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Mella, D., Brevis, W. and Susmel, L. (2020) Spanwise wake development of a bottom-fixed cylinder subjected to vortex-induced vibrations. *Ocean Engineering*, 218. 108280. ISSN: 0029-8018

<https://doi.org/10.1016/j.oceaneng.2020.108280>

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Highlights

Spanwise wake development of a bottom-fixed cylinder subjected to vortex-induced vibrations

Daniel Mella, Wernher Brevis, Luca Susmel

- Proper Orthogonal Decomposition can extract main coherent cylinder motions
- Coherent motion of the maximum cylinder response is an elliptical-type trajectory
- Wake and motion spanwise synchronisation maximised at the highest cylinder response
- Bottom-up desynchronisation develops after the maximum cylinder response is achieved
- 2S and 2P vortex modes observed along the cylinder span and across flow rates

Spanwise wake development of a bottom-fixed cylinder subjected to vortex-induced vibrations

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ARTICLE INFO

Keywords:

Fluid-structure interaction (FSI)
Vortex shedding
Proper orthogonal decomposition (POD)
Bottom-fixed cylinder
Synchronisation
Vortex pattern

ABSTRACT

This study analyses the spanwise wake dynamics and structural response of a bottom-fixed cylinder subjected to a range of open-channel fully developed turbulent flows. The experiments were performed with a Reynolds number ranging between 4.5×10^2 and 1×10^3 . The cylinder free end response and the flow velocity in the wake were measured using Particle Image Velocimetry and image-based tracking techniques. The cylinder had a significant modulated response, from which a Proper Orthogonal Decomposition revealed a clockwise elliptical-type trajectory at the maximum cylinder response. Wake dynamic analysis showed that the maximum response is achieved when the cylinder motion and vortex shedding frequencies are equal (i.e. synchronised) to the natural frequency of the structure measured in still water, and when this equivalence is preserved along the span of the cylinder. As the flow velocity increases, a spanwise bottom-up desynchronisation process develops moving towards the water surface. This process decreases the vortex-formation region strength along the span of the cylinder, reducing the maximum structural response and eventually changing the vortex shedding pattern. Despite the highly three-dimensional experimental conditions under significant turbulent incoming flows, the findings of previous studies based on simpler experimental models can still be used to broadly explain the observed desynchronisation process.

1. Introduction

Vortex induced vibrations (VIV) is a non-linear, self-governed, multi-degree-of-freedom (DOF) phenomenon that occurs due to the interaction between the vortex formation behind a body and its structural response (Williamson and Govardhan (2004)). VIV can be an important contributor to fatigue damage on numerous engineering problems, such as marine risers, large chimneys, heat exchanger tubes, to name a few. Thus, this phenomena has been the subject of constant research in the last decades (see, for example, the extensive reviews of Gabbai and Benaroya (2005); Williamson and Govardhan (2004); Sarpkaya (2004)). An important part of experimental VIV research involves the study of simplified cylindrical models. These experiments usually consist on rigid cylinders forced or free to vibrate in their crossflow direction and subjected to a range of uniform and low-turbulence flows. These simplified models have provided substantial insights into the nature of VIV. Khalak and Williamson (1996, 1997) showed that the mass ratio m^* (ratio between the oscillating structure and displaced fluid mass) has an impact on the range of reduced velocities U_r in which the cylinder response and the vortex shedding frequency are equal, called synchronisation region. Here, $U_r = U_{\text{inlet}} / (f_{\text{water}} D)$, where U_{inlet} is the mean incoming flow velocity, f_{water} is the natural frequency of the structure measured in still water, and D is the diameter of the cylinder. Cylinders with low m^* develop three distinctive

regimes within the synchronisation range: the initial branch, the upper branch, where the maximum response is achieved, and the lower branch. Govardhan and Williamson (2000) related each branch to different vortex shedding patterns using flow visualisation techniques. Williamson and Roshko (1988) used forced-vibration experiments to map these vortical structures as a function of the maximum cylinder displacement and U_r . The researchers observed three vortex patterns or modes: 2S mode (two single vortices per cycle) measured in the initial branch, 2P (two pairs of vortices at every oscillation) observed in the upper and lower branch, and a wake pattern presented only in forced vibration studies, called P+S (single and a pair of vortices per cycle of body motion). Later, Morse and Williamson (2009) found a new vortex mode in the upper branch which they called 2Po. In this mode, a weaker vortex in each pair per cycle was observed.

Different researchers have been trying to determine the applicability of simplified models to cases of increasing complexity, which are closer to engineering applications. Morse and Williamson (2009) satisfactorily predicted the maximum response and wake mode of a free-vibration cylinder using their vortex mode map. Nevertheless, they noted a random component on the cylinder response that could not be reproduced in its forced-vibration counterpart. The effect of the Reynolds number on VIV has been found to be more significant than previously thought. High Reynolds number experiments are characterised by a broader synchronisation range and higher maximum cylinder response (Raghavan and Bernitsas (2011); Wanderley and Soares (2015)). Jauvtis and Williamson (2004) analysed the effects of allowing an additional DOF (crossflow and streamwise response) on

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an elastically mounted rigid cylinder in terms of peak amplitudes, response branches, and vortex shedding modes. They found a new branch (called super-upper branch) for cylinders with $m^* < 6$. Within this branch, peak crossflow amplitudes reached up to $1.5D$, and a new vortex mode called 2T was observed. This new vortex pattern consists on a triplet of vortices each half-cycle of body motion. Additionally, the tested cylinder traced eight-type trajectories throughout its synchronisation range. **Other studies observed different motion patterns, such as elliptical-type (Oviedo-Tolentino et al. (2014)), eight-type, or a combination of both (Kang and Jia (2013)). Kheirkhah et al. (2012, 2016) showed that the trajectory type depends on the structural coupling between the streamwise and crossflow motion. The spanwise variability of tapered, pinned and cantilever cylinders have been used to study complex fluid-structure interactions. Labbé and Wilson (2007) simulated a three-dimensional cylinder and showed the importance of the spanwise length to capture the main features of the flow. Franzini et al. (2014) simultaneously tested a two-DOF cantilever cylinder, and a one-DOF elastically mounted rigid cylinder. Both cylinders had similar mass ratios, diameters, lengths, and damping values. The cantilever cylinder had a broader synchronisation region and a higher maximum crossflow amplitude of $1.15D$ compared to $0.9D$ of the rigid cylinder. Flemming and Williamson (2005) studied the response of a free-vibration, two-DOF pinned cylinder. For small streamwise amplitudes, the response agreed qualitatively well with the one-DOF cylinder of Govardhan and Williamson (2000). However, at large streamwise motions, peak crossflow amplitudes of approximately $1.5D$ and a new vortex mode called 2C, composed of two co-rotating vortices per half-cycle, were observed in the upper branch. In addition, Flemming and Williamson (2005) observed the simultaneous existence of two vortex patterns along the span of the cylinder. Hybrid modes were also found by Techet et al. (1998) on tapered cylinders. Voorhees et al. (2008) studied flow three-dimensionality on a one-DOF free-vibration cylinder. Flow visualisation at different heights along the span of the cylinder showed significant differences with the predictions obtained using the vortex modes map of Morse and Williamson (2009).**

