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## Effort / Near-Wake Correlation on a Towed Cylinder in the Presence of a Free Surface

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**ABSTRACT:** A cylinder ( $D=0.04$  m;  $l/D=16$ ) is towed following a uniformly accelerated and decelerated motion in a visualisation water tank. The vortex effects are observed for acceleration or deceleration values in the range  $[0.06 - 0.15 \text{ ms}^{-2}]$ . The related acceleration number ranges from  $4 \cdot 10^{-6}$  and  $6 \cdot 10^{-6}$ . The Reynolds numbers based on the maximum velocity are varied from 0 to 14000. The drag and lift forces are measured. The cylinder wake pattern is visualised by an embarked CCD camera. The free surface effects are studied by varying the depth parameter  $d/D$  where  $d$  is the FS to the main cylinder top distance in such a way that the Froude numbers based upon the instantaneous velocity lie in the range 0.3 to 1.2. The lift force is analysed in correlation to the free surface profile and the near-wake pattern. The near-wake pattern is analysed either by a visualisation technique or a velocity field obtained by a PIV method.

**KEYWORDS:** Free Surface, Vortex, Drag, Lift, Breaking, Wake, Cylinder

### I. INTRODUCTION

The phenomena of interaction between a free surface and a fixed or moving cylinder have been widely studied in the past. The interaction is responsible for various modifications in the efforts by the cylinder depending on its degree of immersion or its orientation with respect to the typical flow of a marine environment.

### II. RELATED WORK

The study of the flow in the laboratory can therefore give indications on a better understanding of the dynamics of vortices and forces applied to the body [1] [2] [3] (Sarpkaya 1963, Tatsuno 1971, Sulmont 1987). Moreover, this interaction between a cylinder and a free surface concerns many applications in marine engineering as described by Sheridan 1995, Oshkai 1999, Reichl 2005 [4] [5] [6].

This paper is the result of previous work [7] [8] [9], it presents an experimental study of the interaction between a rigid cylinder towed under the free surface (SL) and the impact it has on the parameters which govern the applied efforts. The cylinder is equipped with a force sensor of the KISTLER type and is towed into a uniformly accelerated motion then decelerated to accentuate the effects of vortices and make it easier to observe the phenomena of interaction ([8] and [9] Rajaona 2005, 2009). It is well known that for a uniform flow and a range of the number of Reynolds ranging from 150 to 320000 the vortex shedding is characterized by the number of Strouhal defined by  $fD / V$  which is close to 0.2, where  $f$  is the shedding frequency,  $D$  is the diameter and  $V$  is the flow velocity. The vortex shedding causes fluctuation of pressure forces and oscillation of lift forces at the frequency  $f$  [2]. However, when the structure is close to the free surface, the oscillation frequency increases so that the Strouhal number can reach 0.3 or 0.4 as shown by

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Rajaona (2008) [9]. This is the consequence of the interaction with the free surface, the vorticity transfer of the wake to the SL. Accompanying waves can break up as shown by Duncan [10] (1981) on a towed hydrofoil under the free surface. The Reynolds numbers for this study are in the range from 0 to 14000. The lift force depends largely upon the immersion of the cylinder. For this purpose, we use images resulting from the visualisation and the curve of the forces applied on the cylinder simultaneously. An embarked CCD camera records a video sequence of the evolution of the near-wake and of the SL's profile. We therefore vary the immersion depth  $d/D$  from 0.37 to 5. The results concerning the lift and drag coefficients and the length of the  $L/D$  recirculation zone will be discussed more precisely. Finally, a PIV technique allows the possibility to make quantified observations of the wake.

### III. EXPERIMENTAL SETUP

The entire assembly consists of a cylinder 0.637 m long, with a diameter of 0.04 m placed horizontally under the free surface of a body of water at rest contained in a visualising tank of dimensions 2m x 1m x 1m. The cylinder is equipped at one end with a three component KISTLER force sensor device, only two of which are used to measure the horizontal and vertical forces exerted by the fluid on the bar during the movement. The motion is uniformly accelerated and then decelerated for different values of acceleration corresponding to acceleration numbers ranging from  $4 \cdot 10^{-6}$  and  $6 \cdot 10^{-6}$ . This movement is obtained by a robot which allows the speed control of the model.

