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A Numerical Wave Tank for the 2D Free Floating Body Problem

Giorgio CONTENTO
Department of Naval Architecture, Ocean and Environmental Engineering
University of Trieste
via A. Valerio, 10 - 34127 Trieste - ITALY
Phone: +39-40-6763405 - Fax: +39-40-6763443 - E-mail: contento@univ.trieste.it

Background

Time domain simulations of 2D and 3D fully non-linear motions and loads on submerged and/or surface piercing bodies in the so-called 'body-exact approach' *[Lin-Yue,1992]* are matter of deep interest these days. In the particular case of perfect fluid flow, significant steps have been conducted in the direction of capturing second and higher order diffraction pressures on fixed structures [*Isaacson,1982; Isaacson et al.,1991; Yeung et al.,1992; Kim et al.,1994*] or calculating radiation/impact pressures on rigid bodies with prescribed motions in calm water [*Dommermuth et al.,1987; Zhao et al.,1993*], the solution of the 2D and 3D free-floating body problem being not consolidated exhaustively yet [*Cointe et al.,1990; Sen,1993*].
The characteristics of the incident waves generated by numerical wavemakers with non-linear free surface, being obviously dependent on the amplitude and frequency of the motion of the wavemaker itself, have been shown to be dependent on computational features such as the size of the domain or analogously the number of wavelenghts in the tank [*Lee et al.,1987*], the effectiveness of the non-reflective boundary [*Yeung,1992; Jagannathan,1988*] or damping sponge [*Israeli,1981; Cointe,1990*], the regridding [*Dommermuth,1987*] and the interpolation-extrapolation techniques [*Saubestre,1991; Sen,1993*].
In this perspective, a deep study has been conducted on the generation and propagation of waves by a flap type wavemaker in a 2D numerical tank with perfect fluid and non-linear free surface *[Contento et al.,1994]*. In this paper a robust and accurate 2D numerical wave tank dedicated to the free floating body problem is presented. Details of the adopted implementation for the pressure evaluation on the wetted hull are given and some significative results are then presented.

Formulation, discussion and results

- A 2D rectangular tank is adopted, the left and right boundaries being respectively a flap-type wavemaker (the center of rotation placed on the bottom of the tank) and a non-reflective boundary.
- Usual assumptions are made for the inviscid/irrotational fluid. Laplace equation for the velocity potential yields in the fluid domain. The adopted solver is a Zero Order BEM whereas the time stepping scheme is a 4th-order Runge Kutta method. As already evidenced by other authors *[Sen,1993; Yeung,1992]*, bounds on the amplitude of the motion of the wavemaker related to the frequency must be considered, at least as a realistic simulation is of interest. A wave steepness $\cong 1/15$ can be easily achieved by the present simulation up to 1/8.
- Fully nonlinear kinematic and dynamic boundary conditions are applied. Lagrangian markers or alternatively markers allowed to move over vertical trajectories are used to advance the free surface profile and the potential over a time substep. The regridding is performed at each substep with extreme care in subdividing the free surface profile and repositioning the markers: the present implementation is based on a subdivision by equally long arcs, according to Dommermuth-Yue *[1987]*, showing great efficiency in removing sow-tooth instabilities. No smoothing technique is needed. The markers are repositioned in the middle point of the arc subtending each panel. Interpolation is performed by a spline in tension *[de Boor,1978]*, its end slope being used for extrapolation where necessary. In Figure 4 the smootheness of the trajectory of the starboard intersection of the body of Figure 3 with the free surface reveals the accuracy of the method. At present, some problems are encountered at the intersection when the body profile, during the motion, becomes almost parallel to the free surface (see 'water entry at small deadrise angles').
- The pressure distribution on the wetted part of the body at a given instant is needed to advance the body-motion equations. A simple backward differencing scheme for the evaluation of $d\phi/dt$ at a point P on the body has been discouraged by several authors in litterature due to the occurence of an instability which usually leads to the breakdown of the execution. Cointe has proposed an integral equation for $\partial\phi/\partial t$ as well as Cao with an iterative solution for the acceleration. Isaacson has proposed an implicit scheme. Sen has proposed an iterative process. A new method is here proposed and sistematically applied with good results. The main idea is to take advantage of the Runge-Kutta four intermediate solutions and the values at previous time steps. A second order

differencing scheme from the appropriate values at t-2Δt, t-Δt, t, t+0.5Δt, t+Δt, calculated at time t, is applied at each R-K substep for the derivative $d\phi/dt$ at a point P on the body. The final derivative is the written, according to the 4th order Runge-Kutta scheme, using the four intermediate values. Arbitrarily shaped sections can be run. The regridding of the wetted part of the body profile is performed at each Runge-Kutta substep.

