UNIVERSIDADE DE SÃO PAULO
ESCOLA POLITÉCNICA

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MANIPULATING THE FLOW OVER A CIRCULAR CYLINDER
WITH CONTROL RODS

São Paulo
2022

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Manipulating the Flow over a Circular Cylinder
with Control Rods

Versão Corrigida

Tese apresentada à Escola Politécnica da
Universidade de São Paulo para obtenção do
Título de Doutor em Ciências

Area de concentração: Engenharia Mecânica

Orientadores: Prof. Dr. Gustavo R.S. Assi
Prof. Dr. Peter W. Bearman
Prof. Dr. Oliver R.H. Buxton

São Paulo
2022

Universidade de São Paulo
Escola Politécnica

**Imperial College
London**

Imperial College London
Department of Aeronautics

Joint PhD Programme

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2022

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São Paulo, _____ de _____ de _____

Assinatura do autor: _____

Assinatura do orientador: _____

Catálogo-na-publicação

Cicolin, Murilo Marangon

Manipulating the flow over circular cylinders with control rods / M. M. Cicolin -- versão corr. -- São Paulo, 2022.
153 p.

Tese (Doutorado) - Escola Politécnica da Universidade de São Paulo. Departamento de Engenharia Mecânica.

1.Experimental Fluid Mechanics 2.Flow around Bluff Bodies 3.Flow Control 4.Fluid Dynamics I.Universidade de São Paulo. Escola Politécnica. Departamento de Engenharia Mecânica II.t.

Abstract

The flow past a circular cylinder with control rods at moderate values of Reynolds number is experimentally investigated in this work. The flow topology depends on many parameters, such as Reynolds number (Re), the ratio between the diameter of the cylinders (d/D), number and position of the rods. Preliminary experiments on the sensitivity of fluid forces have shown that the rod's position is the most relevant among all the parameters tested. The hydrodynamic forces suffer the greatest variation when the rod is placed close to the shear layers or the cylinder's surface.

Detailed investigation of the wake with one-rod using fixed values of $Re = 20,000$, and $d/D = 0.1$ has shown that the wake developed three distinct states, depending on the rod's angular position θ . State I is characterised by two distinct vortex streets, downstream of the cylinder and rod, respectively. State II is characterised by a strong jet between the cylinder and the rod and a late separation due to Coandă effect. And in State III the rod acts in the recirculation region, with a relatively lower influence in the flow compared to the other states. In addition, a bi-stable case was observed between the states II and III, with no clear switching frequency between the states and very sensitive to the rod's position.

Adding a second and symmetrical rod to the system turns the mean flow symmetric for States I and III, whereas State II shows an asymmetric mean wake due to a bi-stable behaviour induced by the imbalance of the jets in the near wake. A transitional case was observed between State I and II, with a type of separation not observed for one-rod cases, which showed a reduction of 90% in the fluctuating lift force.

The position of the separation point varied significantly for States I and II compared to that of a bare cylinder. It prompted a significant impact on the hydrodynamic forces acting on the cylinder. The greatest reductions of the mean drag force were observed for State II cases with two-rod: 20% for the combined system and 30% for the main cylinder, both with respect to the bare cylinder case.

Resumo

“Manipulao do Escoamento ao Redor de um Cilindro com Hastes de Controle”

O escoamento ao redor de cilindros com hastes de controle para valores moderados do nmero de Reynolds investigado neste trabalho. A topologia do escoamento depende de vrios parametros, dentre os quais o nmero de Reynolds (Re), a razo entre os dimetros dos cilindros (d/D), nmero e posio das hastes. Experimentos preliminares para avaliar a sensibilidade das foras hidrodinmicas mostraram que a posio das hastes o parmetro mais relevante dentre os avaliados. As foras sofrem maiores variaes quando a haste est prxima ou da camada cisalhante ou da parede do cilindro.

Investigaes detalhadas com apenas uma haste de controle e valores fixos de $Re = 20.000$ e $d/D = 0,1$ mostraram que a esteira desenvolve trs estados distintos, dependendo da posio angular da haste θ . O estado I caracterizado pela presena de duas esteiras de vrtices distintas, a jusante do cilindro e da haste, respectivamente. O estado II caracterizado por um intenso jato entre o cilindro e a haste e uma separao tardia provocada pelo efeito Coandă. No estado III a haste est na regio de recirculao, afetando menos o escoamento em comparao com os outros estados. Adicionalmente, um caso biestvel foi observado entre os estados II e III, sem uma clara frequncia de transio entre eles e bastante sensvel a posio das hastes.

A adio de uma segunda haste, simtrica a primeira, torna o escoamento mdio simtrico nos estados I e III, enquanto que o estado II apresenta uma esteira mdia assimtrica devido a um comportamento biestvel, induzido pelo desbalano da intensidade dos dois jatos na esteira prxima. Um caso transicional entre os estados I e II foi observado, com um tipo de separao no verificado nos casos com uma haste, mostrando uma reduo de 90% da flutuaao da fora de sustentao.

A posio do ponto de separao variou significativamente nos estados I e II em relao ao cilindro liso, especialmente nos estados I e II. Esta variao provocou um grande impacto nas foras hidrodinmicas. As maiores recues na fora mdia de arrasto foram observadas no estado II com duas hastes: 20% para o sistema completo e 30% considerando somente o cilindro principal, ambos em relao ao caso do cilindro liso.

Acknowledgements

I would like to thank my supervisors, Professors Gustavo R.S. Assi, Peter W. Bearman and Oliver R.H. Buxton, for giving me this opportunity and for their guidance through these years. Gustavo, with whom I have had the pleasure to work for the past 10 years, has always supported me through all aspects of university life. Peter, who welcomed my participation in the joint-degree programme since the first day, made an invaluable effort to make it happen, even when I thought it was not possible. His support and encouragement were essential to finish this thesis. Oli has been an excellent supervisor. His honest comments and readiness to review my manuscripts have been essential to this work. I have learnt a lot with you, and could never have wished for better supervisors.

I am grateful to all people I encountered during these years, including students, professors, technicians and administrative staff, both at the University of So Paulo and Imperial College London. It would be impossible to cite them individually without doing any injustice. I am particularly thankful to Krishna Kankanwadi, who helped me in every detail at ICL since my first day in London.

I would like to thank the support of all my family and friends from Brazil, especially my parents, who have always urged me on the PhD path in spite of the distance. I know it has been hard for you too. Above all, my invaluable gratitude to my wife Amanda for her love and patience beyond limits. I dedicate this thesis to you.

Last, but not least, I am thankful for the support of Shell Brasil and CNPq, Brazilian Ministry of Science and Technology, which funded my PhD scholarship through the grant n. 201176/2018-1

Nomenclature

Abbreviations

CFD	Computational Fluid Dynamics
DMD	Dynamical Mode Decomposition
FoV	Field of View
IW	Interrogation Window
KH	Kelvin-Helmholtz instability
OMD	Optimal Mode Decomposition
PDF	Probability Density Function
PIV	Particle-Image Velocimetry
PSD	Power Spectral Density
RMS	Root Mean Square
VIV	Vortex-induced Vibration
WO	Window Overlap

Roman Symbols

C_D	Instantaneous drag coefficient
$\overline{C}_D$	Mean drag coefficient
$\overline{C}_D^*$	Relative mean drag coefficient
C'_D	RMS of the drag coefficient
$\overline{C}_D^{rods}$	Mean Drag coefficient for the control rods
$\overline{C}_D^{ref}$	Mean Drag coefficient for the reference case
C_L	Instantaneous lift coefficient
$\overline{C}_L$	Mean lift coefficient
$\overline{C}_L^*$	Relative mean lift coefficient
C'_L	RMS of the lift coefficient
C'^*_L	RMS of the relative lift coefficient
$\overline{C}_L^{rods}$	Mean Lift coefficient for the control rods
$\overline{C}_L^{ref}$	Mean Lift coefficient for the reference case
D	Diameter of cylinder [mm]
d	Diameter of the rod [mm]

d'	Distance between two separated shear layers[mm]
f	Frequency [Hz]
f_{acq}	Frequency of acquisition [Hz]
f_D	Frequency of vortex shedding associated with the main cylinder [Hz]
f_d	Frequency of vortex shedding associated with the control rod [Hz]
F_D	Drag force [N]
$\overline{F_D}^{total}$	Mean drag force acquired on the total system [N]
$\overline{F_D}^{main}$	Mean drag force acquired on the main cylinder [N]
F_L	Lift force [N]
$\overline{F_L}^{total}$	Mean Lift force acquired on the total system [N]
$\overline{F_L}^{main}$	Mean Lift force acquired on the main cylinder [N]
g	Gap between the end plate and the cylinder [mm]
H_w	Height of water [mm]
L_c	Length of the cylinder [mm]
L_w	Wet length of the cylinder [mm]
L_b	Recirculation length
L_f	Vortex-formation length
N	Number of samples
N_{rod}	Number of control rods
N_{acq}	Number of images acquired
p	Fluid pressure [kg/ms ²]
p_v	Number of vectors in the PIV vector field
r	OMD rank
R_{LL}	Correlation coefficient of lift force
R_{pp}	Correlation coefficient pressure
R_{uu}	Correlation coefficient of u component
R_{XX}	Autocorrelation coefficient for the u component
R'	Distance between the centre of the cylinder and the rod [mm]
Re	Reynolds number [$Re = \rho DU_\infty / \mu = DU_\infty / \nu$]
Re_d	Reynolds number based on the control rod's diameter [$Re_d = \rho dU_\infty / \mu = dU_\infty / \nu$]
St	Strouhal number [$St = fD / U_\infty$]
St^*	Relative Strouhal number

St^{ref}	Strouhal number for the reference case
t	Time [s]
$\bar{T}$	Mean time interval between switches [s]
T_s	Period of vortex-shedding [s]
T_{acq}	Period of acquisition [s]
TI	Turbulence Intensity [$TI = \sqrt{u'^2}/U_\infty$]
u, v, w	Instantaneous velocity components measured along stream-wise, transverse and span-wise directions [m/s]
$\bar{u}, \bar{v}, \bar{w}$	Mean velocity components measured along stream-wise, transverse and span-wise directions [m/s]
u', v', w'	RMS of the velocity fluctuations measured along stream-wise, transverse and span-wise directions [m/s]
u_{xy}	Velocity modulus in the xy plane: $u_{xy} = \sqrt{u^2 + v^2}$ [m/s]
v_t	Tangential velocity, using polar coordinates centred at $(x, y) = (0, 0)$ [m/s]
$\bar{v}_t$	Mean value of the tangential velocity [m/s]
U_∞	Free-stream Velocity [m/s]
U_S	Velocity outer of the shear layers [m/s]
x, y, z	Spatial coordinates measured along stream-wise, transverse and span-wise directions [m]

Greek Symbols

$\Delta\theta$	Angular step between consecutive measurements [°]
Δt	Time interval between adjacent images [s]
Δt_{acq}	Period between two consecutive velocity fields ($\Delta t_{acq} = 1/f_{acq}$) [s]
Δx	Spatial resolution [m]
ϵ_{int}	PIV measurement bias error
Λ	Correlation length [m]
λ^*	OMD eigenvalue
ρ	Specific mass of water [Kg/m^3]
ν	Kinematic viscosity of water [m^2/s]
μ	Dynamic viscosity of water [Kg/ms]
Φ	OMD mode
ϕ	Phase of a vortex-shedding cycle

$\sigma(\epsilon_{int})$	PIV measurement random error
θ	Angular position of the rod [°]
θ_{sep}	Angular position of separation point [°]
ω	Instantaneous vorticity [1/s]

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Chapter 1

Introduction

The flow around bluff bodies is a very important topic in fluid mechanics. It is a common occurrence in daily situations with vast applicability in Engineering, from moving vehicles in fluid flow, like cars, ships and planes, to the flow past static structures like chimneys, cables and bridges. The flow over bluff structures can generate undesirable effects, like the mean drag force, the main factor responsible for the fuel consumption in vehicles, and fluctuating forces, which can induce the structures to oscillate.

The most common way to overcome undesired flow effects consists in modifying its characteristic geometry of the body by external appendices or actuators, thus employing different strategies to deviate or interfere with the flow, and altering the distribution of loads on the body. These strategies, also called “control methods,” are widely used in the Aeronautical, Naval, Mechanical, Chemical, and Civil industries. In the offshore industry, for example, flow control methods are applied to attenuate the effects of sea currents over the structures employed in oil exploration. A typical platform has a series of cylindrical structures exposed to the flow, like cables, risers, umbilicals, mooring lines, comprising a vast range of scales, and which are subjected to phenomena that can potentially harm their operation, such as Vortex-Induced Vibration (VIV), Wake-Induced Vibration (WIV) and Vortex-Induced Motion (VIM). All of these phenomena originate from the vortex shedding mechanism induced by the flow over the bluff body. Some control methods seek to attenuate the hydrodynamic loads by acting directly

Figure 1.1: Typical arrangement of offshore structures in operation. (a) Reproduced from Gardiner (2007) (source: Aker Kvaerner Subsea); (b) Adapted from Lankhorst Mouldings Offshore (2021)

in the vortex formation process, like fairings and splitter plates. In contrast, other methods focus on breaking the correlation along the span of the cylinder, altering the distribution of the vortices, for example, helical strakes. There are also methods that use a combination of the two strategies, such as flexible shrouds or permeable meshes.

Each type of control has pros and cons and is used for different purposes. An ideal device must work for different incoming flow directions and conditions, suppress fluctuating loads induced by vortices and reduce the drag force. In addition, it must be cost-effective, durable, and easy to store and install. These restrictions are sometimes conflicting. For example, strakes effectively suppress VIV but enhance the mean drag, similarly to permeable meshes. On the other hand, fairings are difficult to install and operate despite having a good performance. There is not a single device capable of filling all the criteria. Because of that, there is still research on innovative control methods and a search for novel technological solutions.

Using smaller cylinders as a flow control method for a larger cylinder has emerged among potential new solutions for the problem. This idea was firstly introduced by Strykowski and Sreenivasan (1990) with a scientific investigation on the control of wake using a control rod several times smaller than the main cylinder. Following that, many

researches advanced on the study of the control rods, but limited to very low Re , far from ideal conditions. It can be attractive for the offshore industry and other applications where there is a large number of structures exposed to the flow, as shown in Figure 1.1(a), and for which the arrangement is not optimised. For example, Figure 1.1(b) shows a riser laying operation where a second cylinder is installed at the same time as the main cylinder. The flow past these two cylinders may be very different from the sum of two cylinders isolated. However, the resulting flow could be either beneficial or harmful to the structures, depending on a series of parameters, such as the distance between the bodies and their position with respect to the flow, among others.

This thesis intends to advance the understanding of the flow around circular cylinder with different scales in close proximity throughout a experimental study. It intends to explore the characteristics of the flow at the moderate values of Re , between the very low values, explored in theoretical and numerical studies, and the high values, expected for practical situations. Rather than searching for an optimal position, it focuses on the fluid mechanics involved on it, in order to identify the flow characteristics and its potential as a control method for Reynolds numbers (Re) higher than the onset of vortex shedding. In other words, it is not a optimisation problem but a scientific investigation motivated by a technological application.

1.1 Thesis Structure

The thesis is organised in 8 chapters, including this introduction.

Chapter 2 covers the basic topics associated with the flow around bluff bodies and circular cylinders. The second part has a brief description of flow control methods and strategies, including a review of past studies using one and multiple control rods. It finishes by defining the main objectives of this study.

Chapter 3 explains the details of the experimental set-up for all campaigns of this work. It includes the description of the facilities, models, equipment and techniques employed

over the experiments. It is divided into two parts, the experiments carried out at the University of So Paulo and Imperial College London.

Chapter 4 presents the methodology applied for treating the data of all campaigns. The bare cylinder case is analysed in this chapter to validate the procedures and serve as a reference for the controlled cases.

Chapter 5 presents the results of preliminary experiments on the sensitivity of the flow to many parameters that govern the flow with control rods: Reynolds number (Re), the ratio between the cylinders (d/D), and the rod's position (R'/D and θ). The conclusions of this chapter serve to guide the choice of the parameters for the experiments carried out at Imperial College London.

Chapter 6 explores the effect of one control rod, for a fixed Re and d/D , varying θ . It includes force and high-resolution PIV measurements. It focuses on discussing the three main flow states that were identified, including a bi-stable case.

Chapter 7 investigates the flow with two control rods in the same range of the previous chapter. It is discussed how the symmetric arrangement of the rods alters the flow characteristics.

Finally, chapter 8 concludes this thesis, summarising its main findings and contributions, along with recommendations for future work.

Chapter 2

Literature Review

This chapter describes the main topics discussed in this thesis: the flow past bluff bodies, its instabilities and control methods. It starts with a description of the flow around a circular cylinder, its main characteristics and instabilities in section 2.1. Next, section 2.2 explores flow control fundamentals and strategies applied to circular cylinders and other bluff bodies, and section 2.2.1 focuses on studies using control rods in several applications.

2.1 The flow around a Circular Cylinder

The circular cylinder is one of the most studied geometries in fluid mechanics, due to its simple axisymmetric format and vast applicability. There is a significantly large number of studies describing it, to cite a few the excellent review works of Zdravkovich (1997), Bearman (1984) and Williamson (1996).

The flow is governed by the number of Reynolds ($Re = \rho DU_\infty / \mu = DU_\infty / \nu$), which determines the balance of inertial and viscous forces. Re is considered the single governing parameter for a disturbance-free flow. Examples of disturbances here include free-stream turbulence, wall blockage, roughness, and free surface. For convenience, they will not be considered in this chapter, but any related effects will be discussed in

Figure 2.1: Wake patterns for different values of Re . Reproduced from Van Dyke (1982).

appropriate sections along with the text, such as methodology and results.

For very low values of Re , there is no separation of the boundary layer (figure 2.1(a)). As it increases, up to $Re < 47$, the separation occurs with the development of two recirculation bubbles, and the flow remains symmetric and steady (figures 2.1(b), 2.1(c) and 2.1(d)). From this point, it is possible to identify the three main components of the flow: the boundary layer, the separated shear layer and the near wake, which are the key flow components for a very large range of Re , although they change their characteristics as the flow becomes turbulent.

2.1.1 Vortex Shedding

When Re exceeds the critical value of about $Re \approx 47$, the two recirculation bubbles become unstable and the vortex shedding process starts. It is the dominant feature of the wake for a very large range of Re , the most energetic and that associated to

the most common phenomena regarding fluid-structure interactions. The vortex shedding mechanism is generated by the interaction of the two shear layers separated from the body, which have concentrated vorticity of opposed signs. According to Bearman (1984), “it is the presence of two shear layers, rather than the bluff body itself, that is primarily responsible for vortex shedding. The presence of the body merely modifies the process by allowing feedback between the wake and the shedding of circulation at the separation points.” The typical configuration of the wake after vortex shedding is observed from figures 2.1(e) to 2.1(i). This vortex pattern is also known as Von Krmn street.

Due to the alternate shedding of vortices, the flow is periodic, with a well-defined frequency associated with this phenomenon. It is usually defined in its dimensionless form, also known as Strouhal number ($St = fD/U_\infty$). Figure 2.2 shows the distribution of St with Re . After $Re \approx 200$, St stays close to 0.2 for a very large range of Re . It indicates that U_∞ and D provide a good estimation of the frequency, but St still varies within the range 0.18–0.22. Roshko (1954) proposed a universal Strouhal number by recalculating St using the distance between the two shear layers (d') as the characteristic length and the actual velocity outer of the shear layers as the characteristic velocity (U_S). The result was a plot even closer to a constant value. However, Gerrard (1966) has observed that the constant value varies according to the turbulence level of the flow, and proposed that two characteristic lengths influence the frequency: the vortex-formation length, intended as the average point on the centreline where the shear layer crosses the wake, and the diffusion length, related to the shear layer thickness. Based on that, he was able to explain the variation of the frequency in different circumstances, for example, the addition of a splitter plate in the centreline close to the body, which forced the layers to interact further downstream. In this case, the frequency of vortex shedding increased, despite the enlargement of the vortex-formation length, and it was explained by the variation of the diffusion length.

Figure 2.2: Strouhal number versus Reynolds number. Adapted from Norberg (2001).

2.1.2 Other Instabilities

The formation of a cylinder wake is not a purely two-dimensional process. As Re increases, the flow component in the span-wise direction becomes relevant, and the vortex tubes' distribution varies along the cylinder length. As of $Re = 180$, the first three-dimensional wake instability takes the form of “vortex loops,” also called mode A by Williamson (1992), with the formation of stream-wise vortex pairs due to the deformation of primary vortices. It has a wavelength of approximately 3-4 diameters. For $Re \approx 230$, there is a gradual transfer of energy from mode A to mode B, this latter characterised by finer-scale stream-wise vortices, with a span-wise length of around one diameter (Williamson, 1996). These two instabilities are represented in figure 2.3.

The next relevant instability in the flow appears at around $Re \approx 10^3$, when the transition to turbulence moves upstream, from the near wake to the separated shear layers, developing the Kelvin-Helmholtz (KH) instability. It is characterised by the formation of a series of vortices along each separated shear layer, with a typical frequency several times higher, and a spatial scale lower than the regular vortex shedding mechanism. The critical Re at which this instability starts and its frequency value have been discussed in the works of Bloor (1964), Unal and Rockwell (1988a), and by Prasad and Williamson (1997). The latter provided a comprehensive review including new measurements. They identified that the pattern of vortex-shedding along the span-wise

(parallel or oblique) is a key factor to determine the starting Re of transition. KH occurs for a lower Re if the flow is shedding parallel vortices, i.e., the vortex tubes shed from the cylinder are parallel to the cylinder's axis. If the shedding pattern is oblique, forming an angle with the cylinder's axis, the instability is weaker and starts for a higher Re . This shows the importance of other parameters than Re for the flow development since the shedding pattern is very sensitive to the end effects (Khalak and Williamson, 1996). The KH instability can persist until the transition moves up to the boundary layers, at around $Re \approx 2 \times 10^5$. As for the frequency of this phenomenon, it is several times higher than the vortex-shedding frequency, and the ratio between the two frequencies seems to fit well with $Re^{0.67}$ (Prasad and Williamson, 1997). However, Dong et al. (2006) have shown that for high values of $Re \approx 10^4$, the instability does not show a well-defined peak, but rather a “high spectral-density plateau,” comprising a range of multiple frequencies.

Figure 2.3 illustrates the instabilities involved in the development of the wake combining two- and three-dimensional effects. These are the main key components for the flow for a regime comprised in a moderate Re range below 10^5 .

2.1.3 Fluid Forces

The total force acting on the cylinder has two main parcels, the skin friction force, due to the viscous forces acting on the cylinder wall, and the pressure parcel, obtained by integrating the pressure over the cylinder. As Re increases, the pressure parcel becomes dominant, being responsible for practically the whole drag for $Re > 10^4$. The total fluid force acting over the cylinder can be divided into lift (F_L) and drag (F_D) components, orthogonal and parallel to the flow. They are usually displayed in terms of their dimensionless coefficients (C_D and C_L), by dividing the forces by the dynamic pressure ($\frac{1}{2}\rho U_\infty^2$) and the area projected to the flow (DL_c). The coefficients are also commonly separated into two parcels, the mean and fluctuating value:

Figure 2.3: Instabilities involved in the development of turbulence in the wake for moderate values of Re . Adapted from Williamson (1996).

$$C_L = \frac{F_L}{\frac{1}{2}\rho U_\infty^2 D L_c} = \overline{C}_L + C'_L; \quad C_D = \frac{F_D}{\frac{1}{2}\rho U_\infty^2 D L_c} = \overline{C}_D + C'_D \quad (2.1)$$

Figure 2.4 shows the variation of each parcel with Re , adapted from Zdravkovich (1997), which provides a comprehensive review of studies measuring the forces over the cylinder for a very large range of Re . The figure displays the coefficients according to the flow regime, showing that the coefficients are especially sensitive to where the transition to turbulence occurs. After the onset of vortex shedding, the drag coefficient starts to fall and stabilises around 1.0 for the range of Re where the transition occurs in the shear layers. In the same range, the fluctuating lift coefficient rises from nearly zero to a value of order 0.5. Since the three-dimensional effects play a significant role in C'_L , there is a scatter of data from $Re \approx 10^3$ and 10^5 , as showed by Norberg (2001), where C'_L varies up to 300%, due to the flow's sensitive to end conditions in this range of Re . Khalak and Williamson (1996) observed that the type of vortex shedding (parallel or oblique) explains the variation of C'_L in this range of Re , for which the transition occurs

Figure 2.4: Force coefficients versus Re . Adapted from Zdravkovich (1997).

in the shear layer. It is also known as the sub-critical regime, and it is the region where the experiments comprised in this thesis are. For this reason, most focus is directed in this region. When the transition moves to the boundary layers, the critical regime starts, characterised by the drag crisis. In this case, the energised boundary layers resist more to the adverse gradient pressure, separating further downstream and leading to a higher base pressure, yielding a low mean drag coefficient. Still during the drag crisis, the mean flow loses the symmetry and a positive lift force appears (Bearman, 1969). When the flow is fully turbulent, the mean flow regains symmetry and the regime is called post-critical or trans-critical. In this case, the mean drag and fluctuating lift coefficients are slightly lower than in the pre-critical regime.