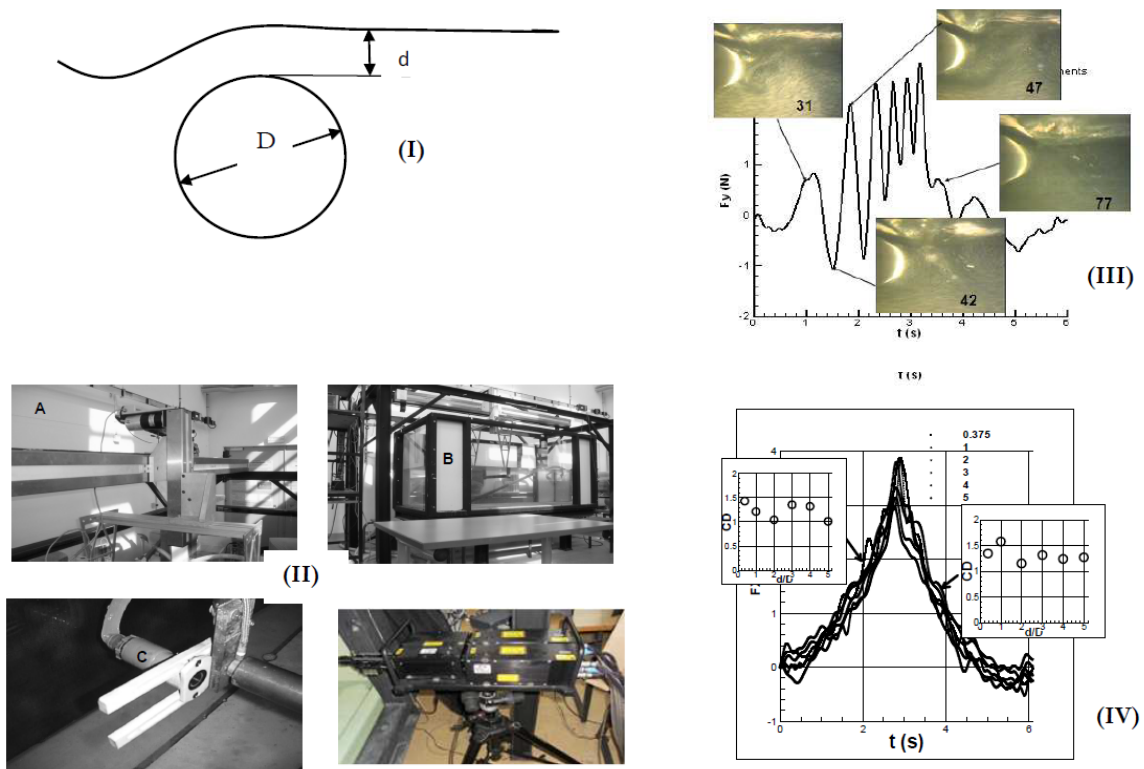


FIG. 1 - (I) Configuration studied; (II) Experimental setup A: Robot; B: tank; C Camera D: TwoQuantel Laser heads for the PIV and (III) wake at various times corresponding to the numbers of the images. The configuration of the near-wake at a maximum or a minimum of  $F_y$  is observable. The very strong distortion of free surface profile can be observed on the images. (IV) Graph shape of the drag force for the 6 depths immersion 0.375D, 1D, 2D, 3D, 4D, 5D.  $F_x(t)$  increases to a maximum then decreases.

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## IV. RESULTS

### AMPLITUDE AND FREQUENCY OF THE LIFT FORCE

The lift coefficient is defined by the following formula:

$$CL_{max} = Fy_{max} / (1/2) \cdot \rho L D \cdot V_0^2 \quad (a); \quad \tau = \frac{tV_0}{D} \quad (b); \quad Ra = aD^3 / V^2 \quad (c) \quad (1)$$

Where  $Fy_{max}$  represents the local maximum of  $Fy(t)$  and  $V_0$  the maximum speed for the acceleration of  $0.15 \text{ m} \cdot \text{s}^{-2}$ . This coefficient is represented as a function of the adimensional parameter  $\tau$ .

