Wake - Free surface interaction in the flow past two horizontal rigid cylinders: preliminary results.

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ABSTRACT: An experimental study of the flow past a set of two horizontal cylinders is presented. The cylinders are towed in a uniformly accelerated and decelerated motion in a visualization tank in order to enhance the vortex effects. The main cylinder (D=0.04 m; L/D=16) is placed in the flow past a front one (d = 0.002; L/D=16). They are towed beneath the free surface and the drag and lift forces are measured. The main cylinder wake pattern is visualized by an embarked CCD camera. The Reynolds number based on the maximum velocity is from 0 to 14000 and the Froude number based on the main cylinder immersion from 0.2 to 1.2 for an acceleration value of $0.15 m.s^{-2}$. It is shown that the near wake is made of a combination of the main cylinder Von Karman vortices and those of the front cylinder. The interference phenomenon and the free surface effects are studied by varying the depth parameter and the two cylinders arrangements.

1 INTRODUCTION

Flow interference has been widely studied in the past. The interference is responsible for various changes in the forces when more than one cylinder is placed in a water stream. Investigations of the flow past a set of two cylinders can provide a better understanding of the vortex dynamics and fluid forces in cases involving more complex arrangements (Bearman 1973, Zdravkovich 1977, 1988, Rockwell 1998). Furthermore the interaction between a cylinder and a free surface is relevant for many engineering technological applications as described in Malavasi 2007, Oshkai et al. 1999, Rajaona 2007).

This paper presents an experimental study of the interference between a set of two rigid cylinders towed beneath a free surface (FS). The rear cylinder is equipped with force transducers. In addition, the cylinders are uniformly accelerated then decelerated in order to enhance the vortex effects rendering the interference phenomenon easier for observations (Sulmont 1988, Rajaona 2005). In the case of solitary cylinder it is well known that for a wide range of subcritical Re numbers the flow is characterized by a vortex shedding for which the Strouhal numbers fD/V take values near 0.2, where f is the natural frequency of the shedding vortices, D is the cylinder diameter and V is the flow velocity. However, when the cylindrical structure is near a free surface the St number is increased due to a complex pattern of the wake (Rajaona 2008). This is a consequence of the interaction between the free surface, the vorticity transfer from the wake to the FS. The accompanying waves can give rise to breakers as shown by Duncan 1981 for a towed hydrofoil. The Re numbers based on the maximum velocity ranges from 0 to 14000. The drag evolution is highly dependant upon the rear cylinder depth.

Our analysis is focused on the effects of the front small cylinder. It is based upon visualization interpretations and drag force measurements. The front cylinder wake “impacts” the main one and therefore the acting drag and lift forces are modified. These forces are measured by using a force transducer and an embarked CCD camera is able to give a video sequence of the near wake pattern. The FS effects are studied by varying the depth parameter. The only results dealing with drag coefficient Cd, recirculation length L/D, near wake pattern and free surface profile are presented. Fluctuating transverse forces and discontinuities phenomena are under investigations.

2 FORMULATION OF THE PROBLEM

A set of two rigid parallel cylinders are towed beneath a free surface. The purpose of the experimental method is to give the near wake pattern and to characterize the interaction between the acting forces, the wave profile and the interference phenomenon. The acceleration (respectively deceleration) value is $a = 0.150\ m.s^{-2}$ (respectively a=-0.150 m.s-2). We study the proximity effects of the small cylinder on to the main one by investigating the wakes interaction and its consequences to the vortex shedding on the main cylinder. Those investigations are conducted on the basis of visualization analysis and force measurements.

