Simulation of wave-body interactions in viscous flow based on explicit wave models

Romain Luquet, Bertrand Alessandrini, Pierre Ferrant, Lionel Gentaz
Ecole Centrale de Nantes
LMF/EHGO, UMR 6598 du CNRS, 1, rue de la Noë, F-44321 Nantes Cedex 03, France

Introduction

Today wave-body interaction problems can be solved numerically by using softwares based on Reynolds Averaged Navier-Stokes Equations (RANSE). So it is possible to take into account vorticity and viscosity effects which can influence hydrodynamic loads and structure of the flows.

However numerical simulations under viscous flow theory still lead generally to large CPU times because of grid requirements to ensure a good propagation of incident waves in the meshed part of the fluid domain. Moreover successive wave reflections on the body and the outer boundaries can affect the incoming wave train and reduce the useable duration of the numerical simulation.

To overcome these difficulties an original method consists in solving the diffracted flow only (Ferrant *et al*., 2003). Thus RANS Equations are modified by splitting all unknowns of the problem in a sum of an incident term and a diffracted term. The incident terms are explicitly described by fully non-linear wave models based on potential flow theory : regular waves are obtained by an algorithm based on the stream function theory of Rienecker & Fenton (1981) and irregular wave trains by a spectral formulation (Ferrant *et al*, 2003b). Thus only the part of the grid in the vicinity of the structure needs to be refined and a stretched grid allows an efficient damping of the diffracted flow far from the body.

Here the splitting of unknowns defined previously is applied to a viscous flow solver (Alessandrini & Delhommeau, 1995). Modified RANS Equations verified by the diffracted flow are named SWENS (Spectral Wave Explicit Navier-Stokes) Equations and have been developed previously (Ferrant *et al*., 2003a).

In the following 2D and 3D results are presented in order to show abilities of the present method. The 2D flow of a regular wave train on an immersed circular cylinder is first studied – see Ferrant *et al.* (2003a) or Luquet *et al.* (2003)– Then a 3D case of a vertical cylinder in waves is shown. In both cases present results are compared with numerical and experimental data.

Definition of SWENS Equations for the diffracted problem

To consider the single diffracted problem, primitive unknowns (Cartesian components of velocity $\left(u^{\alpha}\right)$ with $\alpha \in \{1,2,3\}$, pressure p and free-surface elevation h) are decomposed as follows :

$$\begin{cases} u^{\alpha} = u_I^{\alpha} + u_D^{\alpha} \\ p = p_I + p_D \\ h = h_I + h_D \end{cases} \qquad \alpha \in \{1,2,3\}$$

Variables with the subscripts I and D represent incident and diffracted variables respectively.

This decomposition is then introduced in the set of initial equations assuming that the incident wave flow fulfils the Euler equations and non-linear free surface boundary conditions in potential flow theory :

- Transport equations :

$$\frac{\partial u_D^{\alpha}}{\partial t} + \left(u_I^j + u_D^j - \frac{\partial \nu_t}{\partial x^j} \right) \frac{\partial u_D^{\alpha}}{\partial x^j} - (\nu + \nu_t) \frac{\partial^2 u_D^{\alpha}}{\partial {x^j}^2} + \frac{1}{\rho} \frac{\partial p_D}{\partial x^{\alpha}} = -u_D^j \frac{\partial u_I^{\alpha}}{\partial x^j} + (\nu + \nu_t) \frac{\partial^2 u_I^{\alpha}}{\partial {x^j}^2} + \frac{\partial \nu_t}{\partial x^j} \frac{\partial u_I^{\alpha}}{\partial x^j} + \frac{\partial \nu_t}{\partial x^j} \frac{\partial}{\partial x^{\alpha}} \left(u_I^j + u_D^j \right)$$

- Mass conservation :

$$\frac{\partial u_D^j}{\partial x^j} = 0$$

- Free-surface boundary conditions :

(i) kinematic condition $$\frac{\partial h_D}{\partial t} + u_D^1 \frac{\partial h}{\partial x^1} + u_D^2 \frac{\partial h}{\partial x^2} - u_D^3 = u_I^3 - \frac{\partial h_I}{\partial t} - u_I^1 \frac{\partial h}{\partial x^1} - u_I^2 \frac{\partial h}{\partial x^2}$$

