E-proceedings of the 36th IAHR World Congress
28 June – 3 July, 2015, The Hague, the Netherlands

AN EXPERIMENTAL STUDY OF THE EFFECTS OF FINITE WATER DEPTH AND LATERAL CONFINEMENT ON SHIPS WAKE AND DRAG

CLEMENT CAPLIER(1), GERMAIN ROUSSEAUX(1), DAMIEN CALLUAUD(1) & LAURENT DAVID(1)

(1) Pprime Institute, CNRS, University of Poitiers, ISAE-ENSMA, 86962 Futuroscope Chasseneuil, France
clement.caplier@univ-poitiers.fr

ABSTRACT

Wash waves produced by ships disintegrate river banks and coastal lines. This phenomenon of bank erosion is mainly due to the height of the waves. To understand the influence of the geometry of the water channel, the shape of the boat and its speed on the formation and the amplitude of wash waves, the analysis of the ships wakes in the waterway is essential. This study proposes a comparison of wakes generated by two hulls representative of maritime and river ships. The wakes generated in deep water and shallow water configurations have been measured for different Froude numbers with a non-intrusive optical stereo correlation method, giving access to a detailed and complete definition of the generated wave fields. The results permit to study the influence of both hull and water channel geometries on the ship's wake shape, on the amplitude of the generated waves and on the hydrodynamic response around the hull. The drag of the hulls has also been measured in deep and shallow water configurations with a hydrodynamic balance to highlight the effect of both hull and water channel geometries on the ship resistance.

Keywords: Wake – wash waves – confinement – ship resistance

1. INTRODUCTION

Various factors govern the generation and the amplitude of wash waves: the bathymetry of the water channel, the geometry and the speed of the ship, the speed and direction of the current, etc. When a ship navigates in a confined waterway, the effects of confinement result in the appearance of a bow wave, causing an increase of the drag of the ship (and therefore its fuel consumption). Moreover the shape of the wake changes (lowering of the water level around the hull) and the waves reflects on the river banks. The impact of the waves on the banks causes erosion and the lowering of the water level creates a return current around the hull, causing a sediment transport and deposition in the waterway. That can lead to hazardous situations for ships such as grounding.

To study the impact of wash waves on the environment, the analysis of the wakes generated by the ships is essential. For this, a detailed characterization of the wave field is required. Measurements of ships-generated wakes in towing tanks are generally made with resistive probes, acoustic sensors or laser wave gauges. These punctual or one-dimensional techniques remain limited for the characterization of the whole wake and full-field techniques measuring accurately the water level at different points are thus essential. Moreover resistance tests are necessary to understand the effects of the confinement of the water channel and the shape of the hull on the ship resistance.

The wakes of two hulls representative of maritime and river ships (Caplier et al., 2014) have been measured in a towing tank with an optical measurement method based on a stereo correlation principle (Chatellier et al., 2010; Gomit et al., 2012) which permits a measurement of the whole wake and a fine reconstitution of the generated wave field. The comparison of the wakes for different waterway configurations (deep water, shallow water) and for different ship speeds highlights the effects of the water channel bathymetry and the ship geometry on the forming of wash waves. In a first step, the experimental set-up of the study will be presented i.e. the towing tank, the ship hulls, the stereo correlation method and the hydrodynamic balance. The different configurations that have been studied will be stated and finally the wakes measured for each configuration and the resistance curves will be presented and analyzed. The effects of the bathymetry of the waterway, the shape and the speed of the ship will be identified and quantified through the analysis of the results.

2. THE EXPERIMENTAL SET-UP

2.1 The towing tank and the ship hulls.

The ship wakes have been generated and measured in the towing tank of the Pprime Institute. The canal is 20m (meter) long and has a rectangular section of width W=1.5m. The water level can be set up to 1.2m. The hull is towed by a trolley along the longitudinal axis of the canal at a speed up to 2.35m.s^{-1} (meter per second). During the trials, the hull is kept fixed with a vertical mast so that roll, pitch and yaw motions are impossible.

