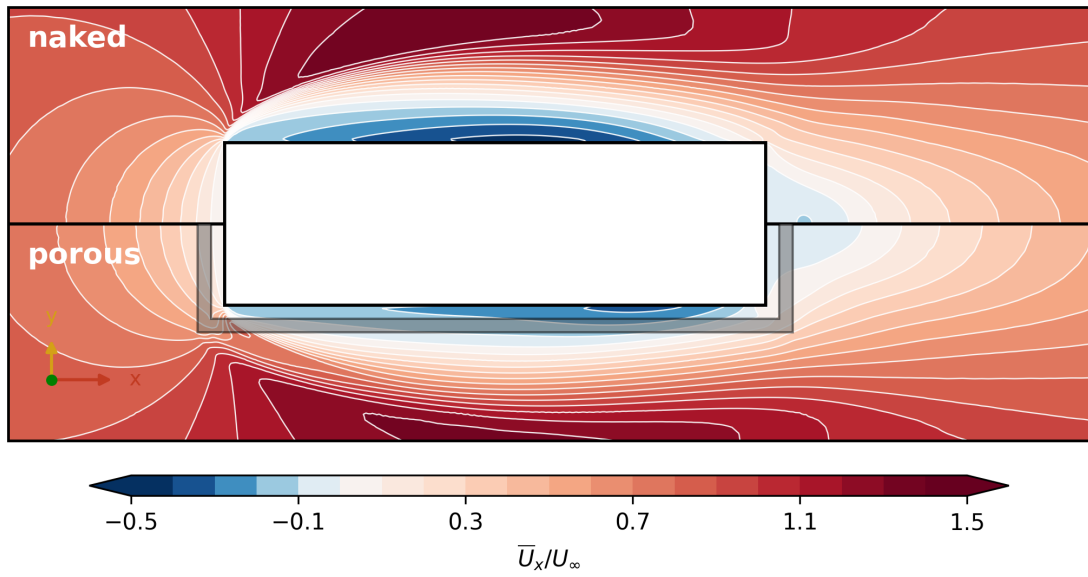


(b) Near-body view.

Figure 5.25: Mean pressure coefficient $\overline{C_p}$: direct comparison between the naked configuration ($k = 0.05$, upper half) and the experimentally calibrated porous screen ($k = 1.8$, lower half). The inner prism is masked in white and straddles the wake centreline; the grey frame on the porous side marks the porous layer. Discrete colour bands are used to aid the eye, and the same colour scale applies to both halves.



(a) Full-wake view.



(b) Near-body view.

Figure 5.26: Mean streamwise velocity $\bar{U}_x/U_\infty$: naked configuration ($k = 0.05$, upper half) versus the calibrated porous screen ($k = 1.8$, lower half), in the same split layout as Figure 5.25. The signed component is shown, so that the $\bar{U}_x = 0$ contour bounds the mean recirculation region and blue denotes reverse flow.

i.e. towards a blunter, more square-like section. Increasing k from 0 to 10 thus traverses the same narrow band of the aspect-ratio classification of Section 5.1, between $B/D = 3.33$ and $B/D = 3.00$, that is spanned when a porous façade is applied to the building.

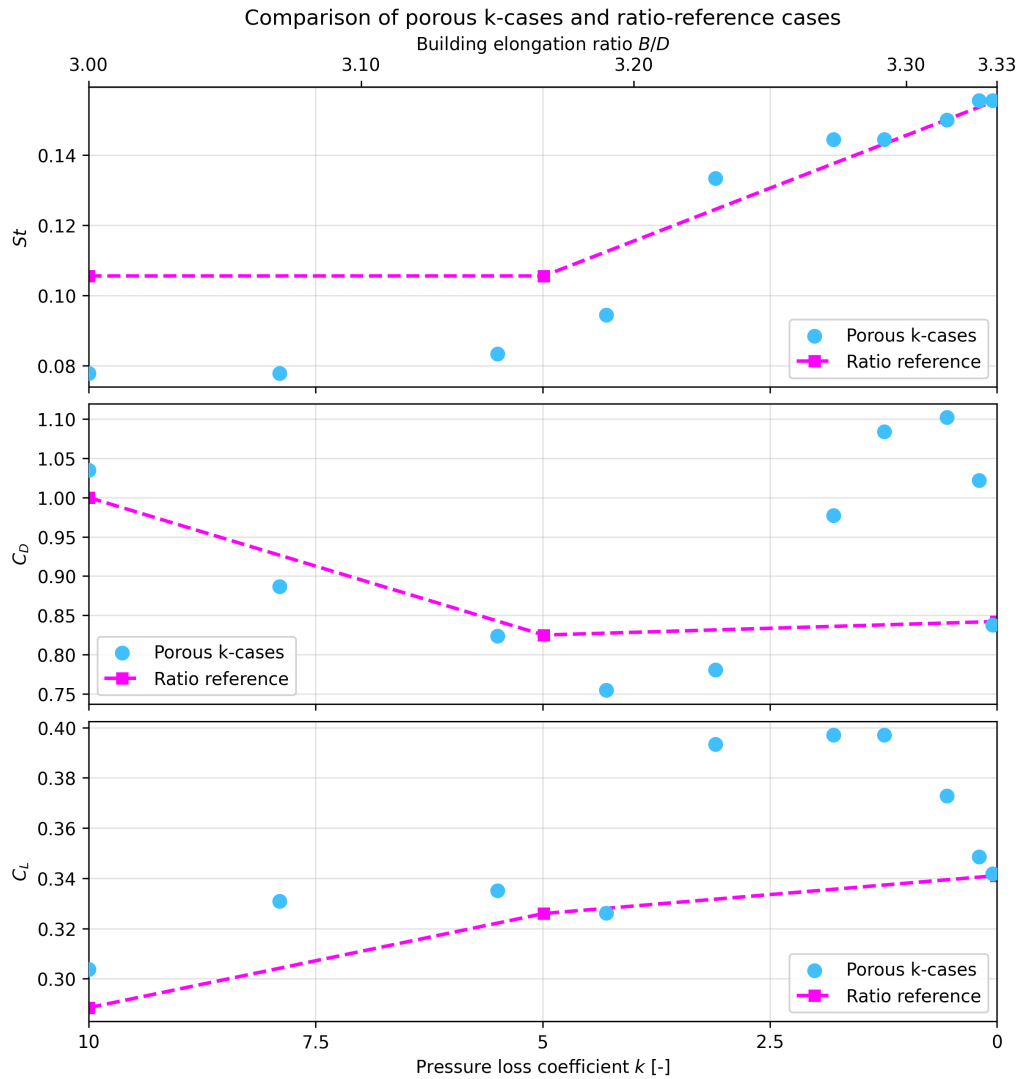


Figure 5.27: Global aerodynamic parameters of the rigid porous configuration plotted against the pressure-loss coefficient k (lower axis, inverted) and the corresponding effective elongation ratio B/D (upper axis). Blue circles: present porous k -cases. Magenta dashed line: *ratio reference* obtained from the naked aspect-ratio sweep of Section 5.1 (Figures 5.1, 5.2 and 5.3), evaluated at the anchor ratios $B/D = 3.00$, 3.20 and 3.33 . The plot is a zoom into the $3.00 \leq B/D \leq 3.33$ band over which the porous façade modifies the apparent slenderness of the prism.

Figure 5.27 makes this correspondence quantitative. The porous k -cases of Figure 5.21 are replotted against an inverted k -axis (resistive on the left, transparent on the right), and the upper axis reports the effective elongation ratio assigned to each limit under the mapping above. Overlaid on the same axes is a *ratio reference* constructed from the naked aspect-ratio sweep of Section 5.1, evaluated at the three anchor points $B/D = 3.00$, 3.20 and 3.33 and interpolated in between. The reference, therefore, represents the behaviour that would be expected if changing k were exactly equivalent to changing the geometric elongation ratio of an impermeable prism.

The Strouhal number (top panel) follows the reference trend closely. The transparent limit reproduces the naked $St \approx 0.15$ of the $B/D = 3.33$ prism, and St decreases monotonically as the

screen is made more resistive, reaching $St \approx 0.08$ at $k = 10$. This is precisely the shift towards lower frequencies discussed in Section 5.3.2.1: a more resistive screen displaces the effective separation contour outward, widens the apparent wake, and lowers the shedding frequency, exactly as a reduction in geometric aspect ratio would. The agreement with the reference confirms that the dominant frequency of the inner-prism branch is governed by the same separation–reattachment competition that controls $St(B/D)$ for naked prisms, and is consistent with the classical rectangular-cylinder data of Okajima [3] and the leading-/trailing-edge interaction described by Deniz and Staubli [31].

The RMS lift coefficient (bottom panel) shows the same qualitative behaviour and the same sign of the trend as the reference, although with larger scatter: the porous cases lie systematically above the ratio reference at intermediate k . This is the expected consequence of the porous mechanism not being a pure geometric change. At intermediate k , the inner and outer separation branches coexist, producing the dual-peak spectra reported in Section 5.3.1, so a fraction of the cross-wind force originates from a mechanism that has no counterpart in the impermeable aspect-ratio sweep. The deviation is therefore physically meaningful: it isolates the part of the lift response that porosity adds beyond a simple slenderness change.

The mean drag (middle panel) departs most strongly from the reference, and for the same reason. The ratio reference, being based on the inner-prism drag of the naked sweep, captures only the load on the building, whereas the porous ensemble redistributes momentum between the building, the screen, and the cavity. As anticipated here and quantified in Section 5.3.2.4, the near-constancy of the total drag of the ensemble masks a pronounced internal redistribution that the single-body aspect-ratio analogy cannot represent. The drag panel of Figure 5.27 should therefore be read as evidence that the effective-elongation analogy holds for the kinematic quantities (St , and to a lesser extent σ_{C_L}) that depend on the geometry of the separation contour, but breaks down for the mean load, whose partitioning requires the dedicated decomposition of the following section.

Taken together, Figure 5.27 establishes a compact physical picture: applying a permeable double-skin façade to the $B/D = 3.33$ prism is, to first order, equivalent to tuning the prism within the narrow elongation band $3.00 \leq B/D \leq 3.33$, with the pressure-loss coefficient k acting as the control knob. The most resistive screen mimics the blunter end of this band, and the transparent screen recovers the naked geometry, while the residual departures from the reference quantify the genuinely porous contributions that motivate the drag decomposition and spectral analysis that follow.

5.3.2.4 Decomposition of the Mean Drag

The mean drag coefficient reported in Figure 5.21 characterises the aerodynamic load on the inner prism alone. It does not, on its own, describe how the freestream momentum is partitioned between the building, the porous envelope, and the cavity flow. To resolve this partitioning, the mean drag is decomposed into three contributions that, together with an independent control-volume estimate, satisfy a momentum balance across the porous layer.

Three estimates are computed from the same simulation data. The drag on the inner prism, C_D^{inner} , is obtained by surface integration of the pressure and viscous tractions on the building patch through the standard OpenFOAM `forces` function object. The drag on the outer envelope surface, C_D^{outer} , is obtained by integrating the pressure coefficient on a ring of probes placed on the outer face of the porous layer, following the procedure used for the $\overline{C_p}$ analysis of Figure 5.22. Both quantities are normalised with the same reference area $A_{\text{ref}} = h d_{\text{bare}}$ so that the bare-

building coefficient remains directly comparable with the values reported in Figure 5.21.

The third contribution, C_D^{porous} , represents the momentum absorbed by the Darcy–Forchheimer volume sink within the porous medium. As a distributed body force it cannot be obtained from any solid-surface integration, and is therefore evaluated as the residual of the momentum balance across the porous layer,

$$C_D^{\text{porous}} = C_D^{\text{outer}} - C_D^{\text{inner}}, \quad (5.3.1)$$

which is exact in the time-mean for a control volume bounded by the outer envelope surface and the building wall. An independent total-drag estimate, C_D^{CV} , is computed from a control-volume momentum balance applied to the time-averaged velocity and pressure fields on a rectangular box enclosing the whole obstacle, providing a consistency check on the surface-based estimates without sharing any of their inputs.