(ii)normal dynamic condition

$$p_D - \rho g h_D - 2\rho(\nu + \nu_t)\frac{\partial}{\partial x^j} u_D^j n_i n_j = -p_I + \rho g h_I + 2\rho(\nu + \nu_t)\frac{\partial}{\partial x^j} u_I^j n_i n_j$$

(iii) tangential dynamic condition $$\left(n_j t_i + n_i t_j\right)\frac{\partial}{\partial x^j}\left(u_I^i + u_D^i\right) = 0$$

In previous equations the terms defined by incident variables (velocities, velocity gradients, free-surface elevations and free-surface elevation gradients …) are explicitly computed knowing kinematics and interface position of the incident flow.

This set of equations will be named in the following SWENS (Spectral Wave Explicit Navier-Stokes) Equations and is solved by a fully-coupled viscous fluid solver developed by Alessandrini & Delhommeau (1995).

2D results

A non-linear regular wave train propagating above an immersed horizontal circular cylinder in deep water is simulated here following the numerical study of Schønberg & Chaplin (2001) and measurements by Chaplin (2001). Parameters of computation are normalised by taking the cylinder radius c and $(c/g)^{1/2}$ as length and time scales respectively. Thus the cylinder submergence is d/c=1.5, the angular frequency kc=0.56 and the amplitude of the fundamental frequency component a/c is 0.107. With these parameters, the Keulegan-Carpenter number is KC=0.15.

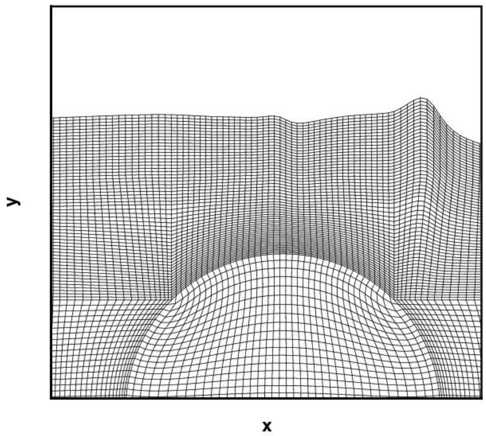
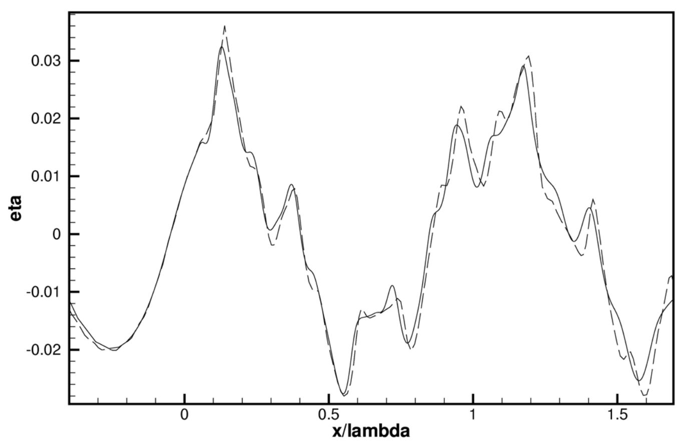


Figure 1 : details of the grid



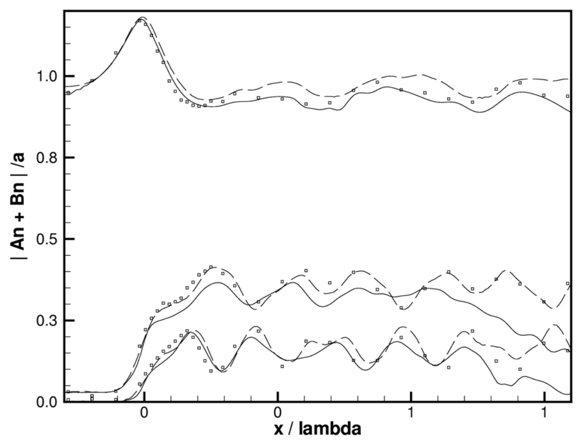


Figure 2 : Left : Free-surface profile beneath the cylinder (centered at *x*=0).
Right : Fourier components of the free surface elevation.
Symbols : measurements from Chaplin (2001); dashed line : computation from Schønberg & Chaplin (2001); solid line : present computation.