2.1.4 Correlation Length

A direct consequence of the three-dimensional structure of vortex shedding is the variation of the flow properties at two different sections. For example, if the flow is not fully two-dimensional, the sectional lift coefficient is different from the lift coefficient measured over the whole cylinder. Theoretically, it is possible to enhance the sectional lift coefficient while suppressing the total lift force by breaking the correlation. The usual

Figure 2.5: Span-wise correlation length versus Re . Adapted from Norberg (2001).

tool to investigate the lack of two-dimensionality is calculating the span-wise variation of some unsteady quantity related to vortex shedding (Bearman, 1984):

$$R_{ee}(e, z) = \frac{\overline{e_1 e_2}}{e^2} \quad (2.2)$$

where e is the quantity under consideration and z is the distance between two given points 1 and 2. The quantity e can be the pressure surface (R_{pp}), sectional lift force (R_{LL}) or the u component close to the separated shear layers (R_{uu}) (Norberg, 2001; Bearman, 1984). Since the mean flow is two-dimensional ($\overline{e_1^2} = \overline{e_2^2} = \overline{e^2}$), the correlation length Λ is defined by:

$$\Lambda = \int_0^\infty R_{ee} dz \quad (2.3)$$

Obviously, the infinite limit cannot be measured at experiments since the integral is limited by the cylinder length L_c . The value of Λ converges if the cylinder is long enough, though. According to Szepessy and Bearman (1992), the three-dimensional flow properties vary little for an aspect ratio $L_c/D \geq 10$. For a circular cylinder, the correlation length tends to decay with increasing Re in the sub-critical range. Figure 2.5 provides a compilation of data for the correlation length versus Re published by Norberg (2001, 2003), which computed Λ using R_{uu} . In the range $10^4 < Re < 10^5$,

Figure 2.6: Classification of methods for flow controlling over a bluff body. Adapted from Choi et al. (2008).

$\Lambda \approx 3D - 6D$, which can also be verified in Sarpkaya (1979).

2.2 Flow control

The main objective behind the idea of “controlling” the flow is to alter the flow characteristics and fluid forces over the body to achieve drag reduction, suppression of vibration, noise reduction, or any other desired effect. For the circular cylinder geometry, Choi et al. (2008) describe different control strategies and mechanisms for that, which are illustrated in the scheme of figure 2.6. It divides the control methods in different categories, depending on the type of the actuator’s input, the region of the flow actuated and its distribution along the span.

The first distinction is about the type of actuation. Passive methods have no power input, are simpler and cheaper, but usually have lower performance when compared to active devices. Examples of passive devices include shrouds (Zdravkovich and Volk, 1972; Sun et al., 2021) and grooves (Lim and Lee, 2002). Active methods, on the other hand, deliver better results than passive ones but are more sophisticated and expensive, especially the closed-loop devices, which have an additional challenge regarding the control function. Amongst the most known active methods, one could cite rotary oscillation (Tokumaru and Dimotakis, 1991) and synthetic jets (Smith and Glezer, 1998;

Figure 2.7: Coordinate system for the case of one cylinder controlled by one rod.

Glezer and Amitay, 2002).

The second distinction is between the boundary layer and direct-wake control. Most strategies intend to anticipate the drag crisis by inducing an early transition to turbulence in the boundary layer. Examples of it are tripping rods (Igarashi, 1986), roughness (Shih et al., 1993; Gven et al., 1980), and distributed passive jets (Clapperton and Bearman, 2018). On the other hand, direct wake control methods seek a modification of the vortex formation, shedding and coherence, acting farther from the cylinder, directly on the wake. Examples of it are splitter plates (Roshko, 1955; Bearman, 1965; Apelt et al., 1973; Anderson and Szewczyk, 1997), short-tail fairing (Assi et al., 2014) and control rods in the wake, this further explored in the next section.

The third distinction regards the behaviour of the control method along the span: 2D or 3D forcing. The basic difference between them is that in the latter, the actuation varies along the span, seeking to alter the three-dimensional flow properties, like helical strakes (Zdravkovich, 1981; Korkischko and Meneghini, 2010) and time-periodic blow suction (Williams et al., 1992; Arcas and Redekopp, 2004). Further examples of passive devices for circular cylinder can be found in Zdravkovich (1981), involving all mechanisms of figure 2.6.

2.2.1 Control Rods

This section focuses on the control using a small body close to the cylinder, with a diameter several times smaller than it, and intended to alter the flow properties. It

is a 2D forcing method that can be particularly interesting to real applications, since many structures involve circular cylinders of different sizes, for example the complex arrangement of tubes and cables in the offshore industry. Control rods are versatile, in the sense that they can act either as a boundary layer control or a direct-wake method, depending on the position; and they can also be employed either as passive devices, keeping the rods fixed, or active devices, for example enabling the rods to rotate (Silva-Ortega and Assi, 2018; Korkischko and Meneghini, 2010) or oscillate (Huang et al., 2006).

The investigation of the use of control rods as an effective control method was pioneered by Strykowski and Sreenivasan (1990), who placed a small-diameter control cylinder in or close to a free shear layer separating from the main cylinder. They observed that the presence of the control cylinder at an appropriate position has the effect of suppressing the absolute instability in the near wake that initiates vortex shedding. This finding generated much interest, but complete suppression of vortex shedding was only obtained up to $Re = 100$. According to Strykowski and Sreenivasan (1990), when vortex shedding was not totally suppressed, its frequency was reduced compared to the bare cylinder. Subsequent researchers have shown that at higher Re , placing a control rod has the effect of reducing drag coefficients and lowering the levels of unsteady forces due to vortex shedding. This finding encouraged further research into seeking the optimum size and position for a control rod with the most beneficial effect.

The flow of a circular cylinder with a control rod is affected by a series of key variables, illustrated in figure 2.7. Besides Re , the flow depends on the position of the rod, R'/D and θ , as well as the ratio between the diameters of the control rod and the main cylinder, d/D . Figure 2.8 provides a compilation of past studies of circular cylinder with only one control rod for $90^\circ \leq \theta \leq 180^\circ$, $0.02 < d/D < 0.33$ and for a range of Re between 60 and 65,000. It shows the positions of control rods in the various studies illustrating the wide range of R'/D that has been investigated.

The results of Dipankar et al. (2007) and Mittal and Raghuvanshi (2001) agree with the findings of Strykowski and Sreenivasan (1990), since their numeric simulations found

Table 2.1: List of studies with a circular cylinder and one control rod found in literature, varying Re , d/D and position, illustrated in figure 2.8.

Study	Re	d/D	R'/D
<div style="display: inline-block; width: 10px; height: 10px; border: 1px dashed black; margin-right: 5px;"></div> Strykowski & Sreenivasan (1990)	60 – 120	0.1 – 0.33	> 0.5
<div style="display: inline-block; width: 10px; height: 10px; background-color: black; border-radius: 50%; margin-right: 5px;"></div> Mittal & Raghuvanshi (2001)	60 – 100	0.14	2.15 – 2.24
<div style="display: inline-block; width: 10px; height: 10px; background-color: black; transform: rotate(45deg); margin-right: 5px;"></div> Dipankar <i>et al.</i> (2007)	63 – 150	0.1 – 0.14	1.5 – 2
<div style="display: inline-block; width: 10px; height: 10px; background-color: black; margin-right: 5px;"></div> Yildirim <i>et al.</i> (2010)	100	0.02	0.9 – 2.1
<div style="display: inline-block; width: 10px; height: 10px; border: 1px solid black; border-radius: 50%; margin-right: 5px;"></div> Alonzo-Garcia <i>et al.</i> (2021)	200	0.2	0.8
<div style="display: inline-block; width: 10px; height: 10px; background-color: black; border: 1px solid black; transform: rotate(45deg); margin-right: 5px;"></div> Zhao <i>et al.</i> (2005)	500	0.25	0.67 – 1.62
<div style="display: inline-block; width: 10px; height: 10px; border: 1px solid black; margin-right: 5px;"></div> Cicolin <i>et al.</i> (2018)	70 – 1,000	0.1	1.4
<div style="display: inline-block; width: 10px; height: 10px; background-color: gray; margin-right: 5px;"></div> Dalton <i>et al.</i> (2001)	100 – 3,000	0.1	1.2 – 1.6
<div style="display: inline-block; width: 10px; height: 10px; background-color: black; transform: rotate(60deg); margin-right: 5px;"></div> Bingham <i>et al.</i> (2018)	9,500	0.13	1.35 – 1.85
<div style="display: inline-block; width: 10px; height: 10px; background-color: lightgray; margin-right: 5px;"></div> Bingham <i>et al.</i> (2018)	12,500 – 17,000	0.13	0.76 – 2.9
<div style="display: inline-block; width: 10px; height: 10px; background-color: darkgray; margin-right: 5px;"></div> Sakamoto & Haniu (1994)	65,000	0.06	0.53 – 0.73

Figure 2.8: Positions of the control rod in the range $90^\circ \leq \theta \leq 180^\circ$ for different cases found in the literature, listed in table 2.1.

vortex shedding suppression for low Re and for similar values of d/D at specific positions of the rod. Still in the range $Re < 100$, and for a smaller diameter of $d/D = 0.02$, Yildirim et al. (2010) did not observe complete vortex suppression, but found a significant attenuation of vortex strength. It also agrees with the findings of Strykowski and Sreenivasan (1990), because they observed that bigger values of d sustained the vortex suppression for a larger range of Re . For a higher rod diameter ($d/D = 0.2$), and higher $Re = 200$, Alonzo-Garcia et al. (2021) did not reach total suppression, but a fluctuating lift reduction of up to 90%, found for $R'/D = 0.8$ and $\theta = 157^\circ$. Dalton et al. (2001) performed numerical simulations varying the position of the rod and Re , in the range $100 \leq Re \leq 3,000$ with $d/D = 0.1$. It has shown how the effectiveness of the rod at a given position changes with a big variation in Re . They observed complete suppression of vortex shedding only at $Re = 100$. For $Re = 3,000$, they reported a drag reduction of approximately 25% when $R'/D = 1.2$ and $\theta = 160^\circ$. The fluctuating lift was also decreased, in their case, by almost 85%. These results confirmed a significant Re dependency on the optimal position of where the rod should be located. This was reinforced by the results of Cicolin et al. (2018), where the control rod was kept at a fixed position ($R'/D = 1.4, \theta = 135^\circ$) and Re was varied. It completely suppressed vortex shedding at $Re = 70$, attenuated the fluctuating forces at $Re = 200$ and had little effect at $Re = 1,000$. At moderate values of $Re = 12,500$ in the sub-critical range, Bingham et al. (2018a) adopted a different approach and used an evolutionary algorithm to search the position of the control rod that minimised fluctuating lift on the main cylinder. The extensive area they covered for placing a control rod is shown shaded in Figure 2.8. They concluded that fluctuating lift could be reduced by 90% using a control rod with $d/D = 0.125$, placed at $R'/D = 1.31$ and $\theta = 116^\circ$. More interestingly, they allowed the rod to oscillate, varying the position and direction, and concluded that a fixed rod, without movement, induced the highest suppression of vortex shedding. Sakamoto and Haniu (1994) carried out a series of experiments at $Re = 65,000$ with a control rod of $d/D = 0.06$, which is the work with the largest Re in this topic. Their sensitivity maps are shown in figure 2.9. They reported drag reductions of up to 30%, but also a significant lift force induced by the rod in the positions where drag

Figure 2.9: Sensitivity maps for the flow around a circular cylinder controlled by a rod adapted from Sakamoto and Haniu (1994). The average coefficients were divided by the average drag of the bare cylinder, whereas the fluctuating coefficients were divided by the fluctuating values of drag and lift observed for the bare cylinder. The maps are out of scale, so that the actual extent of each map can be seen in figure 2.8. $d/D = 0.06$ and $Re = 65,000$.

reduction was the maximum. More interestingly, they observed different flow patterns according to the position of the rod, using smoke to visualise the flow.

The sensitivity of the flow over a circular cylinder was also investigated using adjoint linear stability formalisms, notably the works of Gianetti and Luchini (2007); Marquet et al. (2008); Luchini and Bottaro (2014); Meliga (2017). Small perturbations in the wake, for example those induced by control rods, reduced the growth rate and amplitude of the unstable global mode, which is in agreement with the observations of Strykowski and Sreenivasan (1990). These perturbations induced wake stabilization mechanisms by reducing the shear, that is a source of global instability. The perturbations also changed the vortex shedding frequency and pressure distribution, which can ultimately alter the forces over the body, as showed in Meliga (2017).

The research using adjoint equations for the circular cylinder flow is still restricted to low Re . Nevertheless, not all research on this topic has been limited to a circular cylinder as the bluff body. Meliga and collaborators (Meliga et al., 2016, 2014, 2012)

investigated the sensitivity of flow to small perturbations for bodies with a fixed separation point, extending the Re range up to 22,000. Regarding experimental works with different geometries, Parezanovi and Cadot (2012) performed a comprehensive study of the sensitivity of the wake past a D-shaped cylinder with one control rod. Their study used two control rod diameters, $d/D = 0.04$ and 0.12 . A significant difference between this study and those with circular cylinders is that the separation points on the main body are not free to move. Nevertheless, they identified several flow states with some similarities to those found with a circular cylinder as the main body. According to the position of the control rod, they separated their results into different states, entitled external flow, outer shear, mid-shear and inner shear. The descriptions relate to the positions of the control rod relative to a free shear layer.

Some researchers advanced on the use of control rods to more than one rod. Although most of works focus on the simpler case using a single control rod, a symmetric arrangement is more practical for real applications. However, there are few works using multiple rods over a fixed body, for they are more common for fluid-structure interaction applications. Kuo et al. (2007) used a fixed pair of cylinders with $d/D = 0.125$ at $R'/D = 0.8$ and $\theta = \pm 130^\circ$ varying Re from 80 to 300, and observed a significant attenuation of the fluctuating lift forces. The form drag was also reduced, but the total drag had approximately the same level of the bare cylinder because of the increase in the viscous drag. Yan et al. (2018) performed a detailed investigation of the flow around a circular cylinder with two rods at $Re = 3,900$, using $d/D = 0.05$, $R'/D = 1$ and $\theta = \pm 135^\circ$. They observed an increase in both mean drag and fluctuating lift coefficients, although vortex shedding frequency was reduced. Jimnez-Gonzalez and Huera-Huarte (2017) employed two control rods symmetrically attached to the cylinder as a VIV suppression method, observing up to 70% of VIV suppression for a diameter ten times smaller than the cylinder.

Moving on to cases using multiple rods, Lu et al. (2014) reported full suppression of vortex shedding at $Re = 200$ using six control rods, equally spaced around the circular cylinder at $R'/D = 2$. Silva-Ortega and Assi (2018) carried out experiments from

$Re = 5,000$ to $50,000$, varying R'/D from 0.58 to 0.7 and using 2 , 4 and 8 rods, equally spaced and symmetrically arranged over the cylinder. They reported a mean drag reduction of 50% , with attenuation 80% of fluctuating lift coefficient for the case with 4 rods.

2.3 Objectives

The main objective of this investigation is to advance the understanding of the circular cylinder flow affected by control rods at moderate values of Re . The vast majority of works in the literature focus on the very low Re cases, for which the vortex shedding mechanism starts. However, few works have explored the wake characteristics at moderate values of Re , combining force and wake measurements. In this range of Re , the rod does not seem to suppress vortex shedding totally, but it significantly affects lift and drag forces. Most literature results agree that the flow is more sensitive to a rod placed near the shear layers, but the optimal rod position and their level of suppression vary significantly with Re and d/D . In addition, big variations in the force coefficients are associated with different wake states. Bingham et al. (2018a) show three cases with a rod in different positions where the flow and the force coefficients vary significantly compared to the bare cylinder and each other. Sakamoto and Haniu (1994) observed significant changes in the force coefficients associated with different smoke patterns, but they did not carry out further wake measurements. Parezanovi and Cadot (2012) performed a comprehensive study at moderate Re on the wake of a D-shaped body, identifying different flow states prompted by the control rod. Now, we intend to expand the study for a circular cylinder geometry. The main difference between these bodies is the separation points, fixed for the D-shaped cylinder and variable for the circular cross-section. Because of that, the flow states and their respective force coefficients might differ significantly for a circular cylinder.

The study is experimental, carried out in a water flume, and focused on force measurements and quantification of the wake with Particle-Image Velocimetry (PIV). Initially,

force measurements were acquired over the combined system, cylinder and rods, to evaluate the flow sensitivity to a series of parameters (Re , d/D , R'/D , θ). Then, a detailed investigation was carried out for fixed values of Re , d/D , and R'/D , measuring the forces over the cylinder and the combined system, and capturing planar PIV fields from different regions of the flow. These experiments were carried out for the cylinder controlled by one and two rods.

To summarise, this thesis focuses on addressing the following questions:

- What is the influence of the rod diameter (d) and position (R'/D , θ) on the force coefficients over the cylinder for moderate Re ?
- What are the main flow states developed in the wake of a circular cylinder with a control rod for moderate values of Re ? How do they affect lift and drag forces?
- What are the characteristics of the wake and force coefficients for the cylinder with two rods, symmetrically positioned?
- What is the role of the separation point in the flow topology and force coefficients for the controlled cases?

Chapter 3

Experimental Setup

This chapter describes the equipments and experimental campaigns performed both at USP and Imperial College London. Section 3.1 focuses on the campaigns carried-out at USP, while 3.2 shows the details of the experiments carried out at Imperial College.

3.1 Part I: USP

3.1.1 Facilities and models

The main facility was a water flume with a test section 700mm wide and 7m long, with variable water height and capable of achieving velocities up to 1m/s, in the standard configuration of 700mm $\times$ 700mm cross-section. For the conditions of flow described in the first two campaigns, the free stream velocity varied between 0.15m/s and 0.4m/s, with a turbulence intensity below 3%. $TI = \sqrt{u'^2}/U_\infty$, defined as the ratio between the RMS of fluctuating velocity in the centre of the section and the free stream velocity. Further information about the facility and its characterisation is provided in Assi (2005) and other works on fluid-structure interaction (Cicolin and Assi, 2017; Assi et al., 2006).

Two circular cylinder models were employed, both made out of acrylic tubes with diameters of 50mm and 100mm. The control rods were made of carbon fibre tubes with

Figure 3.1: Main properties and arrangement of the models for the first and second campaigns.

diameters varying from 2mm to 6mm. The blockage ratio, defined here as the ratio between the model cross-sectional area and the area of the test section, was lower than 15% for all cases. Silva-Ortega (2015) performed experiments using the same assembly and concluded that the blockage effect was negligible regarding changes in the unsteady wake, even for the model undergoing oscillations. Considering that only fixed-model experiments were carried out in the present study, a correction regarding the blockage effect has not been employed.

The fluid forces acting on the body were measured by a load cell specially designed to measure lift and drag in two orthogonal directions independently. The load cell was able to measure forces up to 50N with an uncertainty of less than 1%. Assi (2009) provides further details about its construction and characterisation. This same device has also been employed by Cicolin (2015) and Silva-Ortega (2015), which contain further details about its calibration.

3.1.2 1st and 2nd campaigns

Figure 3.1(a) illustrates the general configuration of the experiments, showing the cylinder and the control rods positioned in the test section. A pair of discs supported the rods to the main cylinder at predefined locations about the centre, allowing for differ-

Table 3.1: Experimental properties of the campaigns 1 and 2

Property	Campaign 1	Campaign 2
D	50mm	100mm
d	2 – 5mm	6mm
U_∞	0.2 – 0.4m/s	0.17 – 0.28m/s
L_w	750mm	630mm
f_{acq}	100Hz	100Hz
T_{acq}	120s	180s
N_{rods}	1	2
d/D	0.04 – 0.1	0.06
R'/D	0.6 – 1.5	0.6 – 0.9
θ	90° – 180°	0° – 180°
$\Delta\theta$	10°	10°
Re	10,000 – 20,000	18,000 – 28,000

ent rod positions to be set. One of the support discs also acted as an end plate at the bottom of the cylinder. The whole system was connected to the load cell by the top of the main cylinder. In this configuration, the cell measured the total force over the combined system, i.e., the cylinder and the rods altogether. It implies that in these preliminary experiments the parcel of force acting on each model was not isolated. The acquisition of the signals were done by the software *LabView* through an in-house code especially developed for this type of experiment (Assi et al., 2006). Further details about the campaigns carried out at USP can be seen in table 3.1.

3.2 Part II: Imperial College London

3.2.1 Water flume

All the experiments in Part II were carried out at the water channel of the Department of Aeronautics at Imperial College London. The device is a recirculating, free surface flume with 9m in length and a 0.6m square section. It can be operated at different water

Figure 3.2: Boundary layer profile of the flume for $H_w = 0.6m$ at $U_\infty = 0.4$ m/s.

levels (H_w) and achieve flow speeds up to 1m/s in the standard configuration. The test section, made with glass walls and floor, enables optical access from the four sides, making it suitable for PIV experiments. The flume has a 4:1 contraction and three turbulence-damping screens in order to maintain a high-quality flow in the test section. The experiments were performed within the first 2m of the flume, where the quality of the flow is better. All cases were acquired for the same velocity of $U_\infty = 0.4$ m/s, varying the water level from $0.58 < H_w < 0.6$ m. Figure 3.2(a) presents the velocity profile in this position, together with the turbulence intensity, defined as $TI = \sqrt{u'^2}/U_\infty$ and acquired with PIV for $U_\infty = 0.4$ m/s. The vertical velocity profile was particularly useful to define the distance from the bottom to install the end plate around the cylinder, as will be described later.

3.2.2 Models of circular cylinders and rods

The main model used in the experiments was a circular cylinder made out of an acrylic tube with 50mm of diameter. The total length was $L_c = 540$ mm, so that the aspect ratio of the model was $L_c/D = 10.8$. A disc of 350mm of diameter with rounded edges was placed at the bottom end of the cylinder as an end plate to minimise three dimensional end effects. The model could operated filled with water or air, depending on the campaign. For force measurements, the model was kept as lighter as possible to prevent damaging the load cell. The end plate was connected to the floor through an aluminium support, and kept at a minimal distance from the cylinder to avoid

disrupting the flow and force measurements. For the PIV campaigns, the end plate was connected to the cylinder and the model was filled with water to enable the light sheet to pass through the medium with minimal refraction. A square acrylic plate was placed to enable the cameras to visualise the flow without the interference of the free surface.

The control rods were carbon fibre tubes with 5mm of diameter. The connection between the main cylinder and the rods were made by supports 3D-printed in ABS plastic.

3.2.3 Load cell

The force transducer ATI Gamma IP68 was employed in the force measurements campaign. The device is able to acquire forces up to 65N in two orthogonal directions (x and y) with a resolution of 0.01N and an uncertainty of 1%. It can also support a moment of 5Nm, which makes it ideal for measuring the loads over a long cylinder held from one extremity. The IP68 waterproof protection allows for the load cell to be installed close to the water surface. A plastic shield was added to the outer structure of the load cell to support the control rods. The eigen-frequencies of the system comprising the cell and the model were at least ten times higher than the main vortex-shedding frequency. In order to minimise their effects in the force acquisition, a low-pass filter was applied to all experiments, with a cut off frequency lower than the minimal eigen-frequency.