Both hulls are based on a Wigley hull with a rectangular section (Wigley, 1926). This parabolic hull is mathematically defined by the equation [1] in which *x* and *y* represent respectively the longitudinal and transverse axes of the ship. L represents the length of the hull (L=1.2m) and B its beam (B=0.18m). During the experiments, the draft of the hull is D=0.075m. As a first step, a classical Wigley hull noted WH2 (where 2 reminds the value of the exponent n in the equation [1]) representative of a maritime ship with a block coefficient C_b=0.67 has been analyzed. As the block coefficients of river ships are around 0.8-0.9, another Wigley-based hull noted WH8 (for which n is equal to 8, Eq. [1]) with a block coefficient C_b=0.89 has also been analyzed. Thus it is possible to study the influence of the geometry of the boat on the shape of the generated wakes and on the amplitude of the wash waves.

$$y = f(x) = \frac{B}{2}\left[1-\left(\frac{2x}{L}\right)^{n=2}\right] \qquad [1]$$

2.2 The stereo correlation method and the hydrodynamic balance

The wakes have been measured with an optical measurement method based on a stereo correlation principle (Chatellier et al., 2010; Gomit et al., 2012). Two cameras Jai RM-4200CL that deliver a resolution of 2048 x 2048 pixels and equipped with Nikkor AF 28mm 1:2.8 lenses are placed 1.5m above the water surface. The two cameras focus on the same zone with an opposite angle of ±15° (degree) with respect to the longitudinal axis and 35° with respect to the vertical one. The common field covered by the cameras forms a rectangular zone of dimensions 0.90 x 0.75m^2 corresponding to half the canal width. The acquisition of the images is performed with a R&D Vision system composed by the Hiris software piloted by a synchronization box EG that sets the acquisition frequency to 10 frames per second and the exposure time of the cameras to 10ms. As a first step the cameras are calibrated with a two-dimensional target of points that is displaced along the longitudinal axis of the canal. Before launching the ship and starting the acquisition of the images, the free surface is sowed with floating particles. These particles serve as markers that will follow the deformations of the free surface. To check the reproducibility of the result each measurement is performed three times. Once the images have been recorded by the cameras, a correlation algorithm based on the SLIP library (Tremblais et al., 2013) processes the image pairs and calculates the free surface deformation at each time step with a spatial resolution of 10mm and a precision on the wave height of 0.1mm. Finally, from the wave fields calculated for each of the three measurements, a mean wave field is calculated at each time step and the wake is reconstructed around the hull with a dedicated algorithm. The result is shown on the Figure 1 on which the black color represents the zones where the computing of the correlation is impossible because of either the absence of particles (chased away by the hull in the middle zone of the waterway), too high wave amplitudes on the banks or wave breaking. In addition, the drag of the ships has been measured with a multicomponent dynamometer Kistler 9272 placed between the ship hull and the vertical mast of the trolley. The dynamometer measures three axial forces and a momentum along the vertical axis at a frequency of 1kHz (kilohertz). The ship resistance is taken as the temporal average of the measured longitudinal component of the force opposing to the motion of the ship. The resistance is measured in Newton (1N=1kg.m.s^{-2}, kilogram meter per square second).

3. THE DEEP WATER AND CONFINED WATER CONFIGURATIONS

The speed of the ship U(m.s^{-1}) and the water depth h(m) for each configurations have been determined on the basis of both physical and geometric criteria, to take into account the effects of finite water depth and lateral confinement during the experiments. Moreover, two non-dimensional numbers connecting the different parameters, i.e. the ship length-based Froude number Fr_L and the water depth-based Froude number Fr_h are significant for the comparison of the wakes and the analysis of the results. These non-dimensional numbers are defined in the equation [2] in which g is the gravity in m.s^{-2} (meter per square second).

$$Fr_L = \frac{U}{\sqrt{gL}} \quad , \quad Fr_h = \frac{U}{\sqrt{gh}} \qquad [2]$$

On the one hand, a relation between the water depth, the speed of the ship and the gravity has been defined by Noblesse et al. (2014). This relation leads to a limit value of the height-based Froude number Fr_h=0.58. Above this particular value the effects of finite water depth appear from an undulatory point of view. The water depth can be considered as infinite below this threshold. On the other hand, a classification established by the public institution that manages the French inland waterways - Voies Navigables de France (VNF), courtesy of P.-J. Pompée - gives limit ratios between the geometric parameters of the water channel and the ship, below which the height and lateral confinement is important from a hydraulic point of view. These ratios are h/D<4 for the vertical confinement and W/B<10 for the lateral confinement.