A very refined grid about 60 points per wavelength for the third harmonic (figure 1) has been used to compute the higher order harmonic components of the free surface properly. Such a computation with a 500000 nodes structured monoblock grid takes one week a PC with a processor of 1.5 GHz.

In figure 2 on the left instantaneous free-surface profiles obtained by present computations are compared with potential flow computations made by Schønberg & Chaplin (2001). These profiles are plotted at the instant at which the undisturbed wave field would have a zero up-crossing at x=0. The agreement is quite good but there are noticeable differences : the viscous wave profile has a small phase lag and its local maxima are smaller. Chaplin (2001) concludes that viscous effects would impose a resistance to the fluid motion which is likely to delay the transmission of the wave over the cylinder, explaining the small phase lag.

Figure 2 on the right shows the spatial variations of the first three harmonic components of the free surface elevation. For several locations in the numerical wave tank these components have been computed using a Fourier decomposition of the time history of the free-surface elevation signal in a moving window of one wave period long. Present computations are in good agreement with Chaplin's experiments especially for the first harmonic component (the most influenced by viscosity effects).

3D results

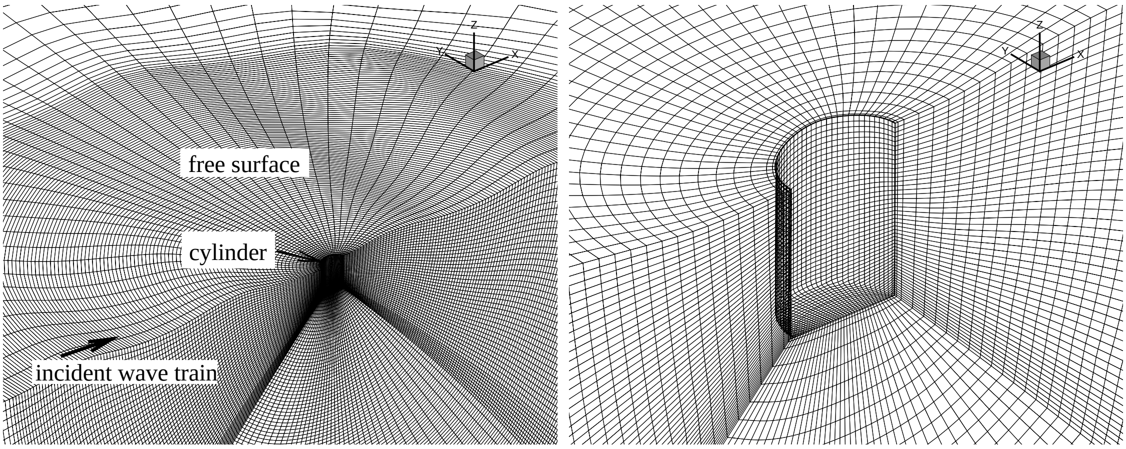


Figure 3 : Views of the mesh around the truncated cylinder

3D computations have been run for a truncated vertical circular cylinder in non-linear regular waves (see the grid on figure 3). The period is 1.8 s, wave height 0.237 m and wave steepness about 4.6 %. The grid has 250000 nodes and the required CPU time is about 90 minutes CPU per wave period on a PC with one processor of 1.5 GHz.

Wave runups (figure 4) and harmonics of horizontal forces have been compared with non-linear potential flow results from XWAVE code (Ferrant, 1998) and/or experimental data from Krokstad & Stanberg (1995) with a very satisfying agreement.

Force components (N)	F1 (N)	F2 (N)	F3 (N)
Non-linear potential theory	485	17.2	11
Experiments	487	19.8	8.2
SWENSE computations	498	16.4	9.8

.

