



Simultaneous measurement of the distributed longitudinal strain and velocity field for a cantilevered cylinder exposed to turbulent cross flow

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Abstract

The structural response of a cantilevered cylinder under free-stream conditions both with low and high turbulence intensity generated by turbulence-generating grids is analysed with concurrent measurements of the velocity field and the distributed strain. The thin-walled cylinder, with a diameter (D) of 50 mm, is mounted in a water flume as a cantilevered beam supported at one end, with 95% of its body submerged and exposed to cross flow yielding a Reynolds number of $Re = 25000$. We employ a novel combination of simultaneous particle image velocimetry and distributed strain measurements using Rayleigh backscattering fibre optic sensors. These sensors are embedded onto the surface of the cylinder to measure the experienced strain (ϵ) of the structure along its spanwise direction, covering both the windward and leeward faces of the cylinder. The sensors fine spatial resolution allows us to discern the influence of the flow on the structural response of the cylinder in two distinct regions of the structure: upstream and downstream of the mean separation location. This differentiation allows us to isolate the local effects introduced by the free-stream conditions on the loading events over the body from the global force generated by the vortex shedding and other coherent motions present within the flow. Distinguishing between these direct and indirect effects helps determine which is more relevant for fatigue-life cycle analysis. The cross power spectral density between the fluctuating velocity field and the strain reveals that the load is dominated by the vortex shedding, and this relationship is intensified with the introduction of free-stream turbulence. It also helps to discern the different dynamics imposed by the two free-stream turbulence conditions.

1 Introduction

Fluid–structure interactions represent a pivotal aspect of engineering that encompasses the dynamic relationship between fluid forces and the response of solid structures exposed to said fluid forces. Understanding and harnessing these interactions is critical for designing resilient and efficient engineering systems. When bluff bodies encounter cross flows, substantial flow-induced forces typically

originate from the alternating vortices produced by the body (Zhou et al. 1999).

Furthermore, in the presence of free-stream turbulence (FST), these structures are exposed to the fluctuating velocity field imposed on their windward side, which may additionally influence the vortex shedding process. Accounting for FST plays a pivotal role in understanding the loads acting on bluff bodies, such as fuel elements in nuclear reactors subjected to the unsteady flow within the reactor's array of rods (Wang et al. 2019), wind turbines exposed to turbulence generated by the wake of upstream turbines within a wind farm (Thomsen and Sørensen 1999), and trees exposed to turbulent flow within a forest or naturally occurring atmospheric turbulence (Sellier et al. 2008).

The circular cylinder, a quintessential bluff body, has been a focal point of intensive research spanning numerous decades. Pioneering contributions by Roshko (1954) and Gerrard (1966) elucidated fundamental aspects of vortex formation, wake characteristics and flow-induced loading. Comprehensive reviews by Bearman and Morel (1983)

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and Williamson (1996) further distil this knowledge. In the examined flow conditions, the Reynolds number takes on a crucial role, influencing the dynamics of a cylinder's separated shear layers and resulting in the consistent occurrence of vortex shedding. This phenomenon engenders time-mean drag and the generation of oscillatory drag and lift forces. These unsteady flow characteristics are then imprinted into the structural response of the bluff body, introducing fluctuating stresses and loads on the wake-generating body. The accumulation of these factors can ultimately lead to structural failure.

A special case of the flow around a cylinder involves the study of finite cylinders (Porteous et al. 2014; Crane et al. 2021; Okamoto and Yagita 1973; Farivar 1981; Fox and West 1993a, b; Essel et al. 2021), where 2D approximations of the flow are inadequate. Unlike typical 2D cases, the flow around finite cylinders, with dependencies on both Reynolds number (Re) and the bluff body's aspect ratio L/D , exhibits increased complexity. This type of flow, common in engineering applications like wind turbine masts and building wakes, introduces 3D free-end effects, resulting in a more intricate shedding pattern compared to the canonical 2D flow scenario (Crane et al. 2021). A thorough exploration of this topic is provided by Porteous et al. (2014), delving into the wake topology of such flows and its correlation with the aspect ratio.

In the current experimental study, the bluff body under consideration is a submerged cylinder with a free end, allowing for the formation of two longitudinal trailing vortices (Fox and West 1993a; Okamoto and Yagita 1973). These vortices are generated by a 3D pressure drop at the cylinder's free end, suppressing the periodic shedding of vortices at the tip. For this analysis, a cylinder with an aspect ratio $L/D = 10$ is affixed as a cantilever, positioned above the water's free surface. This set-up exposes the submerged portion of the cylinder to cross flow, resulting in the development of two spanwise cellular regions: one dominated by alternating regular von Kármán vortices, and the other by tip vortices shed from the free end of the cylinder (see the description of the "Lee Model" in Porteous et al. (2014), for $L/D > 7$). The alternating regular von Kármán vortices shed far from the free end of the cylinder are characterised by $St_2 \approx 0.2$, while the tip vortices are characterised by $St_1 \approx 0.07$ (Porteous et al. 2014; Park and Lee 2000, 2002, 2004). The Strouhal number is herein defined as $St = f \times D/U_\infty$ for every test case, where U_∞ is defined as the average incoming free-stream velocity.

As highlighted by Zhou et al. (1999), the examination of fluid–structure interaction requires techniques enabling the simultaneous acquisition of flow conditions and structural dynamics. Fibre optic sensors, particularly fibre Bragg gratings (FBGs), have been utilised to measure flow-induced strain over bluff bodies in previous studies (Zhou et al. 1999;

Jin et al. 2000; Wang et al. 2019; de la Torre et al. 2021; Zhou et al. 2001). Wang et al. (2019) conducted comprehensive measurements, employing combined temporally resolved 2D particle image velocimetry (PIV), laser Doppler velocimetry (LDV) and strain and deflection measurements using an FBG. This approach provided a single point-wise measurement of the strain experienced by the cylinder. In recent years, another set of fibre optic sensors (Rayleigh backscattering fibre optic sensors (Xu and Sharif 2020)) has emerged, proving effective in accurately instrumenting strain over wind turbine blades (Gûemes et al. 2010) and characterising the loads structures endure by extracting the strain response of the body (Li and Khodaei 2023). Tension and the applied load field to the structures may be reconstructed exploiting inverse finite element methodologies.

