NONLINEAR WAVE-CURRENT INTERACTIONS IN THE VICINITY OF A VERTICAL CYLINDER

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INTRODUCTION

This paper is dedicated to the analysis of wave-current interactions in the vicinity of a three-dimensional body.

Most recently published numerical methods for the solution of this problem were developed within the frame of frequency-domain analysis, with significant contributions including Nossen *et al* (1991), Emmerhof & Sclavounos (1992), Teng & Eatock-Taylor (1995), Malenica *et al* (1995), among others. The advantage of this first approach is to provide results of interest such as wave forces and runups on the structures in a relatively straightforward manner. On the other hand, the mathematical formulation is significantly more complicated than with zero current speed, with specific problems such as secularity (Malenica 1995). There are also a number of practical limitations, such as regular incoming waves and uniform bottom topography only. At last, the perturbation expansion of boundary conditions with respect to wave steepness and current speed limits the analysis to linear or weakly nonlinear phenomena, and up to the author's knowledge, only linearized formulations have been published to date.

In these conditions, as for a number of other problems (Ferrant 1996b), time domain analysis represents a very attractive alternative. Using a time domain Rankine panel method, it is theoretically possible to implement any level of boundary condition approximation, from linearized conditions to fully nonlinear ones, and there is no limitation on the geometry. Of course, due to their computational demand which may be very important, even for recent workstations, the convergence of the numerical models, their stability and accuracy have not yet been sufficiently studied. Generally speaking, there is a remaining lack of confidence in this class of numerical models which will undoubtedly progressively disappear with their development and validation. The applications of time domain analysis to wave-current interaction problems are still scarce, see for example Kim & Kim (1995), and are restricted to the simulation of problems developed to first order in the wave amplitude parameter ε and in the current speed parameter τ.

In the present paper, we present some results of the application of fully nonlinear time-domain analysis to the wave-current interaction problem in the presence of a three-dimensional body. The incoming flow, including regular waves and current, is modelized using a stream function theory (Fenton & Rienecker 1981), and the problem is formulated in terms of the nonlinear perturbation induced to the incident flow by the body, using a formulation initially developed in Ferrant (1996a) for the capture of higher order diffraction effects in the time domain. The nonlinear free surface boundary conditions are updated using a 4th order Runge-Kutta scheme, the boundary value problem being solved at each step using a linear isoparametric boundary element method. An absorbing layer method is implemented for the absorption of diffracted waves. Results presented at the end of this paper concern the computation of the runup on a vertical cylinder in finite depth due to waves and current.

PROBLEM FORMULATION - NUMERICAL PROCEDURE

The simulation strategy is the same as described in Ferrant (1996a). The incident flow, including here acurrent, is prescribed by a stream function theory (Rienecker & Fenton 1981), and the diffraction problem is solved for the perturbation (Φ_D, η_D) induced by the body, defined by:

$$\Phi(x,y) = \Phi_e + \Phi_D \tag{1}$$

$$\eta(x,y) = \eta_e + \eta_D \tag{2}$$

where the subscript e denotes the pure incident flow. With this definition, we obtain the kinematic and dynamic free surface conditions for the perturbation flow:

$$\frac{d\eta_D}{dt} = -\frac{d\eta_e}{dt} - \vec{grad}(\phi_e + \phi_D).\vec{grad}(\eta_e + \eta_D) + \frac{d(\phi_e + \phi_D)}{dz} \tag{3}$$

$$\frac{d\phi_D}{dt} = -\eta_e - \eta_D - \frac{1}{2}\left[\vec{grad}(\phi_e + \phi_D)\right]^2 - \frac{d\phi_e}{dt} \tag{4}$$

where terms from the incident flow at the right-hand side can be evaluated exactly from the stream function wave model, without influence from time or space discretization. The problem being fully non linear, equations (3) and (3) must be satisfied on the instantaneous free surface position, and thus the incident potential may possibly be evaluated above the undisturbed incident wave. This is possible here because of the continuous prolongation of the incident potential above the incident wave. Of course, the formulation described above is not universal and depends on the availability of an explicit model for the incident wave.

On the body surface, the no-flux condition is written:

$$\Phi_{Dn} = - \beta(t) \,.\, \Phi_{en} \tag{5}$$

where b(t) is a scalar function vaying smoothly from 0 to 1 during the first wave period, the simulation starting with Φ_D=0 everywhere in the fluid domain and η_D=0 on the free surface.

A boundary element method is used for the solution of the boundary integral equation formulation of the problem. The method is based on isoparametric triangular elements distributed over the different boundaries. A piecewise linear, continuous variation of the solution over the boundary is thus assumed, and collocation points are placed at panel vertices. Meshes are made of an assembly of different patches, with the assumption of continuous normal on each of them. On intersection lines between two patches, two collocation points are kept at the same geometrical position, and the boundary conditions corresponding to the two surfaces are both satisfied. At the intersection between two solid patches, two Neumann conditions for the two different normals are enforced, whereas at the intersection between solid boundaries and the free surface, both a Neumann (N) condition on the solid surface and a Dirichlet (D) condition on the free surface are satisfied. This discretization scheme reduces the integral formulation to a linear algebraïc system to be solved for the normal velocity on Dirichlet boundaries (free surface) and the potential on Neumann boundaries. This system is made of the influence coefficients of linearly varying distribution of sources on boundary elements. Analytical formulas for the near field, and different approximate formulas for the intermediate and far field of the different panels are implemented. These coefficients are factorized with respect to sources or dipoles density at panel vertices, which are selected as control points. This scheme results in square systems of equations for the singularity distribution on the boundaries of the computational domain, which are solved using a preconditioned GMRES scheme.