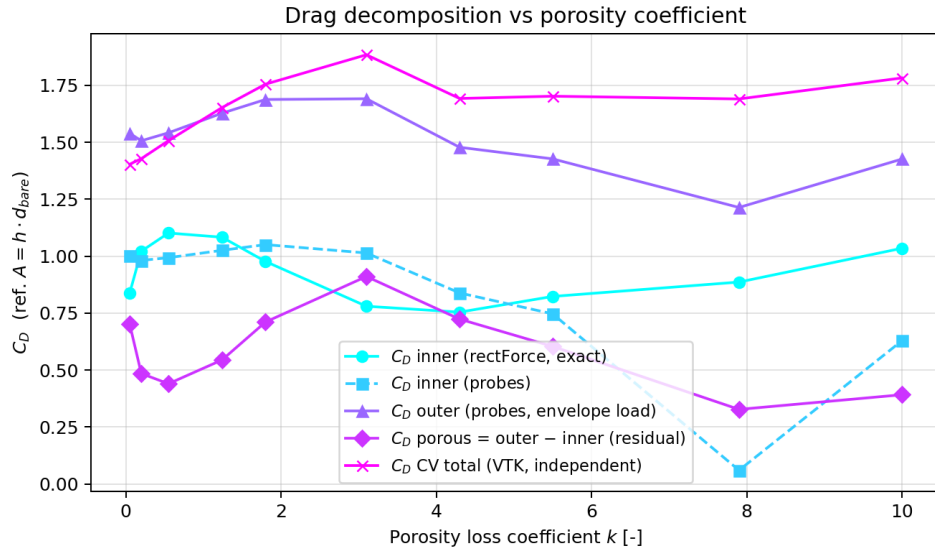


Figure 5.28: Decomposition of the mean drag coefficient as a function of k . C_D^{inner} : drag on the inner prism from surface forces. C_D^{outer} : drag on the outer envelope surface from pressure probes. $C_D^{\text{porous}} = C_D^{\text{outer}} - C_D^{\text{inner}}$: residual momentum absorbed by the porous medium. C_D^{CV} : independent control-volume momentum balance on the time-averaged field. All coefficients normalised by $A_{\text{ref}} = h d_{\text{bare}}$.

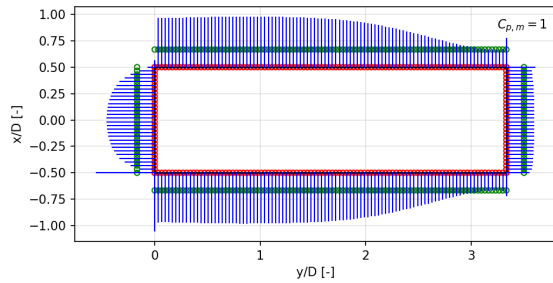
The four coefficients are reported in Figure 5.28 as a function of k . The outer-envelope and control-volume estimates agree closely across the full range of k , confirming that the obstacle, as seen by the freestream, behaves as a coherent bluff body with a total drag coefficient of order unity, weakly dependent on k . The decomposition reveals that this near-constancy of the total load masks a pronounced internal redistribution: as k increases, the porous medium absorbs a progressively larger share of the freestream momentum, while the load transferred to the inner prism drops correspondingly, consistent with the trend already visible in C_D^{inner} of Figure 5.21. In the high-resistance limit, the envelope intercepts the bulk of the incoming momentum, the cavity flow stagnates at near-uniform pressure, and the building experiences only a small residual load — the same mechanism inferred from the $\overline{C_p}$ distributions of Figure 5.22.

This result has direct implications for the structural design of porous double-skin façades: across the range of k considered, the porous envelope acts as a load-bearing aerodynamic element that carries a substantial fraction of the wind load, shielding the inner structure but transferring that load to the screen anchorages. The total aerodynamic load on the building–envelope ensemble

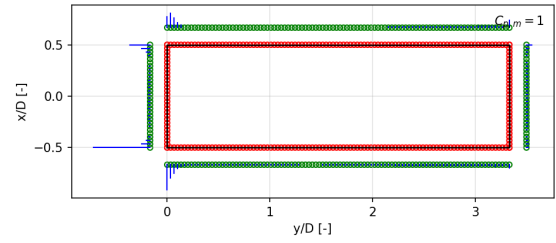
is only weakly modulated by k , while its distribution between the two elements is strongly modulated.

5.3.2.5 Pressure Distributions Around the Perimeter

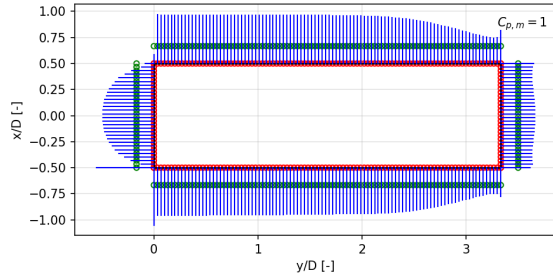
Figure 5.29 reports the mean and fluctuating pressure coefficients around the perimeter of the inner prism for six representative values of k . The figure complements the integrated values of Figure 5.22 by showing how the pressure distribution evolves locally.



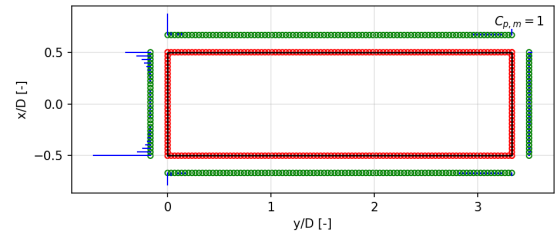
(a) C_p for $k = 0.05$



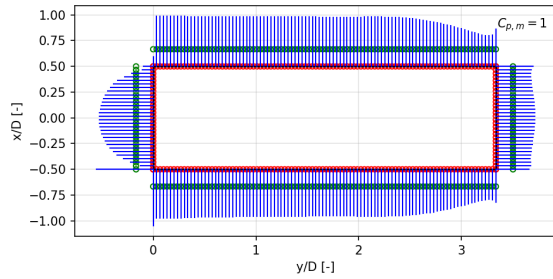
(b) ΔC_p for $k = 0.05$



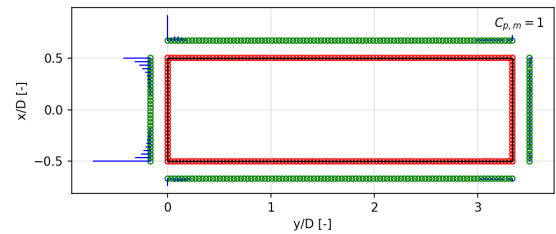
(c) C_p for $k = 1.24$



(d) ΔC_p for $k = 1.24$

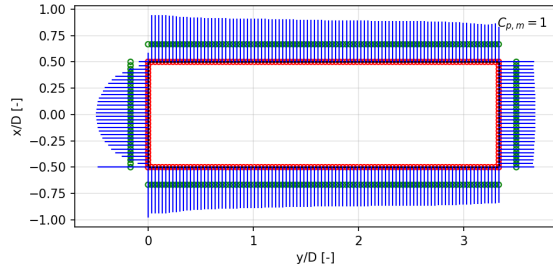


(e) C_p for $k = 1.8$

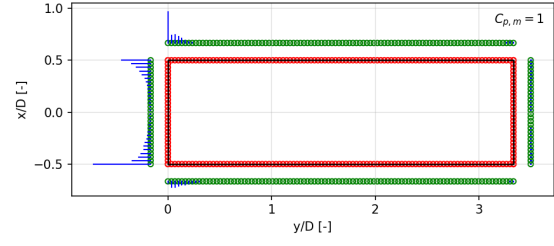


(f) ΔC_p for $k = 1.8$

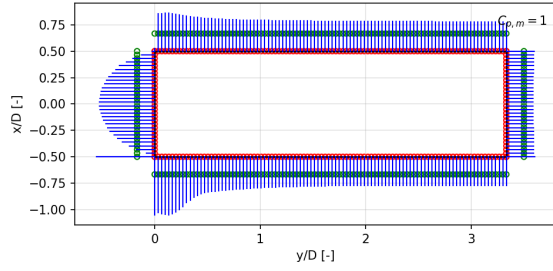
Figure 5.29: Mean (C_p) and fluctuating (ΔC_p) pressure coefficients around the perimeter of the inner prism for various values of k .



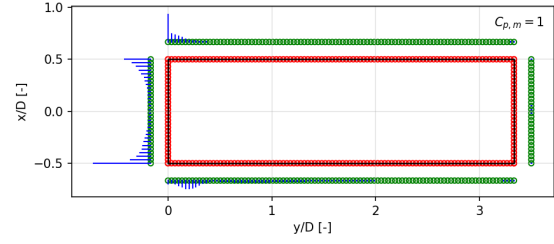
(g) C_p for $k = 3.1$



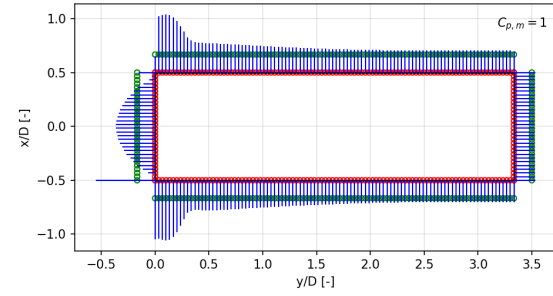
(h) ΔC_p for $k = 3.1$



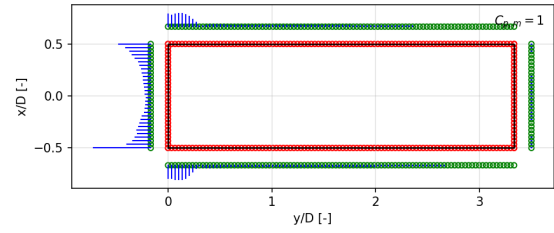
(i) C_p for $k = 4.3$



(j) ΔC_p for $k = 4.3$



(k) C_p for $k = 10$



(l) ΔC_p for $k = 10$

Figure 5.29: Continued: Mean (C_p) and fluctuating (ΔC_p) pressure coefficients around the perimeter of the inner prism for various values of k .

At $k = 0.05$, the perimeter distribution reproduces the qualitative shape expected for a naked rectangular prism: high stagnation pressure on the front face, strong suction at the leading edges of the side faces, and a recovered but still negative pressure on the rear face. The corresponding ΔC_p distribution exhibits the largest fluctuations near the leading edges, consistent with the shear-layer separation mechanism described for the naked case in Section 5.1.

As k increases, the leading-edge fluctuation peaks on the side faces are progressively flattened. At $k = 1.8$ the leading-edge ΔC_p is reduced by roughly a factor of two relative to the open case, and at $k = 10$ the side-face fluctuations are nearly homogeneous along the prism length. This homogenisation is a direct manifestation of the loss of coherence of the alternating shear-layer roll-up. Both the mean and the fluctuating pressure components on the inner façade become more uniform along the perimeter as the screen is made more resistive, in agreement with the experimental measurements of Catania et al. [2].

5.3.2.6 Force Spectra

The power spectral density of the lift force provides direct evidence of the instability mechanisms acting on the porous configuration. The spectra for the six representative values of k are shown in Figure 5.30.

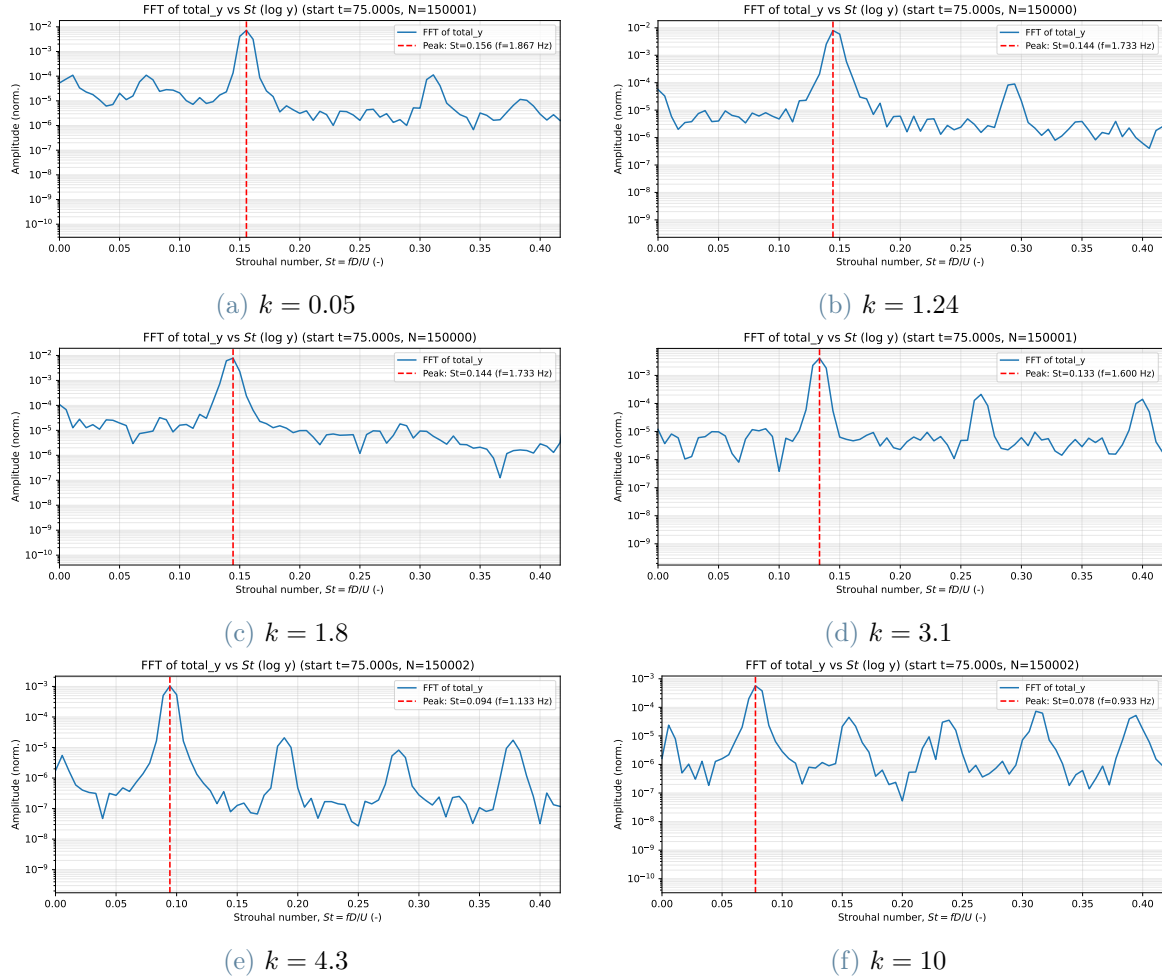


Figure 5.30: Power spectral density of the lift force at various k .