These sensors, aptly named for their reliance on Rayleigh backscattering, leverage a fundamental optical phenomenon that occurs throughout the fibre optic medium. Rayleigh backscattering arises from the interaction between light waves and microscopic density fluctuations (Li 2023; Díaz-Maroto 2018). As the light beam propagates within the fibre, it encounters density variations, resulting in fluctuations that create local scattering points within the fibre (Li 2023; Díaz-Maroto 2018). The Rayleigh backscattered photons originating from these scattering regions travel back along the incident beam's path. The frequency of the backscattered beams is influenced by mechanical stress applied to the fibre, which in turn affects the fibre's density fluctuations. This leads to a frequency shift known as the Rayleigh frequency shift. In contrast, FBGs exploit the introduced periodic changes in the refractive index of the optical fibre, to analyse how external factors such as induced strain impact the shift in the Bragg resonance frequency (Zhou et al. 1999).

The optical frequency-domain reflectometry (OFDR) system exploits the Rayleigh backscattering spectrum occurring in a single-mode fibre (SMF), generated by the random modulation of the refractive index profile along the length of the fibre, to instrument and capture details of the structural response within a distributed sensing network (Kwon et al. 2019). The OFDR system splits the light beam into two portions with the same spectral component but different amplitudes using an optical coupler. The beam with the larger amplitude is directed to the fibre sensing path, while the other serves as a reference signal. A beat signal is employed to identify different positions along the SMF (Li and Khodaei 2023). As various positions of the fibre are exposed to external loads, Rayleigh backscattered light experiences the Rayleigh frequency shift of the beat signal for each position, correlating with locally applied strain using a pre-determined strain-frequency shift of the fibre (Li and Khodaei 2023; Xu and Sharif 2020). The portions of the fibre embedded in the cylinder capture the structural response with fine spatial and temporal resolution,

enabling the extraction of flow-induced effects along the fibre path direction. The frequency of acquisition of the RBS is limited by the OFDR system, currently set at 100 Hz for 10 m length mode fibres. Despite the moderate frequency of acquisition, the sensor network enables the structural response to be captured in a time-resolved fashion with a fine spatial resolution through a single channel. In the present experimental campaign, 560 sensors were used with a single channel. To acquire such an amount of data using strain gauges in a quarter bridge configuration, 1120 channels and respective cabling would be needed, making the complexity of the experiment either intractable, or very close to it. Although FBGs offer less flexibility in accommodating such a large amount of strain sensors in a single fibre optic with similar spatial resolution, these sensors offer an increased acquisition frequency which is currently limited mainly by the acquisition module. Zhou et al. (1999) acquired strain data with an FBG sensor at 3.5 KHz. The dense sensing network of RBS enables the use of a shape sensing algorithm (Xu and Sharif 2020), which would allow for tracking the local deformation/deflection of the body along its full extent. In summary, for a truly distributed sensing network, fibre optic RBS is easily the best choice of metrology while offering reasonable temporal resolution, especially for experiments conducted in a water facility.

For the first time, we couple distributed strain measurements via RBS with time-resolved PIV such that we have concurrent information on the local velocity field and time-varying strain within the wake-generating body, exploiting the spatial resolution of both techniques to examine the proposed fluid–structure interaction.

In the present study, we employ novel fibre optic Rayleigh backscattering sensors (Xu and Sharif 2020; Li and Khodaei 2023), to obtain the structural response of the cylinder to different free-stream and flow conditions, along the longitudinal direction of the structure, concurrent with temporally resolved 2D-PIV. The proposed measurement system allows us to spatially and temporally resolve the fluid–structure interaction, by overlaying the PIV fields of view with the fibre optic path. Furthermore, the used fibre path offers the possibility of distinguishing the endured effects of the free-stream conditions directly imposed on the bluff body, from the modification of the vortex shedding process (Kankanwadi and Buxton 2023), allowing us to separate these two effects (direct and indirect) from the fluid–structure interaction induced by the presence of grid-generated free-stream turbulence. As the measurements are concurrent, correlations between the PIV data and strain data recovered from the fibre optic sensing path are computed. The fibre optic signal is able to capture the main flow events' impression on

the structure and to acquire the clear differences imposed by the two documented FST conditions under analysis.

2 Experimental methodology

The experiments were conducted in the water flume of the hydrodynamics laboratory of the Department of Aeronautics at Imperial College London. The flume was kept at a constant $56 \times 60 \text{ cm}^2$ operating cross section. The test specimen, an acrylic tube with diameter $D = 50 \text{ mm}$, 2.5 mm nominal wall thickness and 524 mm length, was vertically assembled in the midsection of the flume, with 95% body submersion (wet length of $\approx 490 \text{ mm}$). The tip of the cylinder was kept free with 80 mm of distance from the floor of the flume, to allow for the development of tip vortices and downwash into the flow (Porteous et al. 2014). In addition, the cylinder was filled with water to eliminate buoyancy effects. A regular grid was placed upstream of the cylinder to generate background turbulence, to explore the effects of the presence of free-stream turbulence on the strain captured by the sensing network. The FST conditions for the two test cases were characterised prior to the addition of the cylinder to the water flume, at the cylinder's streamwise fixing location. Following (Chen and Buxton 2023; Kankanwadi and Buxton 2020), background turbulence conditions are characterised by turbulence intensity, defined as $\text{TI} = \sqrt{u'^2 + v'^2} / U_\infty$ where u' and v' correspond, respectively, to the streamwise and longitudinal velocity fluctuations, and integral length scale defined by $\mathcal{L} = \int_0^{r_0} R dr$, where R corresponds to the correlation function between $u'(x, y)$ and $u'(x, y + r)$, and r_0 to the first zero crossing of R . The two test cases considered for the current experimental campaign characterised by $\{\text{TI}(\%), \mathcal{L}/D\}$ are denoted by **A** with $\{1.3, 0.08\}$ and **B** $\{6.1, 0.4\}$. Test **A** was characterised by having no turbulence-generating grid, being the free-stream conditions characteristic of the natural turbulence levels in the facility, as previously documented, e.g. Kankanwadi and Buxton (2020), Buxton and Chen (2023). The regular turbulence-generating grid used for case **B** is characterised by having a mesh size of $M = 37.6 \text{ mm}$, with a bar thickness of $t_0 = 5.2 \text{ mm}$, representing an overall blockage of 33.94% to the incoming flow. The incoming free-stream velocity of the flow, without the presence of the turbulence-generating grids, was $U_\infty \approx 0.5 \text{ m/s}$, setting the Reynolds number based on this velocity and D at ≈ 25000 . Under the current experimental campaign, the Froude number was kept at $Fr = U_\infty / \sqrt{gH} \approx 0.2$, in order to neglect surface deformation effects. In each run, the flow was initiated by gradually increasing the speed of the flume until the desired flow velocity was reached. Data acquisition was triggered once the flow had reached a stable state.

