An active controlling technique for a flow around a circular cylinder

H. Oualli[1], S. Hanchi[1] & A. Bouabdallah[2]
[1]*MDF, EMP, Bordj El Bahri, Algiers, Algeria*
[2]*LTSE, Université des Sciences et de la Technologie (USTHB), Algiers, Algeria*

Abstract

In this study we describe the near wake response and flow dynamics associated with experimentally simulated flows around a circular cylinder that is either stationary, superimposed to simple harmonic cross-section variation, or harmonic cross-section variation combined to steady rotation. Results are examined for a Reynolds number Re = 1000 and a fixed vibrating amplitude equal to 5% of the cylinder radius. A large domain of the forcing Strouhal number up to several times the natural shedding frequency of the cylinder in rest is considered.
Keywords: fluid-structure interaction, deforming-rotating cylinder, wake control, drag reduction.

1 Introduction

Bluff body wakes play an important role in the design of a diversity of engineering structures and industrial applications: aerodynamics, heat exchangers, offshore structures.

Control of vortex shedding leads to decreasing the unsteady forces acting on the body and can substantially reduce its vibrations. Flow control may be executed by controlling the boundary layer separation, the shear layers structures and / or the coherent structures dynamics in the body near wake.

Several techniques, such as blowing, suction, surface roughness elements, etc., have already been considered by researchers [1], [2] and [3] presented a fairly comprehensive overview of the various methods for suppressing vortex shedding.

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Smoke visualizations of the flow generated behind a circular cylinder, submitted to both steady rotation (inducing Magnus effect) and cross-section oscillation are performed. A detailed analysis of the resulting flow properties and involved mechanisms together with plausible explanations are addressed.

The main objective is to produce a first assessment as a first step to a reliable response about the possibility to optimize the lift to drag ratio using a combination of the Magnus effect (resulting from cylinder steady rotation) with a modulated near wake generated by harmonic cylinder cross-section variation.

2 Experimental set-up

These experiments were carried out in a Deltalab 38340 Voreppe open circuit channel facility EV 280 type. This consists of a low speed air turbine (0.3 - 3 m/s) with a large Plexiglas tunnel, approximately 1.5 m long, 0.35m height and 0.45 wide with optical access from all sides. The background streamwise disturbance level is less than 1% of the free stream velocity.

The cylinder made of PVC (Polyvinyl Chlorine) walls, figs.1 and 2, is mounted horizontally traversing the test section with the ends linked to two external motors destined to deliver rotating motion of the cylinder shaft and cylinder walls as well. The inside of the test cylinder, as shown by figs. 1 (b) and 2(b), consists of the cylinder shaft entrained in rotation motion (by means of the external motor), rotating cams appropriately transform the rotating motion into diameter variation movement of the test cylinder walls according the following law:

$$a = a_o\,(1 + As\sin(2\pi \times f \times t))$$

Where a is the variable cylinder radius, a_0 is the initial cylinder radius, As is the maximum deformation amplitude set equal to 5% of the cylinder diameter, f is the cylinder forcing frequency in Hertz and t is time in seconds.

Considering the cylinder dimensions, the above relation becomes:

$$a = 0.04\,(1 + 0.005\sin(2\pi \times f \times t)) \tag{1}$$

Flow is thus controlled by the sinusoidal variation of the radius a. The internal deforming system of the cylinder and the test section dimensions imposed an aspect ratio of 5.62.

The flow visualizations were carried out by releasing a horizontal smoke sheet in front of the cylinder created by injecting smoke through a tubing of a smoke generator enabling a steady leakage of smoke through the oncoming flow. The collection of flow visualization images was taken with a digital video camera in a rate of 24 images per second.

The rotating movement is generated by an electrical motor developing a rotation speed N varying from de 0 to 300 rpm. The cylinder axis is clamped to an electrical motor and constrained to move in a rotating motion to generate the

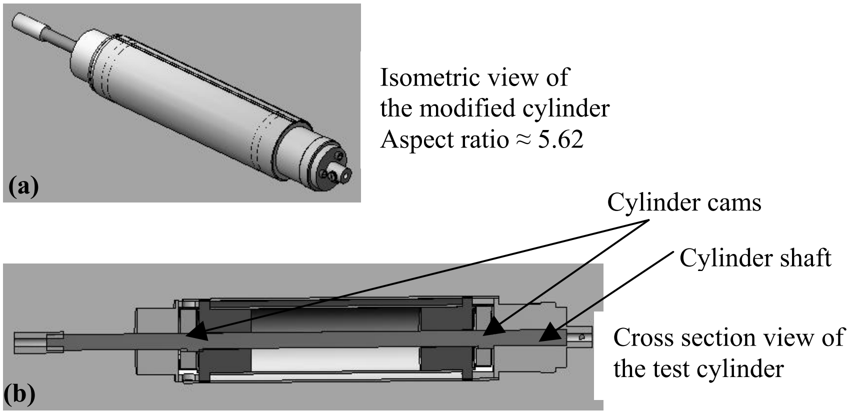

Figure 1: Operating set-up / cylinder deforming mechanism.

