MODELLING DISPLACEMENT WAVES PRODUCED BY SHIP ON ADJACENT SHOALS AND LATERAL INLETS OF NAVIGATION CANALS

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Abstract

Navigation canals in estuaries are typically surrounded by ample natural shoals of much smaller depth and/or by semi-enclosed zones of reduced area. Even if the ship exhibits a relatively weak wake, the very same displacement of her submersed volume may have remarkable effects in the contiguous regions of the canal if water depth is limited.

In a previous work (Di Silvio et al., 2011) the non-stationary currents created by the passing ship was calculated by the superposition of a stationary flow field and a strictly uniform motion (proportional to the ship velocity), transforming an absolute unsteady flow into a relative steady flow. In this work the uniform motion hypothesis is relaxed to consider a more complex and more general domain morphology, concentrating the attention on the effects of the waves on the lateral inlets.

The final resultant flow field is calculated via a simple two-dimensional model, for which different numerical methods of resolution are investigated.

The consequent effects on the surrounding areas result to be dependent on the ship's speed and the geometrical characteristics of the system canal /ship.

Introduction

The water motion created by a rather large ship sailing in a navigation canal excavated through a much shallower area, exhibits sometimes unexpectedly vigorous features even if the stationary waves at the prow and stern of the ship are very small. The basic mechanism responsible for this peculiar flow is the water displacement determined by the hull: the displaced volume, first pushed out of the waterway towards the shoals in front of the advancing vessel, will subsequently leave again the shoals when the vessel has transited. This phenomenon is somehow resembling the (positive) wind puff created on the highway side by an approaching vehicle, immediately followed by a (negative) wind suck when the vehicle goes by. For this reason we suggest to call it displacement wave.

This continuous "circular" flow pattern from the bow to the stern of the ship activated by the displacement wave, is dragged along by the traveling ship but is different from the more visible oscillatory waves (generally shorter and often breaking) created at the bow and stern by fast vessels, although sometimes coexisting with them.

In a previous work (Di Silvio et al., 2011) the non-stationary currents created by the passing ship was calculated by the superposition of a stationary flow field and a strictly uniform motion (proportional to the ship velocity), transforming an absolute unsteady flow into a relative steady flow. Moreover the equations that describe the stationary flow field around the (steady) ship immersed in the undisturbed uniform flow, have been subjected to a number of simplifications which are in principle valid only for low values of the Froude number.

In the present paper, numerical investigation has been carried on to reconsider these simplifications in particular by revising some model's linearizations, as well as by reintroducing the convective accelerations (Bernoulli terms) neglected in the previous paper.

A further important step has been made to relax the uniform flow hypothesis for the incoming stream. This hypothesis is valid, in fact, only if the ship navigates along a straight canal of constant cross-section surrounded by infinitely wide shoals of uniform depth. By the new approach, it will be possible to consider a more complex and more general morphology of the computational domain, including the presence of lateral inlets or tributary channels, as it is often the case in the lagoon of Venice where the model has been applied. In the following section, the complete model will be described and a comparison will be made between its numerical results and the results of the previous simplified approach, taking also into account a few available experimental data.

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Mathematical model

As already observed in the previous paper (Di Silvio et al., 2011), the displacement waves considered here have nothing to do with the water surface disturbances (wakes) created at the bow and stern of a ship which moves at a relevant speed and sustained in their propagation by various instability mechanism where vertical velocities and water surface curvatures play a fundamental role.

Displacement waves, on the contrary, are typical "long waves" which are particularly relevant in shallow water and may therefore be described by 2-D (depth integrated) equations of water flow, called also de St. Venant equations, which can be solved by appropriate numerical procedures.

In order to avoid the numerical difficulties connected with the continuously variable boundary conditions represented by the moving rigid surface of the ship, an alternative method has been adopted which requires only steady-flow 2-D computations. With this purpose the actual instantaneous absolute unsteady flow $\overrightarrow{V_N^A}$ (produced in the still lagoon by the vessel sailing at a constant speed $\overrightarrow{V_N}$) has been decomposed into a relative steady flow $\overrightarrow{V_N^R}$ (observed from the same vessel assumed to be steady) plus the transport flow, namely the uniform speed of the vessel $\overrightarrow{V_N}$:

$$\overrightarrow{V_N^A} = \overrightarrow{V_N^R} + \overrightarrow{V_N} \tag{1}$$