The multi-DOF, variable-amplitude, free-vibration experimental work on VIV has shown substantial differences with the simplified cylindrical models. The two-DOF variable-amplitude bottom-fixed cylinder subjected to VIV provides a compelling case to study how changes in the wake dynamics along the span of the cylinder affect its structural response, a condition commonly found in numerous engineering problems. Previous studies on bottom-fixed cylinders observed and characterised a motion history with a highly dominant coherent response around its maximum displacement and measured the vortex shedding frequency at discrete horizontal planes along the span of the cylinder (see, for example, Franzini et al. (2014); Oviedo-Tolentino et al. (2014)). The identification and characterisation of these coherent responses when the cylinder motion is highly modulated and the variability between the structural response and

vortex shedding synchronisation along the span of the cylinder has not been fully addressed. For this, flow measurements were performed using a two-dimensional Particle Image Velocimetry (PIV) system at one vertical plane along the span of the cylinder and four horizontal planes at different water depths. This high-resolution system allowed to measure the wake dynamics and spanwise vortex shedding as the cylinder is subjected to a range of turbulent flows. Each PIV measurement was synchronised with a camera that recorded the free end displacement of the cylinder. The recordings were analysed with image-based tracking techniques to determine the spatiotemporal displacement of the cylinder.

This paper is organised as follows: a summary of the snapshot POD method is presented in Section 2. Experimental setup of a bottom-fixed cylinder subjected to a range of turbulent flows is given in Section 3. The results are separated into two Subsections: Subsection 4.1 is focused on the characterisation of the cylinder in terms of maximum amplitude, main frequency of oscillation, and coherent trajectory identification using POD. Subsection 4.2 presents the wake dynamics and spanwise vortex shedding variability along the span of the cylinder at different flow velocities. Conclusions are given in Section 5.

2. Proper Orthogonal Decomposition

The Proper Orthogonal Decomposition is a statistical technique based on the decomposition of spatiotemporal data into a linear combination of spatial basis functions or modes (Φ) and their time-dependent modal coefficients (α). POD provides a mathematical definition of energy-relevant structures, arranged in descending order, and a method for their extraction (Brevis and García-Villalba (2011)). As it will be shown later, the cylinder exhibits a single-frequency linear-elastic response along its span due mainly to its low deformation across U_r . Thus, the POD technique is suitable to extract the main coherent trajectories associated with the most dominant frequencies when the cylinder response is highly modulated. A review of this technique can be found in Berkooz et al. (1993); Chatterjee (2000). **Here, the snapshot POD method is briefly described in the context of the cylinder motion history. Detailed information about this technique can be found in Sirovich (1987).**

The spatiotemporal position of the cylinder is expressed in vector form as $\mathbf{x}_c(t_d) = (x(t_d), y(t_d))$, where $t_d = [1, 2, \dots, N]$ and N is the number of data points. Likewise, the fluctuating part of the cylinder response \mathbf{x}_c' is obtained after removing its temporal average ($\bar{\cdot}$) position, $\mathbf{x}_c' = (x', y')$, where $x'(t_d) = x(t_d) - \bar{x}$ and $y'(t_d) = y(t_d) - \bar{y}$. The fluctuating part \mathbf{x}_c' is separated in k vectors of equal size L ($KL = N$) and arranged in matrix form as

$$\mathbf{X} = \begin{bmatrix} x'_1 & x'_2 & \dots & x'_K \\ y'_1 & y'_2 & \dots & y'_K \end{bmatrix} \quad (1)$$

The dimensions of the assembled matrix are $2L \times K$. Each column in Eq. 1 is considered a snapshot and represents the

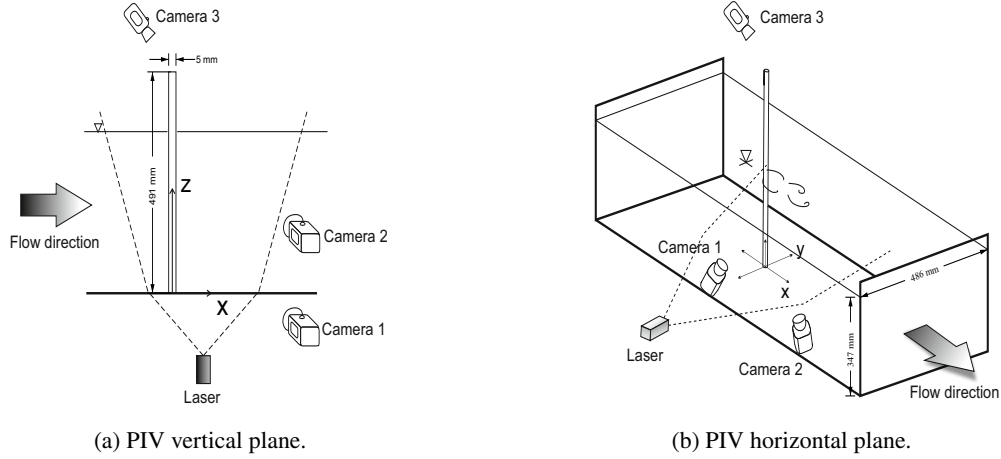


Figure 1: Experimental setup of a bottom-fixed cylinder subjected to a range of turbulent flows. Cylinder oscillations in transverse (y-axis) and longitudinal (x-axis) directions. The z-axis lies along the span of the cylinder. a) Vertical PIV plane. b) Horizontal PIV plane.

167 trajectory traced by the cylinder over L data points. Thus,
 168 the goal of using POD is to find the underlying coherent motion
 169 across all snapshots. Given a number of spatial modes
 170 Φ_n and their corresponding modal coefficient α_n , the POD
 171 method finds the best fit for \mathbf{X} in a least-square sense

$$\left\| \mathbf{X} - \sum_{n=1}^K \alpha_n \Phi_n \right\| \quad (2)$$

172 where $\|\cdot\|$ is the L_2 -norm, and $n = [1, 2, \dots, K]$. The
 173 POD method solves Eq. 2 through the solution of the following
 174 Eigenvalue problem
 175

$$\mathbf{C}\Phi_n = \lambda_n \Phi_n \quad (3)$$

176 where $\mathbf{C} = \overline{\mathbf{X}^T \mathbf{X}}$ is the autocovariance matrix, and λ_n
 177 are the eigenvalues. The POD modes are orthonormal to
 178 each other and the eigenvalues represent the contribution of
 179 mode n to the total variance. The POD modes are usually
 180 arranged in descending order based on their corresponding
 181 λ_n to identify dominant patterns in the data. The relative of
 182 the i -th POD modal value is defined as
 183

$$\varepsilon_i = \frac{\lambda_i}{\sum_{n=1}^K \lambda_n} \quad (4)$$

184 3. Experimental Setup

185 The experiments were performed at the Civil and Structural
 186 Engineering water laboratory, University of Sheffield,
 187 United Kingdom. The flume was covered with clear cast
 188 acrylic sheets, leaving a squared cross-sectional area with
 189 width 486 mm and a longitudinal fixed slope of 0.001 m/m.