At a low pressure-loss coefficient ($k = 0.05$), a single sharp peak at $St \approx 0.156$ emerges, essentially the naked-prism shedding frequency: the open screen barely perturbs the inner prism, whose sharp edges continue to govern the shedding. At a high pressure-loss coefficient ($k = 10$), the spectrum collapses to a single, lower-frequency peak at $St \approx 0.08$, displaced from the naked value and of reduced amplitude: the resistive, near-solid screen displaces the effective separation contour outward, widening the apparent wake and lowering the shedding frequency, so that the shedding is governed by the effective outer contour of the screen rather than by the inner prism.

The most informative cases are the intermediate ones. At $k = 1.8$ and $k = 3.1$ the spectra exhibit two distinct features: a primary peak corresponding to the porous-modified shedding frequency, and a secondary, broader peak at a different Strouhal number. The relative strength of these two peaks varies continuously with k , indicating the coexistence of two instability mechanisms — one associated with the inner rectangular body and one governed by the effective outer contour of the porous screen — rather than an abrupt regime change. This dual-frequency behaviour is consistent with the experimental observations of Catania et al. [2, 21], who reported a similar

split spectrum on the rigid porous configuration at the same aspect ratio.

5.3.2.7 POD Mode Shapes

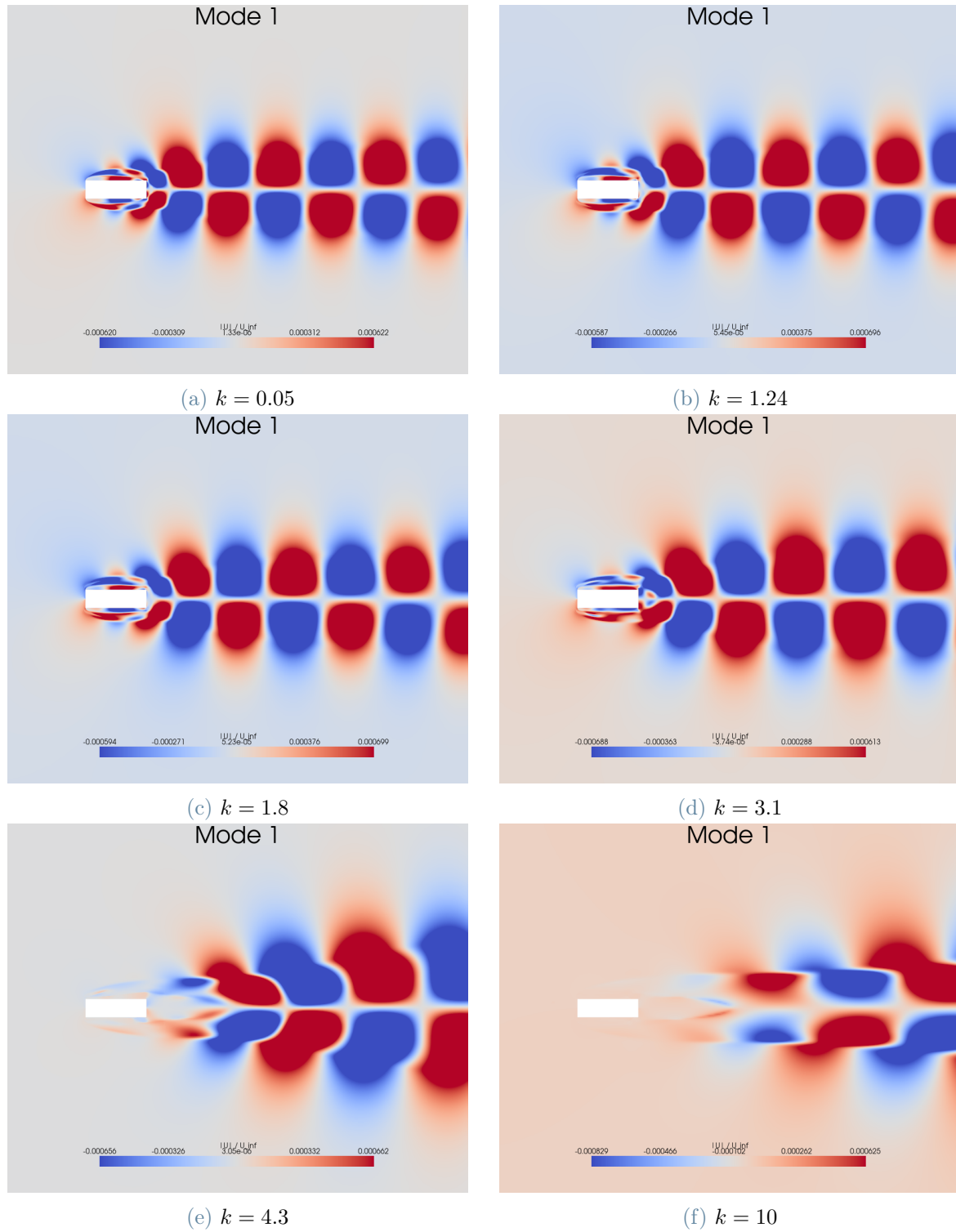


Figure 5.31: First POD mode for various values of k .

The dominant POD modes for the six values of k are shown in Figure 5.31. In all cases, the leading mode retains an antisymmetric structure with respect to the wake centreline, confirming that the alternating shedding mechanism is not destroyed by the porous layer. The differences are quantitative rather than qualitative.

At $k = 0.05$, the mode shape closely resembles the naked-prism dominant mode of Section 5.1, with compact, well-defined high-magnitude lobes in the near wake and a sharp antisymmetric pattern. As k increases, the shear-layer regions thicken, these lobes become broader and less compact, and the mode footprint extends further upstream into the porous slab. At $k = 10$, the leading mode retains its antisymmetric character, but the shedding pattern is markedly less coherent, with the lobes blurring into each other and the wake widening in the cross-flow direction.

The broadening of the high-magnitude regions in the mode shape indicates that the velocity fluctuations — and, by extension, the underlying vorticity production — are spread over a wider region rather than concentrated in compact roll-up zones. This is the spatial manifestation of the lift attenuation observed in Figure 5.21.

5.3.2.8 POD Energy Distribution and Spectral Content

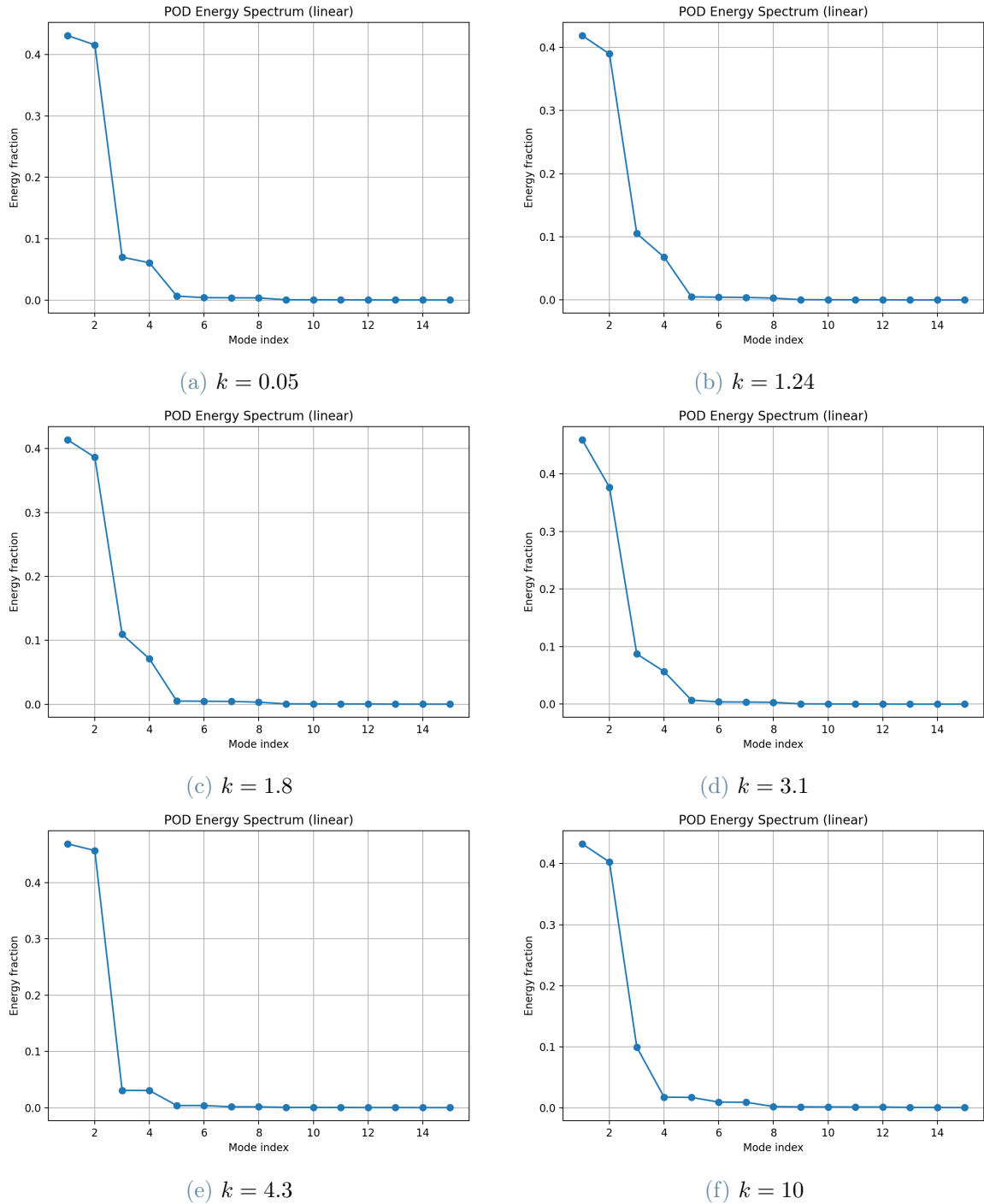


Figure 5.32: POD energy spectrum for various k .

The POD energy spectra for the six values of k are reported in Figure 5.32. At $k = 0.05$, the leading mode pair concentrates approximately the same fraction of the total fluctuating energy as in the naked baseline. As k increases, the energy fraction carried by the leading modes decreases, and the spectrum decays more slowly, indicating that an increasing share of the energy is distributed across higher-order modes.

The temporal spectra of the first POD mode for all simulated values of k are overlaid in Figure 5.33. Three observations follow from this comparison. First, the dominant peak shifts continuously towards lower Strouhal numbers as k increases, confirming the trend already visible in the force spectra. Second, the amplitude of the dominant peak decreases monotonically with increasing k , consistent with the attenuation of the modal energy fraction carried by the leading pair. Third, the spectral content broadens: as k increases the peak becomes less sharp and the off-peak baseline rises, indicating that a larger share of the modal activity is distributed across a wider frequency band.