A typical shape of the transverse force is shown in fig. 1 (III) when the cylinder is driven with  $a = 0.15 \text{ m} \cdot \text{s}^{-2}$ . We observe maxima and minima as well as a "mobile" average, evolving during the movement. We propose to characterise the amplitude and the "frequencies" of the forcelif. The coefficient  $Cy$  is represented by the maxima and minima values of the curves for three immersion depths  $d / D = 3, 1, 0.375$ . Similarly, a moving average of the lift forces is observable it allows the observation of the loss of symmetry of  $Cy(t)$ .

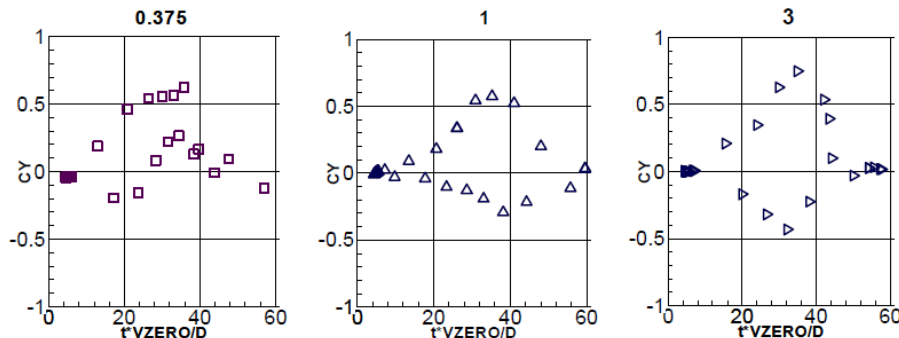


FIG. 2.a - Variation of the lift force as a function of the immersion parameter  $d / D = 0.375, 1, 3$ . The SL effect is observed on the maxima of  $Cy$ . We note particularly the loss of the "symmetry" of the oscillations. The full shape of  $Cy$  is the one of FIG. 1.III

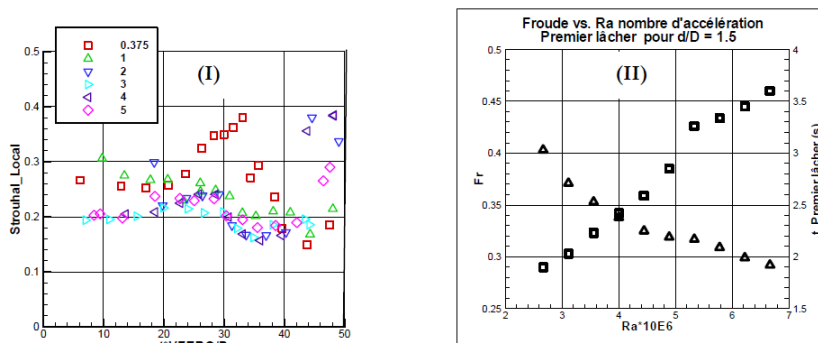


FIG. 2.b - (I) Variation of the local Strouhal number for  $d / D = 0.375, 1, 2, 3, 4$  and  $5$  and  $a = 0.15 \text{ m} \cdot \text{s}^{-2}$ . We note that this number evolves around the value  $0.2$  for depths greater than  $1$ . The proximity of SL to increase the values of  $St$  which can take values close to  $0.4$ . (II) Number of Froude (square symbol) relating to the appearance of the first release for ten values of the number of accelerations see formula (1-c).