A water depth of $H_w = 347$ mm was fixed using a computer-
 190 controlled system and a control gate located at the end of the
 191 flume. The Reynolds number R_e ranged between 4.5×10^2
 192 and 1×10^3 , which corresponds to the maximum flow rate of
 193 the facility. Here, $R_e = U_{\text{inlet}} D / \nu$, where U_{inlet} is the mean
 194 incoming flow velocity, D is the diameter of the cylinder, and
 195 ν is the kinematic viscosity of water. The incoming turbulent
 196 intensity was measured at 5% for all tested flow velocities.
 197 A 5 mm diameter hole with 10 mm depth was drilled on a
 198 squared acrylic base with width 165 mm. A cylinder made of
 199 clear cast acrylic (elastic modulus of 3.2×10^4 Kg cm $^{-2}$)
 200 was inserted into the hole and chemically welded fabricating
 201 a fixed end. The model was placed 10.5 m downstream, ensuring
 202 that the centre of the cylinder coincided with the middle of the
 203 flume's width. The cylinder configuration allowed the opposite
 204 end to vibrate in both the in-line (x-axis) and transverse (y-axis)
 205 flow directions. The z-axis lies along the span of the cylinder.
 206 The cylinder had a diameter of 5 mm, length of 491 mm, and m^*
 207 of 1.41. Figure 1 shows a sketch of the experimental setup.
 208

The measurements were taken using a three-camera PIV
 210 system, consisting of a double-pulsed 532 nm wavelength
 211 Nd:YAG compact Laser of 200 mJ maximum power output,
 212 three MX 4M cameras of 2048x2048 pixel resolution, and a
 213 Programmable Time Unit (PTU) used to synchronise the cameras
 214 and laser trigger times. Higham and Brevis (2018)
 215 used the same water channel and PIV equipment to measure
 216 the wake around multiple obstacles. The water was seeded
 217 with Polyamide 12 of 100 μm mean particle size and 1.06
 218 g cm $^{-3}$ density. Two cameras recorded the spatio-temporal
 219 motion of these particles. Simultaneously, a third camera
 220 recorded the free end response of the cylinder. After adjusting
 221 the cameras and laser position, a calibration plate LaVision
 222 model 309-15 was placed on the desired measurement plane,
 223 and an image was taken. The markers within the calibration
 224 plate were used to correct the measurements for optical
 225 distortions and to establish a correspondence between
 226

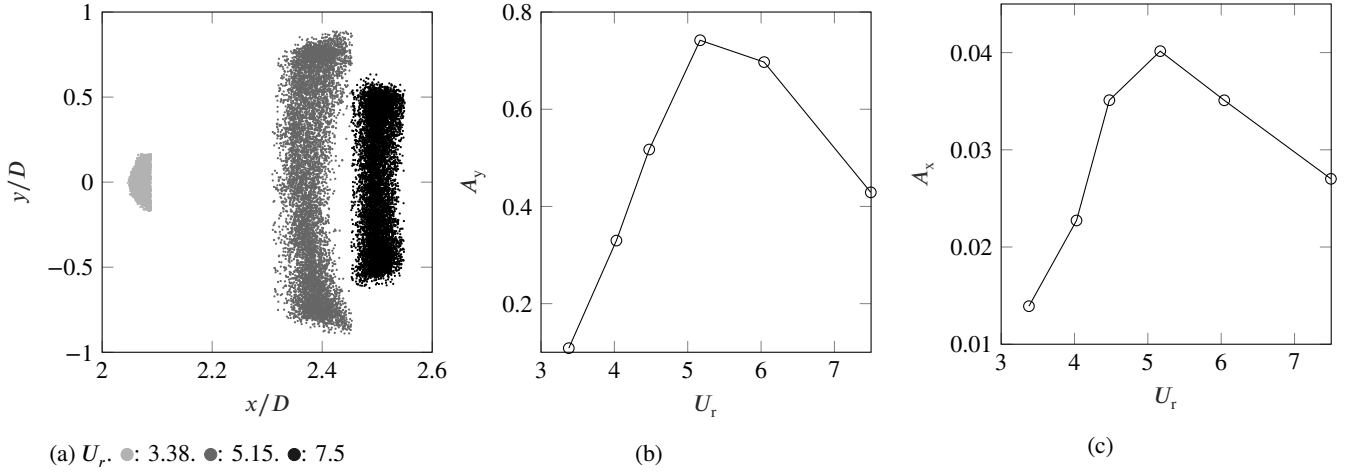


Figure 2: Cylinder free end response at $4.5 \times 10^2 \leq Re \leq 1 \times 10^3$. a) Spatiotemporal displacement. b) Maximum displacement in the crossflow direction. c) Maximum displacement in the streamwise direction.

227 tween a Pixel and real-world coordinates. The wake zone
 228 and cylinder response were measured at six flow rates at 70
 229 Hz for two minutes. The PIV measurement consisted of a
 230 vertical plane through the cylinder centreline and four hori-
 231 zontal planes at $(x, y, z) = (x, y, [20, 34, 52, 60]D)$. Figure 1
 232 shows a sketch of a vertical (Figure 1a) and horizontal (Fig-
 233 ure 1b) measurement. **A multiple-pass correlation process**
 234 **with subpixel accuracy of 0.1 pixels** were used to determine
 235 the flow velocity field from the flow images. An initial inter-
 236 rogration window of 64×64 pixel with two passes, followed
 237 by a 32×32 pixel window with three passes were employed.
 238 In each correlation, an overlap of 75% between interrogation
 239 windows was used to increase the resolution of the velocity
 240 field. **The maximum spatial resolution was 0.39 mm.** The
 241 images of the cylinder free end response were calibrated us-
 242 ing the same procedure but with a smaller calibration plate
 243 LaVision model 058-5. The cylinder response was estimated
 244 using the image-based tracking technique described in Mella
 245 et al. (2019).

246 A free decay test was conducted on the bottom-fixed cylin-
 247 der to determine its damping ratio and the natural frequency
 248 measured in air f_{air} and still water f_{water} . The cylinder was
 249 subjected to a uni-dimensional displacement parallel and per-
 250 pendicular to the flow direction. A PS3 Eye Camera was
 251 placed on the free end of the cylinder and recorded its re-
 252 sponse. Each video sequence was taken at 187 Hz with a
 253 320×240 pixel resolution. The images were calibrated us-
 254 ing the same procedure described for the cylinder free end
 255 response. The results show that the natural frequency mea-
 256 sured in air and still water is equal in both directions, with
 257 values of $f_{\text{air}} = 6.4$ Hz and $f_{\text{water}} = 5.3$ Hz respectively.
 258 Considering a logarithmic decay response, the damping ratio
 259 measured in air was estimated at 4%. The free decay test was
 260 repeated after all the tests were completed with no degrada-
 261 tion on the dynamical properties of the cylinder.