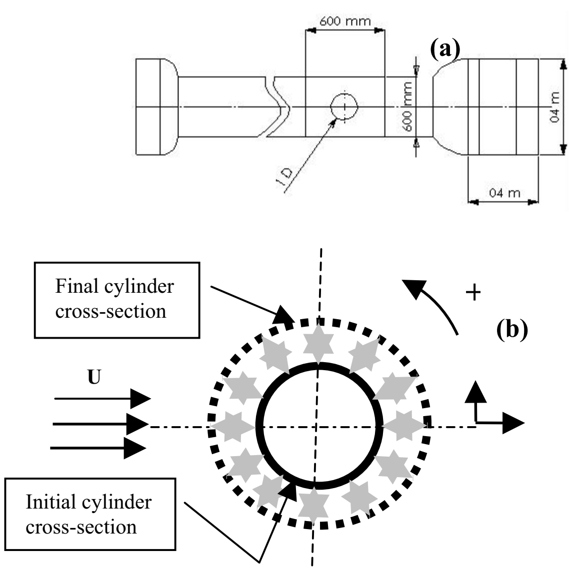

Figure 2: (a) The wind tunnel, (b) schematic diagram of the cylinder side view.

vibrating motion of the cylinder cross section via the integrated mechanism inside the cylinder. The rotating cams mechanism converts the rotary motion of the drive shaft into sinusoidal motion of cylinder walls by a mechanism reported elsewhere in [4] and [5].

The cylinder walls are entrained in a steady rotation by a second electrical motor. With this system, the corresponding forcing Strouhal number, $St_f = f\ D/U_\infty$, is between 0.7 and 15. D and U_∞ are respectively the cylinder diameter and the infinite flow velocity. The non dimensional steady rotating speed considered in this study, $\alpha= \Omega a_0/U_\infty$, is in the wide range of 0 to 11.78, with Ω is the cylinder rotating speed in rpm and a_0 the cylinder radius.

The results are presented for Re=1000. Flow visualizations are carried out to study the behavior of the cylinder near wake in response to combined steady rotation and radial vibration controlling techniques.

The present investigation of the near wake of a circular cylinder superimposed simultaneously to steady rotation and diameter variation is an initial step towards understanding the intricate flow phenomena generated when such active controlling techniques (rotation and radial vibration) are coupled on the actuated flow around a circular cylinder.

3 Results and discussion

A first understanding of the visualization results is deduced from the digital video clips and the video tapes. Separation of the successive video frames into digital images enables compilation of time sequences showing evolution of the nascent vortices, vortices interactions and vortex shedding process. Dye streaks contours are detected and highlighted to interpret the results more clearly. These tracings scale-accurate representations of the near wake regions, showing the surrounding shear layers and the primary vortices in the cylinder vicinity.

The vortex shedding Strouhal number, St_0, for the non controlled cylinder at a freestream velocity of U_∞=3 m/s is determined to be 0.21. This value is in perfect agreement with the universal St-Re relation. The considered Reynolds number, Re=1000, coincides with the subcritical flow regime for which the Strouhal number fluctuates in the range of 0.18-0.22, [6] and [7]. The visualized near wake region for this nominal case at a time where the vortex formation is fully developed is shown in figure 3. The shear layers and the vortex roll-up surrounding the formation region are clearly illustrated on the figure. The shear layers roll-up and the Kàrman vortices are formed in a laminar fashion indicating the absence of Kelvin-Helmholtz instability vortices on the shear layers. [8] carried out experiments for an active control of a circular cylinder using a rotative-oscillating technique for Re=15000, corresponding to the same flow regime. This flow configuration is similar to the flow pattern found by [8] for the nominal case.

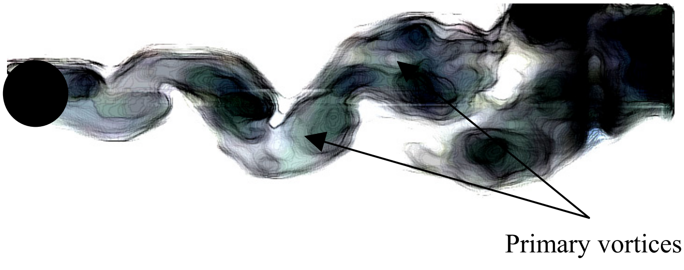

Figure 3: Von Kármán eddy-street behind the cylinder at rest.