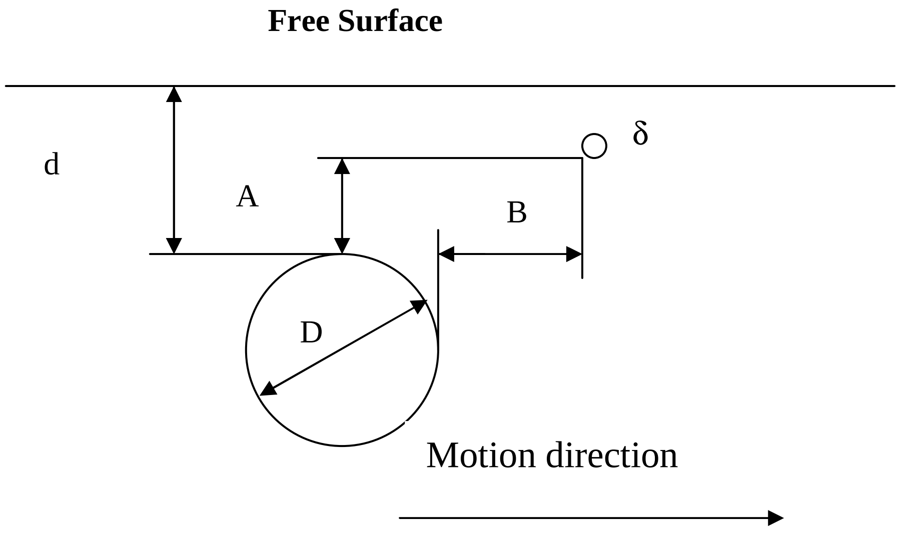

Figure 1: The set of the two cylinders arrangement

The geometrical parameters of the problem are defined as follows see figure 1:

D: main or rear cylinder diameter D= 2R = 40mm
δ: secondary or front cylinder diameter δ = 2mm;
A: the vertical coordinate of the secondary cylinder is A+R
B: The horizontal coordinate is B+R
d: depth of the tandem

The respective values of these parameters are:

A = -0.5D; -0.25D; 0; +0.25D; +0.5D; B = 1D; 2D; 3D; d = 1D; 2D; 3D; 4D; 5D

Thus, for each value of the diameter δ of the secondary body, we have five values of A. For each value of A we have three values of B and finally for each value of B we have five values of d. The experiments cover 75 possible states of the system.

3 EXPERIMENTAL SETTINGS

The experimental device consists in a 2m x 1m x 1m tank filled with water. The Plexiglas tank sides allow the wakes observation. The horizontal tandem spanned the tank and is towed by a 3 axis mechanism for which the only horizontal degree of freedom is used. The motion is obtained by a motor piloted by a numerical command system driven by a PC in such a way that an accelerated/decelerated displacement covers a range of Reynolds numbers – based upon the maximum velocity – from 0 to 14000. The rear cylinder is equipped with a 3D KISTLER force transducer suitable for drag and lift force measurements during the displacement. The camera is used to record the near wake evolution past the rear cylinder including the free surface profile when the cylinder is towed. The water is seeded with RILSAN particles and a light sheet is obtained from a light spot that illuminates a vertical median plane in the medium. It is assumed that the flow is bidimensional since the 3D effects are assumed to be minimized because of the unsteadiness of the motion. The experiment duration is 6s that is to say 3s for the accelerated motion where a = 0.150 m/s2 and 3s for the decelerated one where a = -0.150 m/s2. The whole system is detailed in Rajaona 2005.

4 RECIRCULATION LENGTH

The recirculation length for the main cylinder is defined by the distance from its basis to the saddle point related to the two contra rotating vortex zone in the near wake. The results reported in figure 2 deal with the values A=+0.25D, B=1D and A=-0.25D, B=1D when the parameter δ/D is 0.05. For this experiment, the immersion parameter takes values from 1D to 5D. The FS proximity gives rise to a precocious vortex shedding since the instant at which we can measure L/D is lowered; however the curves slopes are not significantly modified. Furthermore the effect of the small cylinder is enhanced when it is near the FS, A=0.25. That is why the curves slopes are different from a configuration to another. In fact we have observed that a jet like flow is generated when a cylinder moves very closely to the FS (Rajaona 2007)