4. Results

4.1. Cylinder response and modal decomposition

262 Figure 2 summarises the cylinder response over the
 263 range of tested U_r . Figure 2a shows the spatiotemporal free
 264 end displacement at $U_r = [3.38, 5.15, 7.5]$ obtained with
 265 the image-based tracking technique described in Mella et al.
 266 (2019). The mean streamwise free end position of the cylin-
 267 der moves downstream as U_r increases, reaching a maxi-
 268 mum constant displacement of $2.5D$ and an inclination of
 269 approximately 1.5° at the maximum flow velocity. Figure
 270 2a suggests that the total cylinder response is composed of
 271 a main coherent motion with a superimposed random com-
 272 ponent. The visualisation of this large-scale pattern will be
 273 addressed later by means of the POD technique. Figures
 274 2b and 2c show the maximum displacement in the stream-
 275 wise A_x and crossflow A_y direction. Following the defini-
 276 tion of Hover et al. (1998), the maximum displacement in
 277 a given direction is the mean value of the highest 10% of
 278 the recorded response. The maximum displacement in both
 279 directions increases with U_r , reaching a maximum value of
 280 $A_y = 0.74D$ and $A_x = 0.04D$ at $U_r = 5.15$. Then, at fur-
 281 ther increments of U_r , the maximum displacement decreases
 282 reaching $A_y = 0.43D$ and $A_x = 0.03D$ at $U_r = 7.5$. The ra-
 283 tio A_y/A_x ranges from 8 at $U_r = 3.18$ to 19 at $U_r = 6.04$,
 284 indicating an overall predominance of the crossflow motion
 285 over its streamwise counterpart.
 286

287 Eight minutes of displacement data were separated in
 288 vectors of equal length L and arranged in matrix form as
 289 described in section 2. Given a fixed measurement time, the
 290 selection of L is a trade-off between the number of snap-
 291 shots used for POD and the cylinder trajectory traced within
 292 each snapshot. Convergence of the first (average) and sec-
 293 ond (variance) order statistics is achieved at $L = 560$ data
 294 points. Thus, snapshots of $L = 700$ (53 motion cycles on av-
 295 erage) were selected for analysis. The relative modal value
 296 ε_i of the first eight modes ($i = [1, \dots, 8]$) is shown in Figure
 297 3a. The first two modes capture an important part of the total
 298

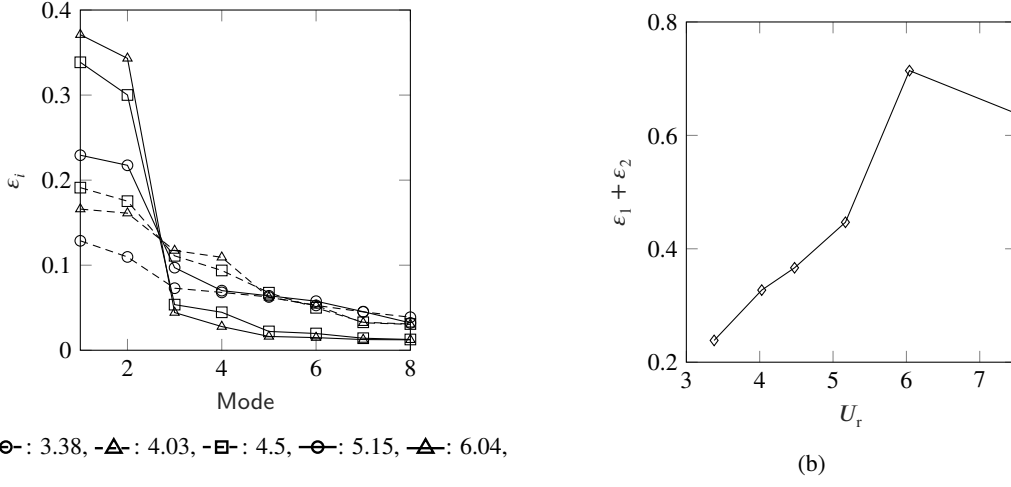


Figure 3: Relative modal values of the cylinder response. a) ε_i , where $i = [1, 2, \dots, 8]$. b) $\varepsilon_1 + \varepsilon_2$

299 variance at higher cylinder responses ($U_r > 5$) as opposed
 300 to lower displacements ($U_r < 5$), from which the relative
 301 energy of higher-order modes are significant. It is expected
 302 that the first two modes contain relevant trajectory patterns
 303 underlying the total displacement for $U_r > 5$ and that the mo-
 304 tion history for $U_r < 5$ has no coherent spatial mode. Figure
 305 3b shows the contribution of $\varepsilon_1 + \varepsilon_2$ at different U_r . $\varepsilon_1 + \varepsilon_2$
 306 increased up to 45% at the maximum cylinder response. Then,
 307 it jumped to 71% when the maximum crossflow displace-
 308 ment decreased from its maximum value of $A_y = 0.74D$ to
 309 $A_y = 0.7D$. Lastly, it decreased to 63% when $A_y = 0.43D$
 310 at the highest tested U_r . This increment in the predomi-
 311 nance of the trajectory pattern to the total body motion after the
 312 cylinder reached its maximum response could be explained
 313 by a transition to the lower branch, characterised by a higher
 314 periodic motion compared to the upper branch (Khalak and
 315 Williamson (1999)).

316 Figure 4 shows the reconstructed displacement signal
 317 adding the spatial modes $\Phi_1 + \Phi_2$. Higher order modes
 318 only contributed to the irregularity of the trajectory pat-
 319 terns for all U_r . Irregular modal shapes were obtained for
 320 $U_r < 5$. Clockwise elliptical-type trajectories were identi-
 321 fied for $U_r = 5.15$ and $U_r = 6.04$. Elliptical trajectories
 322 are associated with strong structural coupling between the
 323 streamwise and transverse motion (Kheirkhah et al. (2012,
 324 2016)). Similar findings were observed in Oviedo-Tolentino
 325 et al. (2014) for a bottom-fixed cylinder with $m^* = 8.13$.
 326 Pure elliptical-type trajectories were observed for $U_r > 5$,
 327 while irregular shapes were obtained at lower reduced ve-
 328 locities. The researchers suggested that irregular shapes could
 329 be associated with a high dependence of the added mass to
 330 low U_r values. A deviation from a pure elliptical-type tra-
 331 jectory is observed at $U_r = 7.5$. A Power Spectral Density
 332 (PSD) analysis of its second spatial mode showed that the
 333 energetic value of the first harmonic in the streamwise di-
 334 rection is 83% of its main frequency. The influence of this
 335 harmonic explains this particular combination between an
 336 elliptical- and eight-type trajectory. Despite the unclear tra-

Table 1

Streamwise and crossflow normalised frequencies of the first two modes at different U_r .