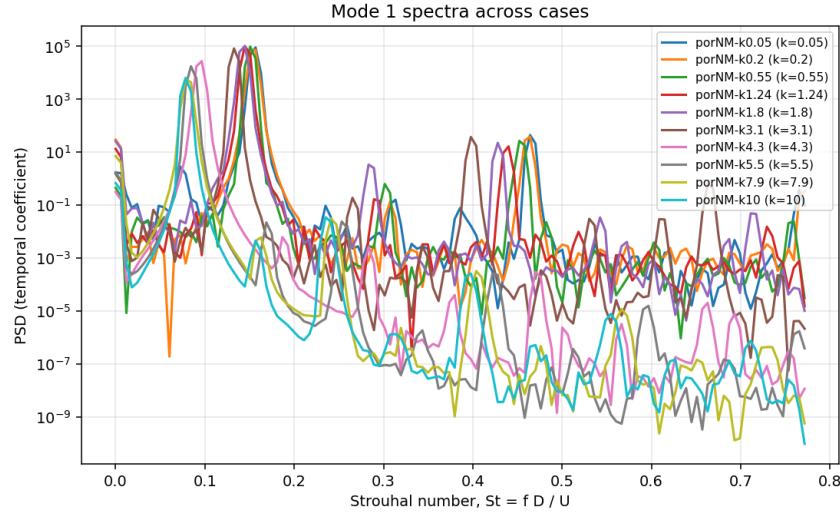


Figure 5.33: Temporal power spectral density of the first POD mode for various values of k .

Together, the mode shapes, the energy spectra, and the temporal mode spectra describe the same underlying mechanism. Increasing the pressure-loss coefficient weakens the dominant large-scale structure, redistributes vorticity production over a wider region, and disperses modal energy across higher-order modes and across a broader frequency range. The result is a less coherent, less concentrated, and lower-amplitude forcing acting on the body — the same forcing that, in the naked case, was responsible for driving lock-in.

5.4 Imposed Oscillations on the Porous Configuration

In the second stage of the analysis, sinusoidal cross-flow oscillations are imposed on the porous configuration to determine whether the modifications observed in the rigid case persist when the body is forced to move, and to identify whether motion-induced synchronisation can still be established despite the weakened intrinsic shedding.

A representative pressure-loss coefficient $k = 1.8$ is selected for this analysis, matching the experimental value of Catania et al. [2]. Three forcing frequencies are considered, chosen to mirror the regime classification adopted for the naked prism in Section 5.2:

- Sub-critical forcing: $f = 0.75 f_{n,p}$;
- Near-resonant forcing: $f \approx f_{n,p}$;
- Super-critical forcing: $f = 1.25 f_{n,p}$,

where $f_{n,p}$ denotes the dominant shedding frequency of the porous configuration in the rigid case at the same k , as identified in Figure 5.30c. Using $f_{n,p}$ rather than the naked-prism f_n as the reference frequency ensures that the regimes investigated here are directly comparable to those of Section 5.2 from a physical point of view, since the relevant intrinsic frequency is that of the actual porous configuration.

5.4.1 Global Response and Force Spectra

The standard deviation of the lift coefficient and the mean drag coefficient as a function of forcing frequency are reported in Figure 5.34. Across all three regimes, σ_{C_L} of the porous configuration is reduced relative to the naked case at the same reduced frequency. The reduction is most pronounced in the sub-critical and super-critical regimes; near resonance, σ_{C_L} recovers towards the naked lock-in value but remains below it.

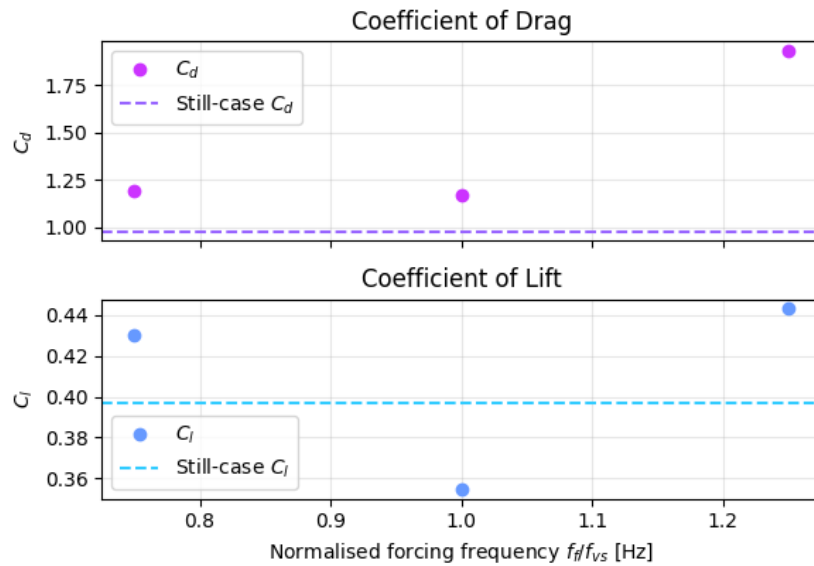


Figure 5.34: Standard deviation of the lift coefficient and mean drag coefficient as a function of forcing frequency, for the porous configuration ($k = 1.8$) compared with the naked baseline.

The lift force spectra (Figure 5.35) clarify the underlying mechanism.

In the sub-critical case, two distinct peaks coexist: one at the imposed forcing frequency f and one at $f_{n,p}$. The peak at $f_{n,p}$ is broader and lower than the corresponding peak in the rigid porous case (Figure 5.30c), indicating that the imposed motion partially disorganises the porous-layer instability without fully suppressing it.

In the near-resonant case, the spectrum collapses to a single dominant peak at f . Compared with the naked lock-in spectrum of Section 5.2, the harmonic content is weaker, and the peak amplitude is lower. Lock-in is therefore achieved, but with reduced spectral purity, consistent with the weakened intrinsic forcing.

In the super-critical case, the spectrum exhibits a dominant peak at f and a secondary, broader peak near $f_{n,p}$. The persistence of this secondary peak mirrors the dual-frequency signature of the naked super-critical case but with a globally lower amplitude.

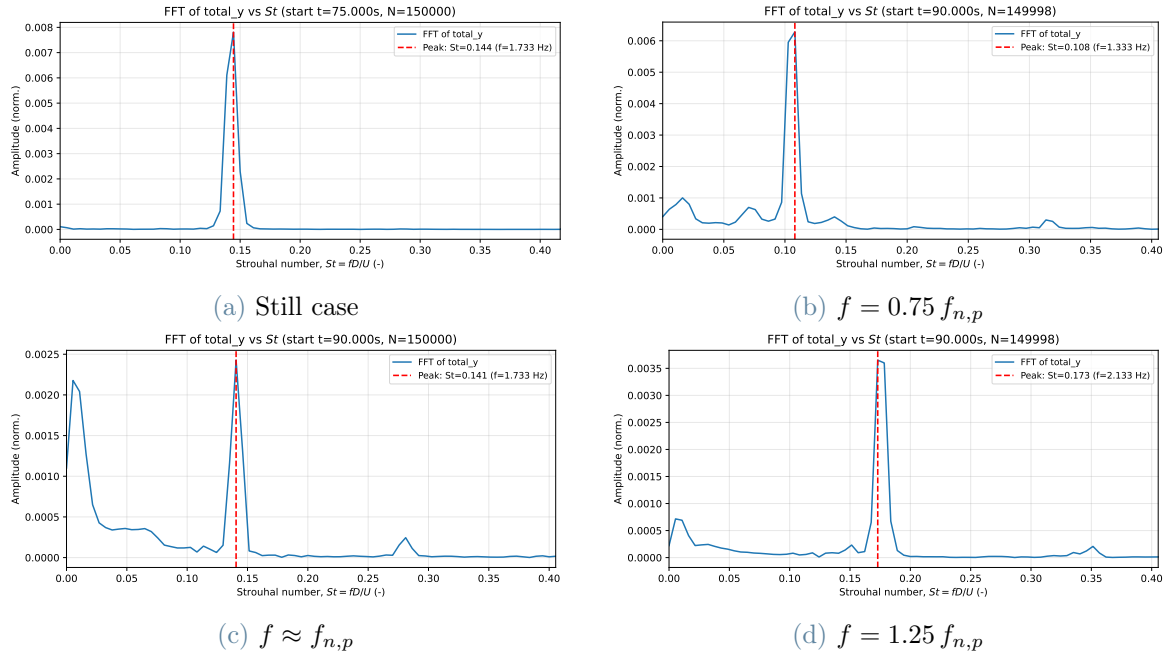


Figure 5.35: Power spectral density of the lift force for the porous configuration ($k = 1.8$) under the three forcing regimes.

5.4.2 Mean Gap-Flow Topology

Beyond the integrated force statistics, the time-averaged fields in the gap reveal how the imposed motion reshapes the cavity flow established in the rigid case. Figures 5.36 and 5.37 show the mean pressure coefficient $\overline{C_p}$ and the mean streamwise velocity $\overline{U_x}/U_\infty$ in the gap region for the three forcing regimes, with the mean streamlines and the $\overline{U_x} = 0$ separation contour (dashed) superimposed. Each field is averaged over an integer number of forcing periods, so the structures shown represent the persistent mean topology rather than any instantaneous phase.

In the rigid configuration at the same $k = 1.8$ (Section 5.3.2.2, Figure 5.24), the gap is occupied by a single, steady recirculation cell seated on the roof, with a moderate suction plateau and a shallow band of reverse flow bounded by a smooth $\overline{U_x} = 0$ arch. This single-cell topology is the reference against which the forced cases are read.

In the sub-critical case ($f = 0.75 f_{n,p}$), the single-cell topology of the rigid case is preserved but smeared. The recirculation broadens, and its core sits near mid-chord ($x \approx 0.45$), while the reverse-flow band remains shallow and weak ($\overline{U_x}/U_\infty \gtrsim -0.17$). This is the mean-field counterpart of the broader, less compact high-magnitude lobes noted for the POD modes (Figure 5.38): the imposed motion perturbs but does not restructure the rigid gap recirculation.

In the near-resonant case ($f \approx f_{n,p}$), the recirculation reorganises. A weaker leading cell forms over the upstream half of the roof while the dominant core migrates downstream (to $x \approx 0.6$) and the reverse flow deepens locally ($\overline{U_x}/U_\infty \approx -0.3$). The downstream displacement of the recirculation core mirrors the downstream shift of vortex roll-up identified in the POD analysis at lock-in, and the stronger mean reverse flow is consistent with the partial recovery of σ_{CL} towards the naked lock-in value.

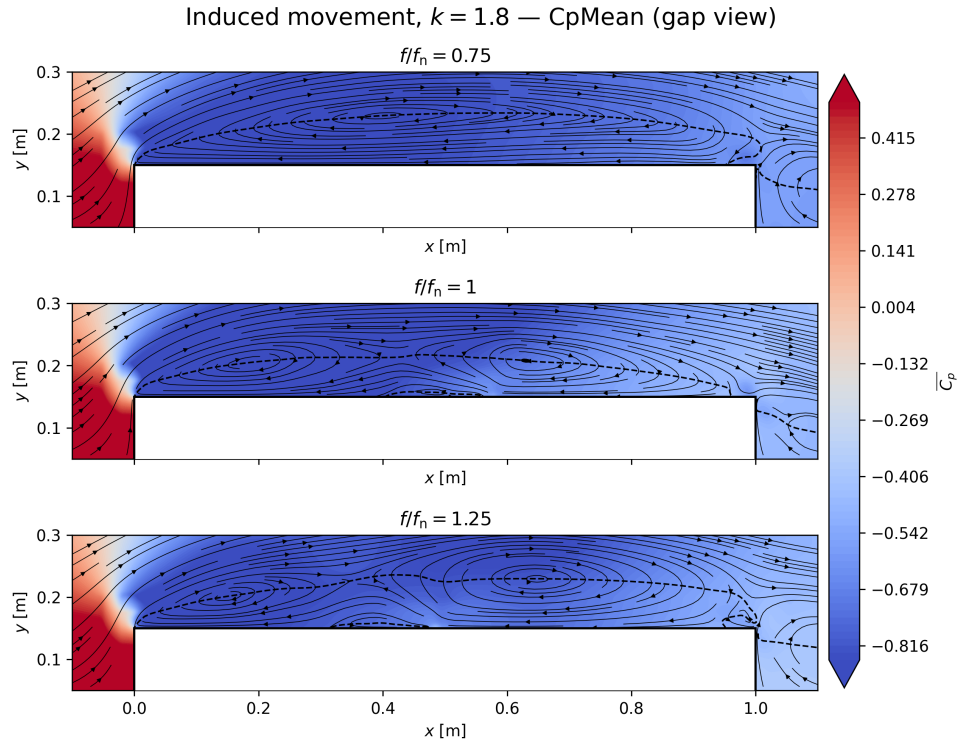


Figure 5.36: Mean pressure coefficient $\overline{C_p}$ in the gap region of the porous configuration ($k = 1.8$) under the three forcing regimes. Dashed line: $\overline{U}_x = 0$ separation contour.