The absolute motion $\overrightarrow{V_N^A}(x,y)$ produced by the vessel may also be obtained as the difference between the absolute motion $\overrightarrow{V_{N+W}^A}$ (produced by the system "ship+waterway", advancing at the speed $\overrightarrow{V_N}$ in an infinite domain of still water) and the absolute motion $\overrightarrow{V_W^A}$ (produced by the system "waterway alone", also advancing at the speed $\overrightarrow{V_N}$ in an infinite domain of still water). Namely:

$$\begin{aligned}\overrightarrow{V_N^A}(x,y) &= \overrightarrow{V_{N+W}^A} - \overrightarrow{V_W^A} \\ &= \left(\overrightarrow{V_{N+W}^R} + \overrightarrow{V_N}\right) - \left(\overrightarrow{V_W^R} + \overrightarrow{V_N}\right) \\ &= \overrightarrow{V_{N+W}^R}(x,y) - \overrightarrow{V_W^R}(x,y)\end{aligned} \tag{2}$$

The flow-fields $\overrightarrow{V_{N+W}^R}(x,y)$ and $\overrightarrow{V_W^R}(x,y)$ can be numerically obtained from the numerical solution of the De St. Venant equations in stationary condition and obviously depend on the instantaneous position P of the ship along the waterway. By repeating the computation with different position $P(t)$, the instantaneous water-flow pattern $\overrightarrow{V_N^A}(x,y,t)$ can be obtained under the hypothesis of negligible local accelerations.

It is interesting to observe that, in the case of a straight waterway with uniform cross section of total width *B*, the expression of $\overrightarrow{V_W^R}(x,y)$ correspond to the uniform "translation flow" as defined in the previous paper (Di Silvio et al., 2011):

$$\overrightarrow{V_W^R}(x,y) = \overrightarrow{V_U}(y) = \overrightarrow{V_N}\frac{h(y)^{1/2}\int_B h(y)dy}{\int_B h(y)^{3/2}dy} \tag{3}$$

Where $h(y)$ is the water-depth of the waterway cross-section (including shoals) in the transversal direction *y*.

Depth-integrate water-flow equations

The superposition procedure adopted to compute the absolute water-flow $\overrightarrow{V_N^A}(x,y)$ (equation (2)) is valid only if the water-flow equations are linear.

In the present paper, the depth-integrated water-flow equations will be written in terms of energy *E* which will include both the potential and the kinetic components (neglected in the previous paper):

$$V_x = -\frac{h\chi^2}{W}\frac{\partial E}{\partial x} \qquad V_y = -\frac{h\chi^2}{W}\frac{\partial E}{\partial y} \tag{4}$$

$$\frac{\partial}{\partial x}\left(\frac{h^2\chi^2}{W}\frac{\partial E}{\partial x}\right) + \frac{\partial}{\partial y}\left(\frac{h^2\chi^2}{W}\frac{\partial E}{\partial y}\right) = 0 \tag{5}$$

where $V_x(x,y)$ and $V_y(x,y)$ are the velocities components in the *x* and *y* directions; *W* is the velocity resultant; *h* is the water-depth; $E = \eta + \frac{W^2}{2g}$ is the local energy; $\eta = z + h$ is the water elevation with respect to the mean sea level; and *z* is the bottom elevation below the mean sea level.

For their linearization, the velocity resultant *W* in equations (4) and (5) is assumed to be constant and equal to the local "translation flow" $\overrightarrow{V_N}(y)$ in uniform conditions (equation (3)). However it is set equal to

$$W = \sqrt{{V_x}^2 + {V_y}^2} \tag{6}$$

for evaluating the water-level *η(x,y)* from the computed local energy *E(x,y)*.

The numerical solution of equations (4) and (5) is carried on over an ample rectangular computational domain which includes the actual planimetric configuration of the navigation canal in the proximity of the ship. For both flow-field $\overrightarrow{\mathrm{V_{N+W}^R}}(\mathrm{x,y})$ and $\overrightarrow{\mathrm{V_W^R}}(\mathrm{x,y})$, the boundary conditions at the upstream and downstream ends of the domain will be prescribed as $q(y) = V_N h(y)$. Moreover, on the downstream end of the domain, the condition

$$E = \frac{W^2}{2g} \tag{7}$$

will be prescribed (*η=0*) at one arbitrary point, while along the lateral sides the no-flux condition will held.

Several numerical approaches have been tested to compute by trial and error the variables *h* and *W*.

Comparison of results

The linearized equations ((4) and (5)), written in terms of energy, have been solved by a finite elements method to determine the velocity-field $\overrightarrow{V^R_{N+W}}(x, y)$, $\overrightarrow{V^R_W}(x, y)$ and, by superposition, $\overrightarrow{V^A_N}(x, y)$, as well as the corresponding energy and water elevation. To obtain the time-history of water-level *η(t)* in correspondence to the water-level gauge where the displacement wave has been recorded, computations have been repeated with different positions of the ship along the waterway. In this way, the effects of lateral inlets along the navigation canal have been evaluated with respect to the computation results provided by the simplified model.