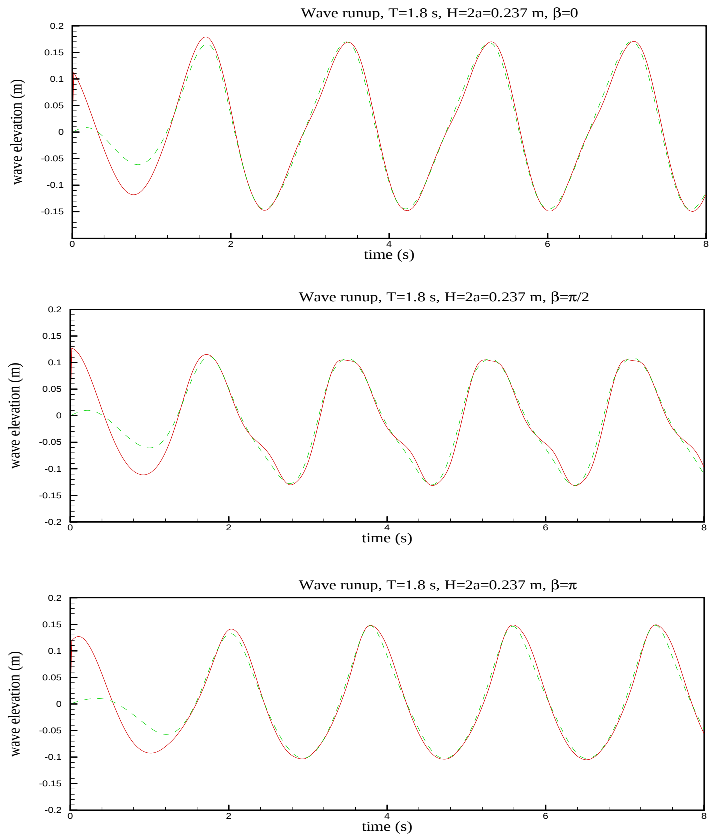


Figure 4 : Wave Runups (β=0 : up wave, β=π/2 : side, β=π : downwave point of the cylinder waterline) dashed line : present method, solid line : Non-linear potential flow results

Conclusion

The diffraction of non-linear regular wave trains in 2D or 3D cases has been studied with an original approach combining a viscous flow solver and an explicit description of the incident waves. Instead of computing the whole velocity, pressure and free surface fields, the diffracted flow only is computed solving SWENS Equations (RANS Equations where variables have been decomposed in incident and diffracted variables).

First results are encouraging and show capability of the method to well simulate wave-body interactions by suppressing usual numerical problems of wave generation in viscous flow solvers.

References

Alessandrini, B., Delhommeau, G. (1995), *A multigrid velocity-pressure-free surface elevation fully coupled solver for calculation of turbulent incompressible flow around a hull*, 9th Int. Conf. Num. Meth. Laminar and Turbulent Flows, Atlanta, pp.1173-1184.

Chaplin, J. R. (2001), *Non-linear Wave Interactions with a Submerged Horizontal Cylinder*, 11th Int. Offshore and Polar Eng. Conf., Stavanger, Vol. 3, pp. 272-279.

Ferrant, P. (1998), *Fully nonlinear interactions of long-crested wave packets with a three dimensional body*, 22nd ONR Symposium on Naval Hydrodynamics, Washington.

Ferrant, P., Gentaz, L., Alessandrini, B., Le Touzé, D. (2003a), *A Potential/RANSE Approach for Regular Water Wave Diffraction about 2D Structures*, Ship Technology Research, vol. 50, no. 4, pp. 165-171

Ferrant, P., Le Touzé, D., Pelletier K. (2003b), *Non-linear time domain models for irregular wave diffraction about offshore*, International Journal for Numerical Methods in Fluids, in press.

Krokstad, J.R.; Stansberg, C.T. (1995), *Ringing loads model verified against experiments*, OMAE'95 Conference, Copenhague.

Rienecker, M.M.; Fenton, J.D. (1981), *A Fourier approximation method for steady water waves,* J. Fluid Mech. 104, pp.119-137.

Luquet, R., Alessandrini, B., Ferrant, P., Gentaz, L. (2003), *RANSE Analysis of 2D flow about a submerged body using explicit incident wave models*, 6th Numerical Towing Tank Symposium, Rome.

Rienecker, M.M.; Fenton, J.D. (1981), *A Fourier approximation method for steady water waves,* J. Fluid Mech. 104, pp.119-137.

Schønberg, T.; Chaplin, J.R. (2001), *Computation of Non-Linear Wave Reflections and Transmissions from a Submerged Horizontal Cylinder,* 11th Int. Offshore and Polar Eng. Conf., Stavanger, vol. III, pp.280-287.