The nominal case (without control) is presented as a reference flow situation for a comparison with visualization results for the formation region and the near wake behind the cylinder superimposed to both radial vibration and steady rotation.

When the cylinder is set into motion the flow developed various features and phenomena as a response to the applied actuating perturbations.

When examining the sequences of video pictures, several shedding modes are identified throughout these flow visualisations. Particularly, the four modes presented by [8] for a cylinder submitted to rotative oscillations and termed *dual shedding mode, global locking mode, local locking mode and the shear layer mode* are clearly identified but as partial modes in this study.

Flow configurations similar to these flow modes are previously observed by [9] for a cylinder subjected to transverse oscillations in a freestream.

An estimation of the drag coefficient is given by [8]. He showed that these shedding modes are accompanied by a substantial drag coefficient reduction (up to 80% of the non controlled case). This is in line with the goal researched through the elaboration of this work, namely lift to drag ratio optimization.
An interesting feature of this flow is the progressive and ordered way in which each mode evolves at the selected values of the frequency and steady rotation of the cylinder.

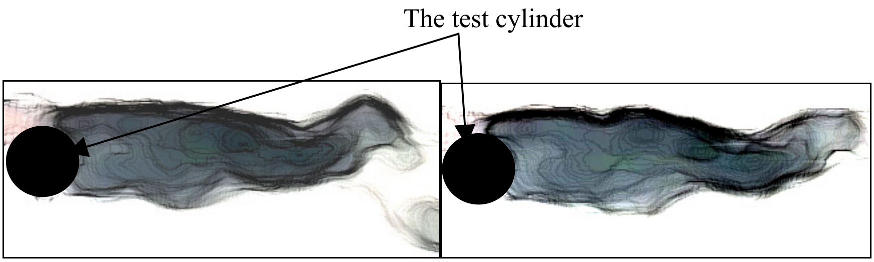

Figure 4: Instantaneous Von Kármán vortex suppression (St_f =0.51, α = 3.94).

In the images of fig. 4 (St_f =0.51 and α =3.94) the wake flow is parallel to the midspan plan (straight and without beating motion) the shear layers developed abrupt instabilities in the form of undulations and kinks without evolving to roll-ups vortices as this can be expected. In this configuration the shedding mechanism seems to be inhibited.

In the current experiments, the modification process (wake undulation) is not limited to the formation region but extends to farther wake behind the cylinder. This undulation phenomenon is thought to be caused by the cylinder walls acceleration during the radius increasing and decreasing motion. In fact, the Kelvin-Helmholtz instability settling in the flow shear layers is strongly enhanced. This tendency is immediately reversed by the steady rotation effect of the cylinder which attenuates the developing instability preventing, thus, roll-ups vortices formation. The cylinder steady rotation seems forcing the cylinder wake to evolve in a straight and parallel direction.

The rotation of a circular cylinder in a viscous uniform flow is expected to deeply alter the wake flow pattern and vortex shedding mechanism. It may reduce the flow-induced oscillation or augment the lift force. The basic physical rationale behind the rotation effect is that as the cylinder rotates in the clockwise sense, the shear layer of the cylinder upper side is accelerated leading to separation delay or suppression. While the shear layer of the cylinder lower side is decelerated and easily separated. Hence, the pressure on the accelerated side becomes smaller than that of the decelerated side, resulting in a mean lift force (this effect is known as "Magnus effect") [10].

This parallel shedding mode may be explained by an unstable equilibrium state resulting from a non linear interaction of the effects induced by the radial vibration from one part and the steady rotation from the other. An evolution to more stable fashions is observed when the steady rotating speed is increased. The mode becomes more persistent accompanied by a largely narrower wake.

If the controlling parameters are maintained constant, the previous mode progressively shifts to a new mode in which the shedded structures rearrange into a more organized mode termed 2P mode following Williamson and Roshko [9] terminology, fig. 5.