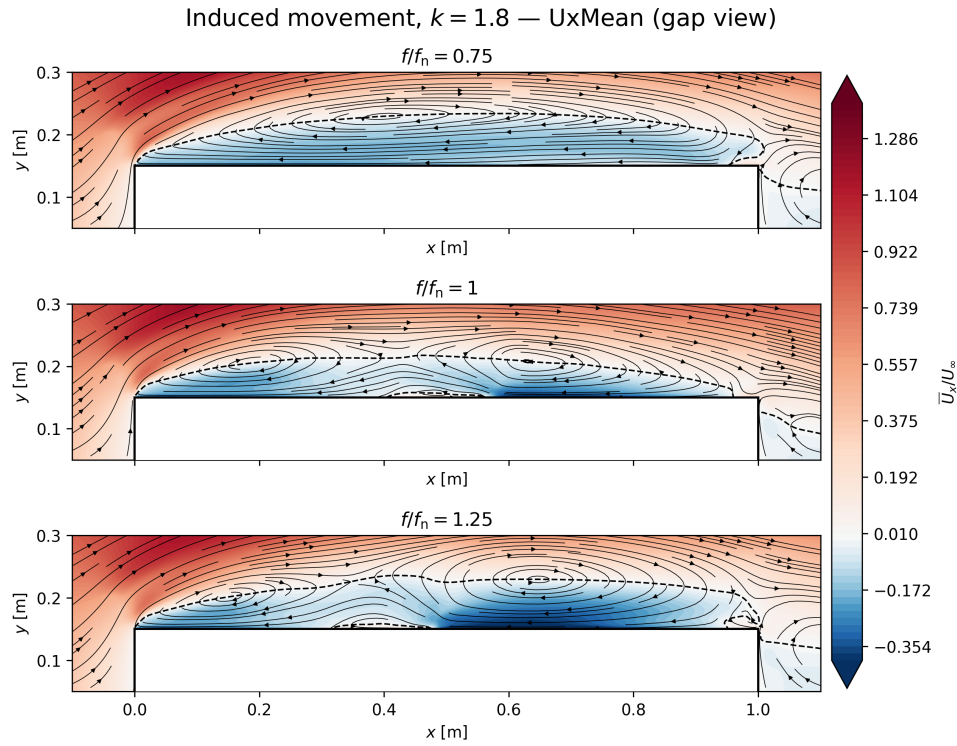


Figure 5.37: Mean streamwise velocity $\overline{U}_x/U_\infty$ in the gap region of the porous configuration ($k = 1.8$) under the three forcing regimes. Blue denotes reverse flow; the dashed line marks the $\overline{U}_x = 0$ boundary of the recirculation.

In the super-critical case ($f = 1.25 f_{n,p}$), the gap flow is most strongly modified. The single cell fragments into a two-cell pattern separated by a saddle near mid-chord, and the reverse-flow lobe is both the deepest (approaching $\bar{U}_x/U_\infty \approx -0.35$) and the most spatially extended of the three regimes. This fragmented mean topology is the time-averaged signature of the mixed, dual-frequency wake organisation reported for the lift spectra and POD modes in the super-critical regime.

Read together, the gap fields show that the imposed oscillation does not suppress the recirculation established by the porous screen at $k = 1.8$; it modulates it. Off resonance, at sub-critical forcing, the rigid single-cell topology is broadly retained but smeared, whereas the mean reverse-flow magnitude and the spatial complexity of the cavity recirculation increase with forcing frequency, reaching their maximum in the super-critical regime. This reinforces the central observation of this section: the porous layer sets the underlying gap-flow structure, and motion-induced forcing reshapes it.

5.4.3 Flow Structures

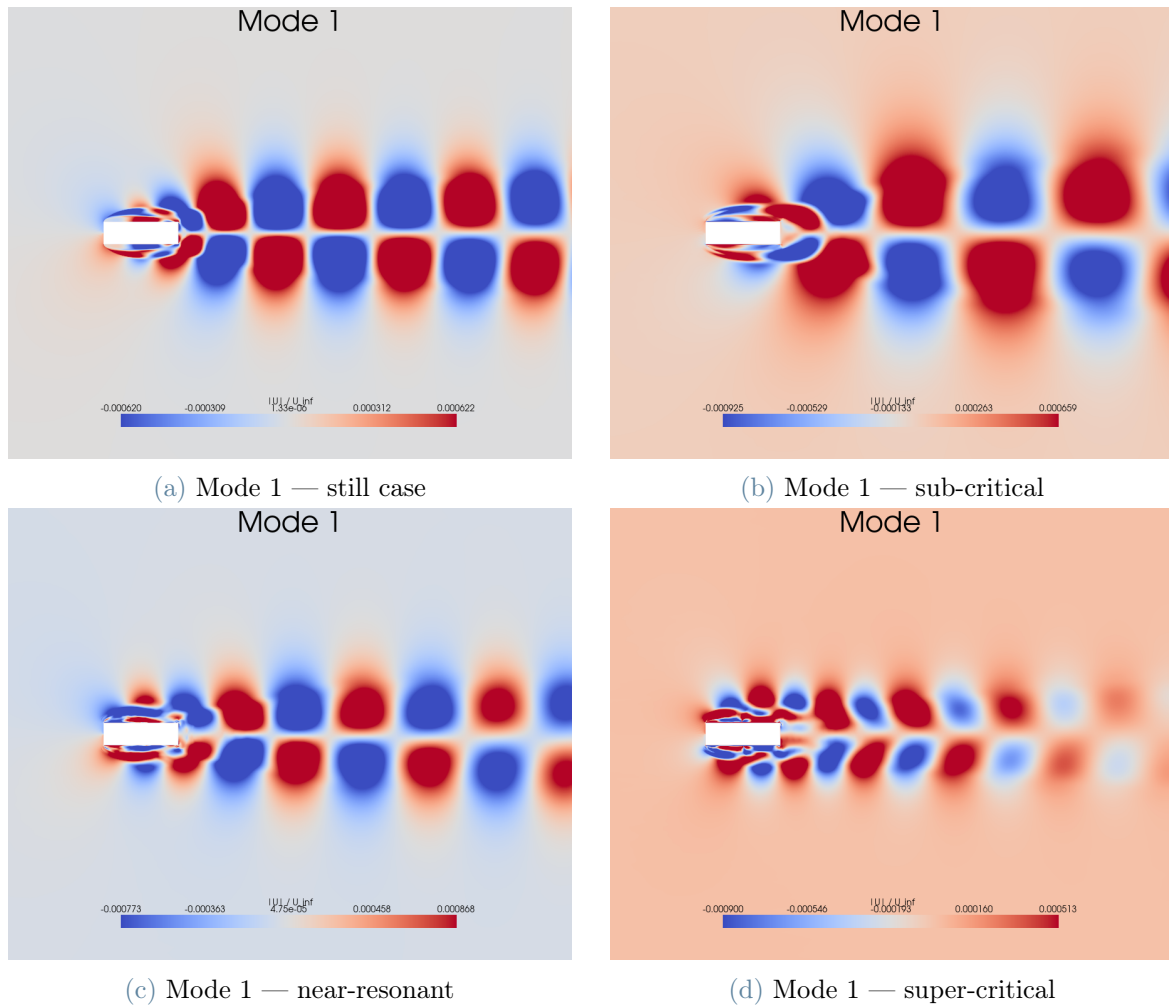


Figure 5.38: Dominant POD mode of the porous configuration ($k = 1.8$) for the three forcing regimes.

The dominant POD modes for the three forcing regimes are shown in Figure 5.38. The wake topology evolves through the three regimes following the same qualitative pattern observed for the naked case in Section 5.2.

In the sub-critical case, the wake retains an antisymmetric organisation, but the high-magnitude lobes are noticeably broader and less compact than in the corresponding naked case, and the shear-layer regions extend further upstream into the porous slab.

In the near-resonant case, the leading mode pair reorganises into a coherent vortex street that is topologically similar to the naked lock-in regime, but with vortex roll-up shifted further downstream and with reduced peak velocity-fluctuation amplitude in the leading mode. The synchronisation mechanism remains operative, but the porous layer alters the spatial location and the intensity of vortex formation.

In the super-critical case, the leading modes exhibit the same diagonal, mixed-pattern structure observed for the naked super-critical regime, but with weaker spatial gradients. The same regime transition occurs around $f_{n,p}$ as occurred around f_n for the naked case, with the porous screen primarily modulating the amplitude rather than the qualitative topology.

5.4.4 POD Energy Redistribution

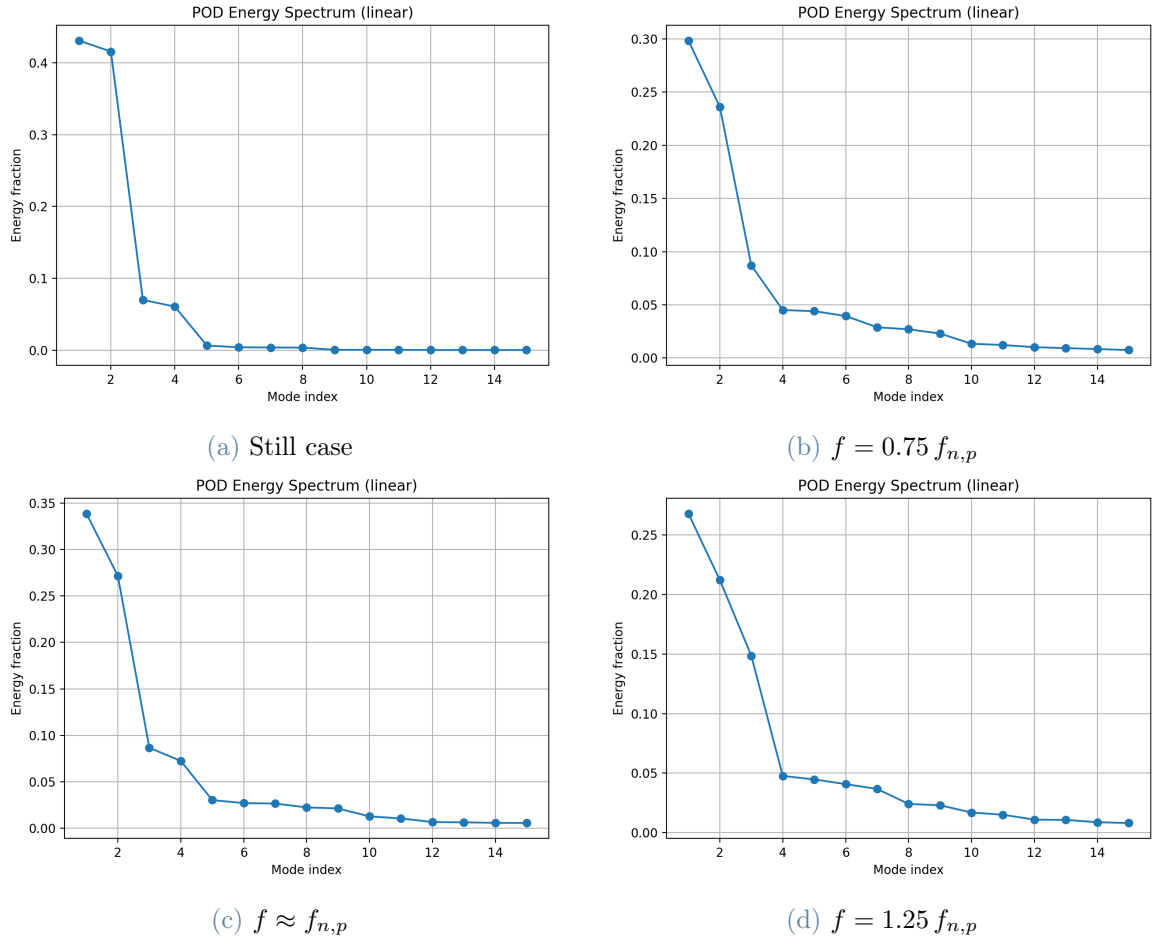


Figure 5.39: Energy spectrum of POD modes for the porous configuration ($k = 1.8$) under the three forcing regimes and the still case as reference.

The POD energy spectra for the three porous forced cases are shown in Figure 5.39. In the near-resonant case, the leading mode pair concentrates a fraction of the total energy comparable to the naked lock-in case, although a slightly larger share leaks into the higher-order modes, consistent with the additional broadband content introduced by the porous layer. In both off-resonance cases, modal energy is more evenly spread across higher-order modes than in the corresponding naked configurations.