3.2.4 Particle-Image Velocimetry

Particle-Image Velocimetry (PIV) has been employed to measure velocity fields around the cylinder and control rod. The illumination source for PIV was the high speed Litron LDY304-PIV, a high-speed, two cavity laser that provides 25mJ of energy per pulse on average (at a constant rate of 1000Hz) with a standard deviation of $\approx 0.5\%$. Each cavity is polarised in a different direction, allowing experiments in different planes, as described in section 3.3.2. The wavelength of the light for both cavities is 527nm and the pulse lasts 7ns. The laser can operate at a frequency between 200Hz and 10,000Hz. Most of the experiments were acquired at lower frequencies (from 15Hz to 200Hz, please

refer to section 3.3.2), which are high enough for a slow speed laser but significant low for a high speed laser. The solution was to operate the laser at a multiple of the acquisition frequency, leaving most of the pulses idle. For this reason, the pulses were synchronised externally using a digital pulse generator. Further details about the laser system can be found in Baj (2018).

The light path was provided by a set of mirrors that direct the laser beam from the laser head through one of the channel's walls. The light sheet is then formed by a set of spherical and cylindrical lenses, the former responsible for collimating the beam and the later responsible for opening the laser sheet in the test section. A polarising beam splitter was employed for illuminating two different planes. The focal lengths and positions of these lenses varied across the experimental campaigns depending on the required Field-of-View (FoV).

The images were recorded by a pair of high-speed cameras Phantom v641 with a resolution of $1,600 \times 2,560$ px, and capable of storing up to 5500 images in the maximum resolution. Different sizes of FoV and number of pixels were used depending on the experiment set-up. Three different types of lenses were used: Nikon 60mm f/2.8, Nikon 70mm f/2.8, and Nikkor 105mm f/2.0. In some applications, a polarised filter was attached over the lenses. The synchronisation between the cameras and the laser pulses was possible through a digital pulse generator Stanford model DG645. It made it possible to operate the laser and the cameras at different frequencies. It also allowed the two laser cavities to operate with a small phase shift, which was necessary for the cases where two planes were acquired simultaneously.

PIV processing

The images were pre-processed and the flow fields calculated using the commercial software *DaVis* 8.4. Initially a Gaussian filter was applied to the PIV data followed by the subtraction of the mean local intensity averaged in a region of 3×3 pixels. Every pixel then had its intensity adjusted between a minimum of 0 and a maximum of 2000 counts. These processes were carried out in order to smooth the image, mitigate

Figure 3.3: Arrangement of the 4th campaign. (a) lateral view of the two configurations and (b) top view

the interference of the image background and prevent vector contamination by high intensity peaks. Flow fields were calculated using a standard multi-pass cross correlation method. The first step had an one pass, 50% window overlap (WO) and a 48 px interrogation window (IW) for all cases. The second and final pass had a different configuration for each camera, shown in table 3.3, including the number of images (N_{acq}), the time interval between adjacent images (Δt) and the spatial resolution (Δx). The final window overlap was 75%, as it improves the estimation of velocity-gradient quantities, as demonstrated by Tokgoz et al. (2012). Since the vorticity fields were a key point in the analysis, the final value of 75% was applied to all cases. As for post processing, an Universal Outlier Detector filter (Westerweel and Scarano, 2005) with size 5×5 px was applied to remove spurious vectors. For each case, the total number of replaced vectors was lower than 1% of the total.

3.3 Experimental Campaigns

3.3.1 3rd campaign: force measurements at ICL

The third campaign was intended to measure the forces over the cylinder and the control rods separately. The main properties of the campaigns, common to all runs, are listed

Table 3.2: Experimental properties of the campaign 3

D	50 mm
d	5 mm 0.1 D
R'	35 mm 0.7 D
L_w	485 mm 9.7 D
θ	$0^\circ - 180^\circ$
$\Delta\theta$	5°
U_∞	0.4 m/s
Re	20,000
Re_d	2,000
f_{acq}	200 Hz
T_{acq}	200 s
N_{rods}	1 and 2

in the table 3.2. The main cylinder was attached directly to the load cell, piercing the water surface, so that the wet length of the cylinder was 485 mm, giving an aspect ratio of 9.7. In order to minimise end effects at the lower end of the cylinder, an end plate was fixed to the floor of the flume. The distance between the floor and the end plate was 75mm, which is larger than the boundary layer thickness, as showed in figure 3.2. The cylinder and the load cell were attached to the channel by a positioning jack, as the forces coefficients are very sensitive to the gap between the end plate and the cylinder. The vertical jack made it possible to check the gap before any measurement, ensuring the same distance was kept for all cases. Further discussion about the ground effect over the force's coefficients is presented in section 4.1.

Hydrodynamic forces were acquired for two different arrangements regarding the position of the control rods, as shown in figure 3.3. In configuration 1, the rod's upper end was fixed in the outer shield of the load cell, whereas the lower end was fixed to the end plate. In this way, the load cell acquired the forces acting on the main cylinder only. In configuration 2, the rod was attached to the cylinder through two rings, allowing the load cell to acquire the forces acting on the combined system, i.e. the two bodies together. In both configurations, the end supports kept constant along the length

Figure 3.4: Arrangement of the 4th campaign.

the distance between the rods and the main cylinder. The supports could be rotated around the cylinder, enabling different angular positions of the control rods to be set. The supports and the control rods were designed such that the deflection of the rods under hydrodynamic loading was negligible.

For each run, the angle was changed with the flume running and the acquisition started approximately 60s after it, which corresponds to approximately 100 cycles of vortex shedding. Two series were carried out for each configuration, one with increasing angles and the second in the other way round. When not stated explicitly, the results refer to the average of these two runs. The load cell was able to export the data in a frequency up to 10kHz. The data was exported at an acquisition frequency of 200Hz, so that each point was the average of the last 50 taken at the maximum frequency. In order to reduce the noise, the exported data was filtered with a low-pass filter at 20Hz.

3.3.2 4th and 5th campaigns: PIV measurements

This 4th campaign was the first intended to measure velocity fields with PIV. It reproduced all the cases of the third campaign (table 3.2) focusing on the near wake of the cylinder with two cameras. It differed from the third campaign regarding the assembly of the model, that was attached directly on the top plate, a transparent acrylic square plate that was partially immersed in the water to prevent the free surface from interfer-

Figure 3.5: Arrangement of the 5th campaign. The beams are coloured in different tones to contrast the two planes. The polarising beam splitter did not alter the frequency and color of the light sheet.

Table 3.3: Experimental properties of the campaigns 4 and 5. The other properties are equal to the third campaign in table 3.2, with the only exception of the wet length, $L_w = 540\text{mm}$ in this campaigns.

	Campaign 4				Campaign 5	
	Camera 1		Camera 2		Camera 1	Camera 2
f_{acq} [Hz]	70	14	200	40	16	16
T_{acq} [s]	42.83	214.1	42.83	214.3	190	190
N_{acq}	3,000		8,575		3040	3040
Δt [μs]	1428		714		1250	1250
IW [px]	16		12		12	12
WO [%]	75		75		75	75
Δx [mm]	1.88		0.75		0.97	1.96
FoV [px]	$1,400 \times 2,400$		$400 \times 2,560$		$1,400 \times 2,560$	$1,400 \times 2,560$
FoV [mm]	165×282		25×160		115×210	230×420

ing in the view of the cameras. The end plate was connected to the cylinder, leaving a 50mm gap from the bottom of the flume in order to avoid interference with the flume's boundary layer. Figure 3.4 illustrates the general arrangement of the 4th campaign. The laser sheet illuminated a horizontal plane passing through the mid point of the cylinder length, and the two cameras recorded two regions on the same plane. Figure 3.6 shows the Field of View (FoV) of each camera. Camera 1 focused on a wider field of view, capturing larger flow structures at a lower frequency, whereas camera 2 focused on narrow stripes, acquired at a higher frequency. The two narrow stripes showed in figure 3.6 were acquired in different experiments. The second camera was intended to capture a smaller field-of-view with a better spatial and temporal resolution. Their data were used to evaluate most of the spectra showed in the chapters 6 and 7. The main PIV properties are listed in table 3.3. The frequency of acquisition was set to be high enough to capture the vortex shedding of both bodies. In a second run, intended to capture longer time series, the same cases were run at a frequency five times lower, since the number of images recorded was limited by to the storage capacity of the cameras. The laser pulsed at a constant rate of 1,400Hz. The acquisition frequency of both cameras was a fraction of it, 70Hz for camera 1 and 200Hz for camera 2. The delay between the PIV images was determined by the interval between the laser pulses. For camera 1, the delay was set to two laser pulses, so $\Delta t = 2/1,400 \approx 1,248\mu s$. Camera 2 used one pulse interval, $\Delta t = 1/1,400 \approx 714\mu s$. The spatial resolution for Camera 1 was $\Delta x = 1.88\text{mm} = 0.038D$ per vector, whereas for camera 2 it was $\Delta x = 0.97\text{mm} = 0.019D$.

The 5th campaign was intended to investigate the three-dimensional flow structures along the span-wise direction of the cylinder at the same time as the two-dimensional wake, which was acquired on the orthogonal plane. Other than the horizontal plane in the middle of the cylinder, a vertical plane passing through the border around $\theta = -90^\circ$ was illuminated. In order to avoid the contamination of the image in one plane by the spread of light from the other, a delay of $200\mu s$ between the two laser sheets was set, which was possible due to the different polarisation of the two laser cavities. The laser path was diverted by a polarising beam splitter, as illustrated in the arrangement of

Figure 3.6: Field of View of the two cameras in the 4th and 5th campaigns.

this campaign shown in figure 3.5. The field of view of each camera in this campaign is shown in figure 3.6, whereas their PIV properties are also included in table 3.3.

A real picture of each campaign carried out in the water channel at Imperial College London can be seen in figure 3.7.

(a) 3rd campaign

(b) 5th campaign

(c) 4th campaign

Figure 3.7: Pictures of the experimental campaigns carried out at Imperial College.

Chapter 4

Methodology & Validation

This chapter explores in details the methodology used for treating the data of all campaigns. The bare cylinder case is used to validate the experimental methods, since there is a vast amount of data available in the literature for this geometry. The same procedures described in this chapter for the cylinder were applied to the controlled cases presented in the following chapters.

4.1 Force coefficients

As pointed out before, the experiments have been carried out in two different configurations. In the first, the hydrodynamic forces were measured over the main cylinder only, whereas in the second the load cell measured the forces over the combined system, cylinder and rods. Lift and drag coefficients were divided into their mean and fluctuating components, as usual ($C_* = \overline{C}_* + C'_*$). For the main cylinder, the measurements obtained in configuration 1 were directly converted into lift and drag coefficients (C_L and C_D). For the control rods, single or in pair, the mean coefficients were obtained by subtracting the loads on the main cylinder (Configuration 1) from the total loads acting on the entire system (Configuration 2):

Figure 4.1: Effect of the gap between the endplate and the bare cylinder into its force coefficients.

$$\overline{C}_L^{\text{rods}} = \frac{(\overline{F}_L^{\text{total}} - \overline{F}_L^{\text{main}})}{\frac{1}{2}\rho U_\infty^2 D L_w} \quad \overline{C}_D^{\text{rods}} = \frac{(\overline{F}_D^{\text{total}} - \overline{F}_D^{\text{main}})}{\frac{1}{2}\rho U_\infty^2 D L_w} \quad (4.1)$$

Since the load cell acquired the instantaneous force over the whole system, the fluctuating coefficients could not be calculated for the control rods.

The flow between the cylinder and the end plate prompted significant changes in the force coefficients depending on the gap. Figure 4.1 shows the variation in both mean and fluctuating lift and drag coefficients for a gap (g) varying from 0 to 0.8 diameters of the cylinder. The values vary significantly for small values of $g/D < 0.2$. Possibly, this effect is related to the type of vortex shedding along the the span-wise direction: parallel or oblique. Khalak and Williamson (1996) performed a similar experiment in a water channel at $Re = 12,000$ and verified that the two types of shedding induced different levels of forces. Comparing their values of C'_L and $\overline{C}_D$ with the present study, the cylinder was expected to shed parallel vortex tubes when the gap was minimal and oblique tubes when $g/D > 0.2$. Since in this work we are focused mainly in the changes

Figure 4.2: Sensitivity of the bare cylinder's force coefficients to the number of samples N . $f_{acq} = 200$ Hz.

induced by the rod in the two dimensional flow, the gap was kept to a minimal distance possible, in order to minimize the gap effect. For all the cases presented hereafter, the gap can be neglected, i.e. $g/D \approx 0$. For the experiments carried-out at USP the end plate was always attached to the cylinder, so there was no gap and the flow was expected to develop parallel tubes.

The period of data acquisition was set in order to ensure the ergodicity of the sample. Figure 4.2 shows the cumulative values for the mean and fluctuating coefficients over time. It shows that all values stabilise at around 100s, varying less than 5% after that. Thus, 100s was used as a minimum period for all cases. In the third campaign, an acquisition period of 200s was set. representing approximately 300 cycles of vortex shedding. The value shown in the square of each box at figure 4.2 is the reference value for the bare cylinder, calculated over the total period of acquisition. The uncertainties displayed at the box refer to the deviation calculated from five different runs. For the cases with the control rods, there is an additional uncertainty of $\pm 1^\circ$ for the position of the rods. Due to the large number of cases, only two different runs were acquired for each case, in a different side of the cylinder, to prevent assembling bias. The results

Figure 4.3: (a) Time series and (b) Spectra of drag and lift forces for the bare cylinder case.

show an agreement within 3% between the two runs for all controlled cases. Figure 4.3 shows the time-series of lift and drag forces and their respective spectra. The dominant frequency in the lift spectrum was used to calculate the Strouhal number.

The results obtained for the bare cylinder are in good agreement with the data in literature. The mean drag, $\overline{C}_D = 1.10$ is closer to the reference value reported by Zdravkovich (1997) ($\overline{C}_D \approx 1.15$) based on several works at a similar range of Re . It should be noted that as well as Reynolds number the free stream turbulence level has an effect on circular cylinder flow. For the parameters used in our investigation, $Re = 20,000$ and a free stream turbulence level of 1.5%, Fage and Warsap (1929) reported a similar value of mean drag coefficient. The fluctuating lift, $C'_L = 0.27$ is also within the range expected for this range of Re . The compilation of data presented in Szepessy and Bearman (1992) and Norberg (2003) show a large scatter of $0.2 \leq C'_L \leq 0.6$ for this range of Re . The reason for that is the flow dependence on other factors rather than Re , such as turbulence intensity, end effects, aspect ratio, surface roughness, among others. When considering experiments carried out in conditions similar to the present work, the agreement is better. Khalak and Williamson (1996) found $C'_L \approx 0.29$ at $Re = 12,000$ and Cicolin and Assi (2017) observed $C'_L \approx 0.22$ at $Re = 20,000$. Both experiments were performed in water channels with one extremity of the cylinder piercing the free surface and the other subjected to ground effects. The fluctuating drag of $C'_D = 0.06$ is also in agreement with Zdravkovich (1997), which reported values from

0 up to 0.2. The mean lift is expected to be zero due to the symmetry of the body. The Strouhal number calculated is $St = 0.195$, which is pretty close to the classical value for circular cylinders, observed for example in the data gathered by Zdravkovich (1997) and Norberg (2001).

4.2 Post-processing PIV fields

4.2.1 Uncertainties estimation

PIV data has four main types of noise, according to Foucaut et al. (2004): physical, specificity of the flow, instrumental and analysis method (peak fitting algorithm). According to Buxton (2014), these errors can be divided into two groups, based on Herpin et al. (2008): the measurement random error $\sigma(\epsilon_{int})$, which is the RMS error corresponding to the absolute value of the measurement uncertainty (with a confidence level of 68%), and the measurement bias error ϵ_{int} , which was shown to be an order of magnitude smaller than $\sigma(\epsilon_{int})$. Herpin et al. (2008) shown that For a 32×32 px interrogation window, the lower limit for $\sigma(\epsilon_{int, floor})$ is 0.06 pixels. This is equal to an uncertainty in the velocity components of 0.5% of U_∞ for the case with the highest resolution (Camera 2 in Campaign 4) and 2% of U_∞ for the with the lowest resolution (Camera 2 in Campaign 5 - the vertical one). The out-of-plane velocities were estimate throughout the RMS of the velocities at intersection of the orthogonal planes in campaign 5. They correspond to an average displacement of 0.1mm, which is ten times lower than the target thickness of the laser sheet (1mm).

It is possible to quantify the noise on experimental data through the autocorrelation function of the velocity fluctuations, as described in Poelma (2004) and Buxton (2014). It relies on the observation that the autocorrelation function for velocity fluctuations computed from PIV data in turbulent flows “spikes” as Δx approaches 0. The shape of the autocorrelation function is not known a priori but it is assumed that it follows a parabola as it approaches $\Delta x = 0$ (Poelma, 2004; Buxton, 2011). Figure 4.4 shows

Figure 4.4: Autocorrelation function from the stream wise (u) component against $(\Delta x)^2$. The dashed line represents a linear extrapolation of R_{XX} to find the value free of noise at $\Delta x = 0$.

the autocorrelation function close to $x = 0$ for the stream-wise velocity fluctuations plotted against $(\Delta x/D)^2$, computing every 4th vector due to the 75% overlap that was used in its processing. The dashed line is a linear extrapolation of R_{XX} in order to model the expected parabolic shape for the autocorrelation function close to $\Delta x = 0$. The dashed line can thus be thought of as the auto correlation function for the actual turbulent fluctuations, whereas the solid line represents the correlation function for the turbulent fluctuations plus noise. An estimate for the variance of the noise can thus be made by taking the square root of the difference between the value for the measured autocorrelation function and the extrapolated autocorrelation function at $\Delta x = 0$ (Buxton, 2011). In the present study, an estimate of the actual error on the PIV data is thus 5% of U_∞ in the worst case for the horizontal plane and 9% of U_∞ in the vertical plane, which corresponds to a pixel displacement of approximately 0.5 px for both cameras. It must be pointed out, however, that the actual error is between these values and the floor $\sigma(\epsilon_{int, floor})$.

Figure 4.5 illustrates instantaneous fields acquired with two cameras focusing different FoV simultaneously. The figure displays the data obtained in the intersection of the FoVs, indicating qualitatively the level of noise expected in these experiments.

Figure 4.5: Validation of the velocity fields acquired by different cameras. (a) Instantaneous values of the component u for different positions along the same x line $(y/D, z/D) = (-0.5, 0.0)$; and (b) Time series for the same point $(x/D, y/D, z/D) = (1.0, -0.5, 0.0)$. Bare cylinder case.

4.2.2 Smart filtering: OMD

The processed velocity fields exported from *DaVis* had high spatial resolution, even those with the largest FoV. Each instantaneous field contained information on both coherent structures and fine-scale turbulent fluctuations. For certain applications where only the coherent structures are the focus of interest, the velocity fields were processed in order to remove those fluctuations less relevant to the large-scale dynamics of the system. The process adopted was a “smart filter”, understood as an operation capable of removing highly damped fluctuations regardless of their frequency or energy content. This is a key factor since the frequency of vortex shedding induced by one control rod is expected to be one order of magnitude higher than that of the main cylinder. Whilst these fluctuations are not especially energetic, they are dynamically important. Optimal Mode Decomposition (OMD) was employed, which is a method proposed by Wynn et al. (2013) as a generalization of the Dynamical Mode Decomposition, first proposed by Schmid (2010). The Dynamic mode decomposition (DMD) relies on the basic idea that there is a linear dependency, approximately constant throughout the sampling period, between successive velocity fields, that can be written as:

Figure 4.6: OMD decomposition for the Bare cylinder case with $r = 30$. (a) Eigenvalues of the matrix $\mathbf{M}$ (λ_n) with respect to the unit circle and (b) Eigenvalues of the OMD modes (λ_n^*) shown in the frequency domain. The relationship between λ_n^* and λ_n is given by equation 4.4

$$\begin{aligned} \mathbf{v}_{n+1} &= \mathbf{A} \mathbf{v}_n, \\ \mathbf{A} &\in \mathbb{R}^{p_v \times p_v} \end{aligned} \quad (4.2)$$

where $\mathbf{v}_n$ is an arbitrary snapshot having length denoted by p_v , which corresponds to the total number of vectors in the PIV vector field, and $\mathbf{A}$ represents the underlying linear system. The DMD algorithm estimates the dynamic properties of $\mathbf{A}$ and its successful adaptation relies on having a sufficiently large ensemble of snapshots. Optimal mode decomposition (OMD) estimates the properties of $\mathbf{A}$ by replacing it with its low rank form $\mathbf{LML}^T$ and solving an optimisation problem for both L and M . For a series of N snapshots, the problem becomes:

$$\begin{aligned} \min \left\| [\mathbf{v}_2, \dots, \mathbf{v}_N] - \mathbf{LML}^T [\mathbf{v}_1, \dots, \mathbf{v}_{N-1}] \right\|^2 \\ \mathbf{LL}^T = \mathbf{I}, \quad \mathbf{L} \in \mathbb{R}^{p_v \times r}, \quad \mathbf{M} \in \mathbb{R}^{r \times r} \end{aligned} \quad (4.3)$$

The OMD eigenvalues (λ^*) are then defined as:

$$\lambda_n^* = \frac{\log \lambda_n(M)}{\Delta t_{acq}} \quad (4.4)$$

where $\lambda_n(M)$ are the eigenvalues of the matrix $\mathbf{M}$ and $\Delta t_{acq} = 1/f_{acq}$ is the period between two consecutive velocity fields. Figure 4.6(a) shows the eigenvalues of the matrix $\mathbf{M}$ obtained for the bare cylinder case with respect to the unit circle. The complex eigenvalues have modulus lower than 1, indicating that they do not increase exponentially with time. The values closer to the circle, i.e. those with the highest magnitudes, are the least damped in time, which means that they are the more important modes regarding the dynamics of the system. Figure 4.6(b) show the real and imaginary parts of λ_n^* , which are the OMD eigenvalues, defined in equation 4.4. The imaginary part is related to the frequency of the OMD mode associated with λ_n^* whereas the real part is linked to its decay rate (Wynn et al., 2013), as it is linked to the magnitude of the eigenvalues of the matrix $\mathbf{M}$. It is interesting to observe that the eigenvalues with higher $\text{Re}(\lambda_n^*)$ in figure 4.6(b) are associated to mean field (with frequency zero), and to the vortex-shedding, with a dimensionless frequency ≈ 0.2 (and its conjugate at -0.2).

The OMD mode associated with each λ_n^* is given by:

$$\Phi_n^* = \mathbf{L} \mathbf{z}_n \quad (4.5)$$

where $\mathbf{L} \mathbf{z}_n$ is an eigenvector corresponding to the eigenvalue $\lambda_n(M)$. A low-order model (LOM) representation of the velocity fields is then given by:

$$\mathbf{v}_{\text{LOM}} = \sum_{n=1}^r c_n \Phi_n^* e^{\lambda_n^*} \quad (4.6)$$

where c_n are the coefficients associated with the OMD modes. These coefficients can be evaluated by projecting the original data onto a basis spanned by the OMD modes. They appear in equation 4.6 because the modes Φ_n^* are given in a normalised form.

Further details about OMD/DMD methods can be found in Wynn et al. (2013) and its

Figure 4.7: Instantaneous vorticity fields (a) before and (b) after the OMD based filtering process. Reconstruction using $r = 24$ for the case with two rods at $\theta = 90^\circ$. $Re = 20,000$.

use to extract coherent modes in flows forced simultaneously by multiple bluff bodies at multiple different length scales in Baj et al. (2015). The low order representation of the velocity fields using OMD fields can be seen as a “smart” dynamical filter, as it keeps the structures more relevant to the dynamics of the flow regardless of their energy content, i.e the velocities are not filtered in relation to their size or time scale but considering their dynamic relevance to the flow. An example of the previous application of such an OMD-based “smart filter” to turbulent velocity data is given in Rodriguez-Lpez et al. (2016) and Baj (2018).

Figure 4.7 shows the same instantaneous field before and after the smart-filtering operation. It is clear that the less damped structures were sustained, notably the main cylinder and two rods wakes, whereas the other high damped turbulent oscillations were removed. In this work, OMD decompositions are used mainly for visualisation purposes, in order to make turbulent fields more comprehensible. All the calculations involving velocity fields, such as time-series and spectra were obtained from raw PIV data.

4.2.3 Instantaneous & Mean fields

A complete cycle of vortex shedding from the bare cylinder is shown in figure 4.8, where ϕ represents the phase in the cycle of vortex shedding from 0 to 2π . The fields were reconstructed using $r = 24$ OMD fields as part of the smart-filtering operation.