2.1 Cross flow-induced strain measurements with RBS

The RBS sensors were embedded onto the cylinder's surface to accurately interrogate the structural response of the cylinder. Figure 1a presents a schematic of the fibre optic sensors layout used, as well as the PIV fields of view (FOV), overlaid with the fibre sensors path. The single-mode fibres (SMF) used in this set of experiments are SM1500 (9/125)P, by FIBRECORE, possessing a polyimide coating with bend insensitivity and enhanced photosensitivity, with a diameter of $125\mu\text{m}$. The fibres were bonded to the cylinder with cyanoacrylate glue, which is not soluble in water, and overlaid with tape to simultaneously help fix the fibres to their intended locations, and provide insulation from water once the body was submerged. The small diameter and weight of the fibres does not affect the flow dynamics and structural response of the body (Zhou et al. 1999). The temperature difference of the water between the various tests is negligible and so, strain measurements obtained by the system consist solely of axial strain of the cylinder induced by the flow. Figure 1b corresponds to a schematic of the cross-plane of the cylinder, where the fibre paths $[\theta_{-45}, \theta_{-135}, \theta_{45}, \theta_{135}]$ are defined, characterised by constant polar

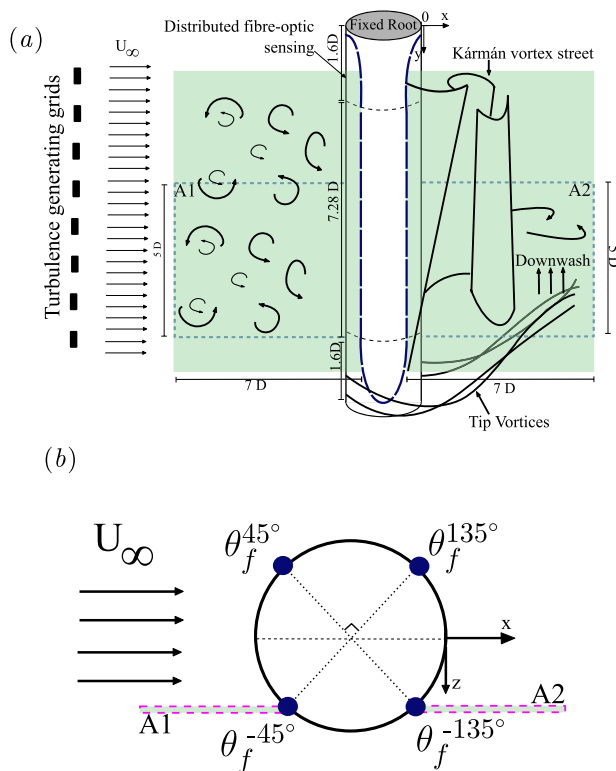


Fig. 1 **a** Experimental schematic of the fibre optic sensing path and fields of view (FOV), and representation of the main flow events over the cylinder; **b** fibre sensing path localisation and nomenclature, represented in an orthogonal plane to the longitudinal direction of the cylinder

angles of, respectively, $\theta_f = [-45, -135, 45, 135]^\circ$, covering the spanwise length, dividing the cylinder into a windward and leeward region (respectively, $\pm 45^\circ$ and $\pm 135^\circ$). The polar location of the sensors along the cylinder was ensured using a Thorlabs rotating mount. In the Reynolds number regime for these experiments in the same facility and similar experimental conditions, flow separation has been seen to occur at $\theta = [101, -103]^\circ$ (Cicolin et al. 2021) in a time-averaged sense.

The location of the sensors was set to capture the localised induced strain upstream and downstream of the shear-layer separation location to be able to analyse the direct effect of free-stream turbulence and wake generation on the body's structural response. The RBS sensing network possesses a spatial resolution of 2.6 mm ($\Delta_{\text{RBS}} = 0.052D$) where each sensing line consists of 140 sensing points, along $7.28D$ (364 mm) in the spanwise direction of the cylinder. The fibre sensing region is initiated $1.6D$ from the root of the cylinder, to avoid extra bending of the fibres when laying the fibre path. This was done to ensure that $R/a > 10^2$, where R corresponds to the radius of curvature of the path, and a to the half width of the fibre. This was done to neglect macro-bending losses within the optical fibre (Xu and Sharif 2020). The strain data were acquired by the OFDR system ODiSI-B, by LUNA Ltd. Data acquisition was triggered between each pair of PIV images used to build the correlation and compute velocity vectors, to have a strain signal associated with each velocity field snapshot. Thus, strain datasets were acquired along the spanwise direction of the cylinder, on the previously mentioned polar positions, concurrently with the velocity field acquisition via PIV. The data were acquired at a frequency of 100 Hz (the maximum acquisition frequency of ODiSI-B), and then treated with a low-pass filter of 15 Hz , and a spatial Savitzky–Golay filter of 4th order to smooth the signal, with a filter kernel extending 15 points along the range of 140 sensing points in each fibre. The RBS network is capable of measuring $\mu\epsilon$ with $\pm 0.1\mu\epsilon$ resolution. The measurements are taken in units of $\mu\epsilon$ and for the remainder of the paper, ϵ shall refer to strain in units of $\mu\epsilon$. Preliminary experiments were conducted to validate the strain measurements obtained from the RBS sensing network. Detailed information on this preliminary experiment and an analysis on the uncertainty of the strain measurements of the current experimental campaign are provided in appendix A.

2.2 Particle image velocimetry measurements

The illumination source for the PIV measurements was a high-speed Litron LDY304 Nd:YLF laser, operating at 1000 Hz . The laser emits a wavelength of 527 nm , with a pulse duration of $20\mu\text{s}$. The laser beam was manipulated with a set of spherical and cylindrical lenses to form a light sheet along the spanwise direction of the cylinder, with an offset of $z \approx D/\sqrt{2}$ with respect to the cylinder's wake centreline. This ensured

that the PIV illumination sheet was overlaid with the fibre optic sensing paths $[\theta_f^{-45^\circ}, \theta_f^{-135^\circ}]$. The PIV FOVs focussed both on the region upstream (A_1) and downstream (A_2) of the cylinder, documenting the full extent of the flow region inducing structural loads. A_2 captured the flow events over the shear-layer separation region of the cylinder, and A_1 the flow events upstream of the cylinder, where the flow is still attached to the body, characterising the experimental conditions to which the cylinder was subjected. Both FOVs consist of a region of ($\approx 7D \times 4D$).