Axis	Mode	U_r					
		3.38	4.03	4.5	5.15	6.04	7.5
X	1	0.76	0.86	0.90	1.01	1.02	1.04
	2	0.76	1.68	0.90	1.01	1.02	1.03
Y	1	0.76	0.84	0.89	1.01	1.02	1.03
	2	0.76	0.84	0.89	1.01	1.02	1.03
	f_c	0.76	0.85	0.90	1.01	1.02	1.04

jectories in Figure 4, the main vibration frequencies of the
 337 first two spatial modes were successfully extracted using a
 338 PSD analysis. The results are summarised in Table 1. The
 339 main frequency in the streamwise f_x and crossflow f_y di-
 340 rection was normalised by f_{water} . Here, the average of the
 341 first mode between f_x and f_y is defined as the main peak
 342 frequency of the cylinder f_c . The results show that f_x and
 343 f_y have similar values throughout U_r , which is consistent
 344 with an elliptical-type trajectory. f_c ranges between 0.76 to
 345 1.03 as U_r increases. The cylinder achieves its maximum re-
 346 sponse when $f_c \approx 1$ at $U_r = 5.15$, which is consistent with
 347 the findings of Oviedo-Tolentino et al. (2014).
 348

4.2. Spanwise synchronisation region

349 Spanwise wake dynamics were analysed using two-
 350 dimensional PIV measurements at a vertical plane through
 351 the cylinder centreline and four horizontal planes at
 352 $(x, y, z) = (x, y, [20, 34, 52, 60]D)$. The lowest flow mea-
 353 surements ($U_r = 3.38$ and $U_r = 4.03$) are not presented in
 354 this section as the results are similar to $U_r = 4.5$. Figure 5
 355 shows the reduced velocity profile at $8D$ upstream from the
 356 centre of the cylinder $U_r(x = -8D, y, z)$. Dashed lines indi-
 357 cate the average incoming reduced velocity. The velocity
 358 profile resembles a parabolic distribution as expected from
 359

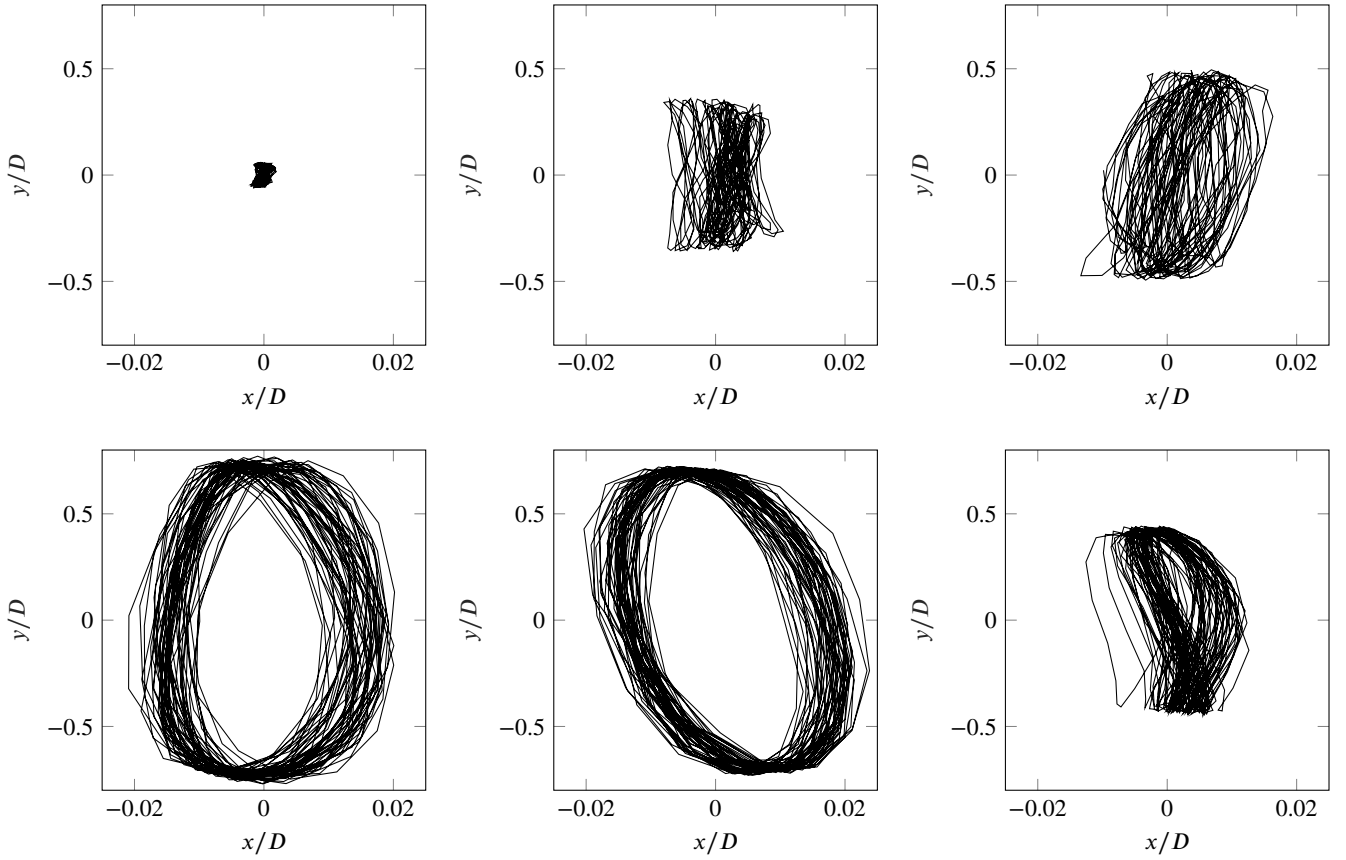


Figure 4: Reconstructed cylinder response from $\Phi_1 + \Phi_2$. From top left to bottom right: $U_r = [3.38, 4.03, 4.5, 5.15, 6.04, 7.5]$.