The figures show the classical Von Krmn vortex street, which is typical for a circular cylinder at moderate values of Re . The vortex shedding mechanism is generated by the interaction of the two separated shear layers with opposing vorticity, as described by Gerrard (1966) and Bearman (1984).

In figure 4.8(a), the top shear layer (defined hereafter as the layer coming from the side of the cylinder with positive y/D with negative-signed vorticity in blue shades), rolls into a coherent vortex at approximately $x/D = 1.5$. At the same time this growing vortex interacts with the lower shear layer, which has positive-signed vorticity in red shades. When this vortex is strong enough, it cuts the bottom layer's feed of vorticity, which culminates in the release of a positive signed vortex, seen in figure 4.8(b) at $x/D = 3$. The bottom layer then starts to roll into a new vortex, which cuts the top layer in figure 4.8(e). The top shear layer then starts to concentrate vorticity and grow again, closing one cycle in figure 4.8(h).

The mean velocity fields, along with the main Reynolds stresses for both u and v components, are shown in figures 4.9. The u' component presents the typical two-lobe shape with maximum values close to the end of the formation region, whereas v' has a single lobe with a maximum value at $x/D = 1.4$. The overall distribution of $u'u'$ and $v'v'$ is comparable to the results of Bingham et al. (2018b) and Perrin et al. (2007), obtained at Re level in the sub-critical range.

Figure 4.10 presents the power spectral density for the u and v components measured at a point placed $1.5D$ downstream in the wake centreline. For v , a clear peak is identified, which is associated with the frequency of vortex-shedding. The u component, on the other hand, has its the main spectral peak at a frequency twice that of v , also associated with vortex shedding. At each cycle, the two vortices with opposing vorticity pass at the same point with a positive value of u and alternate values of v , which explains the difference in the measured frequencies. The Strouhal number was measured at 0.198, which is in accordance both with the values found in the literature (Norberg, 2001; Zdravkovich, 1997) and the forces spectra presented above.

The round black dot in figure 4.9(a) identifies the saddle point where the mean velocity

Figure 4.8: Complete vortex shedding cycle for the bare cylinder case. Vorticity fields calculated from a low order model velocity fields. $Re = 20,000$.

Figure 4.9: Mean velocity fields for the bare cylinder: (a) u and (b) v component. Reynolds stress for the bare cylinder case: (c) $u'u'$ and (d) $v'v'$. $Re = 20,000$.

Figure 4.10: Spectra of u and v components taken at $(x/D, y/D) = (1.5, 0)$.

Figure 4.11: Fluctuating velocity along the wake centreline ($y = 0$). u_{xy} is the instantaneous velocity modulus measured in the plane xy , similarly to the quantity obtained by the Hot Wire Anemometer in Szepessy and Bearman (1992).

is zero ($u = v = 0$). The distance between this point and the centre of the cylinder defines the recirculation length L_b . The vortex-formation length, L_f , is defined as the point where the flow has the maximum velocity fluctuation along the centreline ($y = 0$). In spite of having different physical definitions, both recirculation and vortex formation lengths quantify how far from the cylinder the interaction between the shear layers occurs. For a given Re , larger values of L_b and L_f indicate that the interaction is happening further downstream and it is associated to an increase in the base pressure. Both lengths are sensitive to Re and are expected to decrease with increasing Re within the sub critical range (Norberg, 1998). In this study, the recirculation bubble was calculated with $L_b/D = 1.25$ and the vortex formation length $L_f/D = 1.20$ for $Re = 20,000$. Both values are in good agreement with the literature. Norberg (1998) found a recirculation length of $1.5D$ for $Re = 10,000$, and observed that from this range the value reduced up to $1.25D$ at $Re = 200,000$. As for the vortex-formation length, figure 4.11 shows a comparison between the velocity fluctuations in the centreline in the present study and that in the work of Szepessy and Bearman (1992). The agreement between the plots is remarkable, considering the different levels of Re .

Figure 4.12: Calculation of the separation point angle (θ_{sep}) for the bare cylinder case .

4.2.4 Separation points

The position of the separation points plays an important role on the formation of the wake. It has a relationship with the base pressure and the drag coefficient, so that its determination is relevant for the interpretation of the force coefficients. In order to estimate the position of the separation for the cylinder, two methods were employed using PIV measurements, as illustrated in figure 4.12. The first consisted of identifying the point where the streamlines detached from the surface of the cylinder, as marked in figure 4.12(a). The second consisted of plotting the mean tangential velocity $\bar{v}_t$, obtained through polar coordinates, and considering the cylinder centre as the origin. The separation occur where the first vector off the cylinder's surface shows $v_t \leq 0$, as illustrated in figure 4.12(b). This is equivalent to identifying the point of zero shear stress on the wall. The first vector is at a distance of about 0.9mm ($0.018D$) from the cylinder. The resulting value, the average between the two methods, is shown in figure 4.12(c).

The variation between the two methods was lower than $\pm 2^\circ$ for all cases measured in this work. However, there is an intrinsic uncertainty regarding the estimation of the separation point from PIV fields. It happens due to the size of the FoV relatively to the boundary layer. PIV calculates the average velocity within a certain area, giving no information about the velocity distribution inside the interrogation window. Hence, it cannot determine the exact point where the separation happened in the cylinder wall. Other Experimental techniques used in wind tunnels, such as oil visualisation and

computational tools, provide a better estimation of the separation point when compared to PIV. For example, the θ_{sep} calculated for the bare cylinder in the present study was $\theta_{sep} \approx 100^\circ$, whereas the value usually found in the literature for this range of Re is around $85 - 90^\circ$ at the same Re , according to the comprehensive data compilation by Jiang (2020). The background turbulence intensity can also explain this difference. The most accurate experimental estimations of the separation point are made in wind tunnels where the turbulence intensity is significantly lower than in water flumes. θ_{sep} is expected to be higher in a medium with greater background turbulence. Cagney and Balabani (2019) used v_t to estimate the separation point over a circular cylinder from PIV measurements undertaken in water and obtained a result close to 100° , which is in agreement with the current data. Although any comparison with the literature must take into account the factors listed above, it must be pointed out that the main objective behind the estimation of θ_{sep} in this work is to compare different controlled cases with the bare cylinder. Both the technique and the background turbulence were the same for all cases, which minimises any misinterpretation related to the uncertainty induced by the PIV.

4.2.5 Correlation length

The correlation length was employed in this study to estimate the level of correlation of the main vortical structure along the cylinder span. It is especially useful for determining the relationship between the sectional and the total lift fluctuation acting on a span-wise segment of length L_c . The former is proportional to the vortex strength observed in the horizontal plane with PIV, and the latter is directly measured with the force transducer.

According to Norberg (2003), an approximation for the correlation of the lift coefficient R_{LL} can be obtained through the correlation of pressure R_{pp} or velocity R_{uu} at a position close enough to the separation, i.e. $R_{LL} \approx R_{pp} \approx R_{uu}$, the last two functions acquired close to a line $\theta = \pm 90^\circ$ or close to the separated shear layers. Norberg (2001, 2003) provide an extensive compilation of data acquired using these methods, that have a

good correlation with Re (figure 2.5).

Some observations must be made about the reference z for the evaluation of R_{uu} and the bounds of integration. The vertical field of view covers a span length of approximately $8.5D$. In the two extremities, the flow is affected by end conditions, so a reference z/D close to the limits could underestimate the value of Λ . However, if the reference is chosen at any point in the range $-3.5 \leq z/D \leq 2.5$, Λ varies less than $\pm 0.5D$. Based on that, the reference was chosen at $z/D = 0$. Even though it is not exactly the centre of the cylinder, the two-dimensional flow is known in this position, so it is possible to know exactly to which structure the correlation is being calculated. It is particularly useful for some controlled cases, where the state of the flow varies along the span. Regarding the limits of integration, it was chosen to cover all the field of view, i.e., from $-4.5 \leq z/D \leq 3.5$ to ensure the largest limits possible. However, it must be pointed out that the main objective behind calculating Λ in this study is to compare the correlation between the bare cylinder and controlled cases. Given and the same procedure was employed for all cases, variations in Λ due to the choice of z/D and bounds of integration are negligible.

Figures 4.13(a) and 4.13(b) show an instantaneous u field before and after filtering. The instantaneous field reveals a main vertical structure along $x \approx 1 - 2$ with a series of small fluctuations. They are associated with the main vortex tube and span-wise vortex loops linked to the B-mode (discussed in section 2.12 and figure 2.3). After filtering, the former was kept while the latter was removed. Since the main concern is to evaluate the correlation of the vortex tubes, the two-dimensional structure, R_{uu} shown in figure 4.13(c) was calculated from filtered fields. R_{uu} shows the typical Gaussian curve, with a maximum at $z = 0$. It must be noted that the distribution of R_{uu} is not symmetric, as the value at $z = 3$ is a bit higher than $z = -3$, for example. The reason for that is because the end conditions at the two extremities of the cylinder are different. While there is an endplate at the bottom, the flow in the top is influenced by a square plate partially emerged in the water. It makes the flow to be substantially different for positive and negative values of z . The resulting value for the correlation length

Figure 4.13: (a) instantaneous velocity field for the bare cylinder: (a) raw data and (b) OMD-filtered data. (c) Correlation coefficient along z with the correlation length calculation Λ for the bare cylinder.

is $\Lambda/D = 4.05$, which is in agreement with the data provided by Norberg (2001) in figure 2.5 ($\Lambda/D \approx 4$). The difference between the present value and the literature is small and can be associated with the filtering, which removed small fluctuations, the reference value (z/D), bounds of integration and length of the cylinder. As said before, the calculation of Λ has an uncertainty of about $\pm 0.5D$, and any comparison with the literature must consider the methodology employed in the evaluation.

4.3 Conclusion

The main objective of this chapter was to describe and validate the experimental methods of force and PIV measurements for a bare cylinder. The results are in a consistent agreement with the literature, which indicates that the techniques and tools provide trustful results. The same procedures will be applied for the controlled cases in the next chapters, and the bare cylinder case will serve as the reference case.

Chapter 5

Preliminary Experiments on the Sensitivity of Fluid Forces

This chapter comprises the results of the two first campaigns developed in the NDF Fluid Dynamics Laboratory at the University of São Paulo, Brazil. It evaluates the sensitivity of fluid forces to the main parameters governing the flow, as described in section 3.1: Re , d/D , R'/D and θ . It is expected that the flow may be affected by any of these parameters. The main objective of these preliminary tests is to identify the most relevant cases regarding the force coefficients to narrow down the parameters for the detailed investigation that will follow.

The range for each parameter considered the characteristic flow about a circular cylinder and the physical limitations of the facilities. The Re range is within the moderate range for all experiments. It was limited by the flume's width and maximum flow speed, and the range of operation of the load cell. The rod's diameter d was intentionally chosen to be of at least one order of magnitude smaller than the main cylinder D . The PIV system limited the minimum value of d/D since lower d generates small-scale flow structures at frequencies higher than that generated by the main cylinder; the system ought to be capable of acquiring the scales produced by both bodies. The position of the rod is expressed in polar coordinates R'/D and θ . The range for R'/D covered positions from as near as possible to the cylinder wall to the end of the wake recirculation region. θ ,

on the other hand, was narrowed down to $90^\circ - 180^\circ$ to capture the interaction of the rods with the separated shear layers and near wake. Small rods positioned upstream, near the boundary layer are known to induce a “tripping wire” effect (Alam et al., 2003; Sakamoto and Haniu, 1994), anticipating the drag crisis, an interaction that is out of the scope of this investigation.

The flow around a bare cylinder, without any control rods, served as a reference for the controlled cases. The mean value of drag coefficient was approximately $\overline{C}_D = 1.1$ for all the Re range tested for a configuration without the support disc at the bottom and the end of the cylinder very close to the floor of the flume. This value is very close to the typical value found in literature for the average drag of a circular cylinder, for example in Zdravkovich (1997), also discussed in chapter 3. When adding the support disc, $\overline{C}_D$ increased to 1.2. It is true that the support disc works as an end plate, isolating the cylinder from the boundary layer developed on the floor of the flume. But it also generates some drag of its own. This higher value of $\overline{C}_D$ was used as a reference in this study since the support disc was necessary to hold the rods in all the controlled cases. In this way, the variation in the forces between any two cases is related to the effect of the rods only. The reference value for the RMS of fluctuating lift, C'_L , also calculated with the support disc, varied in the interval $0.19 \leq C'_L \leq 0.23$ for the whole Re range. This variation is within the spread of data observed in literature for the same Re range, as can be verified in the comprehensive data compiled by Norberg (2003). The Strouhal number was calculated from the frequency of lift and found to be between 0.19 and 0.2 for all Re , which also agrees well with the data presented in the literature (for example, Norberg (2001) shows $0.19 < St < 0.21$).

The results for the controlled cases are presented in the form of sensitivity maps. The relative force coefficients C^* are defined in terms of the variation between the absolute value obtained for controlled and the reference cases, as in

$$\overline{C}_L^* = \frac{\overline{C}_L}{\overline{C}_D^{ref}}; \quad (5.1)$$

Figure 5.1: Rod's position for all cases with one control rod

$$\overline{C}_D^* = \frac{\overline{C}_D}{\overline{C}_D^{ref}} - 1; \quad (5.2)$$

$$C_L'^* = \frac{C_L'}{C_L'^{ref}} - 1; \quad (5.3)$$

$$St^* = \frac{St}{St^{ref}} - 1 \quad (5.4)$$

where $\overline{C}_D^{ref}$, $\overline{C}_L^{ref}$, $C_L'^{ref}$, and St^{ref} are the coefficients calculated for the bare cylinder with the support disc. Since $\overline{C}_L^{ref} = 0$, $\overline{C}_L^*$ evaluates the variation in lift induced by the rod in terms of the bare cylinder's total force magnitude $\overline{C}_D^{ref}$. Regarding $\overline{C}_D^*$, $C_L'^*$, and St^* , negative values represent a reduction from the reference, whereas positive values represent an increase.

5.1 Cylinder with one control rod

The cases with one control rod were carried-out for two values of $Re = 10,000$ and $20,000$, two diameters ratios ($d/D = 0.04$ and 0.1), six values of R' ($0.6 \leq R'/D \leq 1.5$) and ten of θ ($90^\circ \leq \theta \leq 180^\circ$) for the rod, which can be seen in figure 5.1 and also in table 3.1. The sensitivity maps of mean drag, mean lift, fluctuating lift and Strouhal number are shown in figures 5.2, 5.3, 5.4 and 5.5, respectively. The colour bars were fixed at the same range for all maps in order to facilitate comparison. For example,

Figure 5.2: Mean drag sensitivity maps for one control rod.

Figure 5.3: Mean lift sensitivity maps for one control rod.

Figure 5.4: Fluctuating lift sensitivity maps for one control rod.

Figure 5.5: Strouhal frequency sensitivity maps for one control rod.

Figure 5.6: Force sensitivity maps of the position of one control rod obtained for $d/D = 0.125$ and $Re = 12,500$: (a) mean drag and (b) fluctuating lift. Adapted from Bingham et al. (2018b)

the total drag with one control rod varied within the range $-0.1 \leq \overline{C}_D^* \leq 0.2$, which means that it was reduced by 10% in the best case and increased by 20% in the worst case, as far as drag reduction is concerned.

The regions in which the rod produced the most significant reduction in mean drag are near the wake recirculation zone, especially at those areas closer to the cylinder wall, for $R'/D \leq 0.7$; and in those points along the centreline ($\theta \approx 180^\circ$). The positions where the rod prompts a larger drag increase are those where the flow developed higher velocities, clearly outside of the recirculation region. This result was not unexpected at first, considering that the forces were acquired over the whole system and that the contribution from the rod's drag is higher in these positions. It does not necessarily imply that the rod in the recirculation region decreases the drag over the cylinder, but any effect at this region seems to be lower or overshadowed by the drag acting on the rod. This hypothesis is reinforced by comparing these results with the map provided by Bingham et al. (2018b), for $Re = 12,500$ and $d/D = 0.125$ in figure 5.6(b), for which drag measurements have been acquired over the main cylinder only. The overall regions of increasing and decreasing mean drag agree with those of the present work but differ in their magnitudes. Within the recirculation region, where the absolute drag on the rod is expected to be lower, the agreement between the maps of figure 5.2 and that of figure 5.6(b) is even closer. For example, in both cases the positions $R'/D = 0.9$ and $\theta = 160^\circ - 170^\circ$ showed an increase of about 5%.

The map of Bingham et al. (2018b) did not include values for $R'/D < 0.75$, precisely where the most significant reductions were observed in the present work. The areas closer to the cylinder, at $R'/D \leq 0.7$, prompted a more significant effect in the total force magnitude compared to those more distant from the cylinder. Figure 5.2 shows that both the greatest drag increase and reduction occurred for $R'/D = 0.6$ and 0.7 , especially in the cases where $d/D = 0.1$.

The sensitivity maps for mean and fluctuating lift are shown in figures 5.3 and 5.4. These data should be analysed cautiously because of the characteristics of the lift force for the bare cylinder. C'_L is particularly scattered in this range of Re . Norberg (2003) has shown a compilation of past studies where C'_L varies up to 300% for the same Re in the range $10,000 \leq Re \leq 20,000$. In addition to that, the lift force was measured over the combined system, so that the contribution of both mean and fluctuating parcel for each body can not be analysed separately. In addition, the value of C'^*_L is different from the sum of the fluctuating lift coefficients at each body. Considering these points, and observing figures 5.3 and 5.4, the main feature is the lack of a clear structure throughout the four plots. For $R'/D > 0.7$, each plot has regions of agreement with the plot of Bingham et al. (2018b) shown in figure 5.6, for example the region close to the recirculation in 5.4(d), but the fact they do not repeat for the four plots limit further conclusions. The point $R'/D = 0.7$ and $\theta = 120^\circ$ with $d/D = 0.1$ at $Re = 20,000$ deserves attention, however, as it showed the largest reduction in the fluctuating lift and mean drag, followed by a huge variation of $\overline{C}_L^* \approx 0.5$. At this point, the mean lift is so large that it makes the total force magnitude similar to the bare cylinder, despite the reduction in drag. This behaviour is similar to that observed by Sakamoto and Haniu (1994) using one control rod of $d/D = 0.06$ in the range $0.55 \leq R'/D \leq 0.72$ at $Re = 65,000$. They observed a region of negative lift for $R'/D \leq 0.6$ and $\theta \approx 90^\circ - 100^\circ$, followed by a significant lift increase at around $R'/D \approx 0.7$ and $\theta \approx 120^\circ$, which also showed the lowest drag over the cylinder, very similar to observed here for $Re = 20,000$. Using flow visualisation with smoke, they identified that the wake had a different flow pattern in this position compared to neighbouring positions. It indicates a change in the state of the wake and reinforces the need for detailed wake measurements to clarify

the development of the flow and the variations in force coefficients.

The sensitivity maps for the Strouhal number is shown in figure 5.5. It must be pointed out that the dominant frequency identified is not affected by measuring the forces over the cylinder only or the combined system, which facilitates the comparison with the bare cylinder and the literature. Figure 5.5 shows a clear structure, the main feature of the plots is the agreement between the region of highest sensitivity throughout the four plots. The rod has the most significant impact on the flow when placed in a region close to the separated shear layer from the cylinder, or in other words, in the vicinity of the frontier of the mean recirculation region. It can be explained by the fact that the shear layers are the responsible for the onset of vortex shedding, the dominant structure on a circular cylinder wake.

The flow sensitivity to a rod close to the shear layer has also been observed for lower values of Re in literature. Computational simulations at $Re = 3,000$ with $d/D = 0.1$ published by Dalton et al. (2001) also found the lowest C'_L , 85% lower than the bare cylinder, in positions close to the shear layer. These results at moderate values of Re are in agreement with the pioneering study of Strykowski and Sreenivasan (1990), which identified this feature for very low Re . They found positions where the rod totally suppressed the vortex shedding, virtually leading C'_L to 0 for Re up to 80. As Re increased, the points of total suppression converged to a narrow region around the separated shear layer's path. For $Re > 80$, vortex shedding was not annihilated, but it was significantly reduced for some positions along with its frequency. These positions are close to the separated shear layer too. Similar behaviour is also shown by studies with bodies with fixed separation points, notably by Parezanovi and Cadot (2012) with a D-shaped cylinder at $Re = 9,500$ and by Sakamoto et al. (1991) with a square prism at $Re = 42,000$. Their sensitivity maps confirmed that the wake was most affected when the rod was around the path of the shear layer. This observation is particularly interesting to narrow down the parameters regarding the rod's position. Significant changes are induced in the wake just by changing the rod's position with respect to the shear layer, for example varying θ for a fixed R'/D . This might be more effective than

mapping a bigger region.

No significant differences were observed between the two values of Re tested for most of the points. It can be also explained by the flow sensitivity to the rod's position with respect to the shear layer. The flow does not change significantly within the range of Re tested, especially if compared with the works of Cicolin et al. (2018) and Dalton et al. (2001), which explored Re of different orders for the rod at a fixed position. Both have observed that the rod prompted different wake responses depending on Re , because the rod's position with respect to the shear layer varied.

Regarding the effect of d/D , the two values induced the same effect of increasing/decreasing at the same Re and position for most cases, where both the maximum increase and decrease happened for $d/D = 0.1$. It indicates that d/D influence over the flow is quite predictable in this range: the larger the rod, the larger the effect. The Strouhal maps in figure 5.5 evidences this.

The only exception was the point $R'/D = 0.7$ and $\theta = 120^\circ$, placed close to the shear layer. The high value of $\overline{C}_L$ for this point in figure 5.3(d) was observed only for $Re = 20,000$ and $d/D = 0.1$. However, it is possible that the same behaviour was not observed for other Re and d/D due to the spatial resolution of the experiments. The distance from this point to its neighbours varied from $0.12D$ to $0.2D$, which can be large enough to capture transitions of flow states. This hypothesis is reinforced by the study of Sakamoto and Haniu (1994), where a high lift force was observed at few points within a small region. It indicates the need for a better spatial resolution in the additional experiments.

5.2 Cylinder with two control rods

The experiments with two control rods were carried out for a fixed value of $d/D = 0.06$, two values of $Re = 18,000$ and $28,000$, at rod positions within $0.6 \leq R'/D \leq 0.9$ and $90^\circ \leq \theta \leq 180^\circ$, as illustrated in figure 5.7. The sensitivity maps of mean

Figure 5.7: Rod's positions for all cases with two control rods

drag, fluctuating lift, and Strouhal number are presented in figure 5.8. The mean lift coefficient was approximately null for all cases due to the symmetry and, for this reason, these maps are not shown.

The drag results can be divided into two different regions, similar to those with one control rod: the cases where the rods are within the wake recirculation and those exposed to high velocities. In the maps of mean drag (figures 5.8(a) and 5.8(b)), the most striking feature is the variation of the drag coefficient between the two regions. The whole system's drag was increased by up to 40% when the rods were positioned outside of the shear layers, exposed to high-velocity flow. Conversely, within the recirculation region, the rod induced a drag reduction of up to 10% at some positions, notably for $R'/D \leq 0.7$ and $\theta \geq 130^\circ$. The maps are qualitatively similar for the two values of Re . Comparing them to the one-rod cases, it is interesting to note that at the positions where $\overline{C}_D^*$ increases with one rod, the drag is twice enhanced with two rods. However, within the recirculation region, where $\overline{C}_D^*$ decreases, the level of reduction is similar for both one-rod and two-rod cases.

The behaviour of the fluctuating lift force was a little different from that observed for the cases with one rod. Within the recirculation zone, the rods induced a small reduction of the fluctuating lift coefficient. For some positions outside the recirculation zone, especially at $R'/D \geq 0.8$, the fluctuating lift increased by more than 100%. These points are identified by the dark red regions in figures 5.8(c) and 5.8(d). The frequency

Figure 5.8: Sensitivity maps for the cylinder with a pair of symmetric rods. $d/D = 0.06$.

of vortex shedding decreased in these points, whereas it remained close to the reference case for the positions within the recirculation zone, as seen in figures 5.8(e) and 5.8(f) for St^* .