The FOVs A_i were obtained with one Phantom V641 in two different non-concurrent experiments, connected to a Nikkor 60 mm lens. The camera had an internal storage capable of storing 5700 images at full resolution (2560 px $\times$ 1600 px), in each run. PIV data were acquired at an acquisition frequency of $f_{acq} = 50\text{Hz}$ for every test. Data were then acquired for a total time of 54.5s (≈ 100 vortex shedding cycles). The resulting images were processed, employing a multi-pass algorithm to estimate the average particle displacement per interrogation window. The final interrogation area consisted of 16×16 px, with 50% overlap, resulting in a spatial resolution of 1.2 mm ($\Delta_{PIV} = 0.024D$). We estimate the uncertainty of the PIV measurements from fitting an osculating parabola to the autocorrelation function over short correlation offsets and observing the difference as $\Delta x \rightarrow 0$ (Poelma 2004). The largest uncertainty of the PIV measurements corresponded to 4.1% of U_∞ . Figure 2a presents illustrative velocity fields with both FOVs for the two test conditions under analysis, and Fig. 2b presents the spanwise distribution of TI content generated by the turbulence-generating grids. The OFDR system was triggered in between two consecutive snapshots acquired for PIV, by providing a +5V signal to the system using a signal delay generator connected to the laser, cameras and OFDR systems. This allows characterisation of the strain field induced by the velocity field. The RBS data were triggered at the highest possible acquisition frequency available with the OFDR system - 100 Hz. As a result, for each PIV record, two RBS records were taken. The first, concurrent with the PIV acquisition, the second with a temporal offset of c. 10ms. Only concurrent structural response data were kept for the cross analysis with the velocity fields. Figure 3 corresponds to the operation diagram used in the experimental set-up.

3 Results and discussion

3.1 Longitudinal strain measurements of the cylinder under cross flow

The presence of free-stream turbulence has been associated with an increased vibration of cantilevered bluff bodies (Wang et al. 2019). Distributed sensing of strain allows

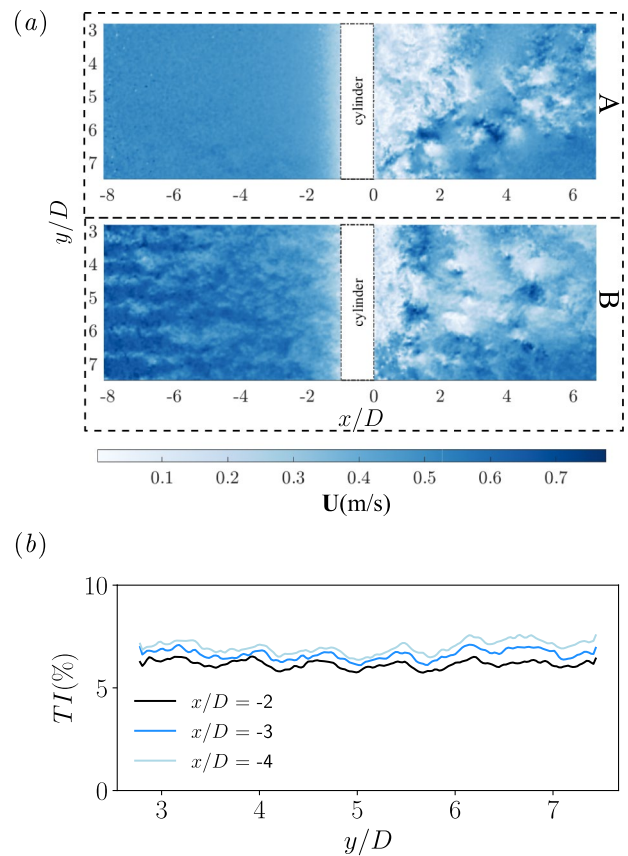


Fig. 2 **a** PIV snapshots of the flow fields of the velocity magnitude U obtained in FOV A_1 and A_2 for the two tested free-stream conditions; **b** characterisation of free-stream TI generated by FST conditions B along the cylinder's spanwise extent

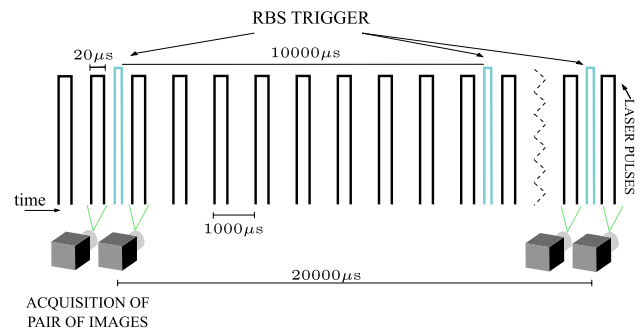


Fig. 3 Operational timing diagram for the experiments

for a better understanding of the evolution of the structural response of bluff bodies, with, and the fingerprint of the various flow phenomena acting on the structure. A Reynolds decomposition is applied to the strain signal to extract the mean ($\bar{\epsilon}$) from the fluctuating (ϵ') strain field:

$$\epsilon(y/D, t, \theta_f^\alpha) = \bar{\epsilon}(y/D, \theta_f^\alpha) + \epsilon'(y/D, t, \theta_f^\alpha). \quad (1)$$

The fluctuating strain $\epsilon'(y/D, t, \theta_f^\alpha)$ is linked to the oscillatory motion associated with the shear-layer separation, and the various free-stream flow structures impacting the cylinder, which are expected to be broadband in nature with a spectrum characteristic of typical turbulence. The acquired strain signal obtained from the RBS sensor network is temporally (t) as well as spatially resolved (y/D), along the cylinder's spanwise direction. In addition, strain is also characterised by the 4 different sensing line polar positions θ_f^α , defined by $\alpha = [\pm 45^\circ, -\pm 135^\circ]$. The mean loads and therefore, experienced mean strain by the cylinder are dictated by the influence of the mean flow on the time-averaged loading events acting on the cylinder, and the fluctuating velocity field is postulated to influence the fluctuating strain field.

Figure 4 corresponds to a contour of the evolution of the probability density function (PDF) of the acquired strain signal by two selected sensing lines, $\theta_f^{-45^\circ}$ and $\theta_f^{-135^\circ}$ along the cylinder's spanwise direction, overlaid by the experienced mean, the $\max||\min$ limits and standard deviation (STD) of the strain. Here, the strain field was smoothed with a savgol filter. The introduction of grid-generated free-stream turbulence enhanced the magnitude of the fluctuating strain, especially near the root (fixing region of the cylinder) where the bending moment is maximum. Furthermore, it also accounted for an increase in the range of maximum and minimum values of fluctuating strain, and increased standard deviation—especially at the root, the location of highest bending stress, both of which are important contributions to the increased gradual accumulation of fatigue damage over time. The PDF of the strain signal also shows a gradual flattening towards the root, especially with the introduction of FST. This is representative of the increased magnitude associated with the strain fluctuations experienced in this region. This in turn is a consequence of the built up bending moment

introduced by the flow events spanning along the cylinder's longitudinal direction.