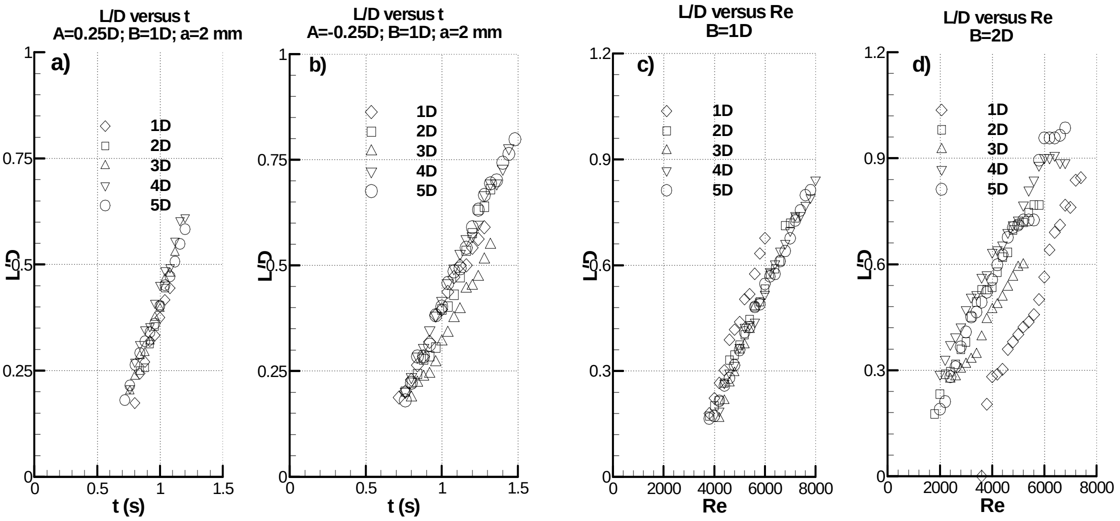

Figure 2. Recirculation length vs time: a) A=+0.25D, B=1D and b) A=-0.25D, B=1D when the parameter δ/D is 0.05 where δ is the front cylinder diameter. c) & d): Recirculation length vs. Reynolds numbers for a solitary cylinder past a grid screen. The grid screen is fixed at B=1D and B=2D in front of the main cylinder

We have compared the actual results with those obtained when a grid screen is placed in front of the cylinder. This means that the front cylinder has been replaced by the screen. This latter is made of rectangular grid for which the wire has circular section and a diameter of 1 millimetre. The results shown on fig. 2c&2d illustrate the fact that the flow past the grid is “homogeneous” contrarily to the case where a front cylinder is used. The curves slopes are very weakly modified by the FS effect when a grid screen is used. As shown for the case B=2D, the curves are gathered and give rise to a behaviour independent to the depth parameter. For the case of B=1D, the FS effects are more significant and the curve corresponding to d =1D is clearly shifted from the others. We see that the recirculation length evolutions for the two experiments are quite similar. In addition, the main cylinder recirculation length is lowered by the front one and a precocious vortex shedding is observed; this result has also been observed when the screen grid has been used in place of the small cylinder.

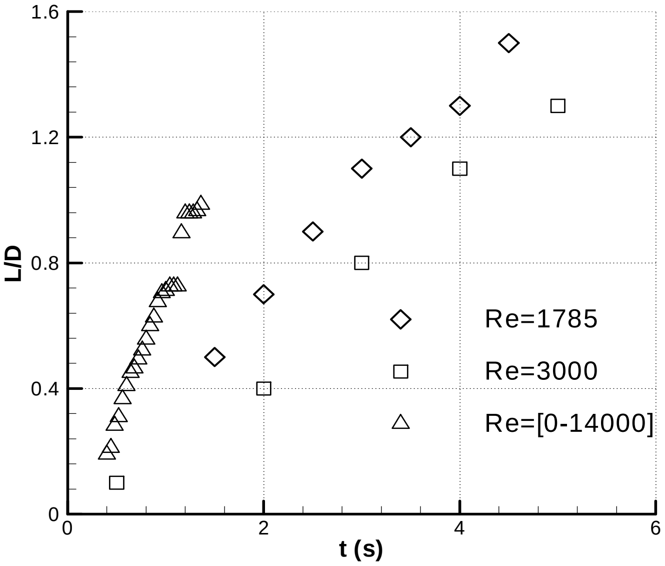

Figure 3. Recirculation length vs time t from various authors for a solitary cylinder without FS effects. Re=1785 is from Rajaona et al; Re= 3000 is from Bouard et al 1981; the delta symbol deals with the present work for a solitary cylinder at d/D=5.