Considering this, the wakes have been measured for two advancing speed U=0.80m.s^{-1} and U=1.20m.s^{-1} and for two water depths h=0.483m and h=0.103m. This set of parameters (Table 1) allows to cover a wide range of height-based Froude numbers Fr_h while staying under the limit length-based Froude number Fr_L=0.50 recently highlighted by Moisy et al. (2013) and discussed by Noblesse et al. (2014), who both argue that the wake angle should diminish with the ship speed but with different explanations. For both deep water and shallow water configurations, the effects of lateral confinement will be the same as the width of the waterway is constant. This lateral confinement will result in the reflections of the waves on the walls of the canal. Moreover, the shallow water configuration will be representative of the navigation in confined water as it takes into account both undulatory (Fr_h > 0.58) and hydraulic (h/D <4) confinement.

The ship resistance has been measured for a range of length-based Froude numbers Fr_L between 0.13 and 0.63 (corresponding to height-based Froude numbers Fr_h between 0.20 and 1.00) for the deep water configuration. As regards the shallow water configuration, the range of the Froude numbers is between 0.18 and 0.54 for the length-based Froude number Fr_L (corresponding to height-based Froude numbers Fr_h between 0.60 and 1.85).

Table 1. The parameters of the experiments.

	DEEP WATER		**SHALLOW WATER**	
h(m)	0.483		0.103	
$U(m.s^{-1})$	0.80	1.20	0.80	1.20
Fr_L	0.23	0.35	0.23	0.35
Fr_h	0.37	0.55	0.80	1.20
h/D	6.44		1.37	
W/B	8.33			

4. RESULTS

4.1 Deep water versus shallow water wakes

The figure 1 represents the different wakes measured for the deep water configuration (a and b) and the shallow water configuration (c and d). The upper part of each wake corresponds to the maritime hull (WH2) whereas the bottom corresponds to the river hull (WH8).

For the deep water configuration (Figure 1 a and b), the wakes correspond to the classical Kelvin wake pattern reflecting on the walls of the canal, whatever the speed of the ship and its shape. This is the typical wake generated by ships navigating in deep waters. This wake pattern is made of a transverse wave system and a divergent wave system superimposing on a line called the caustic of the wake. The caustic forms a typical angle with the ship axis called the Kelvin angle equal to 19.47° for length-based Froude numbers $Fr_L < 0.50$ (Moisy et al., 2013; Noblesse et al., 2014). As a reminder, the deep water wakes have been measured for length-based Froude numbers below this threshold. A geometrical analysis of the deep water shows that the angle for the wakes generated by the maritime hull corresponds to the Kelvin wake of 19.47°, whereas the river hull seems to generate a higher angle. Moreover, the higher block coefficient of the river hull leads to higher waves amplitudes in the wake, especially on the walls of the canal. Indeed, for a ship speed of $0.80m.s^{-1}$, the maximum peak-to-trough amplitudes on the wall (for X between 1m and 2m) is of 2.0cm (centimeters) for the maritime hull and 5.0cm for the river hull, an increase of 150% of the wave height. For a ship speed of $1.20m.s^{-1}$, the increase is less important: the peak-to-trough amplitudes are respectively of 5.3cm and 7.4cm, an increase of 40% of the wave height. In both cases the wash waves generated by the river hull are more destructive.