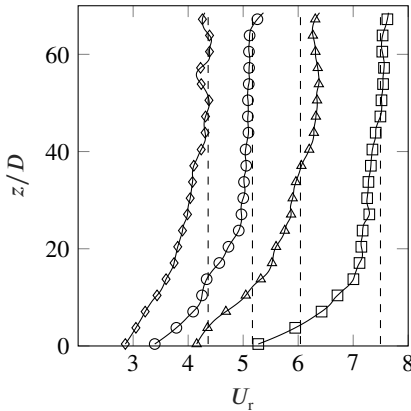


Figure 5: Spanwise reduced velocity profile at $8D$ upstream from the centre of the cylinder. $U_r(x = -8D, 0, z)$. \blacklozenge : 4.5, \bullet : 5.15, \blacktriangle : 6.04, \blacksquare : 7.5. Dashed lines are the average incoming reduced velocity calculated using U_{inlet}

tex shedding frequency f_v to the main peak frequency of the cylinder f_c . The streamwise velocity is decomposed as $u(x, y, z, t) = u'(x, y, z, t) + \bar{U}(x, y, z)$, where u' is the fluctuating component, and \bar{U} is the time-averaged velocity. The PSD of $u'(4.8D, 0, z, t)$ was calculated at each grid point within z . Figure 7 shows the main peak frequency of the PSD normalised by f_c . Across all reduced velocities, there is a region between $9D$ and $16D$ from the bed surface where $f_v < f_c$. This low f_v region is the result of the interaction between a sheared incoming flow velocity, which is produced by the parabolic velocity profile of the open-channel shown in Figure 5, and the presence of the cylinder with a small response amplitude in that region. Analysis of the mean streamwise velocity field downstream of the cylinder showed that $\bar{U}(4.8D, 0, z) \approx U_{inlet}/2$ at $z < 16D$ which is in line with the observed reduction in the vortex shedding frequency in that region. Figure 7a and 7b show good agreement between f_v and f_c at $z > 16D$ for $U_r = 4.5$ and $U_r = 5.15$ respectively. Specifically, Figure 7b shows that the maximum cylinder response is achieved when the equivalence $f_c = f_v = f_{water}$ is preserved along the span of the cylinder, i.e. when the spanwise synchronisation region is maximal. It is worth noting that, despite the parabolic distribution of the incoming velocity profile, the synchronisation region extends from $z = 16D$ up to the free surface. The constrained desynchronised region of $z < 16D$ for all

open-channel flows. Approximately 90% of the average incoming reduced velocity is achieved at $z > 18D$. As will be shown later, the velocity gradient at $z < 18D$ had a limited impact on the spanwise synchronisation between the vortex shedding and cylinder main motion frequency.

The spatiotemporal variability of the streamwise velocity component $u(x, y, z, t)$ was analysed to compare its vor-

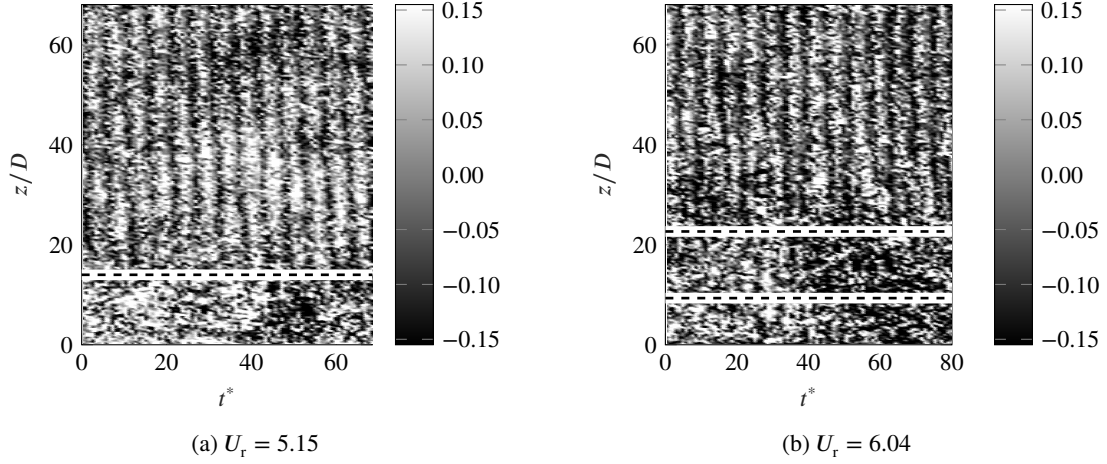


Figure 6: Normalised time series of $u'(4.8D, 0, z, t)/\bar{U}(4.8D, 0, z)$.

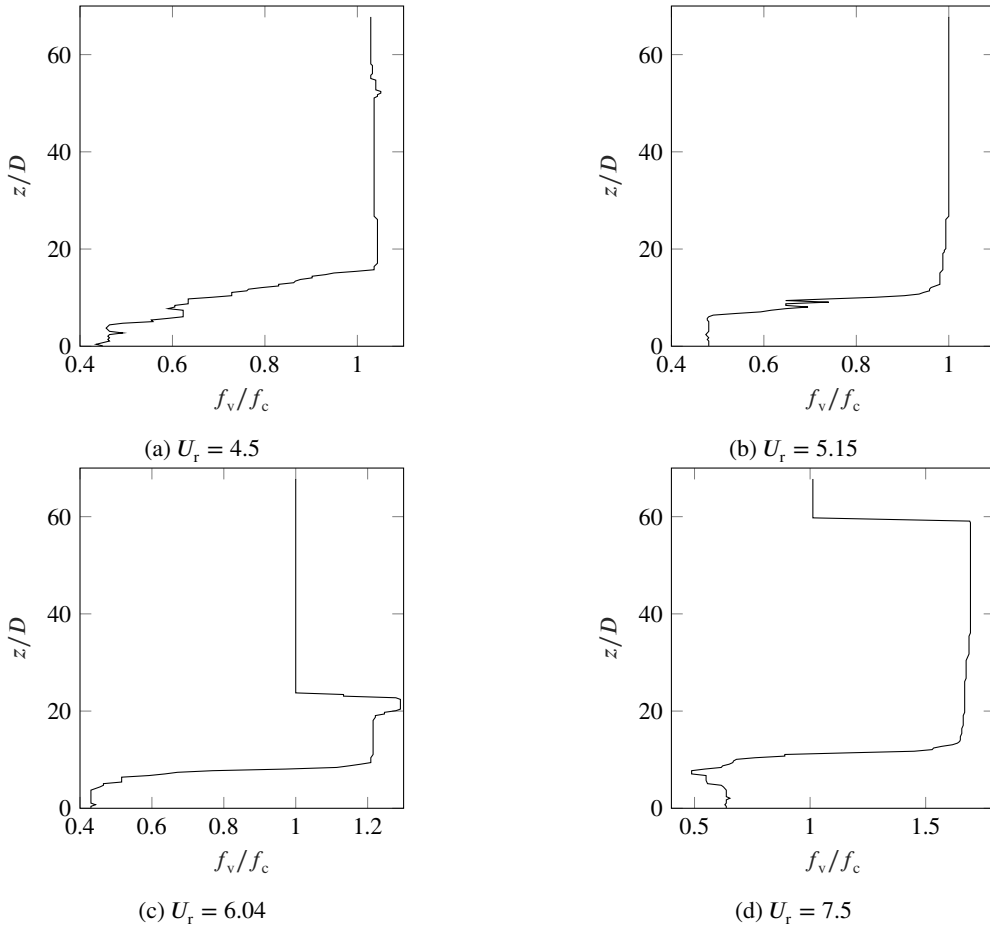


Figure 7: Normalised vortex shedding frequency measured at $4.8D$ downstream from the cylinder centre.