After the solution of the boundary value problem and the computation of fluid velocities at the free surface, free surface conditions considered as ODE's for ϕ and η are integrated in time. A fourth order Runge-Kutta method is used for that purpose, requiring four solutions of the boundary value problem per time step.

The radiation condition is enforced by adding dissipative terms in equations (3) and (4) on the outer part of the free surface mesh.

NUMERICAL RESULTS

The numerical scheme has been applied to the simulation of the diffraction of regular waves by a vertical cylinder in water of finite depth, with or without current. The cylinder radius is equal to the water depth, i.e. R/H=1. and the wavenumber is koH=1.0. The wave amplitude is A/H=0.1, and computations have been performed for current speeds U/sqrt(g/H)=-0.1, 0.0, 0.1.

Figure 1 and 2 compare the time series of the wave elevation at the weather side (Fig.1) and at the lee side (Fig. 2), for the three different values of the current speed. Figure 3 compares the maximum runups along the cylinder waterline in the three cases. Present nonlinear results at zero Froude number seem to be close to the second order model of Büchmann *et al* (1997). However, sensible differences in the influence of the current are observed between their approach, which is based on a perturbation analysis up to second order in the wave steepness and to first order in the current speed, and the present fully nonlinear model.

CONCLUSION

Wave-current-body interactions simulations presented in this paper were based on a fully nonlinear model in which no assumptions regarding the relative magnitudes of wave steepness and current speed are necessary. With the present values of the current and wave parameters, we observe sensible differences between the present fully nonlinear approach and the perturbation analysis results of Büchmann *et al* (1997). These differences remain to be clarified, first by comparing both approaches for lower values of the wave amplitude and current speed, but also by comparing numerical results and experimental values. We hope to be able to report on such comparisons in the near future.

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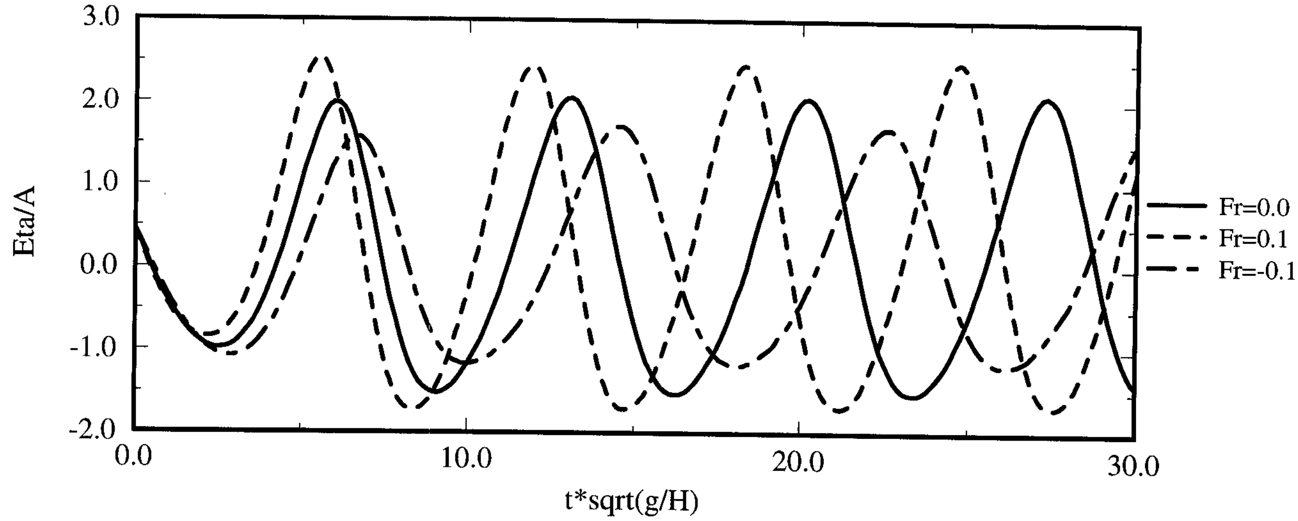