The wakes generated in the shallow water configuration (Figure 1 c and d) are different of the deep water wakes that have been presented previously. For a ship speed of $1.20m.s^{-1}$, the wake is supercritical (Fr_h>1.00) and is reminiscent of the Mach cone observed in supersonic aerodynamics. Indeed, the bow wave generated in front of the ship looks like a supersonic shock wave. Moreover, the transverse waves have disappeared while transferring their energy to the divergent waves. On the opposite, for a ship speed of $0.80m.s^{-1}$ corresponding to a height-based Froude number Fr_h=0.80 the wakes are only made of transverse waves. These wakes are reminiscent of those observed by Scott Russell (1840) during his experiments in waterways. His pioneering work has clearly highlighted the effects of the finite water depth and the lateral confinement on ship wakes, in particular the lowering of the water level around the ship and the generation of a bow wave leading to an increase of the ship resistance. Both phenomena are observed on the measured wakes whatever the speed and the shape of the ship. The hydrodynamic response around the hull is in fact more pronounced in shallow water than in deep water. The coupling of the lowering of the water level with the return current around the hull is destructive for the river banks and plays an important role in the sediment transport and deposition in the waterway. Another effect that would be destructive for the river banks is the wave breaking observed at X=1m for a ship speed of $0.80m.s^{-1}$, especially for the maritime hull (Figure 1c, top). This wave breaking phenomenon can be also dangerous if the ship passes another one. As regards the bow wave, its amplitude is 1.0cm for a ship speed of $0.80m.s^{-1}$ and 4.0cm for a ship speed of $1.20m.s^{-1}$ so the ship resistance will be more important.

4.2 Resistance curves

The resistance curves for the deep water configuration (figure 2, left) show an increasing of the resistance with the speed of the ship for both maritime and river hulls. The oscillations of the resistance for low length-based Froude numbers for the maritime hull correspond to the interaction between the bow wake and the stern wake. In some cases it may be more interesting to go faster to reduce the ship resistance and so its fuel consumption. As regards the river hull which has a superior block coefficient, the displaced volume of water is more important so the total resistance is higher (and so is the fuel consumption). For a ship speed of $0.80m.s^{-1}$ corresponding to the length-based Froude number Fr_L=0.23 the resistance is 5 times higher (from 0.5N to 2.5N). Similarly for a ship speed of $1.20m.s^{-1}$ corresponding to the length-based Froude number Fr_L=0.35 the resistance is 3.3 times higher (from 2.7N to 8.8N).

For the shallow water configuration (figure 2, right) the trends of the curves become different. For a length-based Froude number Fr_L around 0.22 corresponding to a height-based Froude number Fr_h around 0.75 there is a big increase of the resistance. This rise of the ship resistance is perceived as a wall for ships navigating in confined water and they can rarely overcome this. This sharp increase corresponds to the apparition of the bow wave in front of the ship and is higher for the WH8 hull which is representative of river ships in terms of block coefficient. After that step and until a length-based Froude number Fr_L=0.38, corresponding to a height-based Froude number Fr_h=1.31, the ship resistance increases with the speed, but at a higher rate for the river hull. This increase of the ship resistance corresponds to the increasing amplitude of the bow wave. However, after the length-based Froude number Fr_L>0.38, there is a drop of the ship resistance (from 8.0N to 6.0N for the maritime hull). That corresponds to the particular moment when the ship passes ahead the bow wave and kind of surf on it. The ship is then pushed by the bow wave and so the ship resistance is lower. This major effect of the lateral confinement and finite water depth on the ship resistance had also been highlighted by Scott Russell (1840).