To analyze the "frequency" of the oscillations, we represent the lift force according to time  $t$  and for an acceleration number of  $6.67 \cdot 10^6$  and measure the distance travelled between two maxima or two successive minima of the transverse force. The difference between two maxima or successive minima allows us to calculate a report that we call local

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Strouhal. It is therefore appropriate to define this Strouhal number to characterise the "frequency" of the oscillations. To automate this calculation the following operations are carried out for this purpose. The digital derivation of the lift force makes it possible to identify the extrema by determining its zeros. Once these are identified, the displacement of the cylinder is calculated between two successive maxima or minima. This difference is then dimensioned to the diameter of the cylinder. In this way, we have defined a local Strouhal number in the sense that it is defined for moments corresponding to the maxima or minima of  $C_y$ . The results are shown on the plot figure 2.b for five depths of immersion. It is found that this "Strouhal" is on average close to 0.2 for  $d/D = 5$ . When  $d/D = 0.375$  the effect of SL is maximal; which results in a dispersion and an increase in this local Strouhal. It should be noted that in the case of a uniform movement of the cylinder the previous values are equal to Strouhal's number, as was shown in Rajaona (2008).

To explore more finely the effects of the unsteady nature of the flow and see if it accentuates the effects of vortices and thus make their observation easier, as shown in part in Fig. 1. (III), we varied the acceleration from 0.06 to 0.15  $m \cdot s^{-2}$ . This allows an observation into the Froude numbers for which the first release of vortices occurs see Fig. 2.B (II). We see that increased acceleration has the effect of causing an anticipated appearance of the first shedding of vortices. We also observe this phenomenon by measuring the length of the recirculation zone as will be analysed on the free surface effect in section 3.2 Fig. 3.

The drag force is illustrated in FIG. 1 (IV).  $F_x(t)$  is continually increasing until reaching a maximum for the maximum speed of the cylinder then the force decreases. Each phase (acceleration, deceleration) can be characterised by a  $C_M$  coefficient of added mass and a coefficient  $C_D$  defined by the model of equation (2) [3]. This last coefficient takes values between 1. and 1.5.

$$F_x(t) = C_M l \frac{\pi D^2}{4} a + C_D \frac{1}{2} \rho l D V^2(t) \quad (2)$$

It is shown that this  $C_D$  is more sensitive to the free surface effect during the acceleration phase.

## LENGTH OF THE RECIRCULATION ZONE

Fig. 1 (III) shows a jet which appears in the gap above the cylinder during the breaking of the accompanying wave. In addition, this wave surges as the lift force passes by a maximum or a minimum. One way to study free surface effects is to measure  $L/D$  the length of the recirculation zone for different depths of immersion. Fig. 3. shows that  $L/D$  is almost linear as a function of time and hence the instantaneous Reynolds name. Its slope represents the rapidity of the process of destabilization of the recirculation zone, the greater it is the more the first to let go occurs early. The lower end informs on the moment of the separation of the flow, the superior corresponds to the moment of the first let go and thus the number of Froude at which the whirling shedding occurs.