- A Sommerfeld radiation condition is applied at the open boundary as a non-reflective boundary condition, the celerity being evaluated from the momentum equation on the free surface at some markers before the closure of the domain, as suggested by Jaghannathan *[1988]* and revisited by Yeung *[1992]*. The radiation condition is integrated with a 4th order Runge-Kutta scheme, consistently with the free-surface and body-motions equations. Some numerical experiments have been conducted elsewhere*[Contento et al.,1995]* to check the efficiency of the numerical wave filter. Provided an appropriate tuning of the threshold to discard undesired markers is performed, the efficiency is found within 7.5% and 4.3% for incident wave steepnesses respectively 1/15 and 1/45: a Fourier analysis of the records of the free-surface elevation (without the body) obtained from a large set of numerical probes reveals a kind of modulation of the first harmonic component with a spatial periodicity equal to half the principal incident wave lenght. This modulation, evidenced by Yeung *[1992]*, goes up the incident wave train with the wave group velocity (Figure 2) and corresponds to a system of small amplitude standing waves. This reflection must be taken into account in a long term simulation, i.e. when a steady state motion of the body is searched.
- Mass and energy conservation is sistematically monitored during the simulation. The mass error and outflow has been conserved in all the performed computations within 0.2% and 10^{-3} m^2/s respectively. These values are extremely good considering that they refer to long simulations and to steep waves. In the wavemaker problem without body the maximum deviation is typically observed when the wave train reaches the open boundary and the radiation condition starts to work. The energy error is found to be usually within the 0.5% of the amplitude of the power input (Figure 5).
- In the case of prescribed motions of the body in calm water, added mass and damping can be easily derived from the forces/moment records. In Figure 1 the computed heave added mass and damping of an half-immersed circular cylinder with assigned motion are compared with the experimental results of Vugts *[1968]* with an extremely good agreement.
- In the view of a traditional approach to ship motions (ODEs), a parametric identification technique *[Contento et al.,1994]* is applied to the nonlinear ODEs of the body-motion using the numerical records of the motions: this allows to determine any desired coefficient of the ODEs. In Figure 1 the star represents the non-dimensional heave added mass and damping of the half-immersed circular cylinder from the free decay as linear coefficients in the heave equation derived with the parametric identification. The agreement with the experimental results is noticeable. Table 1 summarizes added mass, the linear and cubic damping and restoring coefficients of the ODEs corresponding to the heave and roll free decayes of the sketched body.

References

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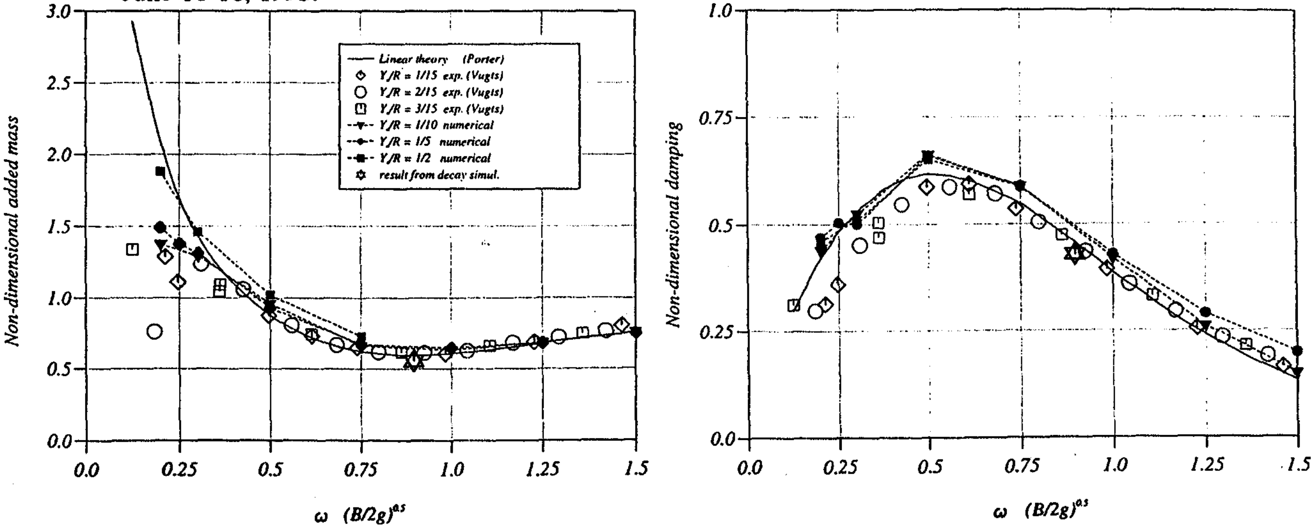