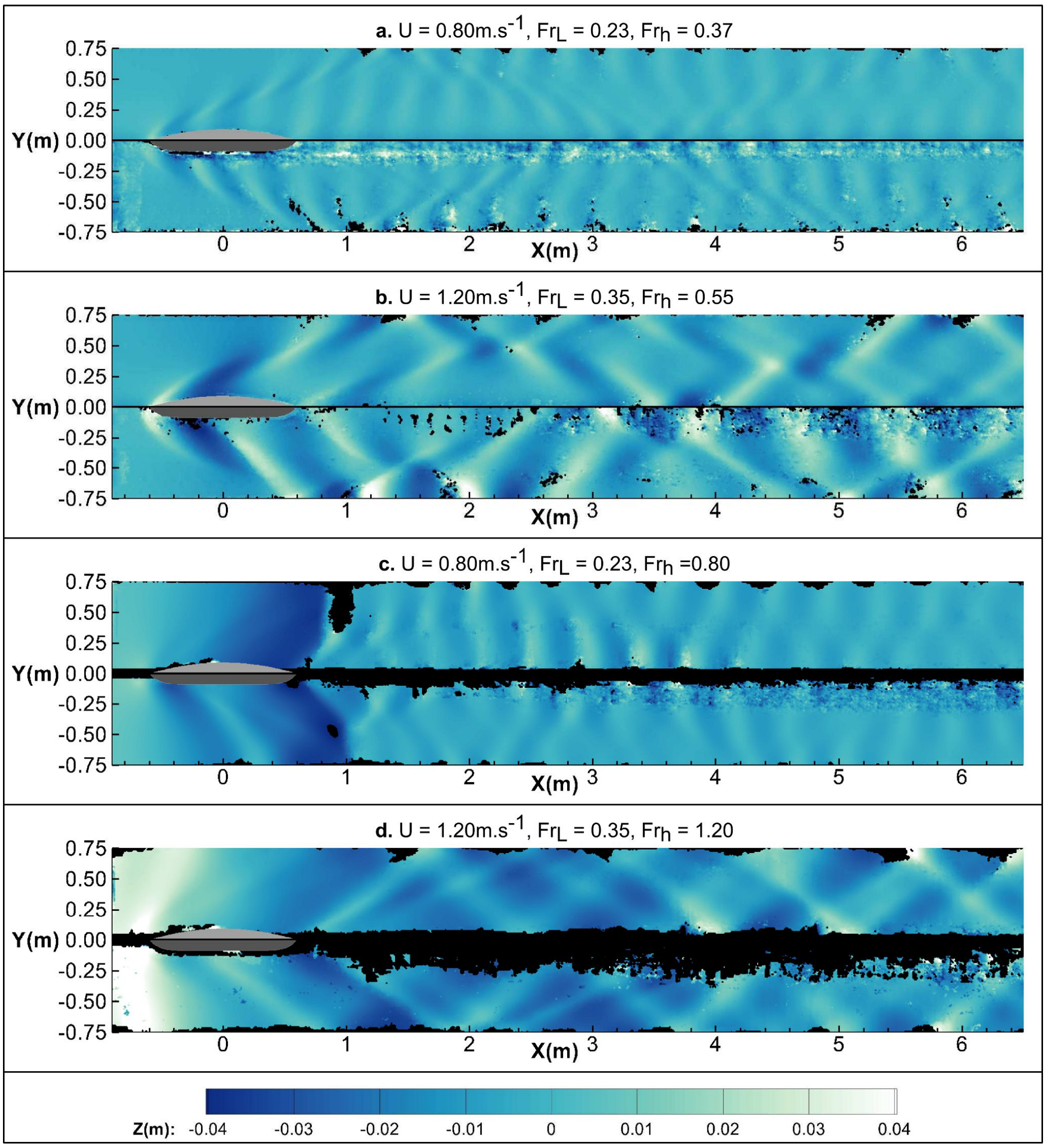

Figure 1. The wakes measured for the deep water (a and b) and the shallow water (c and d) configurations.
The upper part of each wake corresponds to the maritime hull WH2 and the bottom corresponds to the river hull WH8.