The temporal spectra of the first POD mode (Figure 5.40) confirm the same picture: at resonance, a single dominant peak at f with weaker harmonics; off resonance, dual-peak spectra with energy split between f and $f_{n,p}$.

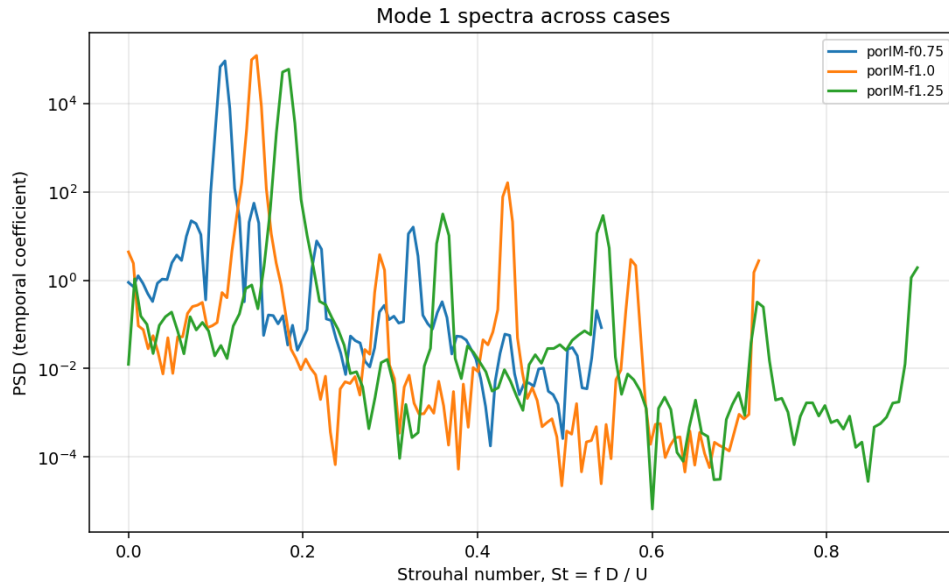


Figure 5.40: Power spectral density of the first POD mode for the porous configuration ($k = 1.8$) under the three forcing regimes.

5.4.5 Comparative Summary

The main features of the naked and porous configurations across the three forcing regimes are summarised in Table 5.4.

	Naked	Porous ($k = 1.8$)
Sub-critical: dominant lift peak	f and f_n (dual)	f and $f_{n,p}$ (dual)
Sub-critical: σ_{CL}	reference	reduced
Lock-in: dominant lift peak	f	f
Lock-in: σ_{CL}	maximum	reduced relative to naked
Lock-in: POD energy concentration	maximum	high, slightly lower
Super-critical: dominant lift peak	f and f_n (dual)	f and $f_{n,p}$ (dual)
Super-critical: σ_{CL}	reduced	reduced further

Table 5.4: Summary of wake characteristics for the naked and porous configurations across forcing regimes.

The central observation is that the porous layer does not prevent motion-induced synchronisation when the forcing frequency is close to the natural shedding frequency of the porous configuration.

The lock-in mechanism remains active, but operates at a reduced absolute amplitude and with reduced spectral coherence. Outside the synchronisation range, the porous layer significantly reduces both the lift fluctuations and the modal coherence of the wake.

Combined with the rigid-body pressure-loss-coefficient (k) sweep, this completes the picture introduced at the beginning of this section. The porous façade modifies the intrinsic shear-layer instability of the body, weakening the spontaneous forcing that initiates VIV; it does not, however, alter the underlying mechanism by which synchronisation, once established, sustains itself. This distinction is central to the engineering interpretation developed in Chapter 6.

Whereas the POD modes of Figure 5.38 summarise the dominant wake structures in a statistical sense, Figure 5.41 resolves the instantaneous pressure field through one full period for each regime, so that the phase-by-phase evolution of the gap and near wake can be compared directly. The colour scale is identical in every panel, and the porous cladding is drawn as a semi-transparent frame; the nine phases (1)–(9) are those marked on the corresponding $C_L(t)$ curve, taken over the natural shedding period in the still case and over the forcing period in the three forced cases. In all four regimes, the windward face carries a steady stagnation overpressure that varies little over the cycle, so the periodic dynamics are carried almost entirely by the alternating suction structures on the roof and in the near wake.

In the still case, the suction lobes form alternately at the upper and lower trailing edges and convect downstream as a regular, antisymmetric street, with cores of moderate intensity and nearly uniform spacing — the spontaneous $2S$ shedding of the porous body and the reference against which the forced cases are read.

Under sub-critical forcing ($f = 0.75 f_{n,p}$), the same alternating arrangement is retained, but the suction cores are visibly broader and paler than in the still case, and their progression no longer repeats identically from one phase sequence to the next. This loss of phase regularity is the instantaneous footprint of the two coexisting frequencies f and $f_{n,p}$ identified in the lift spectrum (Figure 5.35b), and it is the phase-resolved counterpart of the smeared single-cell mean topology of Figure 5.37.

Near resonance ($f \approx f_{n,p}$), the wake is the most coherent and intense of the four. Compact, deep suction cores form close to the body — on the roof and immediately behind the trailing edge — and are shed in a clean alternating sequence, the instantaneous signature of a well-synchronised vortex street. The heightened intensity and organisation are consistent with the single dominant peak of the lift spectrum (Figure 5.35c) and with the partial recovery of σ_{C_L} towards the naked lock-in value, while the downstream location of the dominant core matches the mean-field reorganisation reported in Section 5.4.2.

Under super-critical forcing ($f = 1.25 f_{n,p}$) strong cores still form near the body, but the near wake is markedly more fragmented: several smaller-scale structures coexist within a single phase, and the alternation is far less regular from one phase to the next. This disordered, multi-scale organisation is the instantaneous expression of the mixed, dual-frequency wake reported for the lift spectrum (Figure 5.35d) and of the two-cell mean topology of Figure 5.37.

Read together, the phase-resolved fields confirm the picture built from the force spectra and mean fields: the porous layer does not suppress the periodic wake dynamics but modulates their intensity and coherence, which are greatest when the forcing is tuned to $f_{n,p}$ and progressively disrupted as the forcing moves off resonance.

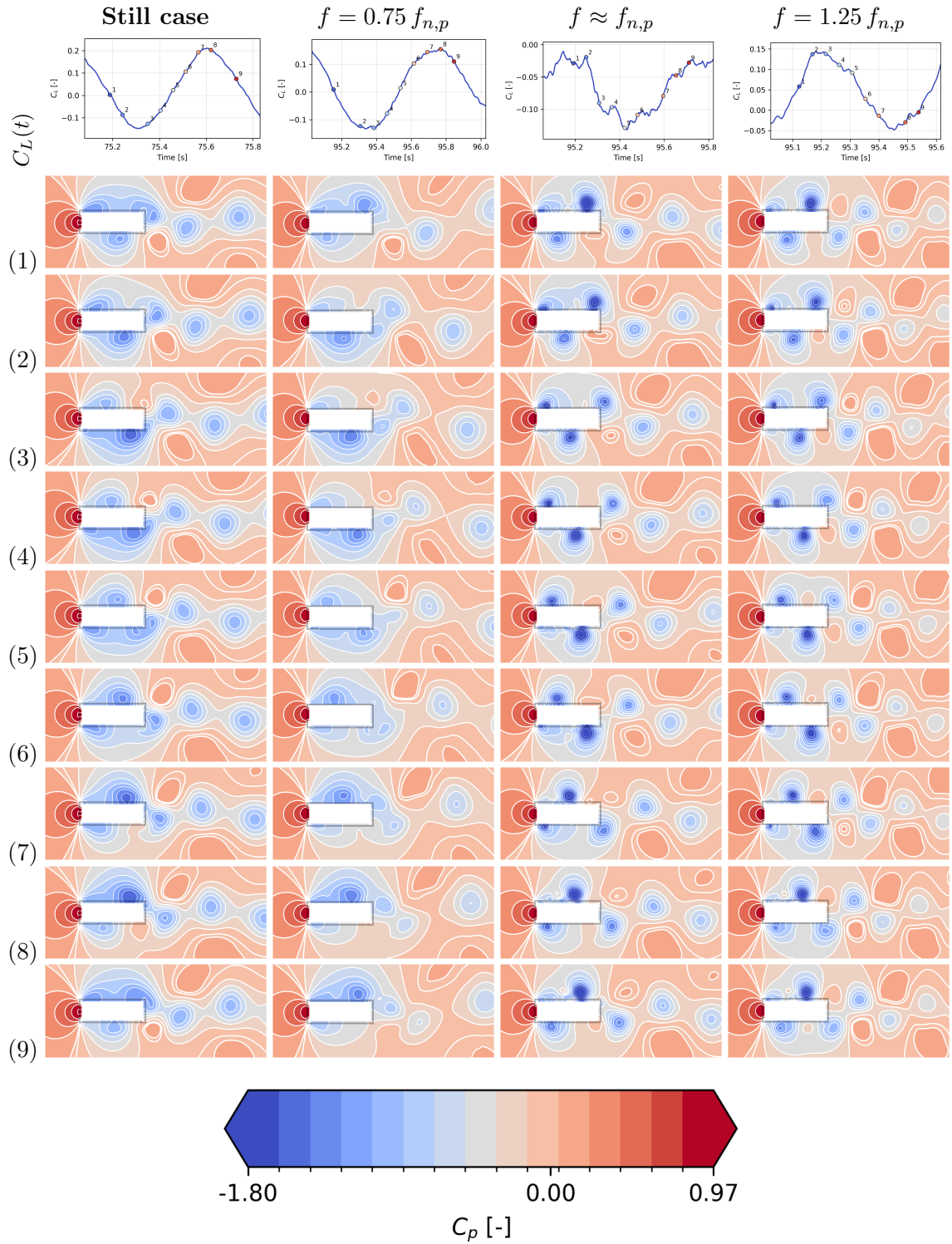


Figure 5.41: Instantaneous C_p field with white iso- C_p lines through one period for the porous configuration ($k = 1.8$): the still case compared with the three forcing regimes. Rows (1)–(9) are the nine equally spaced phases marked on the $C_L(t)$ curves in the top row (the still column uses the natural shedding period, the forced columns the forcing period). The semi-transparent black frame marks the porous cladding; the colour scale is identical in every panel.

6 | Conclusions and Perspectives

This work investigated the aerodynamic behaviour of a rectangular prism with aspect ratio $B/D = 3.33$, with particular emphasis on the transition from vortex shedding to vortex-induced vibrations (VIV) and on the role of a permeable double-skin façade (PDSF) in modifying this process. A two-dimensional URANS framework was combined with proper orthogonal decomposition (POD) to analyse rigid, forced-oscillation, and porous configurations within a single, internally consistent numerical setup, validated against canonical bluff-body cases and benchmarked against a dedicated wind-tunnel campaign. The porous screen was represented through a Darcy–Forchheimer momentum sink governed by a single pressure-loss coefficient k , fixed to the experimentally calibrated value ($k = 1.8$) for the comparison with wind-tunnel data and varied parametrically — from an open, near-naked limit ($k \rightarrow 0$) to a resistive, near-solid limit ($k = 10$) — to isolate the effect of screen resistance.

6.1 Summary of Main Findings

Naked rigid configuration

The rigid-body simulations of the $B/D = 3.33$ prism reproduced the aerodynamic features expected for an aspect ratio sitting in the transitional impinging-leading-edge-vortex (ILEV) regime between pure leading-edge shedding and stable trailing-edge reattachment [3, 13, 4, 31]. Placed within an aspect-ratio sweep bracketed by the square cylinder and the elongated $B/D = 5$ prism, the $B/D = 3.33$ section exhibited intermediate global coefficients: a mean drag coefficient $C_D \approx 0.85\text{--}0.90$ and a Strouhal number $St \approx 0.15$, both within the range reported in the literature for this aspect ratio. The wake was dominated by a single antisymmetric mode pair, consistent with classical alternating shedding, but with broader spectral peaks and slower POD energy decay than in the fully reattached $B/D = 5$ case. These features confirm the intermediate, intermittently reattaching nature of the wake.

A Reynolds number sweep across the investigated range showed negligible variation of C_D , σ_{C_L} , and St , and an essentially invariant POD spectrum. The dominant shedding mechanism is therefore dynamically self-similar within the regime considered, justifying single- Re comparisons for the remainder of the study.

The validation cases on the square cylinder and the $B/D = 5$ prism, which bracket the transitional regime of interest, reproduced the established trends in C_D , σ_{C_L} , and St to within reported experimental scatter [3, 13, 4, 29].