Yan et al. (2018) performed numerical simulations at $Re = 3,900$ for a circular cylinder with a pair of control rods at $R'/D = 1.0$, $\theta = 135^\circ$ and $d/D = 0.05$, which is a point out of the recirculation zone, where the rods are exposed to velocities higher than the free stream. Compared to the bare cylinder, the controlled case increased the fluctuating lift coefficient by more than 100%, the mean drag coefficient by approximately 25%, and decreased the Strouhal number by approximately 10%. These values are consistent with the present results in the same region, notably the points in dark red in figures 5.8, despite the differences in Re . Regarding the positions within the recirculation region, the literature is more sparse, as few works have explored the effect of two rods over a static cylinder. One may argue that the flow between the cylinder and the rod is low within the recirculation zone, and then the control rods effect is similar to that of two short splitter plates. In that case, it could be compared to the work of Bao and Tao (2013), which explored the effect of a pair of parallel plates attached to the cylinder for low $Re = 160$. Their results showed that when the plates were inside the recirculation region ($\theta \geq 140^\circ$) the $\overline{C}_D$ was reduced by up to 20% and C'_L by 70%, which is consistent with the present results, despite the differences in Re . However, any further comparison is limited due to the lack of information on the flow with two rods. It indicates the need for a detailed investigation of the wake.

5.3 Conclusions

A series of experiments has been carried out to evaluate the sensitivity of force coefficients to the main parameters that govern the flow: Re , d/D , R'/D , θ , and the number of rods. The results provided a quick indication of the flow regions most affected by the rods, even though no wake measurements have been made. By combining the results with the data of the literature, we reached the following conclusions:

- Few variations in the force coefficients were observed for varying Re within this particular range. It was not unexpected, given that the flow pattern of a circular cylinder does not vary significantly within this range of Re . For the vast majority of points, the force coefficients had similar values through all the values of Re .
- The control rod diameter showed a more predictable effect on the wake. For the same Re : the larger the rod, the larger the effect. Both the greatest drag reduction and increase were observed for $d/D = 0.1$. The qualitative aspect of the maps varying d/D was quite similar, suggesting that different rod diameters induced the same flow mechanisms.
- The position of the rods close to the shear layer prompted more significant changes in the force coefficients for any given R'/D . The coefficients were also more affected when the rods were closer to the cylinder's wall. However, the distance between two consecutive points might not have been sufficient to capture all the transitions in the wake. For example, the point $R'/D = 0.7$ and $\theta = 120^\circ$ has shown a positive mean lift $\overline{C}_L^* \approx 0.5$ only for $d/D = 0.1$ at $Re = 20,000$, whereas $\overline{C}_L^* \approx 0$ for other values of Re and d/D .
- The direct comparison between the effect of the number of rods is more challenging because the experiments were carried out using different set-ups, for different values of cylinder diameter(D), aspect ratio(L_w/D), and control rod diameter (d). However, the results indicate that the symmetric configuration using a pair of rods annihilated the mean lift force induced by the asymmetry. On the other hand, a second rod enhances the magnitude of drag in regions where drag increase was observed for one rod, but does not significantly alter the reduction level in points where one rod prompts drag reduction.

Based on the points above, the number of cases was narrowed down for the next experiments intended to investigate the wake behaviour. The points below clarify the reasons for each choice:

$Re = 20,000$: Few variations were observed regarding Re in this particular range, so

the preferred value was the maximum possible, considering the cylinder model of 50 mm in diameter.

$d/D=0.1$: The results indicate that, in this range of d/D , the maximum value of 0.1 prompts the most significant changes. In addition, this larger rod approximates the frequency of the two time scales associated with vortex shedding for the cylinder and the rod, facilitating flow measurements by PIV.

$R'/D=0.7$: The points close to the cylinder, for lower R' induced more significant changes in the force coefficients and are also more interesting from the perspective of real applications. Between 0.6 and 0.7, the latter was chosen to allow a larger gap of $0.15D$ between the rod and the cylinder wall, larger than d . Furthermore, wake measurements should include the specific point $R'/D = 0.7$ and $\theta = 120^\circ$, which has shown a peculiar behaviour.

$90^\circ \leq \theta \leq 180^\circ$ The range of angles was not changed since R'/D was fixed, and the next experiments must cover the recirculation region, the shear layer and the regions where the rod is exposed to high velocities. The step was reduced to 5° though, so that the distance between two neighbouring cases is smaller than d .

The next chapters will explore results for this set of parameters.

Chapter 6

The influence of one control rod in the wake

This chapter explores the influence and effects of one control rod acting in the wake in the range $90^\circ \leq \theta \leq 180^\circ$ for a constant $Re = 20,000$, $d/D = 0.1$ and $R'/D = 0.7$. Most of its contents were obtained through the campaigns 3 and 4. The cases were divided into three flow states, including a transitional bi-stable between two states. The chapter starts presenting a diagnostic tool for identifying the states in 6.1, followed by the force coefficients for all cases in 6.2. Then each flow state is explored in a appropriate section in 6.3, 6.4 and 6.5. Section 6.6 describe the bi-stable case and 6.7 summarises the main conclusions of this chapter. Most of this chapter's contents were published in the article "*The Role of Separation on the Forces acting on a Circular Cylinder with a Control Rod*" (Cicolin et al., 2021).

6.1 Identification of states

The development of the wake is substantially changed with the placement of a rod in the range $90^\circ \leq \theta \leq 180^\circ$. The angular positions can be divided into different groups associated with particular flow states, based on the flow characteristics and common with previous researchers. In order to identify the states, PIV was used to measure

Figure 6.1: Time series of $v_t(P)$ for different values of θ .

Figure 6.2: Instantaneous vorticity (left) and velocity (right) fields for each of the three stable dynamical states characterised in this work with one rod.

the tangential velocity component of the flow nearest to the mid point, P , of the gap between the cylinder and the control rod, $v_t(P)$. This velocity proved to be very useful as a diagnostic tool, as it is related to the flow characteristics in the gap between the bodies. Figure 6.1(a) illustrates how the velocity is defined, and time series of $v_t(P)$ are shown in the other plots in Figure 6.1. In order to link flow states to the velocity traces, reference will be made to Figure 6.2(a) which shows instantaneous vorticity and velocity fields for the three stable states observed for one-rod.

For $90^\circ \leq \theta \leq 115^\circ$ the time-mean value of $v_t(P)$ is close to the free stream velocity, and the fluctuating component has a dominant frequency equal to the shedding frequency of the main cylinder. Examples of the flow in this range defined State I, are shown in Figure 6.2(a), and it is characterised by the formation of distinct wakes, developed by the main cylinder and the control rod. Both wakes shed vortices but with very different frequencies and length scales. Moving to $\theta = 120^\circ$ and $\theta = 125^\circ$, an intense jet appears in the gap between the cylinder and the control rod, with $v_t(P)/U_\infty \approx 1.3$ and it is relatively steady, as seen in Figures 6.1(d) and 6.1(e), where the signals have no significant oscillation during the whole period. This jet is a dominant feature of State II, as observed in Figure 6.2(b). The third stable state, State III, was identified for $\theta \geq 135^\circ$. In this state the average value of $v_t(P)$ is close to zero, as shown in Figures 6.1(g) and 6.1(h). The cylinder boundary layer separates sufficiently far upstream of the control rod for the free shear layer to pass above it, leaving point P within the cylinder's recirculation zone. This state is illustrated in Figure 6.2(c) and is characterized by developing a vortex street wake similar to the bare cylinder case. The velocity trace plotted in Figure 6.1(f) for $\theta = 130^\circ$ shows $v_t(P)$ varying over the range $0 - 1.5$, and it is very different to those for the 3 stable states. This is an example from the state showing bi-stability.

Figure 6.3: (a) RMS and spectra of the fluctuating Lift force on the cylinder for the cases $90^\circ \leq \theta \leq 180^\circ$. The solid lines represent the RMS and the peak St of C_L' for the bare cylinder case, respectively. (b) Average hydrodynamic force coefficients over the cylinder (top) and the control rod (bottom). (c) Average hydrodynamic force coefficients over the combined system. The solid grey line represents the mean drag coefficient of the bare cylinder case.

6.2 Force Coefficients

Following the identification of the three states and the bi-stability, measurements of the variation of hydrodynamic force coefficients with θ are shown in Figure 6.3, together with an indication of the ranges of θ occupied by each flow states. The forces acting on the cylinder without a control rod, the bare cylinder, were measured first to serve as reference data. The results are a mean drag coefficient, $\overline{C}_D = 1.10$, a coefficient of fluctuating lift, $C'_L = 0.27$ and a Strouhal number, $St = 0.194$, for which the evaluation and validation are presented in the chapter 4. Note that the fluctuating forces are computed as the RMS values acting on the full span. In Figure 6.3, the bare cylinder values are denoted by a solid gray line. With the control rod in place, the mean lift and drag coefficients acting on it are also presented in Figure 6.3(b), but note that all coefficients are calculated using the diameter of the main cylinder (D) and the free stream velocity. This makes it easier to compare the relative contributions of the main cylinder and control rod to the overall forces. With the addition of a control rod, it can experience lift and drag forces on itself and influence the forces acting on the main cylinder. Hence the total mean force coefficient has been calculated separately for the main cylinder and control rod. Mean drag, lift and total force coefficients for the combined system of cylinder and control rod are shown in Figure 6.3(c).

In State I, the cylinder has a lower drag coefficient comparing with the bare cylinder, a small but positive mean lift coefficient, a level of fluctuating lift similar to the reference and a Strouhal number increasing with increasing θ , but consistently lower than the bare cylinder case. The control rod in State I is exposed to a velocity greater than the free stream velocity and, depending on θ , its drag ranges between 9% and 14% of the main cylinder's drag. Its lift force is negative and acts to offset a small amount of the lift on the main cylinder.

Moving to State II, the mean drag on the cylinder falls by about 10% regarding the reference case. However, the mean lift increased so dramatically that the magnitude of the mean of the total hydrodynamic force acting on the cylinder was higher than for the

reference case. The coefficient of fluctuating lift dropped to a minimum of $C'_L \approx 0.05$ at $\theta = 120^\circ$, indicating an attenuation of vortex shedding and/or a reduction in its span-wise correlation. The lift force's corresponding spectrum did not have a prominent peak in the frequency range normally associated with vortex shedding but scattered values in the range $0 < fd/U_\infty < 0.2$. The control rod exhibited positive values of both lift and drag in State II.

For State III, where the control rod is in the range $135^\circ \leq \theta \leq 180^\circ$, both the mean drag coefficient acting on the main cylinder and the Strouhal number have similar values to those of the bare cylinder. The mean lift coefficient was small and positive, with values less than 0.1. As a result, the total force magnitude acting on the main cylinder was little different from the bare cylinder's drag coefficient. With the control rod in the recirculation zone, it experienced a small negative drag and lift forces. The highest value of fluctuating lift on the main cylinder was observed in this state, with $C'_L \approx 0.34$ at $\theta = 150^\circ$. These 3 flow states and the bi-stable case are analysed in more detail in sections 6.3 to 6.6 and compared with findings of previous investigators.

6.3 State I

State I was observed for the cases with the control rod in the range $90^\circ \leq \theta \leq 115^\circ$. Its main feature is the formation and interaction of two distinct wakes from the main cylinder and the control rod. Downstream this interaction results in a vortex street similar to that formed by a bare cylinder. Figure 6.4 shows a complete cycle of vortex shedding for the case $\theta = 110^\circ$, representing State I. It shows how the two shear layers from the main cylinder developed differently, as the upper boundary layer is influenced by the flow passing between the control rod and the main cylinder. It remains attached for a farther distance than the lower boundary layer, not influenced by a control rod.

The positions of the mean separation points, for various values of θ , are shown in Figure 6.5. In State I, the upper layer separates at a position $\theta_{sep} > \theta$, whereas the lower layer keeps a value similar to the bare cylinder for all cases in the same range. It suggests that

Figure 6.4: Vortex shedding cycle for the case $\theta = 110^\circ$, which is representative of State I. Vorticity fields are calculated from the smart-filtered velocity fields. $Re = 20,000$.

Figure 6.5: $\bar{v}_t$ fields for the cases bare cylinder and $90^\circ \leq \theta \leq 125^\circ$. The separation point (θ_{sep}) for each case was defined as described in the text .

separation of the upper boundary layer is directly influenced by the adverse pressure gradient caused by the presence of the control rod. This is compatible with the flow locally speeding up in the gap between the cylinder surface and the control rod and then decelerating. The attraction force between the two bodies is a further indication of that.

Studies have been carried out by Parezanovi and Cadot (2012) and Sakamoto et al. (1991) into the effect of control rods on the flow around bluff bodies with fixed separation points. There will be some variations in the flow mechanisms in these cases compared with the present experiments where substantial changes in separation position are observed.

The mean drag coefficient over the cylinder is shown plotted in figure 6.6 together with the upper and lower boundary layer separation angles for the range of θ from 90° to 135° . Interestingly, there is very little variation in the lower separation angle across the range of control rod placements. In contrast, the separation of the upper boundary layer

Figure 6.6: Variation of mean drag coefficients and separation points with θ (for which PIV data was available). The solid lines represent the mean drag coefficient and separation point of the bare cylinder case

changes over a wide range of angles. It is known for a bare cylinder that if θ_{sep} moves further round its surface, this results in a drag reduction due to increased pressure recovery ahead of the separation points and hence an increase in the base pressure. This is illustrated in Figure 6.6 where an increase in the upper surface separation angle is accompanied by a reduction in the drag coefficient, and vice versa.

Figure 6.3(b) shows that for all values of θ comprising State I, there is a positive lift force on the cylinder and a negative lift force on the control rod. The signs of these forces are consistent with the upper cylinder boundary layer remaining attached until just beyond the control rod. For State I, figure 6.1 shows that the gap flow has a marked unsteady component due to vortex shedding from the main cylinder, see Figure 6.2(a).

It is observed that the frequency of vortex shedding in State I is lower than that found for the bare cylinder (Figures 6.3(a) and 6.8). Figure 6.7 shows comparisons of mean velocity and vorticity fields between the bare cylinder and the case $\theta = 110^\circ$. A number of factors influence the shedding frequency, including the distance between the separated shear layers and the flow velocity at their outer edges. Gerrard (1966) established that, in addition, the Strouhal frequency is influenced by both the vortex formation length and the lateral diffusion of vorticity within the shear layers. He quantified diffusion by defining a diffusion length related to shear layer thickness and argued that the greater

Figure 6.7: Mean velocity fields, where the gray points mark $\max(\bar{v}^2/U_\infty^2)$, for the cases (a) bare cylinder and (c) $\theta = 110^\circ$ which is typical for State I. Mean vorticity fields for the cases (b) bare cylinder and (d) $\theta = 110^\circ$.

the diffusion length the longer it takes for a vortex to form and hence the lower the Strouhal number. He also reasoned that the longer the vortex formation length, the greater the diffusion length as the shear layer has further diffused ahead of vortex formation. Considering a bare cylinder over a large Re range, it is found that where the drag coefficient falls, it is accompanied by a rising Strouhal number, and vice versa. With a circular cylinder a reduction in drag coefficient is associated with the separation points moving further round the surface and the near wake becoming narrower. Roshko (1954) developed the concept of a universal Strouhal number by using the velocity at the edge of the shear layers at separation as the characteristic velocity and the distance between the shear layers as the characteristic length. For a circular cylinder his analysis supports the finding that as the distance between the shear layers reduces the Strouhal number increases.

Within State I, the Strouhal number and drag coefficient behave in a similar way to the bare cylinder, with the increase in the separation angle with increasing control rod angle

leading to a reduction in drag and an increase in vortex shedding frequency. With the control rod at $\theta = 90^\circ$ the value of the drag coefficient for the main cylinder is very close to that for the bare cylinder, but in Figure 6.3(a) the Strouhal number is significantly lower. Searching for a reason for this, measurements of the vortex formation length were made, following previous researchers. Earlier measurements have been based on a hot-wire traverse along the centre-line of the wake to find the maximum value of the RMS of the longitudinal component of fluctuating velocity. The PIV data was processed to reproduce what a hot-wire probe would have measured. For the bare cylinder, the vortex formation length was $1.29D$ (chapter 4) and this is in good agreement with published data (Szepessy and Bearman, 1992) and with the control rod at $\theta = 110^\circ$ it increases to $1.68D$. Also the PIV data showed a thickening of the upper separated shear layer from the main cylinder caused by interaction with the control rod's wake. According to Gerrard (1966), together these changes would increase the diffusion length, leading to a reduction in the shedding frequency. However, for $\theta = 90^\circ$, the vortex formation length rather than increasing reduced slightly from the bare cylinder value. In the literature vortex formation lengths have mainly been presented for bluff bodies that do not generate a mean lift force. Since in the presence of lift the cylinder wake is deflected at an angle to the free stream velocity, this brings into question how vortex formation lengths should be defined. Since lift coefficients as large as 0.6 were generated in some cases, it was decided not to present further measurements of vortex formation length. The variation in the mean lift coefficients also indicates the difficulty of predicting the vortex shedding frequency of a bluff body using stability theory when separation points are free to move, such as on a circular cylinder. The introduction of a control rod cannot be considered as a small perturbation if there are changes in boundary layer separation positions, using the wake of a bare circular cylinder as the base flow.

Sakamoto and Haniu (1994) carried out experiments with a control rod at $Re = 65,000$ and varied θ between 0° and 180° to find angular positions where the control rod was most effective at reducing fluid forces. In the range of control rod angles herein classified as State I, they also found that the Strouhal number at $\theta = 90^\circ$ was below the value for the bare cylinder. Also, throughout the range of θ in State I, the shedding frequency

Figure 6.8: Comparison of the spectra between State I and the bare cylinder: (a) v at the point of $\max(\overline{v'^2}/U_\infty^2)$ and (b) Lift coefficient.

increased with increasing θ but remained below the value for the bare cylinder. They do not include reasons for this behaviour. States similar to State I can be found in the literature, for example the 'Free Stream' case reported by Bingham et al. (2018a) at $Re = 9,500$ with the control rod at $R'/D = 1.85$ and with $\theta = 142^\circ$. Compared with their bare cylinder, the mean drag coefficient dropped by 8% . As expected, the Strouhal number increased, and in their case it rose by almost 5%, indicating an interaction between the shear layer and the control rod and a change in where separation occurs.

Parezanovi and Cadot (2012) performed a study with a bluff body with fixed separation points, a D-shaped cylinder. They present sketches of four flow fields they observed depending on the position of the control rod. Their 'Outer Shear' (OS) configuration is the closest to State I, with a reduction in drag, due to an increase in base pressure.

It is interesting to note that in the low Re study by Strykowski and Sreenivasan (1990), the rod's wake did not develop vortex shedding, which would have made the interaction with the main cylinder shear layer different from the present study. Figure 6.9 shows in State I the spectrum of v' along the line $x/D = 1.0$. The peaks in $fD/U_\infty \approx 0.2$ and $fD/U_\infty \approx 2.4$ are due to the periodic vortex shedding of the main cylinder (f_D) and the control rod (f_d), respectively. Besides these, two other clear frequency signatures appeared, at $f_d \pm f_D$ with a well defined spatial arrangement, as the highest frequency ($f_d + f_D$) resides between the wakes of the main cylinder and the control rod

Figure 6.9: Spectra along $x/D = 1.0$ for the case $\theta = 90^\circ$ (a). The dark lines represent the signatures of the vortex shedding of the main cylinder (f_D) and the control rod (f_d), as well as the secondary modes ($f_d \pm f_D$), showing their spatial distribution. (b) Spectrum at the point $(x/D; y/D) = (1.0; 0.77)$ where the four modes coexist.

and the other ($f_d - f_D$) resides closer to the control rod's wake. Baj and Buxton (2017) investigated the interactions between wakes produced by a multi-scale array of bluff bodies and identified the same spectral signature with the same spatial arrangement at the intersection of different-sized wakes. Although the geometries and Re were different, the similarity between the spectra and their spatial configuration is remarkable, suggesting that the physical phenomena behind the interaction are also similar. They reported that these frequencies $f_d \pm f_D$ are associated with secondary modes, resulting from nonlinear interactions between the primary shedding modes in close proximity to one another. These modes play an important role in feeding kinetic energy to the residual turbulent fluctuations (understood as u'' in the triple decomposition of a turbulent velocity field $u = \bar{u} + \tilde{u} + u''$ in which $\tilde{u}$ corresponds to the periodic component of the fluctuating velocity). These residual fluctuations in turn are responsible for the majority of the dissipation of turbulent kinetic energy during such multi-scale wake interactions.

6.4 State II

State II was observed for control rod angles $\theta = 120^\circ$ and 125° . Its major feature is that separation of the upper boundary layer moves substantially further round the cylinder,

Figure 6.10: Vortex shedding cycle for the case $\theta = 125^\circ$ which is representative of State II. Vorticity fields calculated from the smart-filtered velocity fields. $Re = 20,000$

as shown in Figures 6.5(e) and 6.5(f). With the rod placed at $\theta = 120^\circ$ and 125° , $\theta_{sep} = 173^\circ$ and 182° , respectively. The relatively high-speed flow developing between the control rod and the cylinder surface acts to energise the cylinder boundary layer, which remains attached for a considerable distance. It is possible that transition to turbulent flow occurs in the main cylinder upper boundary layer leading to the delayed separation, but this could not be verified. The behaviour of the flow is an example of the Coandă effect, and such a fully attached jet would not form on a bluff body with fixed separation points. However, the study by Parezanovi and Cadot (2012) on a D-shaped body revealed a related phenomenon whereby a straight jet penetrated into the near wake, replenishing fluid removed by entrainment by the free shear layers. In a diagram, they show the jet entering the near wake just ahead of their control cylinder. As in the present experiments, this results in a reduction in drag. Following the large movement in the position of the upper separation point on the circular cylinder, the drag coefficient, $\overline{C}_D$ decreased to ≈ 0.98 , which is a reduction of 11% below that of the bare cylinder, whereas $\overline{C}_L$ increased to ≈ 0.55 . These changes result in the magnitude of the mean overall hydrodynamic force acting on the main cylinder being greater than the drag force acting on the bare cylinder. This highlights the danger of considering only the change in the mean drag when using a control rod as a passive flow control device. However, in State II, the control rod effectively reduces fluctuating forces due to vortex shedding. The RMS of the lift force on the main cylinder decreased significantly, especially for $\theta = 120^\circ$ where $C'_L \approx 0.05$, which is more than 80% lower than for the bare cylinder.

In this state, beyond the large change in the flow around the main cylinder, there is also a substantial change in the control rod's wake compared with State I. As a result, the time-mean forces acting on the rod change. For $\theta = 125^\circ$, $\overline{C}_D \approx 0.02$, which is more than 80% lower than the expected value of 0.1 if the rod was exposed to just a free-stream. When considering these values note that all coefficients for the control rod have the main cylinder diameter, D , as the representative length scale. The lift force on the rod changes from being negative in State I to positive in State II with a lift to drag ratio close to 1.0.

Figure 6.11: Mean velocity fields, where the solid line is the contour $\bar{u}/U_\infty = 0$ and the grey diamonds represent the points where v'/U_∞ is maximum. (a) $\theta = 120^\circ$, and (b) $\theta = 125^\circ$ which are both representative of State II.

Figure 6.10 shows a cycle of vortex shedding and illustrates how four shear layers interact to form the combined system's wake. Following the separation of the upper boundary layer on the main cylinder, it reaches the separated shear layer from the bottom of the cylinder in the vicinity of $(x/D, y/D) \approx (0.75, -0.5)$. The jet flow draws down the lower shear layer from the control rod such that it also follows the contour of the main cylinder. The mixing of these three shear layers results in one diffused shear layer with positively signed vorticity. The drawing down of the lower shear layer from the control rod causes a very broad near wake to form with a large region of low speed flow. It is assumed that the resulting pressure recovery in the wake of the control rod is responsible for its large drag reduction. The upper shear layer originating from the control rod with negatively signed vorticity interacts with the diffused lower main cylinder shear layer with positive vorticity to initiate vortex shedding. Visually the vortices forming in the combined system's wake appear weaker than those in State I which is compatible with the reduction in fluctuating lift.

Figure 6.11 presents the mean velocity fields for two cases in State II. As discussed above, the most striking features are the strong jet formed between the bodies and the long region of near stagnant fluid in the wake of the control rod. Figures 6.5(e), 6.5(f), 6.10 and 6.11 clearly show that the upper boundary layer on the main cylinder remains attached up to $\theta_{sep} \approx 180^\circ$. In contrast, the lower boundary layer separates at $\theta_{sep} \approx 100^\circ$. This marked asymmetry in the separation locations is responsible for the large mean lift coefficient which, as shown Figure 6.3, is unique to State II. It is

Figure 6.12: Comparison of the spectra between State II and the bare cylinder. (a) Spectra evaluated at the $\max(v'^2/U_\infty^2)$ point for each case; (b) Spectra of lift force .

interesting to observe that in Figure 6.11 there is a very large difference between the sizes of the two recirculation zones. Whereas in State I the flow was discussed in terms of the wakes of two bluff bodies, in State II the configuration appears closer to a single body with a passage through it that supplies fluid to the near wake resulting in a drag reduction.