As an example, a comparison between the two models is shown in Figure 1 where the role effect of including the Bernoulli terms (although in a linearized form) is indicated, by assuming the same uniform navigation canal.

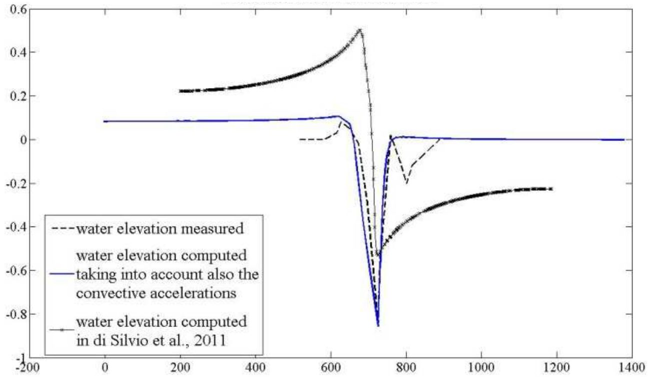

Figure 1: example of a comparison between the recorded level with wave's height provided by the previous model and the present model which take into account the convective accelerations.

In Figure 2 the corresponding results in a planimetric view of the domain around the vessel (identified by the green area) are shown: the velocity field is represented with red arrows (on the left top of the figure one can find the scale of the arrows magnitude) and the water level with respect to the mean sea level is represented by isolines which goes from blue (minimum level computed) to pink (maximum level computed). The irregularities (alternations of very high and very low intensity) of velocity field are numerical artifacts which we are still trying to eliminate.

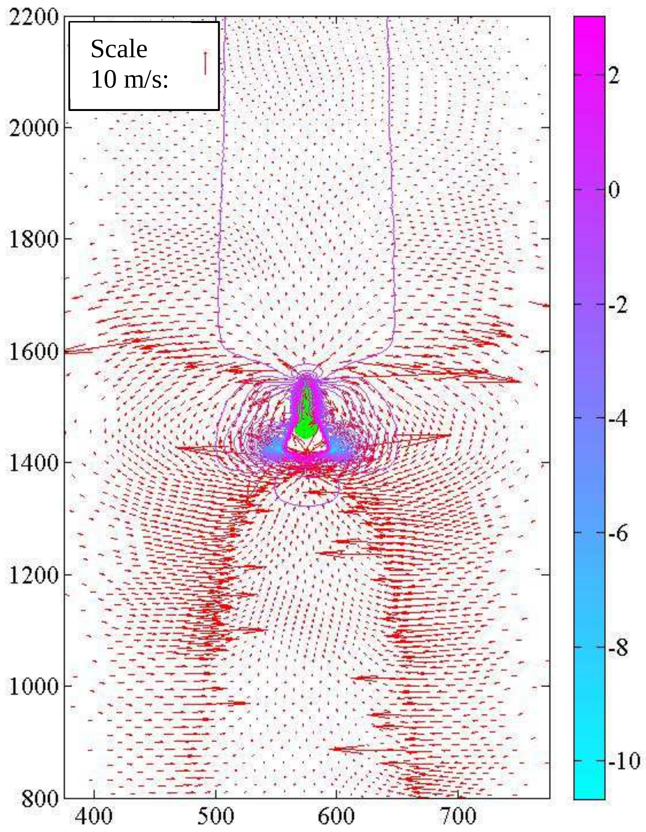

Figure 2: example of the resulting distribution of the water level with respect to the mean sea level and the velocity field by assuming a uniform navigation canal, with a width from 500 to 650 m.

Conclusions

The new mathematical model of displacement waves confirms that these perturbations, produced by a ship sailing along a navigation canal surrounded by wide and shallow shoals, can be described as long waves basically controlled by friction forces.

The wave's height results to be mainly depending on the ship speed and the transversal geometry of the navigation canal, as it was found by the previous model. The comparison with experimental water level records, however, indicates that some features accounted for by the new model can sensibly improve its predictive ability. Among them the inclusion of the connective acceleration (Bernoulli terms) and the planimetric description of the navigation canal (lateral inlets and tributary channels).

References

Di Silvio, G, Dall'Angelo C., Zaggia, L. & Rapaglia,, J., (2011). *Waves produced by ship displacement on adjacent shoals and lateral basins of navigation canals.* 34th Congress IAHR 2011, june 2011, Brisbane Australia.