The difference of the ranges of $\max||\min(\epsilon)$ and $\text{rms}(\epsilon')$ acquired by $\theta_f^{-135^\circ}$ and $\theta_f^{-45^\circ}$ between the represented cases in Fig. 4 is bigger on the windward side of the cylinder, as a result of the direct effect of unsteady (turbulent) inflow impacting on the upstream face of the cylinder (note that the flow is unsteady on the downstream face regardless of whether FST is present or not). However, the separation between both $\max||\min$ and STD limits of the two quantities is felt on the windward face ($\alpha = -45^\circ$), where the unsteady inflow impacts the body, inducing a stronger fluctuating strain magnitude. The cylinder was likely produced by extrusion of polymethyl methacrylate (PMMA), commonly known as acrylic. As a result, the wall thickness of the cylinder varies along its spanwise direction. The spatial waviness observed in the mean statistics, as illustrated in Fig. 4, may be attributed to the changing wall thickness of the cylinder along its spanwise direction.

3.2 Flow and fibre power spectral densities

With the current set of experiments, thanks to the combination of concurrent structural and flow measurements, we may assess the influence of different flow structures on the structural response, identified by their characteristic frequencies. Dynamic modal decomposition (Schmid 2010) is applied to the streamwise velocity fluctuations $\mathbf{u}'$, to identify the least damped motions in the flow, captured within the FOV. The fluctuating velocity field was obtained from a Reynolds decomposition of the velocity field $\mathbf{u}(\mathbf{x}, t) = \bar{\mathbf{u}}(\mathbf{x}) + \mathbf{u}'(\mathbf{x}, t)$, where $\bar{\mathbf{u}}$ corresponds to the time-averaged flow velocity. The mode shapes associated with von Kármán vortex shedding

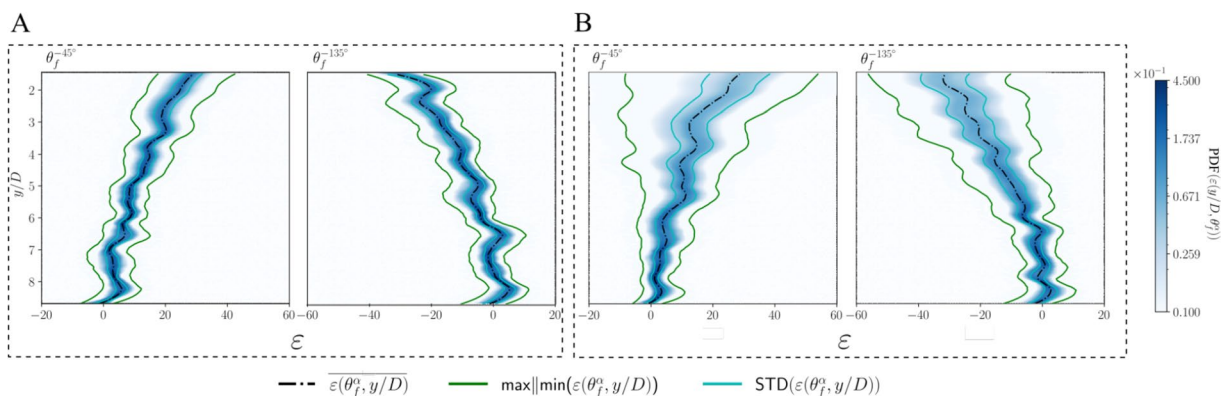


Fig. 4 Longitudinal distribution of the PDF of ϵ , for $\theta_f^{-45^\circ}$ and $\theta_f^{-135^\circ}$, overlaid by the mean strain ϵ , the $\text{STD}(\epsilon)$ and the maximum and minimum limits of strain experienced by the cylinder, for both experimental cases **A** and **B**

with characteristic frequency of $St_2 \approx 0.2$, and tip vortices with characteristic frequency of $St_1 \approx 0.07$ are presented in Fig. 5a and b. The St associated with the mode shapes captured in this experimental dataset are in line with (Porteous et al. 2014; Park and Lee 2000, 2002, 2004).

Focussing on the data retrieved by the mode shapes associated with von Kármán vortex shedding at $St \approx 0.2$, the downwash effect experienced by the cylinder, generated by the free-end condition is noticeable. The wake of the cylinder is severely affected by the inhomogeneous shedding, where it is advected towards the root. This is generated by the mutual interaction between tip vortices shed from the free end of the cylinder and the von Kármán vortex street (Porteous et al. 2014), decreasing the pressure drop experienced in the wake by adding momentum through its free-end region. This is also visible in the PIV snapshots presented in Fig. 2. Wang and Zhou (2009) described a flow structure model for the wake of a finite-length square cylinder, providing insight on the interaction between the generated tip vortices and regular von Kármán vortices. The model suggests that the generated tip vortices are inherently connected to downwash, and the von Kármán vortex street is formed along the cylinder span aside from the free-end region. In the present case, the free-end downwash flow influences the upper part of the arch-type flow structure, resulting in the formation of a pair of streamwise tip vortices near the free end of the cylinder.

The introduction of FST accounts for an increase of the intensity of von Kármán vortex shedding as captured by the DMD modal decomposition and mode shape representation. In addition, the presence of FST also accounts for an

increase in spanwise coherence of these flow structures. This is in line with recent results from Maryami et al. (2020), where the spatial coherence of vortex shedding along the extent of a double fixed cylinder was verified to increase with the introduction of FST.

Figure 6 corresponds to the power spectral density of the strain signal acquired by θ_f^α , $\alpha = [-45^\circ, -135^\circ]$, along the cylinder's spanwise direction, and the flow events present in 4 streamwise locations: $x/D = [0.5, 1, 2, 3]$ acquired by FOV A_2 , for both free-stream conditions under analysis. Vortex shedding at $St_2 \approx 0.2$ is clearly evident in the strain signal of the cylinder. Due to the spanwise-integration effect of the structural response, this frequency in the strain signal is most energetic in the root region. The velocity fields reveal that von Kármán vortex shedding remains relatively spatially coherent in the spanwise direction of the cylinder, away from the 3D effects near the tip (Porteous et al. 2014; Farivar 1981).

The introduction of FST accounts for an increase of the energy content of ε' and u' at $St \approx 0.2$, as well as a broadening of the frequency band to which the energy related to von Kármán vortex shedding is associated. This is especially true in the case where FST was introduced, over the captured strain signal. FST has then been seen to modify the coherent motions shed by the cylinder, resulting in a larger component of the fluctuating strain. This is attributed to an increase in spanwise coherence of the vortex shedding, and increased energy content associated with the shed coherent motion.