Figure 1. Heave non-dimensional added mass and damping of an half immersed circular cylinder. Experimental values from Vugts *[1968]*, numerical values from the present method with assigned motion. The star represents the value from free decays. Shallow water effects in the added mass at low frequencies, evidenced by Vugts in the experiments, are captured by the simulation. Y/R=heave amplitude/radius of the cylinder.

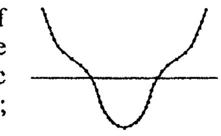
Heave

$\frac{Y_G - Y_{G_0}}{Draft}$	Added mass	Linear damping	Cubic damping	Linear restoring	Cubic restoring	Residual of the fitting
0.10	48.00	364.51	377.01	5457.41	0.00	$4.88x10^{-5}$
0.20	50.97	378.52	536.93	5457.00	0.00	$1.25x10^{-3}$
0.30	53.83	397.36	387.17	5457.41	0.00	$4.40x10^{-4}$
0.40	60.13	461.46	169.44	5457.41	0.00	$7.00x10^{-4}$

Roll

ϑ_0(deg)	Added inertia	Linear damping	Cubic damping	Linear restoring	Cubic restoring	Residual of the fitting
5	3.19	0.23	11.75	148.56	1313.92	$4.53x10^{-5}$
10	3.24	0.50	10.77	148.56	420.74	$1.60x10^{-3}$
15	3.58	1.06	9.30	148.56	329.34	$6.70x10^{-3}$

Table 1. Dimensional coefficients of the nonlinear motions equations (ODEs) of the body sketched aside derived with a parametric identification technique from numerical free decay records with different initial static displacements of the body. Mass=150 kg; Inertia= 20 kgm^2; KG=0.25 m; B=0.485 m; T=0.385 m.