Figure 6.12(a) shows spectra of v'^2/U_∞^2 at the point in the wake where it is maximum and also shows spectra of C'_L . The spectral peaks for State II cases are lower with respect to the bare cylinder case , particularly for $\theta = 120^\circ$.

The flow patterns close to the rear of the main cylinder for $\theta = 120^\circ$ and $\theta = 125^\circ$, shown in Figures 6.2(b) and 6.10 respectively, are similar but show differences a short distance further downstream. For $\theta = 125^\circ$, there is evidence of regular vortex shedding, while for $\theta = 120^\circ$ the wake structure is less well organised and there is mixing of opposite sign vorticities. Figure 6.2(b) shows this mixing leads to lateral diffusion of the shear layers and an apparent lack of regular vortex shedding. The spectra plotted in Figure 6.12(a) and 6.12(b) confirm the weakening of regular vortex shedding in State II as the angle of the control rod is reduced. They are also compatible with the observation that the lowest value of C'_L was found in State II for $\theta = 120^\circ$. It is interesting to note in Figure 6.13(a) that the time series of lift for $\theta = 120^\circ$ has a weak fluctuation at a frequency close to the vortex shedding frequency for the bare cylinder. It can also

Figure 6.13: Time series of the forces of bare cylinder and cases in State II. (a) Lift and (b) Drag.

be observed in the time series for the drag force in figure 6.13(b). Hence, it cannot be concluded that vortex shedding has been totally suppressed, but rather it has been substantially weakened.

In State II the main cylinder's upper boundary layer appears to pass between the cylinder and the control rod and if there was a free shear layer there is no evidence of it impacting on the control rod. A related State found in the literature is the Type D case reported by Sakamoto and Haniu (1994) at $Re = 65,000$. By measuring the time-averaged pressure distribution around the main cylinder, they were able to identify a short separation bubble at the position on the cylinder closest to their control cylinder. In the State II the bubble was verified for $\theta = 125^\circ$ but not for 120° , where the boundary layer remained attached up to $\theta_{sep} \approx 180^\circ$.

6.5 State III

State III is characterised by the control rod being positioned within the recirculation zone of the main cylinder and is found to occur for $\theta \geq 135^\circ$ up to $\theta = 180^\circ$. The prominent feature of State III is the von Krmn vortex street formed by the interaction between shear layers shed from the main cylinder in a form very similar to the bare cylinder case. Figure 6.14 shows a cycle of vortex shedding for the combined system

Figure 6.14: Vortex shedding cycle for the case $\theta = 135^\circ$ which is representative of State III. The vorticity fields are calculated after the application of the OMD-based smart-filter to the velocity fields. $Re = 20,000$.

Figure 6.15: $\bar{v}_t$ fields for the cases of (a) bare cylinder and (b) $\theta = 135^\circ$ which is representative of State III. The separation point (θ_{sep}) for each case was defined as described in the text.

with the control rod at $\theta = 135^\circ$. The upper shear layer from the main cylinder passes above the control rod, after which it is drawn into the near wake and forms a vortex as it interacts with the separated shear layer originating from the boundary layer on the lower half of the main cylinder, thereby forming a vortex street. In the figure, due to the shadow formed by the rod above the main cylinder, it is not possible to follow the path of the upper shear layer to the control rod. Evidence that the majority of the negative sign vorticity in the upper shear layer has originated from the main cylinder is provided by the absence of vorticity of significant strength and opposing sign being shed from the lower half of the control rod. The reason for this is that the control rod is situated in a recirculation region where the fluid velocity is very low, as indicated in figure 6.1(g).

In State III, the upper separation point on the main cylinder does not vary as significantly as in the previous two states. Figure 6.15 shows that with $\theta = 135^\circ$ the separation points remain close to those for the bare cylinder, $\theta_{sep} \approx 100^\circ$. The position of the upper separation point could not be measured for the other angles in State III due to the presence of the shadow of the rod in the PIV fields. However, it is reasonable to assume that the separation positions will not vary significantly for $\theta > 135^\circ$ since as the angle increases, the control rod moves further from the upper shear layer. This would explain why the force coefficients in State III remain relatively close to the values

Figure 6.16: Mean velocity fields, where the gray points square define $\max(\overline{v'^2}/U_\infty^2)$, for the cases (a) $\theta = 135^\circ$ and (b) $\theta = 140^\circ$.

for the bare cylinder case .

The main effects due to the presence of the control rod in State III are related to changes in the near wake. Figures 6.16 show the time-averaged velocity fields for the cases associated with State III. The recirculation length was extended in both cases when compared to the flow around the bare cylinder; it increased from $1.25 D$ to $1.75 D$ and $1.39 D$ for the cases $\theta = 135^\circ$ and 140° , respectively.

For $\theta \geq 140^\circ$, the control rod had a limited effect on the development of the shear layer and hence on the wake as a whole. These results suggest that the primary effect of the control rod in this State III is to divert the top separated shear layer, thereby forcing the interaction further downstream relative to the bare cylinder. As for the control rod, it is notable that it has a negative drag for all θ values tested, indicating that it is in a reversed flow within the near wake. As an interesting consequence, the total drag of the combined system, i.e. cylinder and control rod, is lower than for the bare cylinder for all cases investigated in State III.

6.6 Bi-stable case

Figure 6.1 reveals that states I, II and III yield distinctive time series for $v_t(P)$, with a well-defined mean value and frequency of oscillation. Figure 6.1(f) shows $v_t(P)$ with the control rod at $\theta = 130^\circ$ and it is clear that its characteristics are quite different

Figure 6.17: Instantaneous vorticity fields and streamline patterns for $\theta = 130^\circ$: (a) bi-stable - A and (b) bi-stable-B. Switching between the states can be viewed in figure 6.19.

Figure 6.18: Force measurements at $\theta = 130^\circ$. (a) time series and (b) Power spectral densities.

to those for the other states. The trace switches between high ($v_t(P)/U_\infty \approx 1$) and low ($v_t(P)/U_\infty \approx 0$) velocity at time intervals that are significantly longer than those associated with the vortex shedding. Figure 6.17(a) presents an instantaneous vorticity field for $\theta = 130^\circ$ at a time instant for which $v_t(P)/U_\infty \approx 0.1$ whilst figure 6.17(b) presents an instantaneous vorticity field in which $v_t(P)/U_\infty \approx 1$. It is clear that there is a fundamentally different flow structure at the two time instants and the case $\theta = 130^\circ$ is a bi-stable case. Non-stable flow configurations have also been found in previous literature on controlling bluff body wakes with control rods.

Sakamoto and Haniu (1994) ($Re = 65,000$) observed a tri-stable case (in which their type D flow pattern resembles the current State II) and Parezanovic et al. (2015) identified a bi-stable phenomenon in the flow over a D-shaped cylinder with a leeward control rod.

The bi-stable states will be referred as Bi-stable A ($v_t/U_\infty \approx 0$) and Bi-stable B ($v_t/U_\infty \gtrsim 1.0$). For Bi-stable A the combined wake of cylinder and control rod develops a von Kármán vortex street. The vorticity field has features in common with those in State III. When Bi-stable A switches to Bi-stable B, the velocity at point P between the main cylinder and control rod increases significantly, and a jet forms between the two bodies. When this happens, the upper boundary layer on the main cylinder finally separates close to $\theta_{sep} \approx 180^\circ$, after which it interacts strongly with the separated shear layer originating from the bottom of the cylinder. This means that Bi-stable-B is visually similar to State II. Close inspection of the streamline pattern in Figure 6.17(b) indicates the presence of a short separation bubble forming on the main cylinder at an angular position close to that of the control rod. As previously stated, Sakamoto and Haniu (1994) observed a short separation bubble in their type D flow pattern at $Re = 65,000$, whereas in the present study $Re = 20,000$. However, the geometric parameters in the two studies are quite similar, and it is plausible that the closeness of the control rod to the main cylinder surface plays an important role in the formation of a separation bubble. It is proposed that the reason for the switching back and forth between Bi-stable states A and B is due to the formation and breakdown of

Figure 6.19: Time series and Probability Density Function of v_t (top) and time duration of the two states in the bi-stable case (bottom). (a) first run and (b) second run, which is five times longer.

a short separation bubble.

Previous studies have noted that placing the control rod close to the separating shear layer is very favourable for reducing both drag and fluctuating lift. As highlighted by figure 6.3 the overall hydrodynamic force (on both the main cylinder and the combined system) is a minimum for the case $\theta = 130^\circ$. For the cylinder only, the drag is slightly higher than in State II, but the mean lift drops significantly from $\overline{C}_L \approx 0.5$ in State II to $\overline{C}_L \lesssim 0.1$ in the bi-stable case, yielding a total force coefficient of ≈ 0.99 , more than 10% lower than for the bare cylinder. Dalton et al. (2001) found the greatest reduction of mean drag and fluctuating lift when the rod was placed in the middle of the shear layer ($R'/D = 1.2$; $\theta = 160^\circ$; $Re = 3,000$) and Bingham et al. (2018a) reported a drag reduction of 15% and attenuation of the RMS of lift of 66% for a rod placed in the middle of the shear layer, although further away from the cylinder ($R'/D = 1.5$; $\theta = 155^\circ$; $Re = 9,500$). The far wake patterns in those cases were stable and the latter was visually similar to State Bi-stable-B, however, it must be pointed out that in both cases the rod was placed far enough from the cylinder to induce the boundary layer reattachment as observed in State II and Bi-Stable B.

Figure 6.20: Comparison of spectra between the two runs. (a) Power Spectral Density of v_t and (b) Spectra of v' at the point $(x/D; y/D) = (1.5; 0)$.

The time series and spectra of the forces over the main cylinder are presented in figure 6.18. The main peaks in the spectra at $fD/U_\infty \approx 0.2$ are related to vortex shedding, which occurs for both states. No characteristic frequency of switching could be observed in the signal as there is no distinct peak at a frequency lower than the vortex shedding. As for the rod, the average net force is very close to zero in the bi-stable case ($|\overline{C}_D| < |\overline{C}_L| < 0.01$), as seen in figure 6.3(b). There is no information about its instantaneous values because the forces were not measured directly on the rod. Based on the average values, however, we consider that the level of the forces on the rod at Bi-stable A is similar to State III, producing negative drag and lift while State Bi-stable-B produces positive drag and lift, similarly to State II. We conclude that the switching between states is hence responsible for the minimal mean force magnitude on the rod.

In order to acquire data on the switching process between bi-stable states, a second run was carried out with an acquisition period five times longer than the first. While these two runs were acquired in nominally the same configuration ($\theta = 130^\circ$) the apparatus was assembled from scratch for both runs, yielding a small uncertainty in the precise angular position of the control rod.

Figures 6.19(a) and 6.19(b) show the Probability-Density-Functions (PDFs - top right hand plots) of the time series of $v_t(P)$ (top left hand plots) for the two runs. Both runs exhibit bi-stable behaviour with $v_t(P)$ varying from lower velocities, which characterise

Bi-stable-A, to high velocities typical of Bi-stable-B. However, the distribution of velocities for the two runs is different. The first run has a modal peak at $v_t(P) \approx 1.2$ whereas the distribution of the second is concentrated around $v_t(P) \approx 0$. A threshold of $v_t(P)/U_\infty = 0.6$, which is equidistant from the modes of the PDFs for the first and second runs, was thus defined to delimit Bi-stable state A and Bi-stable state B. The time series were divided into periods during which the flow resided in a particular state before switching. In total N switches of state were recorded and these are displayed in the bottom plots of figures 6.19(a) and 6.19(b). In particular, the flow's residence time in a particular bi-stable state before switching is denoted by the grey bars. The blue lines show the cumulative mean residence times of the flow in each state, plotted on the right-hand axes. In the first run, the flow started in Bi-stable B for a period of $\approx 20U_\infty/D$ and then switched to Bi-stable state A, where it remained for approximately $\approx 10U_\infty/D$ and so on. In total, the flow switched 12 times in the first run and 43 times in the second run. Considering $T_s = 1/f_s$ as the period of one cycle of vortex shedding for the bare cylinder, the mean residence time in Bi-stable A was approximately $0.6T_s$ in the first run and approximately $3T_s$ in the second run. The mean residence time in Bi-stable B was approximately $1.5T_s$ in the first run and $0.4T_s$ in the second run.

From the PDFs and switching statistics we conclude that despite a nominally identical configuration of $\theta = 130^\circ$ the two runs are biased towards different bi-stable states, and the dynamics of the residence times/switching between the states behave differently for each run. Further, the mean residence time in the bi-stable states converges for both runs. Thus, the flows of the first and second runs are fundamentally different and not simply the result of unconverged statistics or unrepresentative sampling during the shorter of the two experimental runs. Considering that the system has a setting angle error of about $\pm 1^\circ$, the position of the rod was likely subtly different between the two runs. It reveals the high level of sensitivity of the flow in the Bi-stable case $\theta = 130^\circ$. This high level of sensitivity to the precise angular position of the control rod makes this configuration an ideal test case for high-fidelity computational fluid dynamics.

Figure 6.20(a) shows the spectra of $v_t(P)$ for the two runs. In spite of their different

time series, the spectra are quite similar, as no distinct frequency associated with state switching was found for any run. Instead, the spectra have close to a -2 slope at low frequencies. This is consistent with the rapid transitions between bi-stable states, resembling a step, having a random nature to their occurrence, giving rise to a low-frequency cut-off in the spectrum with a -2 power law (Grandemange, 2013). The spectra obtained from the time series of v at $(x/D; y/D) = (1.5; 0)$ revealed that the intensity of vortex shedding was higher in the second run, and its associated frequency was lower for the first run. These spectra can be explained by the observation that during the short run the flow spent more time in State Bi-stable-B, in which the vortex shedding process is weaker and its frequency lower than in State Bi-stable-A, which is similar to State III.

6.7 Conclusions

Experiments were carried-out for the main cylinder with one rod varying the angular position in the range $90^\circ \leq \theta \leq 180^\circ$, for a constant $Re = 20,000$, $d/D = 0.1$ and $R'/D = 0.7$. The cases were divided in three groups, identified by a diagnostic tool derived from the PIV fields. Three stable states were identified, including a bi-stable case between two states. The main conclusions are the following:

- A new method was introduced to identify the flow states. Using PIV, the component of the flow velocity normal to a line between the centres of the cylinder and control rod was recorded at the mid-point of the gap between the bodies. Each flow state was found to have a characteristic value of the ratio of the local mean velocity to the free stream velocity and a distinctive variation of velocity with time.
- State I, identified at $\theta = 90^\circ$ to 115° , is characterised by the formation of individual vortex street wakes from the cylinder and control rod. In common with other states, there was very little movement of the separation position of the boundary

layer on the side of the cylinder opposite to the control rod. In this state, separation of the upper boundary layer moved to just beyond the angular position of the control rod. There was no significant change in the mean drag of the main cylinder, but it developed a small mean lift force.

- In State II, $\theta = 120^\circ$ to 125° , there is a large delay in the separation of the cylinder boundary layer and an energetic jet forms following the contour of the main cylinder. While there is a reduction of about 10% in the drag coefficient, a mean lift coefficient of about $\overline{C}_L \approx 0.55$ develops. As a result of the high lift, the total mean force acting on the combined body of cylinder and control rod is greater than the mean drag on the bare cylinder. However, fluctuating lift was substantially reduced for $\theta = 120^\circ$, with the RMS of lift force fluctuations decreasing by more than 80% due to the weakening of vortex shedding.
- State III develops over the range $135^\circ \leq \theta \leq 180^\circ$, where the control rod remains within the recirculation zone of the main cylinder. The separation points and the drag coefficient are close to those of the bare cylinder, and with the control rod in the recirculation zone it experiences a small negative drag force.
- A finding regarding the flow structure is that the free shear layer arising from the separation of the upper boundary layer on the cylinder is deflected by the control rod and not split as observed by other investigators, where the control rod was placed relatively further from the main cylinder. In State I the free shear layer passes between the cylinder and the control rod whereas in State III the free shear layer passes over the control rod. In State II the boundary layer appears to remain attached until well after passing below the control rod, in a manifestation of the Coandă effect.
- A bi-stable case exists for $\theta = 130^\circ$ where the flow switches between Bi-Stable A, with characteristics very close to State III and Bi-Stable B, where there is delayed final separation, similar to State II. It was found that a small change in the control rod's angular position, of about $\pm 1^\circ$, would influence the time the flow was in one or other of Bi-Stable states A and B.

Chapter 7

The influence of a pair of control rods on circular cylinder flow

This chapter focuses on the effects of two control rods symmetrically arranged close to the cylinder in the range $90^\circ \leq \theta \leq 180^\circ$. One of the wake characteristics with one control rod, presented in the previous chapter, is the lack of symmetry of the mean flow and the mean lift generated on the cylinder. The addition of a second rod is intended to overcome this effect by inducing a symmetric mean flow, and possibly reducing the drag level to a greater extent.

Initially, the force coefficients and identification of states are presented in section 7.1. The cases were divided in groups according to the characteristics of their force coefficients and the tangential velocity in the mid gap v_t , the same diagnostic tool used in the previous chapter, now computed for the two sides of the cylinder.

The cases were divided into three main states, which have characteristics in common with previously identified states in chapter 6. The detailed description of each state is presented in sections 7.2, 7.4 and 7.5. States I and III have remarkable similarities with the cases with one rod but develop symmetric time-mean flows. Surprisingly, State II is not symmetrical, despite the position of the rods, but shows a bi-stable behaviour. Additionally, the case $\theta = 115^\circ$ has shown a wake pattern distinct from the other states

Figure 7.1: (a) Spectra of the Lift force on the cylinder for the cases $90^\circ \leq \theta \leq 170^\circ$. The horizontal lines represent the values of C'_L and St for the Bare Cylinder case. (b) Average lift and drag coefficients on the cylinder and drag on the rods. The black line on top represents the mean drag coefficient of the Bare Cylinder case.

in the mid-section. It is in the transition between States I and II and it is discussed in 7.3. Section 7.6 summarises the main findings of this chapter.

7.1 Force coefficients & Identification of states

Figure 7.1 show the hydrodynamic force coefficients for the cylinder with two rods in the range $90^\circ \leq \theta \leq 170^\circ$. The reference lines for the bare cylinder are shown as a continuous line on each graph. The figure on the left shows the variation of the RMS of fluid force on the main cylinder, whereas the graph on the right shows the average coefficients for the cylinder solely, the pair of rods, and the combined system. As a

Figure 7.2: Force coefficients on the cylinder and rods. Comparison between the cases with one and two control rods.

Figure 7.3: Definition of the tangential velocities in points P and Q used as diagnostic tool for the cases with 2 rods.

first approach to categorise the states with 2 rods, the force coefficients, especially their frequency signature, are used together with v_t in both sides (defined in figure 7.3) to classify the different cases. Figure 7.2 shows the force coefficients plotted against the same cases with one rod, presented in the previous chapter, which supports the identification of states. Figure 7.3 illustrates how the tangential velocity is calculated at the two points, P and Q , corresponding to the midpoint in the gap between the cylinder and the rods. Notice that for both sides, positive velocity is towards the centreline. The time series of v_t for the two points are shown in figure 7.4 for $90^\circ \leq \theta \leq 140^\circ$.

In the range $90^\circ \leq \theta \leq 110^\circ$, the fluctuating lift spectra are characterised by a continuous line, representing a consistent frequency signature, at a value lower than the bare cylinder but with a trend to increase with θ . These frequencies are also lower than that formed by state I cases for one-rod (figure 7.2(e)), but with a similar slope. No mean lift was observed, indicating a symmetric mean wake, and the fluctuating lift coefficient is consistently higher than the bare cylinder. The mean drag on the cylinder has values close to the bare cylinder, with a trend to decay as θ increases, while it is between 20% to 35% higher than the bare cylinder when considering the whole system. It follows the same trend of state I for one-rod. The drag on the rods is approximately twice as high as the one-rod cases. It is not unexpected since the force on the two rods were acquired together. For the same reason, the average lift on the rods could not be evaluated. Still in the range $90^\circ \leq \theta \leq 110^\circ$, both $v_t(P)$ and $v_t(Q)$ have an average value larger than U_∞ and an oscillation at the same frequency of the main system's vortex shedding (figures 7.4(a), 7.4(b) and 7.4(c)). $v_t(P)$ and $v_t(Q)$ are anti-correlated,

Figure 7.4: Time series of $v_t(P)$ and $v_t(Q)$ for different values of θ .

which indicates that they are shifted by a phase π during a cycle of vortex shedding. These cases were grouped as State I, as both the behaviour of v_t at P and Q and their frequency signature are very similar to that observed for one control rod in State I.

The cases $\theta = 120^\circ$ and 125° showed a non-zero average lift in spite of their symmetrical geometric configuration. Their fluctuating lift coefficient is very low, up to 80% lower than bare cylinder, and characterised by an absence of a clear oscillation frequency. Their mean drag coefficients are the lowest observed, reaching up to a 30% of reduction for just the cylinder and 20% for the combined system at $\theta = 120^\circ$. The behaviour of v_t at P and Q are distinct, evidencing the wake's lack of symmetry. Whereas v_t is higher than U_∞ on one side, the other has positive values fluctuating around $0.5U_\infty$, both without a dominant frequency of oscillation. The highest value in $v_t(P, Q)$ is similar to the cases with one rod at state II, indicating a strong flow between the cylinder and the rod. There are also similarities between $\theta = 120^\circ - 125^\circ$ and state II for one rod regarding the force coefficients, notably the fluctuating lift and the mean drag coefficients. These cases were grouped as State II and will be further explored and discussed in section 7.4.

The case $\theta = 115^\circ$ is in the transition between state I and II. It has a mean lift coefficient close to zero, indicating a symmetric mean wake. v_t at P and Q are anti-correlated and oscillating in a well-defined frequency. These characteristics are in common with state I cases. On the other hand, the average values for v_t are much lower than State I, and the fluctuating lift and mean drag coefficients for the case $\theta = 115^\circ$ are similar to those of state II. The frequency plot has a peak at around $fD/U_\infty = 0.16$, detached from the signatures of state I and state II. Such behaviour was not observed for one rod and, based only on force coefficients and v_t , $\theta = 115^\circ$ was classified as a transitory case between States I and II. This case will be further discussed in section 7.3 with the analysis of its wake. It is the most interesting case regarding the suppression of fluctuating lift forces, of about 90%, without a drag penalty, as it shows 20% of mean drag reduction for the cylinder and the same level of the bare cylinder for the whole system.

Moving to the cases $\theta \geq 130^\circ$, the lift spectra show a frequency signature well defined from $\theta = 130^\circ$ to 170° , detached from the other cases. The mean lift is close to zero for all cases, indicating a symmetric mean wake. the value of $v_t(P)$ and $v_t(Q)$ in figures 7.4(g) and 7.4(h) are close to zero, indicating a very low flux of fluid between the bodies. In general, the force coefficients for these cases are very similar to state III cases observed for one rod, as shown in figure 7.2, especially the frequency signature. Given this similarity, all cases $\theta \geq 130^\circ$ were grouped within State III. For $\theta = 130^\circ$, the fluctuating lift and mean drag coefficients are 70% and 20% lower than the bare cylinder, respectively. Although the values are closer to state II, it is grouped in state III because of its frequency and the behaviour of v_t . For larger values of θ , both coefficients increase, the fluctuating lift reaches a value 20% higher than the reference at 150° , while drag reaches the same level of the bare cylinder. The value of drag on the rods has a very small magnitude in state III, so that the value on the combined system is practically the same as the main cylinder's. These cases are further explored and discussed in section 7.5.

7.2 State I

The main characteristic of State I is the formation of a distinct wake past each control rod, which interacts with the shear layers separated from the cylinder to form the combined system's wake. The near wake for each rod is very similar to that observed for one-rod State I, as the flow past the rod develops a vortex street similarly to an isolated cylinder, with a well-defined frequency f_d . However, the rods' symmetrical arrangement produces a wake substantially different when compared with the one-rod case, and it clarifies some effects not observable for one rod in the previous chapter.