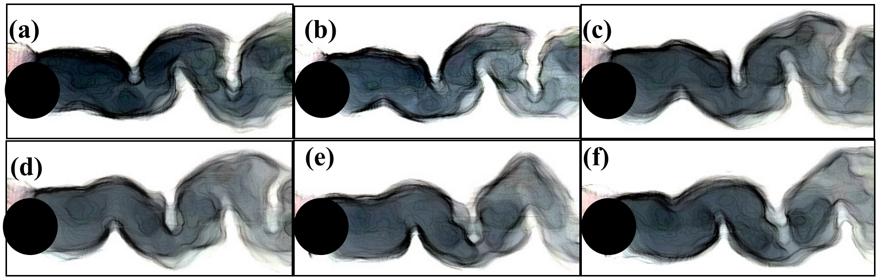

Figure 5: 2P shedding mode for α = 0.175 and St_f= 0.47/ wavelength variation.

The wake configuration is clearly seen to be of 2P-type in fig. 5. Two vortex pairs are shed per cycle of radial cylinder oscillation and the vortex pairs rapidly diverge away from the wake axis. The 2S-type wake pattern shown in fig. 3, where two vortices are shed from the circular cylinder per shedding cycle is markedly different from the 2P mode shown in fig. 5. In the former (2S mode), the vortices remain close to the wake axis as they convect downstream. The latter wake pattern (2P mode) is seen as indicating synchronisation with respect to cylinder motion as reported by [11] and [9].

The coherent synchronized wake patterns observed for the excitation regime frequencies within the synchronized regime is not preserved indefinitely over the oscillation cycles. Flow visualization results of the near wake and formation regions illustrating its evolution are given in fig. 6 corresponding to oscillation frequency St_f=0.87.

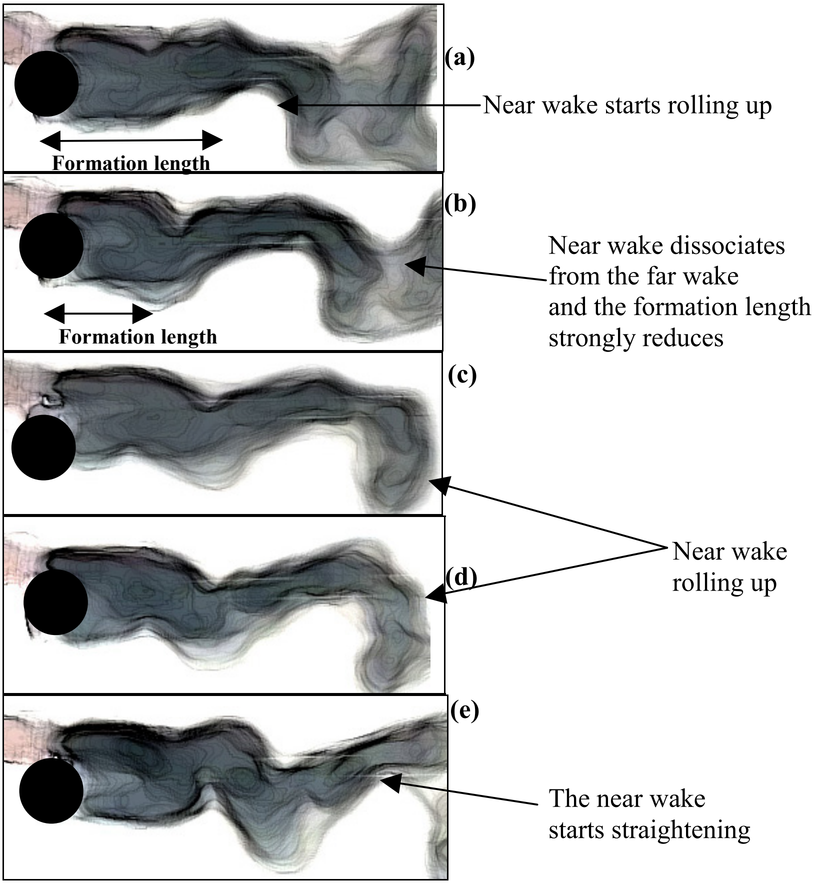

Figure 6: Near wake rolling up shedding mode, ($St_f = 0.87$ and $\alpha = 3.94$).

A comparison the images of this figure shows that the regular 2P mode shifts progressively to a new 2P wavy mode characterized by a horizontally beating wake and a variable wave number of the Von kàrman eddy street forming behind the cylinder with a rate of roughly 35% as estimated from the visualisations. The observed periodic variation of the instability wavenumber is seen in the current experiments to be accompanied by a substantial increasing and decreasing of the vortex formation length.

Though the excitation frequency, $St_f = 0.7$ (close to the 3-superharmonic synchronization value), is largely higher than those corresponding to the fundamental lock-in regime, $0.15 \leq St_f \leq 0.22$, the wake pattern persists in the 2P mode without relaxing to the usual Karmàn mode (2S) as this is reported by both [11] and [9]. On the other hand, for higher rotating speeds of the cylinder, $\Omega \geq 33$ rpm, the visualizations reveal appearances of the 2S mode as a subsidiary configuration considering its existence duration. This indicates that the steady rotating effect of the cylinder remains dominant throughout the whole spanned range.