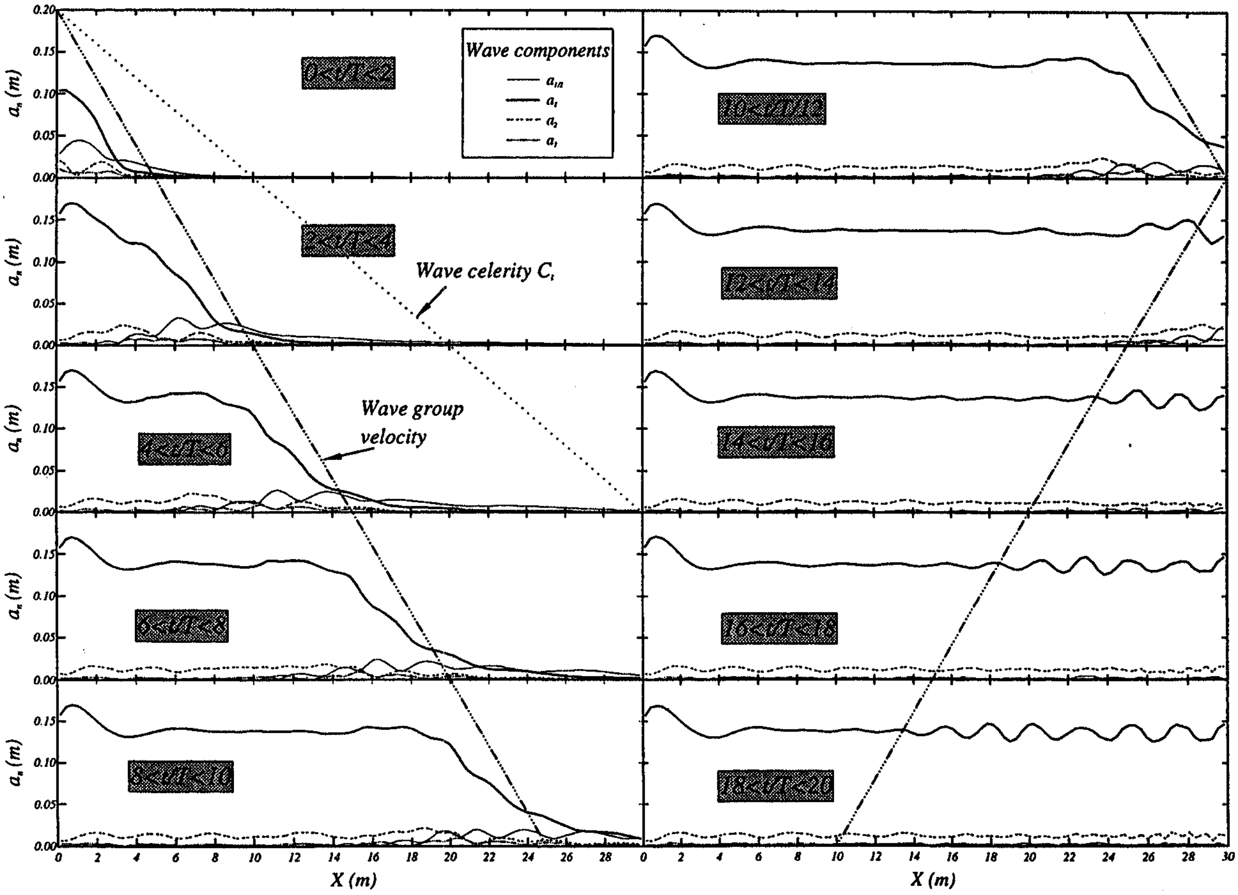


Figure 2. Wave components from a Fourier analysis along the tank at different intervals during the transient of generation. The wave front propagate with the group velocity. Standing waves appear and propagate from the end of the tank due to a small amplitude reflected wave of the same frequency of the principal wave. Other standing waves are found near the wavemaker. The comparison with the results of Yeung *[1992]* is very good. The amplitude of the reflected wave is strongly dependent on the steepness of the incident wave.

[L_{tank}=30m=6 wavelenghts λ; depth=λ; wavemaker angle=1°; wave steepness ≅ 1/16 ; 20 markers per wavelenght; Δt/T=1/100]