A comparison with results obtained by Rajaona et al. 2003 and Bouard et al. 1981 is reported on the figure 3. The slope curve related to our work is higher. These discrepancies are mainly due to the range of Reynolds numbers. In addition, Bouard experiments were conducted with very weak turbulence rate. The experiments by Rajaona et al. were conducted far from the FS and with a higher turbulence rate.

5 DRAG FORCES MEASUREMENTS

The drag force acting on the rear cylinder is modelled by a Morison equation:

$$Fx = \frac{1}{2}\rho\frac{\pi D^2}{4}L\cdot C_m\cdot\dot{V} + \frac{1}{2}\rho\cdot L\cdot D\cdot C_d\cdot V^2 \qquad (1)$$

where *Cm* is the added mass coefficient and *Cd* is the drag coefficient. When the “tandem” is uniformly accelerated we can have the horizontal *x* displacement by:

$$x = \frac{1}{2} \cdot a \cdot t^2 \Rightarrow 2 \cdot x \cdot a = \gamma^2 \cdot t^2 \Rightarrow t^2 = \frac{2x}{a}$$

where a is the acceleration value. By inserting this value of t^2 in equation (1), we have

$$Fx = \frac{1}{2} \rho \frac{\pi D^2}{4} L \cdot a \cdot C_m + \frac{1}{2} \rho \cdot L \cdot D \cdot C_d \cdot 2 \cdot a \cdot x$$

In a non dimensional form we have:

$$\frac{F_x}{\frac{1}{2} \rho \frac{\pi \cdot D^2}{4} \cdot a \cdot L} = C_m + C_d \cdot \frac{8}{\pi} \cdot \frac{x}{D} \qquad (2)$$

A similar derivation can be applied to the deceleration motion. The equation (2) shows that the drag force is linear with the non dimensional displacement *x/D.*
The Cd values are discussed in this work and further investigations are needed for the added mass measurements. The reason is that the Cm value was too low compared with the cylinders mechanical inertia inducing significant error. The present results correspond to:

- δ = 2 mm, A= +0.5D B =1D, 2D, 3D and the depth parameter d/D = 1, 2, 3, 4, 5

The depth parameter effect is illustrated in fig. 4. It is shown that Cd is increased when the FS parameter d/D is equal to 1 for δ = 2 mm. Cd takes values about 1.2 as for a subcritical flow regime. We have observed that the FS effect is dependant upon the diameter of the front cylinder. For a higher diameter a “mask effect” gives rise to a decrease of the Cd despite of the low values of the depth parameter.

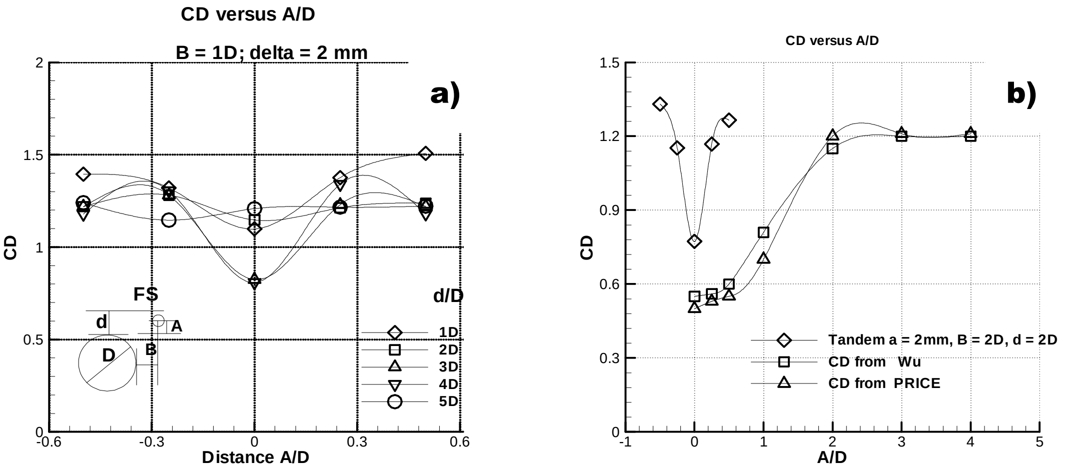

Figure 4. Cd values against A/D values for B=1D, d = 2 mm. CD values are increased for A/D=0.3-0.6.