We highlight the energy content in the strain data in the low-frequency band of $St_2 \approx 0.08$ spread along the longitudinal direction. This is attributed to the fluid–structure natural frequency, estimated from a free decay test. The increase in energy content of the low-frequency structural response spectra with the introduction of FST may be associated with the shed tip vortices. Despite this, the structural dynamics are still largely driven by von Kármán vortex shedding.

3.3 Cross power spectral density between mapped flow and strain data

To perform correlations between flow and strain data, we define the cross power spectral density (CPSD), as a two-point statistic between the flow and strain data, evaluating the correlation between these two signals in both frequency-space and in space:

$$\begin{aligned} \text{CPSD}(St, x/D, y/D, \alpha) &= S_{u', \varepsilon'} \\ &= S_{u'}(St, x/D, y/D) \times S_{\varepsilon'}^*(St, y/D, \alpha) \end{aligned} \quad (2)$$

where $S_{u', \varepsilon'}$ corresponds to the Fourier transform of the cross correlation function between the two signals in consideration, and $S_{u'}$ and $S_{\varepsilon'}$ correspond to the Fourier transforms of

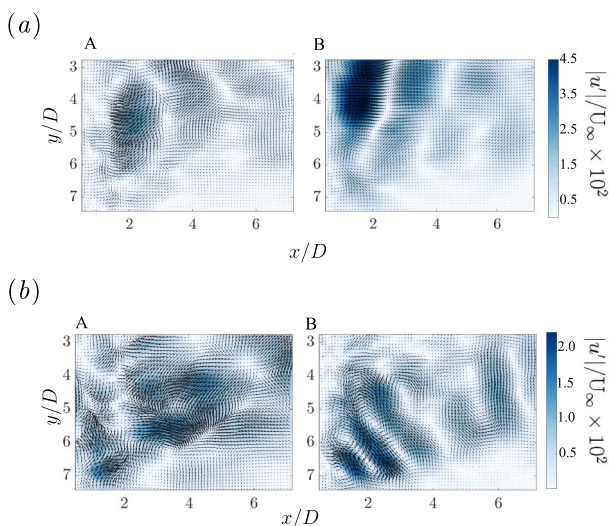


Fig. 5 Dynamic modal decomposition of the main flow structures shed by the body, under the two experimental test conditions: **a** corresponds to the vortex shedding mode shape and **b** to the tip vortex mode shape

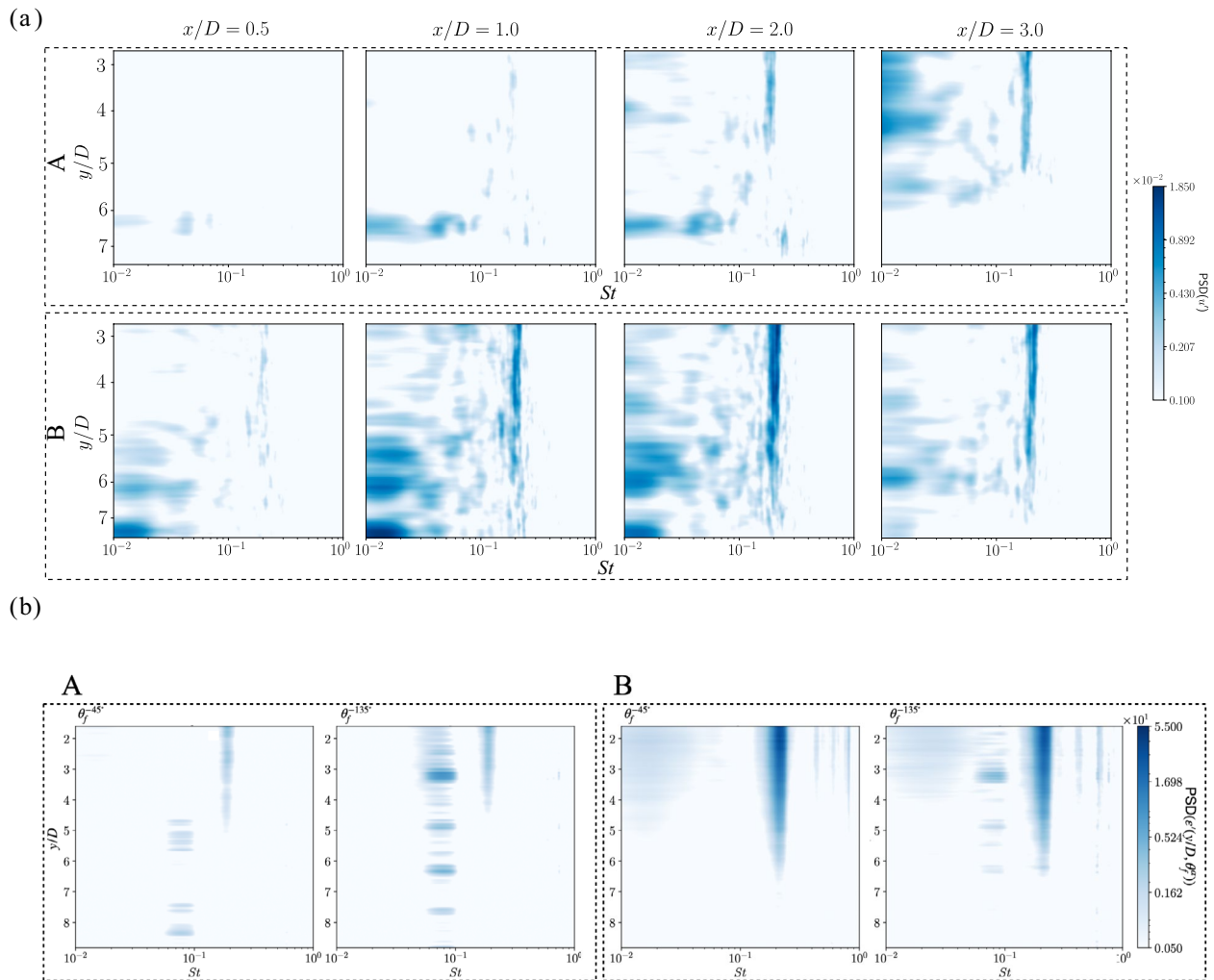


Fig. 6 Spanwise distribution of the power spectral density of **a** u' at $x/D = [0.5, 1, 2, 3]$, captured by A_2 , and **b** $\epsilon'(y/D, \theta_f^\alpha)$, $\alpha \in [-45, -135]^\circ$ for test cases **A** and **B**

the streamwise velocity and strain fluctuations. To build these correlations, data acquired from planes A_1 and A_2 were combined with strain data obtained concurrently from $\theta_f^{-45^\circ}$ and $\theta_f^{-135^\circ}$, respectively, isolating the flow and structural response upstream and downstream of the cylinder. As the PIV spatial resolution is finer than the strain resolution attained by the fibres ($\Delta_{PIV}/\Delta_{RBS} \approx 0.45$), the PIV mesh was mapped to the strain sensing mesh to correlate spatially and temporally the flow to the strain attained from the fibres. Figure 7 consists of a representation of the contours of the obtained CPSD, defined by equation 2, along the longitudinal direction of the cylinder y/D , for the experimental FST conditions **A** and **B**, for 5 streamwise locations, covering the near wake of the cylinder ($x/D = [-2, 0.5, 1, 2, 3]$). At the streamwise station $x/D = -2$ the CPSD is computed with data acquired from $\theta_f^{-45^\circ}$ and A_1 , and for the remaining stations with the data from $\theta_f^{-135^\circ}$ and A_2 .