U_r is expected to have a small impact on the maximum cylinder response due to its proximity to the cylinder fixed end. At higher U_r , Figure 7c shows an increment of f_v between 1.2 and 1.3 at $9D \leq z \leq 25D$. Likewise, at the maximum tested U_r , f_v jumped from 1.01 to between 1.65 and 1.70 at $13D \leq z \leq 59D$. In terms of maximum crossflow displacement, A_y reaches its maximum value of $0.74D$ when

the synchronisation region is maximal. Then, A_y decreased 5.4% and 39.7% when the desynchronised region extended $17D$ and $53D$, respectively. Figure 6 shows the time series of $u'(4.8D, 0, z, t)$, normalised by $\bar{U}(4.8D, 0, z)$, for $U_r = 5.15$ and $U_r = 6.04$. Here, the normalised time was defined as $t^* = tU_{inlet}/D$. Wake patterns are clearly visible for both U_r . The extension of these wake patterns, delimited by hori-

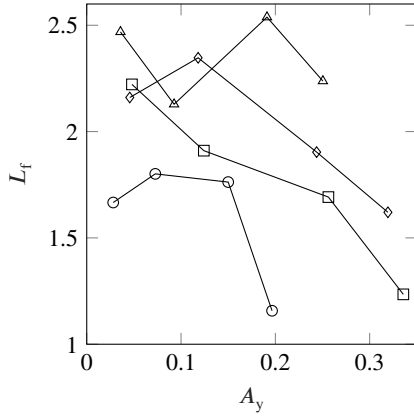
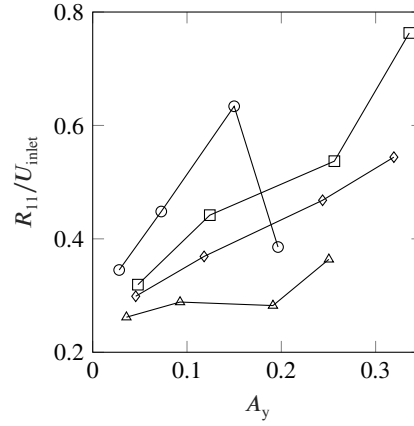

 (a) U_r , \circ : 4.5, \square : 5.15, \diamond : 6.04, \triangle : 7.5.

 (b) U_r , \circ : 4.5, \square : 5.15, \diamond : 6.04, \triangle : 7.5.

Figure 8: L_f and maximum R_{11} at different water depths.

407 zontal lines, coincided with the regions where $f_v = f_c$. The
 408 additional horizontal line in Figure 6b delimits an interme-
 409 mediate region where $f_v > f_c$. Overall, Figure 6 and 7 show
 410 the development of a bottom-up desynchronisation process,
 411 starting at $z = 16D$ and moving towards the free surface as
 412 U_r increases.

413 Wake dynamics as the desynchronisation process devel-
 414 ops are analysed in terms of fluctuating velocity fields. Fig-
 415 ure 8 shows the vortex formation length L_f and the max-
 416 imum normal Reynold Stress $R_{11} = \overline{u'u'}/U_{inlet}^2$ along the
 417 wake centreline at $(x, y, z = [20, 34, 52, 60]D)$. The for-
 418 mation length corresponds to the downstream distance from
 419 the cylinder surface where the maximum R_{11} is achieved.
 420 L_f and the maximum R_{11} are plotted against its correspond-
 421 ing local maximum crossflow cylinder displacement $A_y(z)$,
 422 which was estimated assuming a linear-elastic response. A
 423 general reduction of L_f is observed as $A_y(z)$ increases in
 424 the synchronised region (see $U_r = [4.5, 5.15]$ in Figure
 425 8a). In contrast, the maximum R_{11} increases with $A_y(z)$.
 426 These results are in line with Bearman (1984), which indi-
 427 cated that higher cylinder displacements lead to stronger
 428 and shorter vortex formation near the cylinder with a subse-
 429 quent stronger vortex shedding. At $U_r = 6.04$, L_f increases
 430 from $2.16D$ to $2.35D$ as the plane of measurement moves
 431 from a desynchronised region ($z = 18D$) to a synchronised
 432 one ($z = 34D$). Then, L_f restores its inverse relationship
 433 with $A_y(z)$ for $z > 34D$ in the synchronised region. At
 434 $U_r = 7.5$, where only $z \geq 59D$ is synchronised, L_f ranges
 435 between $2.2D$ and $2.5D$ and no clear trend is observed. In
 436 contrast, the maximum R_{11} slowly increases from 0.26 to
 437 0.28 throughout its desynchronised region ($z < 59D$) and
 438 then jumps to 0.36 at $z = 60D$, where the cylinder and wake
 439 are still synchronised. A significant reduction in L_f and max-
 440 imum R_{11} is observed at $z = 60D$ for $U_r = 4.5$. The R_{11}
 441 distribution along the wake centreline shows a double peak in
 442 its vortex formation region which suggests the confluence be-
 443 tween two vortex pattern configurations. Nevertheless, fur-
 444 ther research needs to be conducted to analyse this particular
 445 case.

446 The desynchronisation process described above can be
 447 partially explained by the particular characteristics of the
 448 tested bottom-fixed cylinder. Flemming and Williamson
 449 (2005) showed that, for small streamwise amplitudes, cylin-
 450 ders with two- and one-DOF free-vibration agree qualita-
 451 tively well. Furthermore, Williamson and Roshko (1988)
 452 indicated that the synchronisation range, dependent on the tim-
 453 ing between the cylinder-fluid acceleration, increases with
 454 the cylinder displacement. The bottom-fixed cylinder has a
 455 dominant crossflow response up to 19 times its streamwise
 456 counterpart. Consequently, the range of crossflow response
 457 acceleration along the span of the cylinder, which dimin-
 458 ishes to zero approaching its fixed end, is largely responsi-
 459 ble for the range of U_r in which synchronisation occurs. As
 460 U_r increases and the cylinder motion is significant, the syn-
 461 chronisation region along the span of the cylinder is maxi-
 462 mal, and the vortex shedding frequency is locked-in to the
 463 cylinder motion frequency. This relationship is preserved
 464 at higher U_r until $f_c = f_{water}$, where the maximum cylin-
 465 der displacement is achieved. Then, at further increments of
 466 U_r , the cylinder displacement near its fixed end is not able
 467 to reach the needed increment in acceleration to sustain a
 468 synchronised condition, and desynchronisation occurs. As a
 469 consequence, the vortex region strength along the span of
 470 the cylinder decreases with a subsequent reduction in the
 471 cylinder response. This desynchronisation process is en-
 472 hanced as the desynchronised region develops towards the
 473 water surface, with a higher percentage of the cylinder re-
 474 sponse along its span being unable to sustain lock-in, reduc-
 475 ing the overall strength of the vortices, and causing a sys-
 476 tematic reduction in the cylinder response. Further changes
 477 are observed in the vortex pattern as the desynchronisation
 478 region progresses. Figure 9 shows the contours of normal
 479 Reynold stress $R_{11} = \overline{u'u'}/U_{inlet}^2$ at $z = [34, 52, 60]D$. Im-
 480 portant changes are observed as z increases, specifically at
 481 $z = 60D$. Following the contour distribution in Govardhan
 482 and Williamson (2001), a transition from 2S vortex mode
 483 (Figure 9a) to 2P (Figures 9b and 9c) is observed. Then,
 484 Figure 9d suggest a transition back to a 2S vortex pattern