Figure 7.5 shows one complete cycle of shedding for the case $\theta = 90^\circ$, representative of State I. The two vortex streets past the rods are clearly identified. At each side of the cylinder, the boundary layer of the main cylinder separates at a point $\bar{\theta}_{sep} > \theta$ on average and the shear layer starts to roll into a vortex in the recirculation zone. Meanwhile,

Figure 7.5: Vortex shedding cycle for the case $\theta = 90^\circ$, which is representative of State I with 2 rods. Vorticity fields are calculated from the LOM velocity fields. $r = 30$; $Re = 20,000$.

Figure 7.6: (a) variation of u'_{xy} along the centre line for all cases within the State I range. (b) Distribution of v' for the cases $\theta = 90^\circ$ (top) and 110° (bottom)

the vortex street past the rod on the same side follows the path of the cylinder's shear layer, interacting with it. At the end of the formation, around $x/D \approx 1.5$, the rod's wake is dragged into the recirculation zone with the vortex rolling from the cylinder. This can be observed in figures 7.5(a) and 7.5(b) for the top side, and in figures 7.5(e) and 7.5(f) for the lower side.

Following the discussion about the vortex-formation length for the one-rod cases, and considering that for two-rods the flow is not biased by asymmetry, the fluctuation of the velocity in the xy plane centreline (u'_{xy}) was calculated. The plots are shown in figure 7.6(a). All cases have a similar trend, with two peaks along the centreline, the first at $x/D \approx 1$, and the second at $x/D \geq 2$. For the bare cylinder, only one peak is observed at $x/D \approx 1.2$.

Investigating the fluctuation of the v component in figure 7.6(b), it is possible to observe that there are also two peaks, placed exactly on the centreline. To investigate the nature of these peaks, figure 7.7 presents the spectra of the v component along the vertical lines x/D where the peaks occur. The dominant frequency for both cases occurs at $fD/U_{\infty} \approx 0.17$, which is the dominant frequency of vortex shedding f_D . The other significant peaks, in order of magnitude, are its harmonics. Other than those, at

Figure 7.7: Spectra of v/U_∞ along a constant x/D line where the peaks were observed. $\theta = 110^\circ$.

$x/D = 1.1$, there are frequency spikes corresponding to the wake of each control rod f_d and its interaction with f_D , $f_d \pm n f_D$, ($n = 0, 1, 2, 3$). These latter frequencies have a defined spatial arrangement, with the highest frequencies $f_d + n f_D$ between the rods' wake and the recirculation zone, and the lowest frequencies $f_d - n f_D$ residing closer to the rods' wake. These signatures and their spatial arrangement are very similar to that observed for the cylinder with one control rod (described in chapter 6) and for a multi-scale array of bluff bodies (Baj and Buxton, 2017), indicating that the same physical phenomenon is responsible for the additional modes in these cases. In addition to that, it is interesting to notice that these high-frequency peaks happen within a narrow region ($y/D \approx \pm 1.0$) at $x/D = 1.1$ and do not appear at $x/D = 2.4$. On the centreline, most of the fluctuation is associated with f_D and its harmonics. It indicates that the high-frequency structure formed past the rods has a limited influence on the wake development, and the two peaks observed in figure 7.6(a) are not related to them.

Since the two peaks on the centreline are associated with the same frequency, the velocity fields were phase-averaged to filter other oscillations than f_D , including the vortex shedding from the rods. The phase-averaged fields are shown in figure 7.8, which illustrates the formation process of the two peaks. In figure 7.8(a), the separated shear layer from the cylinder is rolling into a vortex in the recirculation zone, with concentrated negative-signed vorticity in blue. Simultaneously, the whole wake past the superior rod is being dragged into the recirculation zone. Its positive-signed vorticity, in red, is being cancelled by the interaction with the two layers with negative-signed

vorticity in its vicinity, as seen in figure 7.8(b). In figure 7.8(c), the shear layer with concentrated vorticity coming from the rod crosses the centre line, after undergoing a large curvature. Meanwhile, the vortex formed by the shear layer separated from the cylinder reaches its maximum strength. The vorticity distribution, together with the plots of absolute velocity in the plane (u_{xy}), clearly shows two distinct layers crossing the centreline at $x/D \approx 1$ and $x/D \approx 2$, one coming from the shear layer separated from the cylinder and the other from the outer shear layer separated from the rod. Both layers in blue keep moving and, in figures 7.8(e) and 7.8(f), the shear layer coming from the rod acts to cease the vorticity feeding of the vortex with positive-signed vorticity that is forming at the bottom of the image in red at around $x/D \approx 2.5$. Simultaneously, the separated layer coming from the cylinder with positive-signed vorticity starts to cease the feeding of negative-signed vorticity to the bigger vortex in blue, at $x/D \approx 1$. An analogous process happens from figures 7.8(g) to 7.8(l) in the other side of the bodies, completing the cycle.

For a bare cylinder, the vortex shedding mechanism is induced by the interaction of the two shear layers separated from the cylinder. The peak in the u_{xy} plot defines the vortex-formation length, and it is associated with the end of the formation region of each vortex. For the controlled cases, the two peaks are associated with the formation of two vortices. The first, at $x/D \approx 1$, originates from the shear layer separated from the cylinder and the second, at $x/D \approx 2$, is derived from the shear layer coming from the rods.

To the best of the author's knowledge, this peculiar behaviour of State I, with two pairs of vortices per cycle, is not mentioned in the literature. It is in part explained by the few works using a symmetric pair of rods rather than a single rod. In one of them, Yan et al. (2018) performed numeric simulations for a cylinder with a pair of control rods with $R'/D = 1$ and $d/D = 0.05$ at $Re = 3,900$. They observed the formation of distinct wakes past the rods and an increase of the dominant period of vortex shedding shown in the time series. Their plot of $\overline{v'v'}/U_\infty$ is similar to the present study, with two peaks, one at a position x/D before and the other after the peak of the bare cylinder.

Figure 7.8: Phase-averaged fields for the case $\theta = 110^\circ$. Vorticity (top) and velocity magnitude (bottom).

Figure 7.9: v_t fields for the cases (a) bare cylinder and (b) 110° with 2 rods. The separation point (θ_{sep}) was estimated using both the mean streamlines patterns and the tangential velocity v_t . It is estimated that θ_{sep} is accurate to within $\pm 2^\circ$.

However, they do not give further explanation for this behaviour, as the paper has a different focus. Given the similarities between their case and the present State I cases, regarding the fluid forces and flow characteristics, it is presumed the same phenomenon occurs in both cases. Further research must be carried out to confirm this, in any case.

The vortex-formation length can be used as a tool for investigating the frequency behaviour of bluff bodies Gerrard (1966). As discussed in the previous chapter, this parameter, together with the distance between the shear layers and their velocity at the separation point, is used to predict a universal value for the dimensionless frequency of a bare cylinder. However, it is not appropriate to interpret the frequency behaviour of State I cases, as the nature of wake has shown to be more complex than the classical vortex street formed by two shear layers. The two peaks observed in figure 7.6(a) are associated with the formation of two vortices, originating from the shear layer of the main cylinder and the rod, respectively. Two vortices are formed at each side during one cycle, synchronized at the same frequency f_D . Hence, there is not a unique vortex formation length for the wake. Similarly, it is not possible to determine a single distance for the separated shear layers, because there are effectively six of them. The rods in State I can not be interpreted as a small perturbation in the flow, and the dominant frequency results from different mechanisms when compared to the bare cylinder.

The dominant frequencies for the State I cases have a clear trend to increase with θ , as

Figure 7.10: Drag coefficient and θ_{sep} for the cases at State I.

observed in figures 6.3 and 7.2(e). Two effects contribute to this phenomenon. For a circular cylinder, it is well-known that the frequency of vortex shedding increases when the distance between the shear layers decreases (Roshko, 1955). As θ increases, the vertical distance between the rods shortens, as does the distance between the outer shear layers. The distance between separated shear layers from the cylinder is also reduced. As it is shown in figure 7.9, $\theta_{sep} > \theta$ for all cases in State I. These two effects combined induce the frequency to increase with θ during the range of State I.

As θ increases, $\overline{C}_D$ for the cylinder decreases, reaching a minimum value 8% lower than the bare cylinder at $\theta = 105^{\circ}$. This reduction can be explained by the alteration of the mean separation point θ_{sep} , similar to what was observed for one-rod State I cases. Figure 7.10 shows a comparison between θ_{sep} and $\overline{C}_D$, where θ_{sep} refers to the average value of the two shear layers. It indicates that as θ_{sep} increases, the mean drag decreases, due to the pressure recovery on the cylinder and the consequent increase in the base pressure.

Comparing two-rods State I with one-rod, both the maximum increase and reduction in mean drag coefficient were larger in the former. In addition, The two-rods cases annihilated the mean lift force, due to the symmetry of the mean flow. The fluctuating lift coefficient, however, was larger for the two-rods cases than for one-rod. C'_L was higher than the bare cylinder by an extent of between 20% and 40% over the State I range. Based in figure 7.6, where the velocity fluctuation for State I is consistently

Figure 7.11: Correlation length for all cases with two rods. It is calculated using the u component along the range $-4.5 \leq z/D \leq 3.5$ in the position close to $\theta = 90^\circ$, and using $z = 0$ as reference. This process was based on Norberg (2003).

lower than for the bare cylinder, there is no indication that the sectional lift force is larger in State I. The increase in C'_L may be linked to a more correlated flow along the span, considering the fluctuating lift force was acquired from the top of the cylinder. In fact, figure 7.11 shows that the span correlation length Λ is higher than the bare cylinder for all cases in State I. The pair of rods in this state promote correlation of the two-dimensional structures of the flow, turning the C'_L measured at the top higher than the bare cylinder. It is linked to the smaller variation of the separation point position over one cycle of vortex shedding, compared to the bare cylinder. The pair of rods turn the vertical separation lines more correlated. It should be noted that the distance between the separation points θ_{sep} is the lowest for $\theta = 110^\circ$, and still Λ is higher than the bare cylinder.

It is interesting to observe that, using a body with fixed separation points and a similar value of d/D , Parezanovi and Cadot (2012) reported a strong correlation when the rod were in the recirculation zone, which agrees with the results for state III. For other regions, however, the correlation did not vary as significantly as in the state II (or the transitional case) of figure 7.11. It indicates the importance of the separation point

Figure 7.12: Vortex shedding cycle for the case $\theta = 115^\circ$. Vorticity fields are calculated from the LOM velocity fields. $r = 30$; $Re = 20,000$.

movement for the correlation length of circular cylinders.

7.3 Transitional case

This section reports the case $\theta = 115^\circ$, which is a transitional case between the states I and II. Figure 7.12 shows a cycle of vortex shedding for this case in the horizontal plane, which exhibits a transitional separation type at both sides of the cylinder, resulting in a distinct wake pattern. The boundary layer at each side of the cylinder separates at an angular position $\theta_{sep} < \theta$, in a position similar to that observed for the bare cylinder case. The separated shear layer's path then encounters the rod and interacts with it, producing a layer with vorticity spread over a larger region when compared to the bare cylinder. These two layers interact further downstream, initiating the main vortex shedding mechanism of the wake.

The vortex shedding mechanism in the transitional case is substantially different from State I. In the former, each shear layer coming from the cylinder interacts with each

Figure 7.13: (a) mean velocity field and (b) variation of u'_{xy} along the centreline for the case $\theta = 115^\circ$.

other after having interacted with the rod, so that the graph of u'_{xy}/U_∞ in figure 7.13 shows only one peak. In State I, the shear layers coming from the cylinder start interacting with each other just after the separation, whereas the layers coming from the rods are dragged into the wake further downstream. Because of that, the graph in State I shows two peaks (figure 7.6) and two pair of vortices per cycle (figure 7.8). Another indication that the two cases are different is the frequency signature provided in figure 7.1, where the dominant frequency for the transitional case is detached from States I and II.

The interaction of the layers that produce the vortex shedding mechanism occur further downstream when compared to the bare cylinder and the other controlled cases. Figure 7.13 shows that both the recirculation length and vortex-formation length are the largest among all the cases. This explains the low value of the mean drag coefficient, almost 20% lower than the bare cylinder, since the increase in the recirculation length is associated with a higher base pressure. Considering the whole system, cylinder and rods, the total drag is practically the same as the bare cylinder. As for the lift force, the mean coefficient is zero, indicating a mean symmetric flow, and the fluctuating coefficient is $C'_L \approx 0.04$, almost 90% lower than the bare cylinder and the lowest among all cases. This behaviour turns this case particularly interesting for real applications, from offshore engineering to aeroacoustic, because it reduces significantly the fluctuating forces with no drag penalty and without a drift force on average.

As mentioned before, the wake developed in this case is originated by the early separation

ration of the boundary layer ($\theta_{sep} < \theta$), which induced the layer to interact with the rod's wake firstly than with the separated shear layer coming from the other side of the cylinder. To the best of the author's knowledge, there is no work in literature with a similar separation type for a cylinder controlled by two rods symmetrically arranged. It is interesting to point out that the transitional separation type was not observed for any one-rod case in this work. However, some characteristics of the case $\theta = 115^\circ$ are similar to cases in literature with one rod placed farther to the cylinder and in the middle of the shear layer. Dalton et al. (2001) observed, for a circular cylinder and a control rod placed at $R'/D = 1.3$ in the middle of the shear layer path, the vortices were shed further downstream, inducing attenuation of up to 80% in fluctuating lift and reducing the drag by a small proportion. Strykowski and Sreenivasan (1990) observed the suppression or attenuation of vortex shedding followed by a drop in its frequency for very low Re , and attributed these effects to the diffusion of vorticity induced by the rod. The larger diffusion would make the vortices weaker and take a longer time to roll up to a critical shedding point, decreasing the frequency. They also predicted that using a pair of rods would enhance the effects. For the case $\theta = 115^\circ$ at $Re = 20,000$ using two rods, it was observed that the layer resulting from the interaction between the rod's wake and separated shear layer has a vorticity level similar to the bare cylinder but diffused over a wider region rather than concentrated around the shear layer's path, which confirms the observation of Strykowski and Sreenivasan (1990) for very low Re . It indicates that this effect is not limited to lower Re cases, since the present work has a Re over 100 times higher than Strykowski and Sreenivasan (1990).

The horizontal wake pattern of the case $\theta = 115^\circ$ could indicate a new state, since it has characteristics distinct from the states I and II. However, this was kept as a transitional case due to two main reasons. First, it was observed for only one value of θ , and only in the two-rod configuration. Second, the separation type observed in the horizontal plane ($z/D = 0$) does not develop along the whole span-wise length of the cylinder. Differently from the other three states, where the same separation type was observed for the whole length, the transitional case show different types of separation along the span-wise direction. In order to explore this feature, figure 7.14 illustrates the typical

Figure 7.14: (a)-(d): Instantaneous vorticity and velocity fields in the horizontal and vertical planes, representative of the four separation types. (e) Definition of the probes' position and the criteria for the diagnostic tool using u/U_∞ . The y position of the probe was determined by the intersection between the two planes, whereas x was chosen considering two positions upstream and downstream of the rod, respectively.

Figure 7.15: Distribution of the separation types along z/D for the case $\theta = 115^\circ$. (a) instantaneous field for the u component and (b) distribution for the whole period of acquisition

vorticity and velocity fields for the State I, transitional and State II cases, defining four types of separation. The type I is characterised by a well defined vortex-street past the rod and a late separation of the boundary layer over the cylinder, at an angle $\theta_{sep} > \theta$ on average. The field for the u component shows a high velocity in the regions before and after the rod. For the transitional type, there is an early separation ($\theta_{sep} < \theta$) and the shear layer follows the path of the rod, interacting with the rod's vortex street. The value of u is lower before and higher just after the rod, as shown in figure 7.14(b). The separation II is characterised by a jet between the cylinder and the rod, which leaves a large region of stagnated fluid behind the rod. It has two distinct types, A and B. In the former, there is a strong jet between the bodies, with only one separation around 180° , and in the latter the flow separates and reattaches forming a separation bubble between the cylinder and the rod. In both cases u is very low just after the rod but for the type II-A it is very high before the rod, whereas it is not for II-B.

A diagnostic tool was employed to identify the different separation types from the velocity fields using the u component, the only captured by both horizontal and vertical planes. The main idea is to identify, for each instant, the distribution of the separation

types along the z/D direction in the vertical plane together with the separation types of the two sides of the model at $z/D = 0$. Figure 7.14(e) illustrates the position of the probes and criteria for identifying the types. It relies on the observation that, for each type of separation, the values of u in the positions before and after the rod has a distinct combination, as discussed in the last paragraph.

Figure 7.15(a) shows an instantaneous velocity field for the case $\theta = 115^\circ$, where the variation of the separation types along the span is evident. The transitional type is dominant in the middle of the body, whereas the regions close to the extremities show the separation type II. The plot on the right (figure 7.15(b)) presents the distribution of the separation types along the whole period of acquisition. The transitional type is the dominant type in the region of about four diameters in the centre of the model, whereas the types II (A and B) are more common in the extremities. Assuming an alike distribution on the other side of the cylinder (for positive y), the wake pattern observed in figure 7.12 develops over approximately half of the cylinder's length. It is also observed in the flow downstream the cylinder in figure 7.15(a), the regions in dark red around $x/D \approx 3$ indicate a correlated vortical structure. It also explains the low value of correlation length (Λ) calculated for this case.

Although this wake pattern develops over a limited extent of the cylinder length, it is the most energetic structure of the flow. Figure 7.16 shows an agreement between the frequency peaks of the lift force and v'/U_∞ at the point where it is maximum ($x/D = 3.75$). This frequency is associated with the vortex-shedding mechanism in this case. It is relevant to point out that the forces and PIV measurements were measured with slightly different experimental conditions and, in spite of the sensitivity of this case to end conditions, they reveal the same peak.

7.4 State II

The State II was observed for the angles $\theta = 120^\circ$ and 125° with two rods, where the separation type II occurs on the two sides of the cylinder. The wake is characterised

Figure 7.16: Comparison between the spectra of lift force and the v component of velocity at the location of maximum v'/U_∞ for the case $\theta = 115^\circ$.

by a bi-stable behaviour, as shown in figure 7.17. The type of separation II is characterised by a jet induced by the presence of the rod towards the centreline, as observed for one-rod cases (figure 6.10). When two rods induce the same effect at opposing directions, one predominates, biasing the wake towards one side. This effect turns the wake asymmetric, despite the symmetric configuration of the model.

In order to investigate the switching process between the two states, the variable $v_t(P) - v_t(Q)$ is introduced. It is the difference between the tangential velocities in the mid-gap between the two sides of the model, according to the definition illustrated in figure 7.4. $v_t(P) - v_t(Q)$ is related to the net flux of fluid into the near wake and its orientation. Positive values indicate a wake biasing towards the bottom of the figure and inducing a positive lift over the cylinder. In contrast, negative values indicate $v_t(Q)$ stronger than $v_t(P)$, so that the wake is biased towards the top of the figure and induces a negative lift force on the cylinder.

Figure 7.18 shows the time series and distribution of $v_t(P) - v_t(Q)$ for the two angles of State II. The two cases have shown very different behaviour regarding the average time spent in each state. For $\theta = 120^\circ$, the transition from one state to another is very slow, so that it was observed only once through three different runs, each one with an acquisition time superior to 300 cycles of vortex shedding for the bare cylinder (T_s). It indicates that the switching process for the case $\theta = 120^\circ$ is very slow, and the data

Figure 7.17: Two instantaneous vorticity fields showing the two typical states of the bi-stable flow in State II.

collected is statistically insufficient to determine its average time. However, the single transition observed in run 1 is important to show that the case $\theta = 120^\circ$ has a bi-stable behaviour, and its wake asymmetry is not the mere result of the misalignment of the model. For the case $\theta = 125^\circ$, the average period spent in each state is shorter than for $\theta = 120^\circ$, for various transitions were observed for a single run in figure 7.18(b). The PDF shows two clear peaks for $v_t(P) - v_t(Q)$ around 1 and -1, characterising the bi-stable behaviour. The average time spent at each state was calculated using 0 as the threshold between the states, and the result is shown in figure 7.19(a). The cumulative average times, plotted in blue, converge to slight different values, which is probably a consequence of small variations in the assembling, resulting in a misaligned model. The average time spent at each side is of about 10 times T_s , indicating that the switching phenomenon has an average period of one order longer than the vortex shedding period. However, this there is not a distinct frequency associated with the switching process, as can be observed in figure 7.18(b), for the spectrum has no peaks.

The nature of the switching process appears to be random, and it can be observed through figures 7.18 and 7.19(b). The spectrum in the former agrees with a -2 power law at low frequencies, which is consistent with random transitions (Grandemange, 2013). The latter plot shows in black a histogram of the probability that the interval between two successive transitions is greater than $t/\bar{T}$ (where $\bar{T}$ is the mean interval between switches) and the curve in red is $P = e^{t/\bar{T}}$. The good agreement between the black and red curves indicates that the transitions constitute a Poisson process (Mood et al., 1974). This bi-stable process in State II resembles the flip-flopping phenomenon of a pair of

Figure 7.18: Distribution of $v_t(P) - v_t(Q)$ for the State II cases (a) Time series and Probability Distribution Function (PDF) for the case $\theta = 120^\circ$ showing three different runs. (b) Time series, PDF and spectrum of $v_t(P) - v_t(Q)$ for the case $\theta = 125^\circ$.

cylinders of the same size put side-by-side. In both cases, the symmetric configuration of the models does not result in a symmetric wake but a bi-stable behaviour of random nature between two anti-symmetric states (Kim and Durbin, 1988) and very sensitive to the position of the models.

In the search for such a different behaviour between the cases $\theta = 120^\circ$ and 125° , it was observed that the type of separation on each side plays an important role. Figure 7.20 shows the combination of the separation types occurring at the two sides of the cylinder. The upper side ($y > 0$) is represented in the horizontal axis, whereas the lower side ($y < 0$) is represented in the vertical axis. The value for each cell represents the time spent on each configuration as a percentile of the total acquired time (T_{acq}). For the case $\theta = 120^\circ$, the figure 7.20(a) shows that the cylinder has predominantly a separation type II-A in one side whereas the other has the type II-B, illustrated in figure 7.20(c). For the case $\theta = 125^\circ$, the dominant configuration combines two separation types II-B, occurring simultaneously at each side. It indicates that the pair II-A+II-B is more stable in time than pair II-B+II-B. It is not unexpected at first, since the jet

Figure 7.19: (a) Time duration of each state for the case $\theta = 125^\circ$. Up/down refers to the side which the wake is biased. Grey plots represent the absolute time at each state and blue plots represent cumulative average. (b) Histogram of the probability of one transition to be longer than $t/\bar{T}$ compared to the curve $e^{-t/\bar{T}}$

on the side without the bubble is stronger, so the jet in the side with the separation II-A is much more probable to prevail against the jet coming from the other side with separation II-B. When the type II-B happens at the two sides, the difference between them is smaller and more subject to smaller variations that lead to a change in v_t , turning the period of each state shorter. In other words, the formation of a bubble induces more fluctuations in the flow that a layer totally attached to the body.

It is also interesting to observe that the side developing II-A separates at an angular position θ_{sep} farther than the II-B due to the Coand effect, and one may argue that this is the cause of the asymmetry of the wake. However, the work of Chauhan et al. (2019) observed an asymmetric flow for a square cylinder controlled by two rods, where the Coand effect does not happen at all. We believe that the imbalance between the jets coming from the two sides is the key factor behind the flow asymmetry and the bi-stability. However, further research must be carried out to confirm this.

Regarding the forces, both cases $\theta = 120^\circ$ and 125° showed a significant reduction of the fluctuating lift coefficient but a non-zero mean lift coefficient, induced by the bi-stability (figure 7.1). Figure 7.21 shows the time-series for the two cases with their respective spectra. From the time-series, it is clear that the case $\theta = 125^\circ$ achieves larger instantaneous values than 120° , and its mean coefficient is lower only because it has multiple transitions where the case $\theta = 120^\circ$ stayed at the same state for the

Figure 7.20: Distribution of the separation types of the two sides of the cylinder (top) and instantaneous vorticity fields of the dominant pattern (bottom) (a)-(c) $\theta = 120^\circ$ and (b)-(d) $\theta = 125^\circ$.

whole acquisition period. It also explains the lower fluctuating lift of the case $\theta = 120^\circ$. Despite the small differences, both cases are within the lowest fluctuating lift coefficients, with a reduction of about 75% for the case 120° and 60% for 125° , both with respect to the bare cylinder case. The spectra on the left show that most of the energy is concentrated at low frequencies, but for the case $\theta = 120^\circ$, there is a peak at around $fD/U_\infty \approx 0.16$, which is associated with a vortex shedding mechanism formed downstream in the wake. Figure 7.22 shows a complete cycle of vortex shedding phase-averaged at this frequency, obtained from a time-series where the wake was biased to the bottom during the whole period. It shows the formation of a vortex street after $x/D \approx 2.5$, similar to that observed for State II with one rod, despite the differences on the very near wake around the main cylinder.