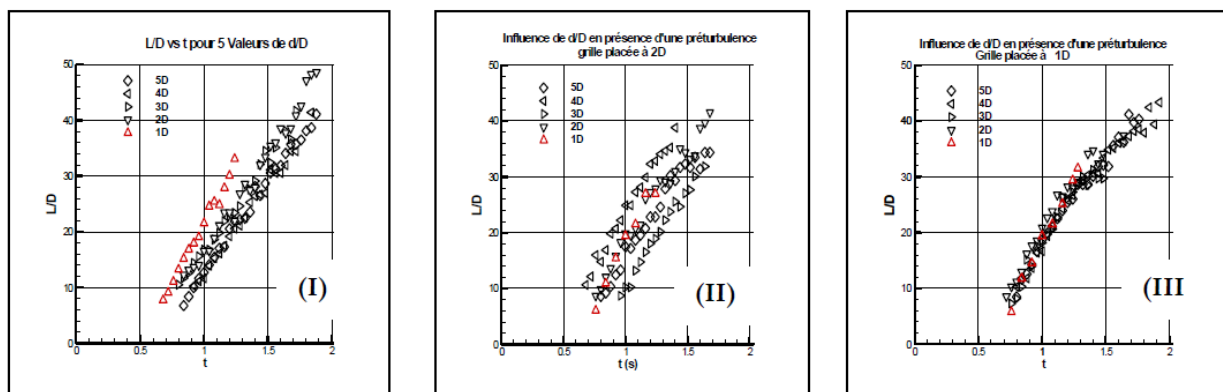


FIG. 3 - Variation of the length of the recirculation zone for  $d/D = 1, 2, 3, 4$  and  $5$ .  $L/D$  is studied (I) with the only turbulence present in the tank, (II) with a pre-turbulence grid placed at  $2D$  of the cylinder, (III) with a grid of pre-turbulence placed at  $1D$  of the cylinder. It is noted that the combined effect of free surface and pre-turbulence delays this separation of the flow and anticipates the moment of the first shedding.

It can be observed in FIG. 3 (I) that the free surface accelerates the process as the red curve is steeper than the others. Likewise, in Figure 3 (III) the grouping of the curves indicates the existence of a unique behaviour of flow with respect

to the feeding of the vorticity recirculation zone. In all cases, the presence of the free surface creates an anticipation of the first shedding.

### SURF WAVE SURGE AND VELOCITY FIELD

To illustrate the variation of the velocity field behind the cylinder, a PIV technique has been implemented. The camera is mounted on board. The PIV assembly consists of 2 laser heads, Twins BSL, BIG SKYQuantel lasers that generate flashes when powered by 2 charge boxes, ICE 450, BIGSKY Quantel Laser. The flashes are synchronised shooting by the pulses generated by a boxR & D Vision EG + connected to the control computer. The flow is inoculated with particles of RILSAN with an average size of a few microns. These particles are illuminated and filmed by a camera PULNIX Dual Tap AccuPIXEL, RM-6740 CL with a resolution of 640 x 480 pixels with a lens of 25 mm. The lens used has a focal length of around 30 cm to allow sharpness of the image's particles for a laser plane in the middle of the display body. The processing of the velocity field is performed by the DirectPIV software.