Compared with results obtained previously by Sulmont et al. 1988 at high Re for a solitary cylinder, the actual results show, as expected, that the turbulent onset flow leads to decreasing of the Cd values whatever the way used to obtain such flow either by the front cylinder or the grid screen. For a depth parameter higher than 5 the Cd values are about 0.6. These results are similar to Sarpkaya results for a solitary cylinder. From the point of view of the turbulence effect, the Cd value is lowered when the turbulence rate is increased. This phenomenon is classically known. It is attributed to a displacement of the separation point to the basis of the cylinder. If the A+R parameter is varied from positive to negative values a symmetric variation of the Cd values is observed with respect to the vertical axis (see fig. 4). This observation is available as far as the depth parameter remains higher than 2. This behaviour is observable for a front cylinder of 2 mm diameter and to a lesser extent for a diameter of 8 mm. A comparison of our results to those by Price 1976 and Wu 2002 (see fig. 4b) shows that the behaviours of the drag forces are similar but the Cd values are very dependant upon the size of cylinders, since in their experiments the cylinders had the same diameter and A=-R. Cd values are increased in both experiments from 0.6 or 0.7 to 1.2. But four our experiments the jump in Cd is noticed in the gap parameter from 0. to 0.5 for d/D = 3. and for Wu and Price from 0. to 2D without a free surface.

6 NEAR WAKE PATTERN AND FREE SURFACE PROFILE

The near wake pattern has been analyzed by using the video sequence recorded by the embarked camera. This sequence has been transformed into separated frames for each time step with a rate of 25 pictures per second and a FS profile is extracted from each image. Once the frames are obtained, each of them is filtered in such a way that a black and white color is retained. A threshold level is then chosen in order to lead to a streamline figure. This process is illustrated on figure 5 where a complex near wake is detailed. Four vortices can be clearly seen: two shed from the front cylinder quoted 1 and 2 and two “massive” vortices quoted 3 and 4 shed from the rear cylinder. It is possible to follow the trajectory of these four vortices as far as they remain in the camera field. In addition, the FS profile can be observed and measured from each picture and an evolution of the FS profile is derived.

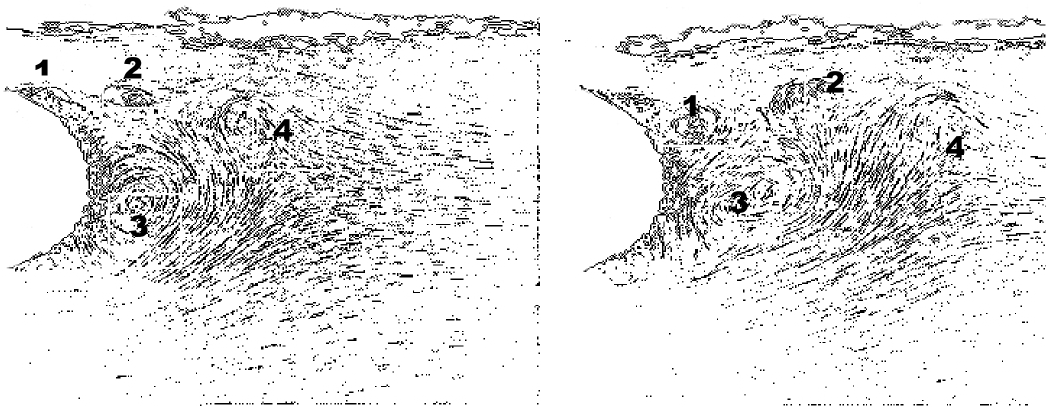

Figure 5. Photography of the near wake pattern d/D=0.375, t= 1.20 s, and t=1.32s, A=0.5D, B=2D, Four vortices are observed: two small vortices from the front cylinder 1&2 and two others from the rear cylinder 3 and 4. The vortex 1 has left the cylinder and is attracted by 3, while 2 migrates to FS.