The mean drag forces were also significantly reduced in State II when compared to the bare cylinder. The reduction was about 20% for the main cylinder and 15% for the whole system for $\theta = 120^\circ$. For $\theta = 125^\circ$, the mean drag coefficient was 30% smaller

Figure 7.21: Comparison between the lift force of the cases $\theta = 120^\circ$ and 125° . Time series (left) and spectra (right).

considering only the cylinder and 20% for the whole system. A possible explanation for the reduction with two rods resides in the injection of momentum in the near wake by the two jets, driven by the low pressure in the near wake. It is consistent with the observations that both layers reattach over the cylinder, leading to a later separation due to the Coandă effect. This feature of the two-rod cases is different from one-rod. In the latter, the jet coming from one side leads the shear layer on the other side to separate earlier, creating a recirculation region dislocated from the centreline and inducing a large lift coefficient. In Sakamoto and Haniu (1994) or in the previous chapter (Cicolin et al., 2021), for example, the drop in drag force was followed by a surge in lift, keeping the total force magnitude at a level similar to the bare cylinder. For two rods, however, the magnitude of the lift force is not large enough to alter the level of the total force magnitude. For both cases, $\theta = 120^\circ$ and 125° with two-rod, the mean force magnitude is practically equal to the mean drag. It indicates the two-rod has potential for real applications as a drag reduction device.

7.5 State III

State III comprises the cases $130^\circ \leq \theta \leq 170^\circ$, and its main characteristic is the formation of a wake pattern similar to the bare cylinder's. Figure 7.23 shows a complete cycle of vortex shedding for the case $\theta = 135^\circ$, representative of State III. The two separating shear layers from the cylinder pass over the control rods, interacting downstream to form a pair of alternating vortices per cycle.

Figure 7.22: Vortex shedding cycle for the case $\theta = 120^\circ$. Vorticity fields are calculated from the LOM velocity fields. $r = 30$; $Re = 20,000$.

Vortex shedding is the main feature of the wake, and the only frequency peak identified in the velocities' spectra, since there is no vortex street past the rods. Although the cases form a clear frequency signature, their force coefficients vary significantly. From $130^\circ \leq \theta \leq 150^\circ$, the fluctuating lift coefficient surges from 0.08 to 0.4, followed by a significant increase in drag, from 0.9 to 1.1, and a drop in frequency, from $fD/U_\infty = 0.21$ to 0.19. From $150^\circ \leq \theta \leq 170^\circ$ the trend is reversed, the fluctuating lift decreases to 0.25 and drag to 1.0, whereas the dimensionless frequency increases to 0.205. In order to investigate the causes of this behaviour, figure 7.24(a) shows the distribution of the fluctuating velocity u_{xy} on the centreline. For $\theta = 130^\circ$, the maximum position occurs further downstream, around $x/D = 2$, and reduces as θ increases. For 150° the distribution is remarkably similar to the bare cylinder's. For higher values, $\theta = 160^\circ$ and 170° , u_{xy} distribution is shifted downstream again.

Figure 7.24(b) shows the mean drag coefficient and the recirculation length for the State III cases. The recirculation length is calculated as the distance from the origin to the saddle point in the centreline, where $\bar{u} = \bar{v} = 0$. It increases from $\theta = 130^\circ$ to 150° , and then starts to decrease. There is a remarkable correlation between the drag coefficient and the recirculation length. Bearman (1965) reported a correlation between the base pressure and the recirculation length for a body with fixed separation points.

Figure 7.23: Vortex shedding cycle for the case $\theta = 135^\circ$, which is representative of State III with two rods. Vorticity fields are calculated from the LOM velocity fields. $r = 30$; $Re = 20,000$.

Figure 7.24: (a) Fluctuating velocity along the centreline and (b) Variation of the mean drag coefficient and the recirculation length for the cases in State III.

For the circular cylinder, the mean separation point moved backwards regarding the bare cylinder due to the increase in the base pressure. It can be observed in figure 7.26 around $x/D = 0$, although the exact position of the mean separation point could not be determined due to its closeness to the FoV border. This variation in θ_{sep} is however limited to a few degrees around $\pm 90^\circ$, thus having a very low effect on the drag.

The cases with longer vortex-formation and recirculation lengths have a lower drag and fluctuating lift coefficient, and a higher frequency. These correlations occur for the one rod cases too. In state III, the rods' main effect is to prevent the interaction of the two shear layers, forcing it to happen further downstream, enlarging the recirculation and vortex-formation lengths, and prompting a reduction in mean drag and fluctuating lift coefficients. For example, the greatest drag reduction happens for $\theta = 130^\circ$, where the mean drag coefficient is 20% lower than the bare cylinder, with a 70% reduction of the fluctuating lift coefficient. The dimensionless shedding frequency, on the other hand, increased from 0.19 to 0.21.

A possible explanation for the increase in the dimensionless frequency is that the rods make the separated layers thinner, leading one vortex to form more quickly. This interpretation was proposed by Parezanovi and Cadot (2012) for a D-shaped cylinder controlled with a single control rod and was based on Gerrard's model (Gerrard, 1966). It assumes that the Strouhal number is governed by the balance of the vortex-formation length and diffusion length. Even though the former is enlarged, the channelling of

Figure 7.25: Mean vorticity vertical distribution at a position $0.05D$ just after the rod. For the Bare cylinder, $x/D = 0.7$.

the flow reduces the latter to a greater extent, prompting an increase in the Strouhal number. Although the body in the study of Parezanovi and Cadot (2012) was different from the circular cylinder, the resulting wakes are similar, especially in state III where the separation point movement is more limited, i.e. oscillates with a lower amplitude over a cycle compared to the bare cylinder, and their mean position moves little. The works of Cimbalá and Garg (1991), using a cylinder and a small splitter plate, and Bao and Tao (2013) with circular cylinder and a small control rod point to the same direction, an increase in St induced by a thinner shear layer. Figure 7.25 shows the distribution of vorticity along a vertical line for a x/D position just after the control rod. The channelling effect of the rods for $\theta = 130^\circ$ is evident, as the two shear layers are thinner than the bare cylinder, with a concentration of vorticity, identified by the dark lines, in a smaller region.

As the rods move further inside the recirculation zone, they affect the shear layers less and facilitate their interaction. As a consequence, the recirculation length decreases, the mean drag and the fluctuating lift coefficients increase, reaching values close to the reference value. For $\theta = 150^\circ$, the flow has characteristics very similar to the bare cylinder, which can be observed through its main coefficients (figures 7.1 and 7.24) and velocity distributions (figures 7.24 and 7.26).

As the rods move in the direction of the centreline, they start to affect the interaction of the two shear two layers, leading the vortices to roll up further downstream. It

Figure 7.26: Streamlines and mean u field for the cases of State III. Figure 7.27: Spectra of (a) lift force and (b) v component at the point where v'^2 is maximum. $\theta \geq 130^\circ$

induces an enlargement of both recirculation and vortex-formation lengths, increasing the base pressure and reducing the drag. For $\theta = 170^\circ$, the mean drag is almost 10% lower than the bare cylinder. The shedding frequency in this case is higher than for the bare cylinder, and it is also due to the reduction in the diffusion length. Figure 7.25 show that the shear layers are thinner, with more concentrated vorticity, than the bare cylinder for $\theta = 170^\circ$.

The effect of the rods in the cases closer to the centreline can also be compared to a short splitter plate. Apelt et al. (1973) carried out a series of experiments with circular cylinders with splitter plates in the centreline with variable sizes. Their results for shorter plates are very similar to the case $\theta = 170^\circ$, with drag reduction, enlargement

Figure 7.28: All types of separation observed for cases with one and two rods. Orange dots identify the separation point for each type. The transition I/II was observed for two rods only.

of recirculation length and Strouhal number. Gerrard (1966) observed an increase in St using a short plate in the centreline, pointing out the role of the plate on this, channelling the shear layers. Kiyoun and Haecheon (1996) performed numerical simulations with the same geometry for low values of Re , and their results for short plates also agree with the case $\theta = 170^\circ$.

Another relevant point to consider is that the correlation length Λ/D is higher than the circular cylinder for all cases in state III, as observed in figure 7.11. It indicates that any reduction in fluctuating lift is associated with the weakening of two dimensional vortex rather than a lack of correlation along the span-wise extent. It explains why the case $\theta = 150^\circ$ has a fluctuating lift about 10% higher than the bare cylinder, despite having a 2D wake very similar to the bare cylinder. In fact, figure 7.27 shows a good agreement between the spectra of the v component at a xy plane and of the fluctuating lift coefficient. This effect is not unexpected, given that one of the rods' effects in this state is to reduce the movement of the separation point during each cycle of vortex shedding, which favours the span-wise correlation.

7.6 Conclusions

The cases with two rods in the range $90^\circ \leq \theta \leq 170^\circ$ were analysed with force and PIV measurements of the wake. The cases were divided in groups, using the same diagnostic tool of the one-rod cases and the force measurements. Three major states were identified, including a transitional case between states I and II. The main conclusions are the following:

- There is a good agreement between each state with one and two rods. The frequency signatures for each state is similar, as well as the level of their force coefficients and the behaviour of v_t . The type of separation is similar for both cases, as shown in figure 7.28. The only exception is the case $\theta = 115^\circ$, the transitional case between states I and II, which developed a separation type (figure 7.28(c)) and wake not observed for one-rod cases.
- States I and III have a high level of flow structure correlation through the span-wise direction of the cylinder, since Λ/D is higher than the bare cylinder for all cases in both states. The rods made the separation lines to be more two dimensional, so that the C'_L measured at the top of the cylinder is closer to the sectional lift force. For example, the bare cylinder and the case $\theta = 150^\circ$ have very similar characteristics in the two dimensional wake, but C'_L is higher in the latter due to its higher Λ/D . The transitional case $\theta = 115^\circ$, however, have a Λ/D lower than the bare cylinder, revealing a lack of correlation, which is related to the variation of the separation type along the span-wise direction (z/D). State II has a low λ/D due to the weakening of the vortex-shedding mechanism.
- State I: The flow is characterised by the formation of two distinct vortex streets past the control rods with a well-defined frequency f_d . These structures synchronise with the shear layers separated from the cylinder at a frequency f_D , resulting in a wake pattern different from the typical bare cylinder's wake. At each cycle, two vortices are formed on each side of the system, one related to the separated shear layer from the cylinder and the other from the rod.

The total drag over the system is enhanced by up to 30% when compared to the bare cylinder. When considering only the main cylinder, the drag tends to decay with θ , reaching an 8% reduction at $\theta = 105^\circ$. The reduction is associated with the movement of the separation points over the cylinder surface, as $\theta_{sep} > \theta$ for all cases. The fluctuating lift is significantly higher than the reference case, typically between 5% and 30% higher.

- The transitional case $\theta = 115^\circ$ developed a type of separation not observed for one rod cases, where the shear layer separates from the cylinder at a position $\theta_{sep} < \theta$ and then the control rod's wake captures it. The total system's wake results from the interaction of the wakes from the two rods, which occur further downstream, at $x/D > 3$. This case was the most efficient at reducing the fluctuating lift coefficient, 90% lower than the bare cylinder, with no drag penalty.
- State II occurs at cases $\theta = 120^\circ$ and 125° and is characterised by a bi-stable behaviour, where the wake switches between two antisymmetric states. The nature of the process is random, but the characteristic time interval between two switches was very different for $\theta = 120^\circ$ and 125° . The type of separation on the two sides of the cylinder is different for each side, and it seems to be a relevant factor in determining the time scale of the switches. Regarding the force coefficients, both cases have significantly reduced the mean drag coefficient, up to 20% for the combined system at $\theta = 125^\circ$. The fluctuating lift was significantly reduced in both cases too, reaching an 75% reduction for the case $\theta = 120^\circ$.
- State III comprises the cases $\theta \geq 130^\circ$. The wake is very similar to the bare cylinder's, as it results from the interaction of two shear layers only. These cases define a clear frequency signature, but their coefficients vary significantly. Drag coefficient and recirculation length showed good correlation, as the separation points moved little compared to other cases, making the cylinder similar to a body with fixed separation points. Drag reduction was associated with enlargement of the recirculation length, which increases the base pressure. The increase in frequency was associated to the concentration of vorticity in the shear layer, shortening the

diffusion length, in comparison with the bare cylinder.

From $130^\circ \leq \theta \leq 150^\circ$, the fluctuating lift coefficient surged from a reduction of 70% to an increase of 30% relative to the bare cylinder, followed by a significant drag increase, from 20% lower to the same level as the bare cylinder, and a drop in frequency, from $fD/U_\infty = 0.21$ to 0.19. From $150^\circ \leq \theta \leq 170^\circ$, the fluctuating lift decreases to the same level of the bare cylinder and drag reaches a value 10% lower, whereas the frequency increase up to 0.205. This can be attributed to something resembling a splitter plate effect.

Chapter 8

Conclusions and Suggestions for Future Work

This chapter summarises the most relevant points that have been discussed in the previous chapters. Most of them are listed in the conclusion sections at the end of the previous three chapters. Nevertheless, it summarises the main findings of this thesis.

Flow sensitivity to d/D , R'/D , and θ at moderate values of Re

A series of experiments have been carried out to evaluate the sensitivity of force coefficients to the main parameters that govern the flow. The results provided a quick indication of the flow regions most affected by the rods. For the vast majority of points, the force coefficients had similar values for all Re , indicating that the flow does not vary significantly within this particular range of Re tested. The ratio d/D has shown a predictable effect: the larger the rod, the larger the flow interaction effect. Considering the ranges of the parameters, the position of the rod has the most significant effect on the hydrodynamic forces. The force coefficients were most affected when the rod was placed close to the cylinder's surface, and for a given value of R'/D , the flow was most affected when the rod was close to the separated shear layer. These observations agree with the literature for a circular cylinder at lower Re and bluff bodies with fixed separation

points, like D-shaped and square cylinders. However, a specific point at $R'/D = 0.7$ and $\theta = 120^\circ$ showed a peculiar behaviour for $d/D = 0.1$ and $Re = 20,000$, with a mean lift force of the same order of the mean drag and a significant reduction of the fluctuating lift force. These results lead us to focus the wake investigation for fixed values of $R'/D = 0.7$, $d/D = 0.1$, and $Re = 20,000$, varying θ .

Flow states observed for one and two-rod cases

Three stable states were identified for the cases with one rod through the velocity v_t at the mid-point of the gap between the bodies. For the two-rod cases, the same separation types observed for one-rod occurred on the other side, characterising the same flow states.

State I is characterised by the formation of two individual vortex streets past the cylinder and the control rod, each with a distinct frequency signature. The boundary layer coming from the cylinder separates at an angular position downstream of the control rod, as shown in figure 7.28(b). For the two-rod cases the mean flow is symmetric, and the main frequency is twice as lower than the bare cylinder as the one-rod cases, which indicates the amplification induced by the second rod. Each rod develops an individual wake with frequency f_d , which synchronises downstream with the cylinders wake at a frequency f_D . Phase-average fields at f_D show that two vortices are shed on each side per cycle, one formed by the separated shear layer coming from the cylinder and the other related to the control rod's wake.

State II, observed from $\theta = 120^\circ$ to 125° , is characterised by a strong jet following the contour of the main cylinder, a later separation due to the Coandă effect, and a large recirculation region past the rod. It can either present a recirculation bubble or not. The vortex shedding is significantly attenuated, and its frequency is lower than that of the bare cylinder. For one-rod, the jet induces a high mean lift coefficient, of the same order of the mean drag coefficient. State II is associated with the particular case observed in the preliminary experiments ($R'/D = 0.7$, $d/D = 0.1$ and $\theta = 120^\circ$).

For the two-rod cases, the separation type II occurs on both sides but the resulting wake is not symmetric. A bi-stable behaviour was observed, where the wake was biased towards one side at a time, without a clear switching frequency. This phenomenon is random and the average time spent at each side is sensitive to the position of the rods. Apparently, there is a relationship between the type of separation occurring on each side and the average time the wake spends at each side since separation type II-A is related to longer periods. However, further research must be carried out to confirm this.

In State III the control rod remains within the recirculation zone of the main cylinder, not showing its own vortex street. The wake is very similar to the Von Krmn street past a bare cylinder. These cases are simpler than the other states because only two shear layers contribute to form the wake, and the cases with one and two rods are very similar. They both have a frequency signature and force coefficients close to the bare cylinder case. The main effect of the rods is to disrupt the communication between the two shear layers. For $\theta \approx 130^\circ$, it does so by channelling the shear layers and forcing them to interact further downstream, whereas for $\theta \approx 170^\circ$ it prevents the interaction of the shear layers in the near wake. In both cases, both the recirculation length and base pressure are increased. State III also increases the correlation of the vortical structure along the span-wise direction.

In addition to the three states, a bi-stable case was observed for $\theta = 130^\circ$ with one rod, where the flow switches between the states bi-stable A (with characteristics similar to State III), and bi-stable B (similar to State II). The flow topology is very sensitive to the actual position of the rod. The switching process has no defined frequency and seems to be a random process.

In the transition between States I and II, a different wake pattern was observed at $\theta = 115^\circ$ for two-rod only. It is illustrated in figure 7.28(c). The shear layers separate ahead of the rods, but the latter still develop their own wake. This case showed a remarkably long recirculation length and consequently a high base pressure. However, it was observed for only a short length in the span, of about three diameters.

The role of the separation point

The average position of the separation point has varied significantly in two of the three states, impacting the wake development and the force coefficients.

In State I, the flow developed high velocities in the gap between the cylinder and the rod, and separated in an angular position further downstream when compared to the separation around a bare cylinder. The position of the separation point tends to increase with θ , so that $\theta_{sep} > \theta$ for all State I cases. This variation was associated with the drag reduction observed for the cylinder. The high velocity flow in the gap induced an attraction force between the cylinder and the rod.

In State II, the strong flow between the cylinder and the rod made the separation to occur further downstream, close to 180° , due to the Coandă effect. It was induced either by the reattachment of the flow over the cylinder surface, or the prolongation of the boundary layer's extension. This effect is associated with the drag reduction observed in State I, although a significant lift coefficient was also observed for one-rod. For the two rods, however, the same phenomenon occurs on both sides. The two jets inject momentum in the near wake, increasing the pressure and reducing the average drag significantly. Due to the presence of a pair of rods, the lift force is not as significant as for one-rod cases. Interesting to note, for the cases with two-rod in State II, the recirculation zone is very reduced compared to all other cases, due to the Coandă effect.

In State III the separation point position varies little compared to the bare cylinder, so that its influence over the wake and the force coefficients is limited.

Effectiveness regarding hydrodynamic forces reduction and potential applications

Considering the force coefficients of the controlled cases from a flow control perspective, the three states also showed different results. It must be pointed out that the range

of Re this thesis is different from most real applications, but the states observed can guide future solutions in flow control.

In State I, the rods are exposed to high velocities, so the system with one and two rods produced a higher mean drag coefficient than the bare cylinder for all cases. For one-rod cases, the mean drag coefficient is approximately 10% higher than the bare cylinder, while it reaches up to 30% for two-rod. The typical drag coefficient for the rod is around 0.15, also higher than the expected for a single isolated rod exposed to the incoming flow. Regarding the main cylinder, however, the drag force tends to decrease with an increase in θ , as a direct consequence of the movement of the separation point discussed above. The highest mean drag reduction is about 10%. The fluctuating lift was increased for all cases with two rods, more than 20% higher than the bare cylinder. It is associated with the increase in the correlation length along the span, since the rods turned the flow separations lines to be more two dimensional. In addition, the wake of the control rod synchronises with the vortex shedding mechanism coming from the cylinder. Although State I is interesting from the fluid dynamics perspective, specially the interaction between wakes of different scales, it is not attractive for flow control applications, since the main force coefficients were increased.

State II has the most interesting cases regarding mean drag reductions, and it is also very effective on reducing the fluctuating lift coefficient. For one rod, drag is reduced by 10%, but the high mean lift coefficient turned the total force magnitude to be of the same level as the bare cylinder. The fluctuating lift, however, was reduced approximately 70%-80% compared to the bare cylinder. These cases might be interesting to applications where a delay in separation is desired, for example the flow around foils and blades. With the second rod, the mean lift coefficient decreased to approximately 0.1, whereas the mean drag coefficient was reduced more, reaching 30% reduction for $\theta = 125^\circ$. Considering the total system, cylinder and rods, and the total force magnitude, the mean force coefficient is approximately 20% lower than the bare cylinder, and the fluctuating forces approximately 75% lower, making this case especially interesting for a vast number of applications where both mean drag and fluctuating lift reductions are

required.

State III, in general, presented force coefficients of the same level as the bare cylinder, as their wakes were very similar. However, the case $\theta = 130^\circ$ with two rods deserves attention, because it reduced the fluctuating lift by 80% and the mean drag by 15%. State III is also effective at reducing the levels of fluid force on the rod, since it is not exposed to high velocities. It might be interesting for applications where a secondary and more fragile structure is deployed alongside a main cylinder, for example in the offshore engineering.

The transitional case with two rods at $\theta = 115^\circ$ has shown the greatest reduction of the fluctuating lift force, approximately 90% lower than the bare cylinder, with no drag penalty. It did not show a mean lift force, making it particularly interesting for applications regarding attenuation of fluctuating forces, such as aeroacoustics.

8.1 Suggestion for Future Work

There is a series of questions originated from the present thesis that could be investigated in future research. Some of them are listed below:

- *Re* effect: The experiments carried out in this thesis advanced the current understanding from very low to moderate values of *Re*. However, they are still in the sub-critical range. It would be interesting to investigate the behaviour of the wake in the critical and post-critical regions, considering both the scientific interest and practical applications. These are especially relevant for State II, in which the rod interferes the most with the boundary layer and where the most favourable results were observed. Furthermore, the extension of each of the three flow states presented here is unknown, nor are there different states at higher *Re*.
- The natural progression for this type of control is to prospect its effectiveness in suppressing flow-induced vibrations, for example, VIV. Suppressing the fluctuating lift forces might be insufficient to prevent flow-induced vibration when the

model is free to oscillate. Hence, the best cases regarding fluctuating lift attenuation could not be effective at VIV suppression. Further experiments should gradually increase the degrees of freedom of a dynamic system free to respond to flow excitation, considering the different scales of the bodies. For example, a possible new experiment could allow the whole system to oscillate, evaluating its behaviour under VIV. Another possible direction is to allow the rods to move around the cylinder. The influence of the rod's vibration over the forces on the cylinder and in the wake as a whole is unknown.

- The bi-stable case observed around $\theta = 130^\circ$ deserves a more detailed investigation. Further experiments should focus on the flow between the cylinder and the rod, capturing the nature of the incoming boundary layer. In addition, more variations of θ should be investigated, with a more accurate determination of the angle θ . Another possible investigation regards the behaviour of the bi-stability along the span-wise direction. Also, the high level of sensitivity to the precise angular position of the control rod makes this configuration an ideal test case for high-fidelity computational fluid dynamics. Similarly, the bi-stability observed for the State II cases with two-rod deserves attention. Further research, experimental and/or numeric, should focus on understanding the nature of the bi-stability, the causes of the different time scales observed and the role of the rods' position.
- The transitional case $\theta = 115^\circ$ is efficient in attenuating the fluctuating lift forces with no drag penalty. However, it is unclear whether the wake pattern observed at mid-span can occur for the whole length as an independent state for this level of Re . Further measurements should be concentrated around this value of θ and different end conditions for the cylinder.

Publications

Author's publications related to the present thesis:

- Cicolin, M.M.; Buxton, O.R.H.; Assi, G.R.S.; Bearman, P.W. . The role of separation on the forces acting on a circular cylinder with a control rod. *Journal of Fluid Mechanics*, v. 915, p. A33, 2021
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