An attempt to quantify vortex formation lengths for a cylinder vibrating frequencies in the range, $0.37 \leq St_f \leq 15$ and a constant steady rotation $\Omega_1 = 23$ rpm is now discussed.

While the vortex formation length is rather well defined for flows past a stationary cylinder, difficulties arise when the cylinder is forced to vibrate radially and rotate steadily around its axis, for the following reasons:

(i) The shear layers are subject to alternating repulsion and attraction movement induced by the cross-section increasing and decreasing respectively.

(ii) There are three vortex processes contributing to vortex formation: (a) those applicable to natural vortex formation from a stationary cylinder ([12], [3], and [13]), and (b) shear layers undulations in the form of roll-ups successions mainly induced by the radial acceleration of the cylinder walls with the cross-section variation. The vortex formation length is thus dependent on the process which gives rise to the vortices, [8] and the manner in which these formed vortices interact (before and after they are shed) is intricate and complex.

(iii) [11] reported that the more important effects of the steady rotation are: (a) Inducing of a continuous fluid layer that rotates with the cylinder in such a way that the stagnation and separation points around the cylinder are shifted from the wall within the stream. The thickness of this layer is found to increase with the rotating rate but decreases with Reynolds number increasing. (b) Destroying of the vorticity symmetry generated from the cylinder because of the difference between the relative fluid-to-wall velocity on each side of the cylinder (one side moving in the freestream direction and the other moving opposite to it). So, eddies with different size and strength are created. (c) Eddies detachment is accelerated and the vorticity evacuating process within the stream is likely to be modified.

Representative vortex formation lengths L_f are estimated as suggested by [10]. L_f is the streamwise distance from the axis of the cylinder to the core of fully formed vortex. It is determined for several vibrating frequencies with a fixed cylinder rotating speed were determined in the first case and for a fixed vibrating frequency and various rotating speeds in the second case.

These formation lengths are evaluated from images of the formation region in which a fully formed vortex was clearly seen when the shear layers were quasily straight. The results are plotted in figures 7(a) and 7(b). In the first case, the vortex formation length is evaluated for the fixed rotating nondimensional rate $\alpha = \Omega D/2U_\infty$ equal to 1.78.

As the forcing Strouhal number, St_f, is augmented the formation length increases with a jump of 73% and decreases in a rather sharp way until it reaches a minimum of $L_f/D = 1.9\text{-}2$ at $St_f = 2.96$. As the forcing Strouhal number is increased above 3.64 the formation length seems stabilizing around a constant value of $L_f/D=3$.

It comes out from the above results that an optimization of lift to drag coefficients ratio $(C_L/C_D)_{opt}$ can be obtained for an optimal vortex formation length reduced by the right value of the rotation rate α_{opt} and maintained around this value by fixing the right value of the forcing Strouhal number St_{fopt}.

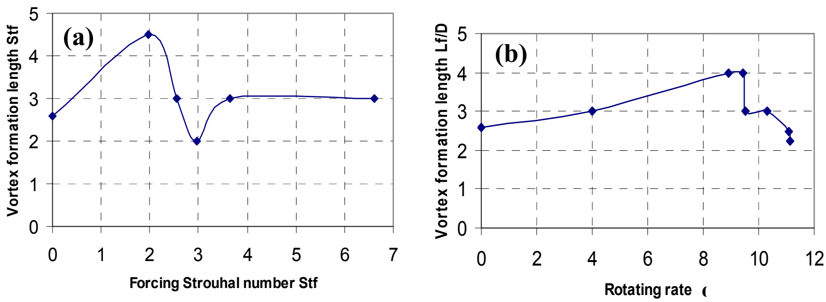

Figure 7: Vortex formation length L_f/D evolution.

4 Concluding remarks

It is noted that when the cylinder is actuated using cross-section variation and steady rotation the Von Kármán eddy street is re-arranged in such a way that four structure evolving modes prevail and become dominant in the flow dynamics.

Various features and phenomena are noticed. This illustrates a remarkable similarity with modes reported in several studies and devoted to rotative oscillation.

When the main controlling parameters, α and St_f are increased, the 2P mode seems to become dominant throughout the spanned ranges of the steady rotation rate and forcing Strouhal number.

To answer the central question related to an optimization of lift to drag coefficients ratio, it is established that the obtained results favourably encourage further quantitative exploration in order to be definitely fixed about the problem.

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