Forced oscillations on the naked prism

Imposed sinusoidal motion was applied at forcing frequencies between $0.5 f_n$ and $2 f_n$. Three distinct wake regimes were identified:

- *Sub-critical forcing* ($f < f_n$): the wake retained a classical 2S shedding pattern [18]. The POD spectrum was dominated by the intrinsic shedding frequency, with the forcing acting as a weak perturbation. The first mode pair concentrated the majority of the fluctuating energy.
- *Lock-in* ($f \approx f_n$): the shedding frequency synchronised with the imposed motion. POD energy became strongly concentrated in the leading conjugate pair, and the lift spectrum collapsed to a sharp peak at f together with its harmonics. The drag coefficient reached its maximum near resonance.
- *Super-critical forcing* ($f > f_n$): the wake transitioned toward a mixed-mode regime exhibiting features of both 2S and P+S shedding [18]. Modal energy was redistributed across several POD modes, and the lift spectrum showed competing peaks at both f and f_n , indicating incomplete synchronisation.

The combined force and modal analysis revealed a monotonic relationship between modal coherence and aerodynamic amplification: peak lift fluctuations coincided with maximum modal dominance during lock-in, while spectral and modal dispersion in the super-critical regime were associated with reduced peak amplitude.

Porous configuration: pressure-loss-coefficient sweep

A parametric study on the pressure-loss coefficient k of the porous screen, performed on the rigid model, revealed a continuous and monotonic transition between the open, near-naked limit ($k \rightarrow 0$) and the resistive, near-solid limit ($k = 10$):

- Lift fluctuations were progressively attenuated as k increased, dropping by roughly an order of magnitude between the most open case ($k \lesssim 0.2$, which recovers the naked prism) and the most resistive case ($k = 10$).
- The dominant Strouhal number shifted from $St \approx 0.15$ at low k (open screen, near-naked) towards $St \approx 0.08$ at high k (resistive screen), indicating that, as the screen is made more resistive, the effective separation contour is progressively governed by the outer envelope rather than by the inner sharp edges. Across this range, k behaves as an effective elongation ratio, tuning the apparent slenderness of the prism within the narrow band $3.00 \leq B/D \leq 3.33$.
- For intermediate k , the lift spectrum showed two distinct peaks, signalling the coexistence of an inner-body shedding mechanism and an outer-screen instability with comparable energy content. This dual-frequency behaviour is consistent with the experimental observations of Catania et al. [2, 21].
- The leading POD mode lost spatial coherence as k increased: the vortices became broader and less compact, and modal energy was redistributed across higher-order modes.

- A control-volume decomposition of the mean drag showed that the total load on the building–screen ensemble remained of order unity and only weakly dependent on k , while its partitioning changed markedly: as k increased, the porous screen intercepted a growing share of the incoming momentum and the load on the inner prism dropped correspondingly.

These integral trends were corroborated by the time-averaged fields and the experimental benchmark: as k increased, the mean recirculation migrated downstream and broadened — the kinematic counterpart of the Strouhal-number reduction — and the inner-façade pressure fluctuations flattened, in close agreement with the measurements of Catania et al. [21]. The benchmark reproduced the mean drag and lift fluctuations within the scatter expected of a two-dimensional URANS model.

Taken together, these results show that the porous screen redistributes vorticity production over a wider region and dissipates part of the momentum that would otherwise feed coherent shedding, weakening the spontaneous forcing without destroying the alternating mechanism that generates it.

Porous configuration: forced oscillations

When sinusoidal motion was imposed on the porous configuration at $k = 1.8$, the wake behaviour depended strongly on the proximity of the forcing frequency to the modified shedding frequency of the porous case, $f_{n,p}$. Near resonance, the system reorganised into a synchronised state qualitatively similar to that of the naked prism under lock-in, with concentrated POD energy and a single dominant force peak, although with reduced absolute amplitude and lower spectral purity. Away from resonance, the wake retained a mixed spectral signature, with competing contributions from screen-driven shedding and imposed motion. The time-averaged gap flow confirmed this picture: the single roof-mounted recirculation cell of the rigid case was smeared but preserved under sub-critical forcing, reorganised with a downstream-shifted core at resonance, and fragmented into a two-cell pattern under super-critical forcing — the mean-field signature of the regime transitions identified in the spectra and POD modes.

This indicates that the porous layer acts primarily on the *intrinsic* instability mechanism, weakening the coherence of self-sustained shedding, but does not prevent motion-induced synchronisation once a sufficiently energetic oscillation is established.

6.2 Interpretation and Implications

The results distinguish two mechanisms that are often conflated in the discussion of VIV mitigation: the intrinsic shear-layer instability that drives vortex shedding around a stationary body, and the motion-induced synchronisation that sustains large-amplitude oscillations of an aeroelastically responsive structure. The porous layer modifies the first by attenuating vorticity production and broadening the separated shear layers, which reduces the spatial and temporal coherence of the aerodynamic forcing during the initial cycles of motion. This is reflected both in the attenuation of σ_{C_L} and in the redistribution of POD energy away from the leading mode pair as the screen is made more resistive.

Once structural motion is established and reaches sufficient amplitude, however, the coupled fluid–structure system can still reorganise into a synchronised regime that locks onto the imposed

displacement. In this regime, the porous façade modifies the absolute force levels and the wake topology, but the underlying lock-in mechanism remains active. This explains the experimental observation of Catania et al. [2] that the onset of VIV in porous configurations is markedly dependent on initial conditions: under build-up conditions, the weakened forcing fails to ignite lock-in, while under externally perturbed conditions, the system can still synchronise.

From an engineering standpoint, the PDSF therefore acts as a *threshold-raising* mitigation device rather than as a universal suppression mechanism. Reducing the coherence of the stationary-body forcing, it increases the effective excitation level required for spontaneous VIV onset, which is the relevant scenario for slender high-rise buildings exposed to atmospheric wind. This conditional behaviour should be acknowledged when porous envelopes are considered as a mitigation strategy: the design should target the onset regime, not simply the post-onset amplitude. The mean-drag decomposition adds a second, complementary design consideration: across the full range of k , the screen behaves as a load-bearing aerodynamic element, shielding the inner structure but carrying a substantial fraction of the wind load itself, which must then be transferred to the screen anchorages.

6.3 Limitations and Future Work

Several limitations of the present study should be made explicit so that the scope of the conclusions is properly delimited.

The CFD framework was two-dimensional and based on URANS turbulence modelling. This formulation cannot capture spanwise decorrelation of vortex shedding nor the three-dimensional shear-layer instabilities that influence the absolute magnitude of fluctuating forces on slender prisms [34, 4]. This is reflected in the systematic underprediction of C_D and overprediction of σ_{C_L} relative to the wind-tunnel measurements of Chapter 4. For the naked configuration, the Strouhal number and the qualitative wake topology are nonetheless reproduced accurately. For the porous configuration, however, the simulations resolve the higher-frequency shedding branch associated with the inner prism, whereas the experimental dominant peak corresponds to the lower-frequency branch governed by the outer porous envelope; the absolute porous Strouhal number, therefore, cannot be quantitatively compared without a three-dimensional formulation. The trends with k and forcing frequency are expected to be representative, but absolute force levels and the dominant porous frequency should be interpreted with these caveats.

The porous layer was represented through a homogenised Darcy–Forchheimer momentum sink with a single pressure-loss coefficient k , following the reduced-order approach of Pomaranzi et al. [20]. This formulation reproduces the integrated pressure drop across the screen but does not resolve the pore-scale flow, jet-like emissions on the inner side of the screen, or the directional anisotropy of the resistance for skewed incidence angles. Recent work on pressure–velocity jump conditions and lamellar screens [37, 38] suggests that more sophisticated formulations may be required when local pressure distributions on the inner façade or cavity ventilation are of primary interest.

The study was restricted to a single aspect ratio ($B/D = 3.33$), a fixed cavity width, and a uniformly distributed screen porosity. The transitional ILEV regime characteristic of this geometry is particularly sensitive to small modifications of the separating shear layers, so the trends reported here cannot be directly extrapolated to fully separated ($B/D \lesssim 2$) or fully reattached ($B/D \gtrsim 5$) configurations without further investigation.

Finally, the imposed-motion approach used here decouples structural dynamics from the aerodynamic response. While this is appropriate for isolating the aerodynamic mechanisms of the porous layer, a fully coupled fluid–structure simulation would be needed to capture the build-up and saturation of free oscillations and to determine the modified critical Scruton number — the mass–damping parameter governing VIV susceptibility — of porous configurations.

Future work should therefore extend the analysis along several complementary directions:

- three-dimensional LES simulations to assess spanwise coherence effects, recover absolute force levels, and resolve the outer-envelope shedding branch that dominates the experimental porous spectra;
- fully coupled aeroelastic simulations to quantify the effective Scruton number threshold under porous envelopes and to reproduce the initial-condition dependence observed experimentally [2];
- parametric studies on cavity width, porosity distribution, and porosity orientation, including non-uniform layouts that may locally exploit shear-layer dynamics;
- refined porous models with pressure–velocity jump or anisotropic resistance formulations [37] to better capture inner-façade pressure distributions relevant for cladding design;
- extension to atmospheric inflow conditions, including turbulence intensity and integral length scales representative of urban environments.

Final Remarks

The contribution of this thesis is twofold. First, it provides a controlled numerical characterisation of the vortex-shedding and forced-oscillation response of a $B/D = 3.33$ rectangular prism, quantifying how modal coherence and aerodynamic forcing co-evolve across the sub-critical, lock-in, and super-critical regimes. Second, it isolates the aerodynamic role of a permeable double-skin façade within the same framework, showing that the screen raises the threshold for spontaneous VIV onset rather than suppressing the synchronised state once it is established. These results provide a physically interpretable basis for the design and assessment of permeable envelopes on slender structures, and a starting point for the three-dimensional, fully coupled, and experimentally validated studies outlined above.

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List of Symbols

Variable	Description	SI unit
Geometric quantities		
A	Oscillation amplitude	m
A_{ref}	Reference area used for force normalisation, $A_{\text{ref}} = h d_{\text{bare}}$	m ²
$AR, B/D$	Aspect ratio of the rectangular section	–
B	Along-wind dimension of the section	m
D	Cross-wind dimension of the section	m
d_{bare}	Cross-wind dimension of the bare (inner) prism	m
h	Height of the section used for force normalisation	m
H	Total height of the building model	m
H/B	Height-to-width ratio of the model	–
x, y, z	Streamwise, cross-flow, and vertical coordinates	m
Flow quantities and dimensionless numbers		
f	Frequency (generic)	Hz
f_n	Natural frequency of the structure	Hz
$f_{n,p}$	Dominant shedding frequency of the porous configuration	Hz
f_s, f_v, f_{vs}	Vortex shedding frequency (used interchangeably)	Hz
p	Static pressure	Pa
$\mathbf{U}, U$	Velocity vector / its magnitude	m/s
U_{∞}	Free-stream velocity	m/s
$\overline{U}_x$	Mean (time-averaged) streamwise velocity component	m/s
U_{cr}	Critical wind speed for VIV onset	m/s
U^*, U_r, U_R	Reduced velocity, $U_{\infty}/(f_n D)$	–
Re	Reynolds number, $\rho U_{\infty} D / \mu$	–
Sc	Scruton number, $2\pi m_1 \xi_1 / (\rho B D)$	–
St	Strouhal number, $f_s D / U_{\infty}$	–
I_u	Streamwise turbulence intensity, $\sqrt{u'^2}/U$	–
Co, Co_{max}	Courant number and its maximum over the domain	–
y^+	Dimensionless wall distance (near-wall resolution)	–
Aerodynamic coefficients		
C_D	Drag coefficient	–
$\overline{C_D}, C_{D,m}$	Time-averaged drag coefficient	–
C_D^{inner}	Drag coefficient on the inner prism	–
C_D^{outer}	Drag coefficient on the outer porous envelope	–
C_D^{porous}	Momentum absorbed by the porous medium, $C_D^{\text{outer}} - C_D^{\text{inner}}$	–