Figure 1: Wave elevation at the weather side. R/H=1.0; A/H=0.1; koH=1.0

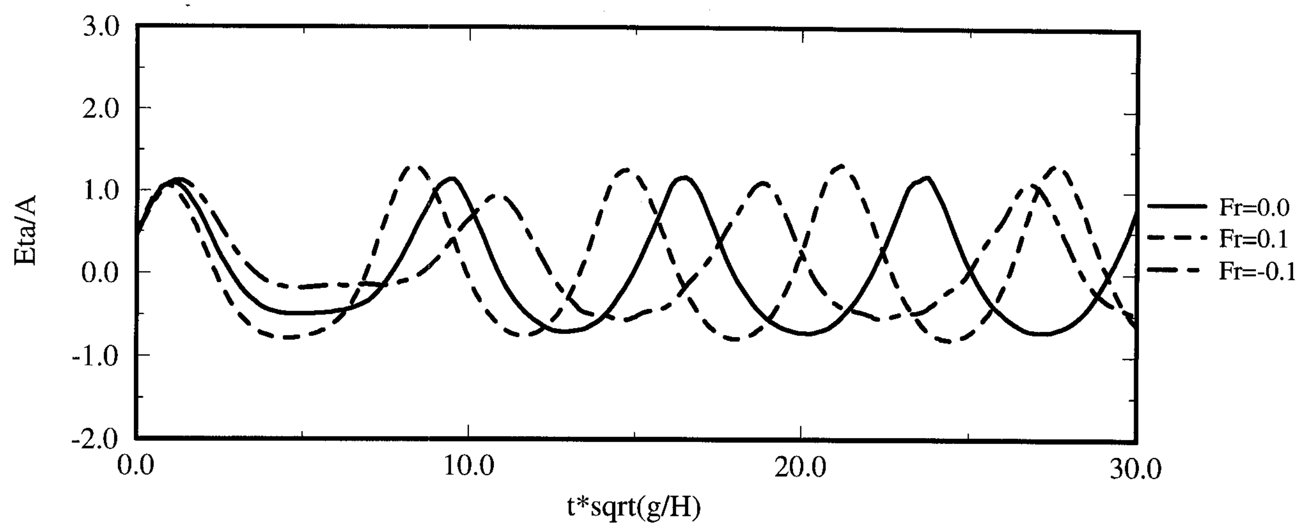

Figure 2: Wave elevation at the lee side. R/H=1.0; A/H=0.1; koH=1.0

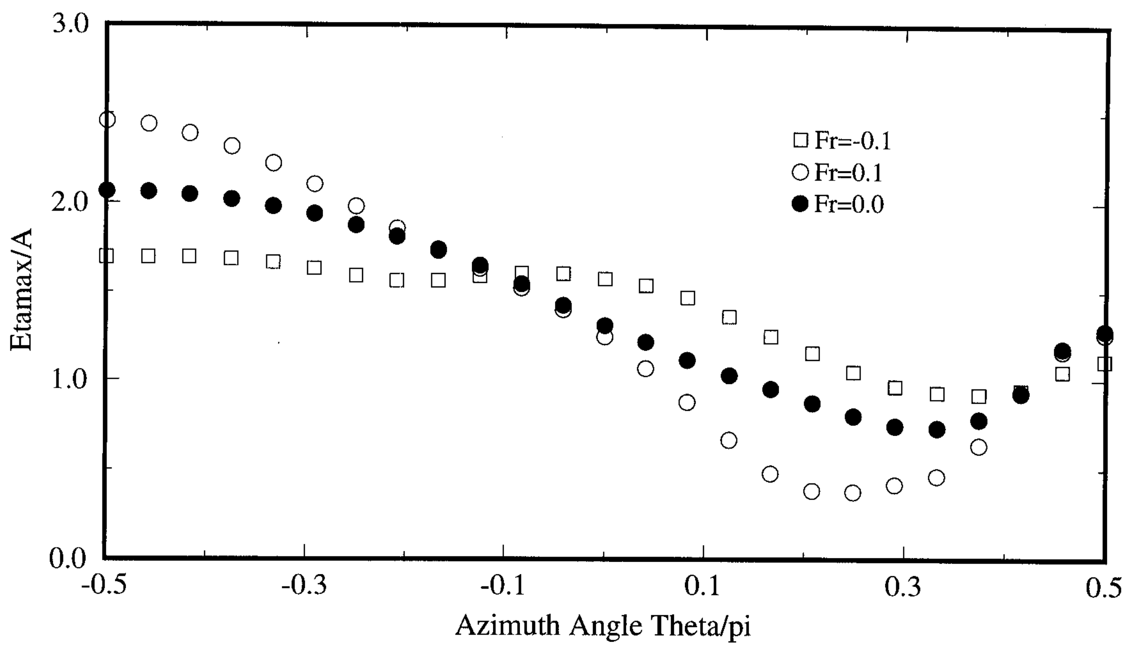

Figure 3 : Maximum wave runup. R/H=1.0; A/H=0.1; koH=1.0

DISCUSSION

Grilli S.: Did I correctly understand that you initialize your computations with a streamfunction, wave everywhere in the domain? Wouldn't this cause initial transient response that may affect the initial oscillation observed in your runup height. These, hence, may not be entirely physical.

Ferrant P.: Yes, the initial conditions correspond to the undisturbed incident wave in the domain, without body. The body is introduced through the Neumann condition which is multiplied by a smooth ramp function going from 0 to 1 during the first wave period.
Of course this procedure produces unphysical transients, but they die out very quickly and a periodic steady state is reached within less than two periods.
Relevant results such as forces and runups are then derived from the steady state part of the solution.