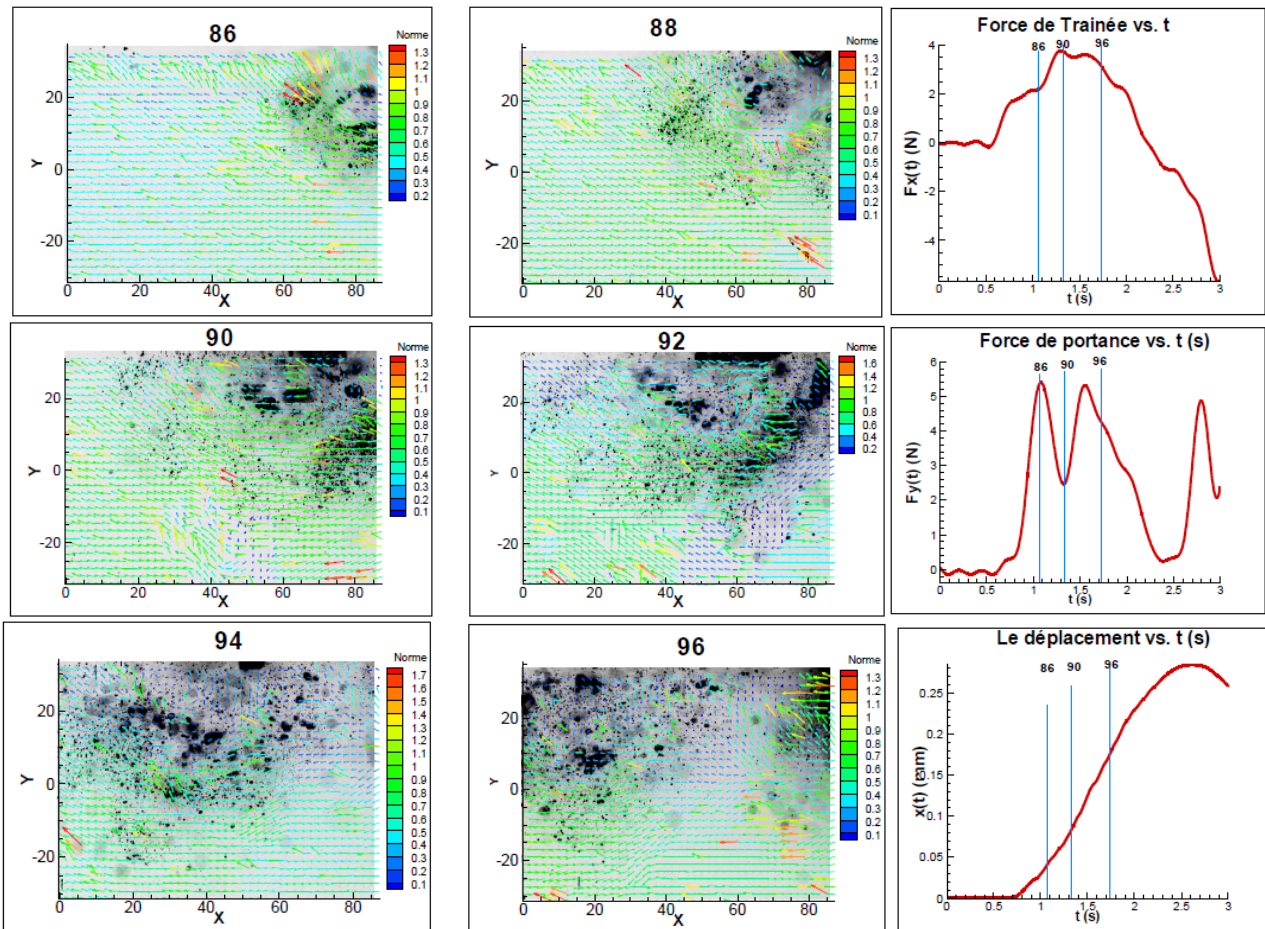


FIG. 4. Velocity field and forces applied on the cylinder in the case of the acceleration phase in the presence of a breaking of the accompanying wave for an oscillatory movement characterised by an amplitude of 260 mm, a frequency of 0.250 Hz an immersion parameter of  $d/D$  of 0.7. The numbers 86 to 96 correspond to the moments marked by the vertical lines. The field is superimposed on the image used when calculating the field. Black dots represent the bubbles resulting from breaking. The colour of velocity vectors is associated with their norm.

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Figure 4 illustrates the velocity field behind the cylinder during a wave surge and during an acceleration phase for an experiment where the cylinder makes a go return. The onboard camera clearly shows the variations within a turbulent zone where several large bubbles appear which are convected by the flow. During this, the area is the seat of diffusion which results in an enlargement. During this process the bubbles of large sizes are split into several small ones. The red curves on the right of Fig.4 show the evolution of the drag force (I), the lift force (II) and the movement of the cylinder (III). To facilitate, the interpretation was superimposed on the measured velocity field a photograph of the flow. Correlation from the velocity field to the forces  $F_x(t)$  and  $F_y(t)$  is obtained by reading the numbers of the analysed pairs and the dates they are processed, and these dates are represented by the blue verticals. Speed average in the jet undergoes very strong variations during the surf.

## V. CONCLUSIONS AND PERSPECTIVES

We presented an experimental technique adapted to the study of the correlation between the near-wake and the forces applied on a cylinder in unsteady movement. We have shown that maxima of the lift force are used to characterise the coefficients  $CL$  which vary in the range 0 to 0.6. Similarly, the introduction of the local Strouhal number makes it possible to characterize the frequencies of the oscillations. This number takes values close to 0.2 at moderate depth  $d/D = 3, 4, 5$ . However the proximity to the free surface may give values close to 0.4. The kinematic characteristics of the near-wake could be studied by using a camera embedded in a measurement chain PIV. Despite the difficulties of implementation, it is possible to observe the capture of bubbles of size medium and their convection / diffusion during the process. Similarly, the average speed in the jet at the top of the cylinder undergoes very strong variations during the breaking.

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