Continued on next page

Variable	Description	SI unit
C_D^{CV}	Total drag from control-volume momentum balance	–
C_L	Lift coefficient	–
C'_L, σ_{C_L}	Standard deviation (RMS of fluctuating part) of the lift coefficient	–
C_p	Pressure coefficient	–
$\overline{C_p}, C_{p,m}$	Mean (time-averaged) pressure coefficient	–
$\Delta C_p, \text{std}(C_p)$	Standard deviation of the pressure coefficient	–
F	Aerodynamic force (generic)	N
F_D, F_L	Drag and lift forces	N
$F_y(t)$	Instantaneous cross-flow force	N
Structural quantities		
c	Viscous damping coefficient	N s/m
k_s	Structural stiffness	N/m
m	Structural mass per unit length	kg/m
m_1	Modal mass per unit length (first mode)	kg/m
m^*	Mass ratio	–
ξ	Structural damping ratio (generic)	–
ξ_1	Structural damping ratio of the first mode	–
ω	Angular frequency, $2\pi f$	rad/s
ω_n	Natural angular frequency of the structure	rad/s
Porous-medium model (Darcy–Forchheimer)		
$\mathbf{D}$	Viscous (Darcy) resistance tensor	m^{-2}
$\mathbf{F}$	Inertial (Forchheimer) resistance tensor	m^{-1}
k	Scalar pressure loss coefficient of the porous screen	–
$\mathbf{S}_m$	Volumetric momentum source term in the porous region	N/m^3
ε	Geometric porosity of the screen	–
Proper Orthogonal Decomposition (POD)		
N	Number of snapshots	–
M	Number of spatial degrees of freedom	–
$\mathbf{q}_i$	i -th flow snapshot vector	varies
$\bar{\mathbf{q}}$	Temporal mean of the snapshot ensemble	varies
$\mathbf{q}'$	Fluctuating (mean-subtracted) flow field	varies
$\mathbf{X}, \mathbf{X}'$	Snapshot matrix and its mean-subtracted form	varies
Σ	Diagonal matrix of singular values, σ_i	varies
$\mathbf{U}_{\text{SVD}}, \mathbf{V}$	Left and right singular-vector matrices	–
σ_i	i -th singular value of $\mathbf{X}'$	varies
$\phi_i(\mathbf{x})$	i -th POD spatial mode	varies
$a_i(t)$	Temporal coefficient associated with mode ϕ_i	varies
E_i	Energy fraction of mode i , $\sigma_i^2 / \sum_j \sigma_j^2$	–
r	Rank of the mean-subtracted snapshot matrix $\mathbf{X}'$	–
R	Truncation rank of the POD expansion	–
w_k	Cell-volume weight in the discrete inner product	m^2
Fluid properties		
μ	Dynamic viscosity	$\text{kg}/(\text{m s})$
ν	Kinematic viscosity	m^2/s

Continued on next page

Variable	Description	SI unit
ρ	Fluid density	kg/m ³
k_t	Turbulent kinetic energy (k - ω SST closure)	m ² /s ²
ω_t	Specific dissipation rate (k - ω SST closure)	s ⁻¹
Subscripts and superscripts		
1	First (structural or modal) quantity	—
bare	Bare (inner) prism, without porous envelope	—
cr	Critical condition (e.g. for VIV onset)	—
D, L	Drag and lift quantities	—
m	Mean (time-averaged) value	—
n	Natural value	—
p	Quantity associated with the porous configuration	—
ref	Reference value	—
r, R	Reduced quantity	—
s, v, vs	Vortex shedding quantity	—
∞	Free-stream condition	—
inner, outer	Inner prism, outer envelope	—
porous	Quantity attributed to the porous medium itself	—
CV	Quantity obtained from a control-volume balance	—
*	Non-dimensional quantity	—
$\overline{(\cdot)}$	Time average	—
$(\cdot)'$	Fluctuating part (or RMS, depending on context)	—

List of Figures

1.1	Isozaki tower in Milan's CityLife district.	1
1.2	Porous façade of the SDA Bocconi campus.	2
2.1	Flow around a cylinder at different Reynolds numbers [8].	5
2.2	Strouhal number vs Reynolds number for flow behind a circular cylinder [11] . . .	6
2.3	Illustration of shedding regimes for different aspect ratios of a square cylinder. Streamlines are shown in black, and the pressure contour is represented with the colour gradient [12].	7
2.4	Vortex shedding frequency for rectangular cross-subsections with different B/D ratios [14].	8
2.5	Drag coefficient versus elongation ratio B/D of a rectangular prism with sharp edges. [15]	9
2.6	RMS Lift coefficient vs elongation ratio B/D of a rectangular prism with sharp edges. The present study indicates [16].	9
2.7	Schematic representation of the damped oscillator model.	11
2.8	Dependence of frequency on flow velocity during lock-in [17].	11
2.9	Dependence of VIV amplitude on reduced velocity for a 4:1 rectangular cylinder, adapted from Tang et al. [7]. In the original reference the reduced velocity is denoted U_R , which is equivalent to the present definition $U^* = U/(f_n D)$	12
2.10	Canonical vortex shedding modes for oscillating bluff bodies, adapted from Williamson and Roshko [18].	14
3.1	Computational mesh showing local refinement around the rectangular cylinder and in the wake region.	18
3.2	The effect of mesh coarseness on non-dimensional parameters.	22
3.3	Schematic view of the reduced order modelling of the porous layer: comparison between the physical system (left) and the PDSF system in the computational domain (right). Reproduced from [20].	23
3.4	POD energy spectrum showing the energy fraction associated with each decomposed mode. The spectrum is reported on both linear and logarithmic scales to highlight the dominance of the leading modes and the rapid decay of energy in higher-order modes.	27
3.5	The first two POD modes for the rectangular-cylinder wake, highlighting the antisymmetric vortex-shedding structure and phase-shifted modal pairing.	28
3.6	Mode one of the decomposed flow for the square cylinder at $Re = 7.36 \times 10^4$. With this method $St = 0.119$ for the first two modes.	31
3.7	Second POD mode of the decomposed flow for the 5:1 rectangular cylinder at $Re = 7.4 \times 10^4$, showing the dominant antisymmetric vortex shedding structure.	33
4.1	Model in the wind tunnel (naked and porous) [21].	35
4.2	Floor 5, $U = 4$ m/s. Red dots: experimental results, blue bars: CFD results of their experiment. Mean and RMS pressure coefficients (naked vs porous) [21]. . .	36

4.3	Comparison between the power spectral density of the force coefficients measured at floors 2,5,8 (coloured lines) and the one calculated from the CFD simulation (blue squares) at $U = 4$ m/s. Power spectral density of force coefficients. [21] . . .	37
4.4	[21].	38
4.5	Porous configuration, $U/U_{cr} = 1.02$. Spectra of Lagrangian force components of floors 2,3,4,5. The vertical dotted black lines highlight the St number associated with porosity and motion-induced Vortex Shedding [21].	39
5.1	Overlay of the present CFD cases on the Strouhal-number classification for rectangular prisms adapted from Deniz and Staubli [31]. The red markers indicate the configurations investigated in the present work.	42
5.2	Overlay of the present CFD drag coefficients on classical drag-coefficient trends for rectangular prisms. The blue markers indicate the configurations investigated in the present work.	42
5.3	Overlay of the present CFD RMS lift coefficients on classical fluctuating lift-coefficient trends for rectangular prisms [16]. The blue markers indicate the configurations investigated in the present work.	43
5.4	Spectral content of the aerodynamic forces in the cross-flow direction.	44
5.5	Energy spectrum of the POD modes for the $B/D = 3.33$ prism.	45
5.6	Power spectral density of the temporal coefficients associated with the first four POD modes for the investigated aspect ratios.	46
5.7	Spatial distribution of the first four POD modes for the $B/D = 3.33$ prism. . . .	47
5.8	Comparison of global aerodynamic parameters as a function of Reynolds number. . . .	48
5.9	Comparison of the temporal POD coefficients for different Reynolds numbers. . . .	49
5.10	Regime map for flow past oscillating cylinder, adapted from Williamson and Roshko [18]. Both porous and naked cases from this researches experiments have been added to the plot.	50
5.11	POD modes for sub-critical forcing ($f = 0.75f_n$) showing classical alternating 2S vortex shedding.	51
5.12	POD energy spectrum for $f = 0.75f_n$	51
5.13	POD modes for Lock-In Regime forcing ($f \approx f_n$)	52
5.14	POD modes for super-critical forcing ($f = 1.25f_n$) showing mixed mode vortex shedding.	53
5.15	POD energy spectrum for $f = 1.25f_n$	54
5.16	Power spectral density of the first POD modes for $f = 0.75f_n$	55
5.17	Power spectral density of POD modes at lock-in ($f \approx f_n$).	56
5.18	Power spectral density of POD modes for $f = 1.25f_n$	57
5.19	Spectrum of lift force at various forcing frequencies f	58
5.20	Comparison of drag and lift coefficients across forcing regimes.	59
5.21	Global aerodynamic parameters as a function of k for the rigid porous configuration. . .	62
5.22	Mean pressure coefficient on the four faces of the inner prism as a function of k . . .	63
5.23	Mean pressure coefficient field $\overline{C_p}$ for the rigid porous configuration. The inner prism is masked in white.	64
5.24	Mean streamwise velocity field $\overline{U}_x/U_\infty$ for the rigid porous configuration. The signed component is shown so that the $\overline{U}_x = 0$ contour bounds the mean recirculation region; blue denotes reverse flow. The inner prism is masked in white. . . .	65
5.25	Mean pressure coefficient $\overline{C_p}$: direct comparison between the naked configuration ($k = 0.05$, upper half) and the experimentally calibrated porous screen ($k = 1.8$, lower half). The inner prism is masked in white and straddles the wake centreline; the grey frame on the porous side marks the porous layer. Discrete colour bands are used to aid the eye, and the same colour scale applies to both halves.	67

5.26	Mean streamwise velocity $\overline{U}_x/U_\infty$: naked configuration ($k = 0.05$, upper half) versus the calibrated porous screen ($k = 1.8$, lower half), in the same split layout as Figure 5.25. The signed component is shown, so that the $\overline{U}_x = 0$ contour bounds the mean recirculation region and blue denotes reverse flow.	68
5.27	Porous k -cases mapped onto an effective elongation ratio	69
5.28	Decomposition of the mean drag coefficient as a function of k . C_D^{inner} : drag on the inner prism from surface forces. C_D^{outer} : drag on the outer envelope surface from pressure probes. $C_D^{\text{porous}} = C_D^{\text{outer}} - C_D^{\text{inner}}$: residual momentum absorbed by the porous medium. C_D^{CV} : independent control-volume momentum balance on the time-averaged field. All coefficients normalised by $A_{\text{ref}} = h d_{\text{bare}}$	71
5.29	Mean (C_p) and fluctuating (ΔC_p) pressure coefficients around the perimeter of the inner prism for various values of k	72
5.30	Power spectral density of the lift force at various k	74
5.31	First POD mode for various values of k	75
5.32	POD energy spectrum for various k	77
5.33	Temporal power spectral density of the first POD mode for various values of k	78
5.34	Standard deviation of the lift coefficient and mean drag coefficient as a function of forcing frequency, for the porous configuration ($k = 1.8$) compared with the naked baseline.	79
5.35	Power spectral density of the lift force for the porous configuration ($k = 1.8$) under the three forcing regimes.	80
5.36	Mean pressure coefficient $\overline{C}_p$ in the gap region of the porous configuration ($k = 1.8$) under the three forcing regimes. Dashed line: $\overline{U}_x = 0$ separation contour.	81
5.37	Mean streamwise velocity $\overline{U}_x/U_\infty$ in the gap region of the porous configuration ($k = 1.8$) under the three forcing regimes. Blue denotes reverse flow; the dashed line marks the $\overline{U}_x = 0$ boundary of the recirculation.	81
5.38	Dominant POD mode of the porous configuration ($k = 1.8$) for the three forcing regimes.	82
5.39	Energy spectrum of POD modes for the porous configuration ($k = 1.8$) under the three forcing regimes and the still case as reference.	83
5.40	Power spectral density of the first POD mode for the porous configuration ($k = 1.8$) under the three forcing regimes.	84
5.41	Instantaneous C_p over one shedding period: still vs. forced, porous	86

List of Tables

3.1	Comparison of present simulation results ($Re = 7.36 \times 10^4$, URANS, $B/D = 1$) with published data for square cylinders at $Re \sim 10^4$ – 10^5	29
3.2	Comparison of present simulation results ($Re = 7.4 \times 10^4$, URANS, $B/D = 5$) with published data for rectangular cylinders at $Re \sim 10^4$ – 10^5	32
4.1	Comparison between experimental aerodynamic quantities measured on a section of the rectangular cylinder and reference data from the literature. Statistics are obtained from rigid-model tests at $U = [3, 4, 5, 6, 8]$ m/s. For the experimental results, only floors 3–5 are considered [21].	39
5.1	Comparison of global aerodynamic parameters for fixed rectangular prisms without porous cladding.	44
5.2	Wake characteristics across forcing regimes.	54
5.3	Comparison of porous-configuration aerodynamic quantities between present CFD ($k = 1.8$, rigid model) and the wind-tunnel measurements of Chapter 4. The experimental Strouhal number range encompasses both the single-velocity peak and the multi-velocity statistic of Table 4.1.	60
5.4	Summary of wake characteristics for the naked and porous configurations across forcing regimes.	84