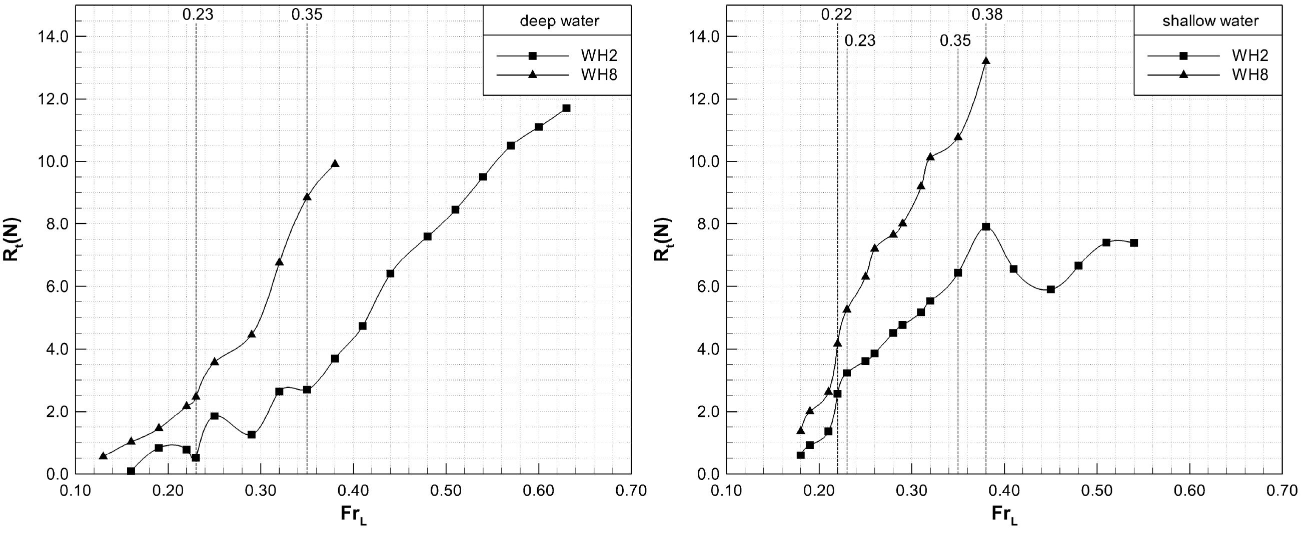

Figure 2. The total resistance R_t(N) versus the length-based Froude number Fr_L for the deep water (left) and shallow water (right) configurations.

5. CONCLUSIONS

This experimental study has permit to measure ships wakes generated by a maritime and a river ship for different configurations of the waterway. Different types of wakes have been identified and their analysis has highlighted the effect of the block coefficient on the amplitude of the generated waves in a deep water configuration. For a shallow water configuration, the bow wave and the lowering of the water level, which are the major effects of the confinement, have been identified and quantified. As the optical measurement method gives a detailed and precise reconstruction of the wakes, their analysis in the spectral domain is possible. It will permit to measure the angle of the wake more precisely, to isolate the hydrodynamic response around the hull and to study the energy repartition between the different wave systems (Gomit et al., 2014). Finally, the resistance measurements for different ships speeds have permit to identify the effects of the block coefficient of the hull on the ship resistance in both configurations. For the shallow water configuration, the effect of the bow wave on the ship resistance has been emphasized and quantified.

REFERENCES

Caplier C., Rousseaux G., Calluaud D. and David L. (2014). Etude expérimentale des effets de hauteur d'eau finie et de confinement latéral sur les sillages de navires en bassin des carènes. *14èmes journées de l'Hydrodynamique, Val de Reuil, France*.

Chatellier L., Jarny S., Gibouin F. and David L. (2010). Stereoscopic measurement of free surface flows. *14th International Conference on Experimental Mechanics, Poitiers, France*, 6.

Gomit G., Calluaud D., Chatellier L., David L. and Frechou D. (2012). Développement et applications de techniques de mesures optiques pour l'analyse de sillages de navire en bassin des carènes. *13èmes journées de l'Hydrodynamique, Chatou, France*.

Gomit G., Rousseaux G., Chatellier L., Calluaud D. and David L. (2014). Spectral analysis of ship waves in deep water from accurate measurements of the free surface elevation by optical methods. *Physics of Fluids* 26, 122101.

Noblesse F., He J., Zhu Y., Hong L., Zhang C., Zhu R. and Yang C. (2014). Why can ship wakes appear narrower than Kelvin's angle ? *European Journal of Mechanics – B/Fluids*, 46 (0), 164-174.

Rabaud M. and Moisy F. (2013). Ship wakes : Kelvin or Mach angle ? *Physical Review Letters*, 110:214503.

Scott Russell J. (1840). Mr Scott Russell's Researches in Hydrodynamics. *Transactions of the Edinburgh Royal Society*, XIV, 47-109.

Tremblais B., David L., Arrivault D., Dombre J., Thomas L. and Chatellier L. (2010). Simple Library of Image Processing (SLIP). *Licence CECILL DL 03685-01*.

Wigley WCS. (1926). Ship wave resistance. A comparison of mathematical theory with experimental results. Spring Meetings of the 67th Session of the Institution of Naval Architects, XIV:124–141.