As seen in the spanwise distribution of the power spectral densities of both acquired strain, and the fluctuating streamwise flow field velocities, the introduction of FST accounts for an increase in the energy content of the frequency band associated with von Kármán vortex shedding on the CPSD contours. In addition, a broadening of the frequency range associated with this flow phenomenon is also seen both in the structural response and in the flow development, being more pronounced in the structural response signal. The energy distribution of the CPSD contours shows that the regular von Kármán vortex shedding is the dominating flow structure that yields a structural response. This is true for both cases **A** and **B**, where in **B**, the introduction of FST accounts for an increased energy content in a broader range of frequencies, along an increased spanwise extent. The increased magnitude and spanwise extent of the “energy content” of the CPSD with the introduction of FST is a consequence of both an increased magnitude, and spanwise

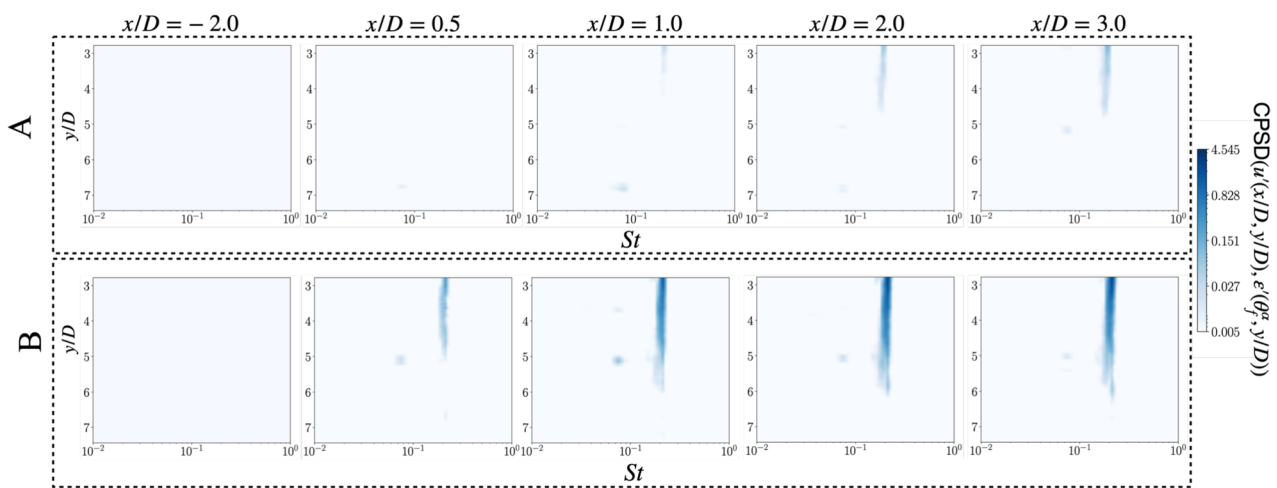


Fig. 7 Cross power spectral density between the fluctuating velocity field downstream of the cylinder, projected into the strain's sensing points obtained by $\theta_f^{-45^\circ}$ and $\theta_f^{-135^\circ}$, at different streamwise locations, for the two experimental conditions tested. The free-stream region of

the flow is projected onto the strain in the windward region of the cylinder ($\theta_f^{-45^\circ}$), and the downstream streamwise stations to the strain in the leeward region of the cylinder ($\theta_f^{-135^\circ}$)

coherence of the von Kármán vortex shedding. This combined effect enhances the global structural response to the shed flow structures, resulting in an increased correlation between the velocity and strain fields. The fact that FST broadens the frequency band at which vortex shedding is initiated leads to a broader band of “energetic” frequencies in the CPSD.

The CPSDs seem to show that the cylinder's structural response is insensitive to the small-scale frequencies introduced by the presence of FST, and embedded within the wake of the cylinder itself. The bluff body is then more susceptible to the generation, modification and deformation of large coherent flow structures, observable both with the acquired CPSD between the windward and leeward fibre sensors. The cylinder response, and therefore the loads to which it is subjected to, acts as a low-pass filter, responding to the flow's low-frequency content, generally associated with large scales. In addition, the cylinder only responds to the spatially coherent motions within the flow. It is then conceivable that a low energy, but spatially coherent flow structure could trigger nonzero CPSD although not in this case as such flow structures do not exist. Furthermore, the CPSDs between data upstream of the cylinder and strain at the windward face of the body are deprived of energy, with and without the introduction of FST, when compared to the energy content of the CPSD for the streamwise stations downstream of the cylinder. This suggests that despite the increased magnitude of intermittent large-strain events that are associated with the direct effect of the FST (see Fig. 4), these do not contribute significantly to the relative energy of the CPSD. We conclude that the structural response of the cylinder (in a statistical sense) is primarily governed

by the large, regular motions within its wake (i.e. the indirect effect of FST). Accordingly, the indirect effect of the presence of FST prevails over the direct impact; however, intermittency introduced via the direct impact of FST can still be significant.

4 Conclusions

To the authors' knowledge, this is the first time that RBS are used to study the flow-induced structural dynamics of a bluff body. Furthermore, this is the first time that temporally resolved PIV is exploited to concurrently measure the velocity field surrounding a wake-generating bluff body to thereby link unsteady flow phenomena to the (distributed) fluctuating strain. In addition, this is also the first time that a RBS network is used to measure turbulence.

As seen by Zhou et al. (1999), the introduction of fibre optic sensors onto a cylinder under a cross flow accounts for negligible effects on the structural response and surrounding flow dynamics. We conduct novel measurements combining 2D-PIV and a RBS network simultaneously, capturing the respective flow structures that excite the structure. The RBS sensing network allows for the acquisition of strain data, with a fine spatial resolution along the spanwise direction. The used configuration of the sensing network also allows us to characterise the strain field before and after the shear-layer separation of the flow. This allows for the interrogation of fluctuating strains induced by the incident free-stream turbulence as well the strains induced by the global deflections of the cylinder, i.e. analysing the direct and indirect effect of FST. The former related to

the direct imposition of a fluctuating velocity field on the windward face of the bluff body, and the latter related to the modification of the vortex shedding process in the near wake of the cylinder, thereby separating both contributions to the overall fluctuating loads acting on the bluff body.