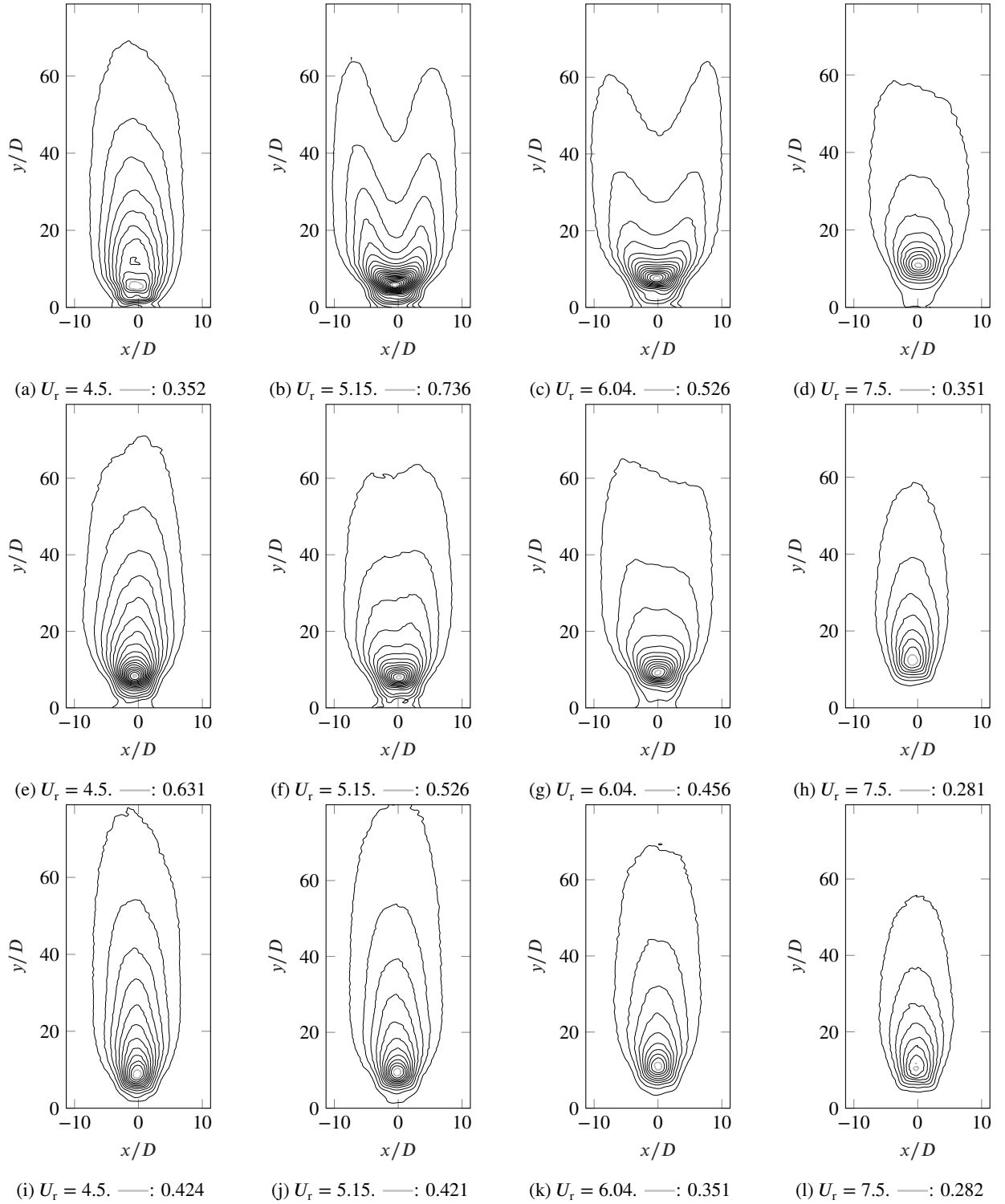


Figure 9: Contours of $\overline{u'u'}/U_{\text{inlet}}^2$ (contour interval = 0.035) at $z = 60D$ (a-d), $z = 52D$ (e-h) and $z = 34D$ (i-l). Grey line: maximum contour value.

485 at the highest U_r . A 2S-2P dual-mode configuration is observed
 486 across the span of the cylinder for $U_r = 5.15$ (Figures
 487 9b, 9f, and 9j) and $U_r = 6.04$ (Figures 9c, 9g, and 9k).

5. Conclusions

This study analyses the spanwise vortex shedding dynamics and structural response of a bottom-fixed cylinder subjected to a range of open-channel, fully developed turbulent flows. Planar PIV measurements and a synchronised

single camera were used to capture the flow around the wake region and the cylinder free end response. The results showed that the POD technique successfully uncovers the main trajectory patterns in cases where the cylinder response is highly modulated. The patterns uncovered for the tested cylinder correspond to a clockwise elliptical-type trajectory for $U_r > 5$. A deviation from a pure elliptical-type trajectory was found at $U_r = 7.5$, which is given by the relation between the main streamwise frequency of its second spatial mode and its first harmonic. Wake dynamic analysis showed that the maximum response is achieved when the cylinder motion and vortex shedding frequencies are equal (i.e. synchronised) to the natural frequency of the structure measured in still water, and when this equivalence is preserved along the span of the cylinder. As U_r increases, the cylinder displacement near its fixed end is not able to reach the needed increment in acceleration to sustain a synchronised condition, and desynchronisation occurs. As a consequence, the vortex strength is reduced across the span of the cylinder with a subsequent decrement in the cylinder response. As U_r is further increased, the desynchronised region progresses towards the water surface alongside further decrements in vortex strength and a systematic reduction in the cylinder response. Changes in the wake dynamics as the desynchronised region progresses and the cylinder response decreases showed a transition from a 2S-2P dual-mode configuration at the highest cylinder response to a predominant 2S mode. The results showed that, despite the highly three-dimensional experimental conditions under significant turbulent incoming flows, the findings of previous studies based on simpler experimental models can still be used to broadly explain the observed bottom-up desynchronisation process.

Acknowledgement

Work supported by a Doctoral Scholarship from CONICYT/ Concurso para Beca de Doctorado en el Extranjero.

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