It is well known that the vortex shedding frequency depends upon the diameter of the cylinder via the Strouhal number. Specifically this frequency is higher for the smaller cylinder at same flow regime in such a way that the shed small organized vortices reach the main cylinder before this one begins to shed its own vortices. We have observed that the small vortices impacting the main cylinder have some influence on the boundary layer on the upper side of the main cylinder and provoke a displacement of the separation point on the main cylinder. Furthermore it has an anticipating effect on the vortex shedding of the rear cylinder. These secondary vortices are fully developed before mixing with the recirculation zone of the rear cylinder. This mixing phenomenon modifies its recirculation length (see fig.2). The relative spatial frequency of these secondary vortices *l*/D values range from 0.425 to 0.625.

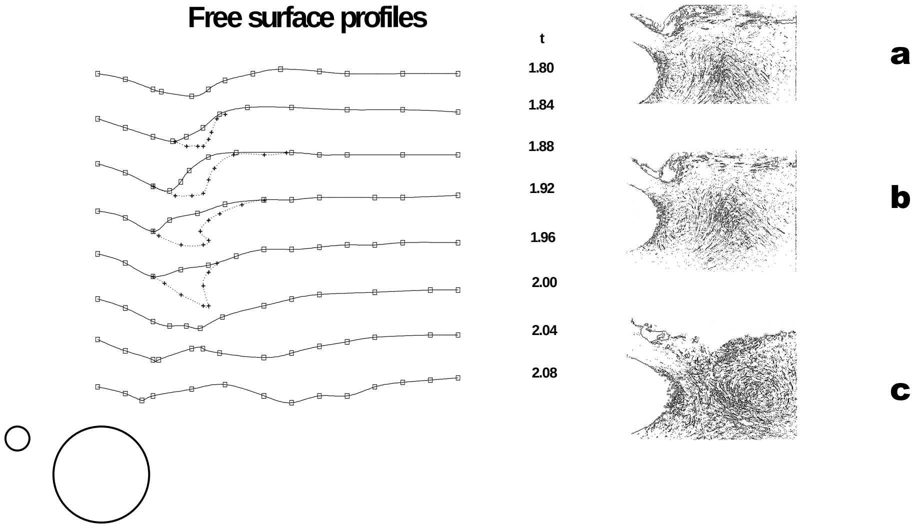

Figure 6. Photography of the free surface profile d/D=0.375, A =0.5D, B=2D, t=1.80-2.08 s. The FS profile has been deduced from the photography. Three photos a, b, c are shown for times t=1.88s for a), t=1.88s for b), t=2.04s for c). A jet like pattern is shown on the upper side of the main cylinder as for the case of a solitary cylinder.

Eight FS profiles are shown for time values in the range from 1.80s to 2.08s. These profiles are interesting since a spilling breaker appears during this part of motion, similar to those described by Duncan 1981. Specifically, one can observe the evolution of the FS profile in photos a), b), c) see figure 6. It is also observable that a large coherent vortex migrates from the near wake to the FS once the FS breaker disappears at t = 2s. The wave front includes a turbulent zone shown by the dotted line at t = 1.84-1.96.

7 CONCLUSIONS

An experimental investigation of the near wake past a set of two parallel staggered cylinders towed beneath a free surface is presented. The experiments are conducted in a visualization tank. An accelerated/decelerated motion is used in order to enhance the vortex dynamics rendering easier their observations. A light sheet is used to visualize the near wake past the rear cylinder and a video sequence is recorded by an embarked camera. Some features of the vortex dynamics in the near wake are described. The measurements of the recirculation length L/D past the rear cylinder show that the vortices shed from the front cylinder provoke an anticipated vortex shedding. The CD takes values near 1.2 as expected when the depth parameter d/D is higher than 1. CD values are increased when d/D is lower than 1. FS profile shows the inception of a breaker at each vortex shedding and a vorticity transfer to the FS. The wave profiles are similar to those related to a towed hydrofoil except that the phenomenon is only observable at each vortex shedding due to the unsteadiness of the cylinders motion.

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