The introduction of FST enhanced the magnitude of ϵ' , especially near the root where the bending moment is maximum and where the stress accumulation is also maximum. Both the rms and max||min range of ϵ' followed the same trend, contributing to the gradual accumulation of fatigue damage over time. FST also contributed to an increased spanwise coherence of von Kármán vortex shedding as seen from the captured flow energy content in the different frequency bands, resulting in a bigger contribution of the structural response associated with this flow structure. Furthermore, the acquired strain was seen to accurately describe the extent of the flow structure throughout the FOV domain. The PDF of ϵ' is highly affected by the presence of FST, especially at the root of the cylinder which is the region of highest experienced strain, with a discernible increased flattening. This resulted from an increase in intermittency of the experienced fluctuating strain over the extent of the cylinder, culminating into larger intensities at the root region, due to the integration of induced structural stresses concentrating in this area.

Furthermore, the spatial evolution of the CPSD between strain and flow data was analysed. The main contribution to structural strain has been seen to be generated by the interaction between the cylinder and the coherent flow structures shed into the wake. The injection of FST accounts for an increase in both coherence in the spanwise direction, resulting in a bigger contribution to ϵ' in this frequency band, and energy associated with these scales. Furthermore, we have shown that the structural response shows little correlation with other frequency scales other than the ones shed by the cylinder. Despite the enhancement of intermittency of high-magnitude fluctuating strain events induced by the direct effect of FST, the indirect influence of FST prevails, largely governing the structural dynamics of the cylinder, significantly contributing to the flow-induced loading events and ultimately structural damage.

Appendix: RBS validation preliminary experiment and uncertainty estimation

The validity and uncertainty of the measurements attained by the RBS network were firstly assessed through a preliminary static experiment. This experiment was designed to compare the data acquired by the RBS with simultaneous data retrieved by strain gauges located next to the RBS

sensing network. The used fibres and acquisition system for this experiment were the same as the ones used in the main experimental campaign. A PVC cylinder was set as a cantilever, fixing one of its ends and placing a known weight of 1.024 Kg on the other end. The cylinder was 400 mm long with a wall thickness of 2.5 mm. Two strain gauges (SG1 and SG2) were set at two streamwise stations $x = [0.15, 0.35]$ m, simultaneously with a RBS sensing network. The strain gauges had a gauge length of 10 mm and a gauge resistance of $120 \pm 0.3 \Omega$.

Figure 8a presents the obtained data from the static test. The obtained results from the strain gauges agreed extremely well with the RBS. Taking into account the difference of gauge length between the two measurement techniques (2.6 mm for the RBS network and 10 mm for the strain gauges),

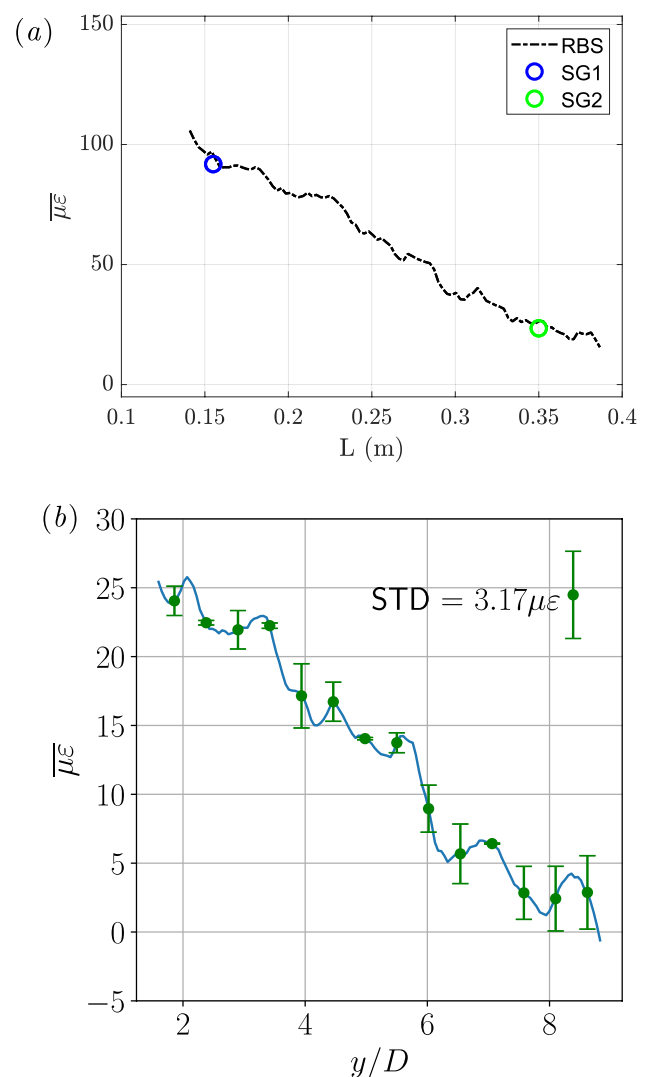


Fig. 8 **a** Strain measurements obtained from preliminary static load tests, to compare data retrieved from two strain gauges and the RBS sensing network; **b** mean time-averaged strain between two repeated tests of the global experimental campaign, under FST conditions A

the region instrumented by the strain gauge accounts for ≈ 4 RBS sensors. The variability of the time-averaged strain between the neighbouring sensors of the strain gauge locations in the two streamwise locations corresponds to $\Delta = [5.42, 1.94]\mu\epsilon$. This difference is considered to be sufficiently small to validate the RBS technique.

This evidence combined with the representation of the imprint of classical flow structures such as von Kármán vortices, and tip vortices onto the structural response suggest that this type of sensors provides reliable data for fluctuating structural responses to an unsteady inflow.

The structural response dataset obtained in this experimental campaign is composed of 2 independent runs, associated with the concurrent PIV upstream and downstream of the cylinder. Figure 8b corresponds to the averaged mean strain between the two tests, overlaid with the relative error between the two datasets. Taking the mean strain field between each two individual acquisitions, we estimate the largest uncertainty to be $3.17\mu\epsilon$, occurring close to the free end of the cylinder. As the strain in this region is smallest, the product of being far from the largest stress concentration at the root, the signal to noise ratio (SNR) decreases, affecting the uncertainty in this region. The largest estimated uncertainty at the root was $1.98\mu\epsilon$.

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Declarations

Competing interests The authors declare no competing interests.

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