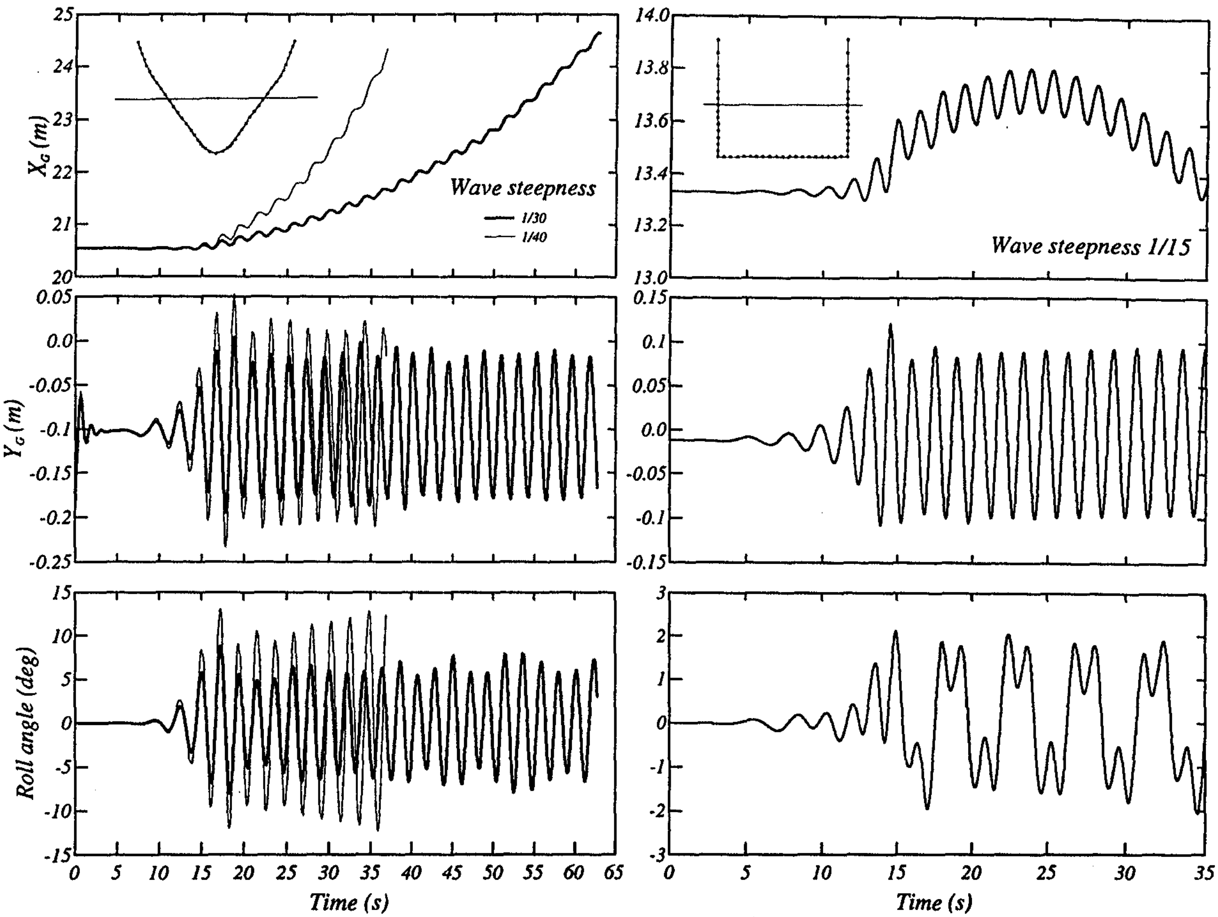


Figure 3. Sway, heave and roll of the bodies sketched above.
Left: Incident wave steepness approximately 1/40 and 1/30. The motions start from the upright position but not in hydrostatic equilibrium. The shifting of the oscillations is due to the strong sway.
Right: Subharmonic roll oscillation: the wave period is approximately one third of the body natural roll period. [L_{tank}=30m=6λ; depth=λ; wavemaker angle=1°; 33 markers per wavelenght; Δt/T=1/100]

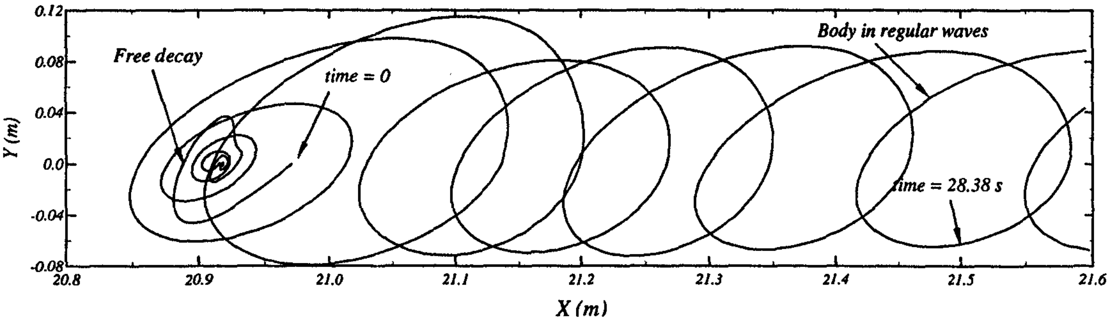


Figure 4. Trajectory in the absolute frame of reference of the intersection between the free surface and the body at starboard corresponding to motions of Fig. 3 (left) with incident wave steepness 1/40.

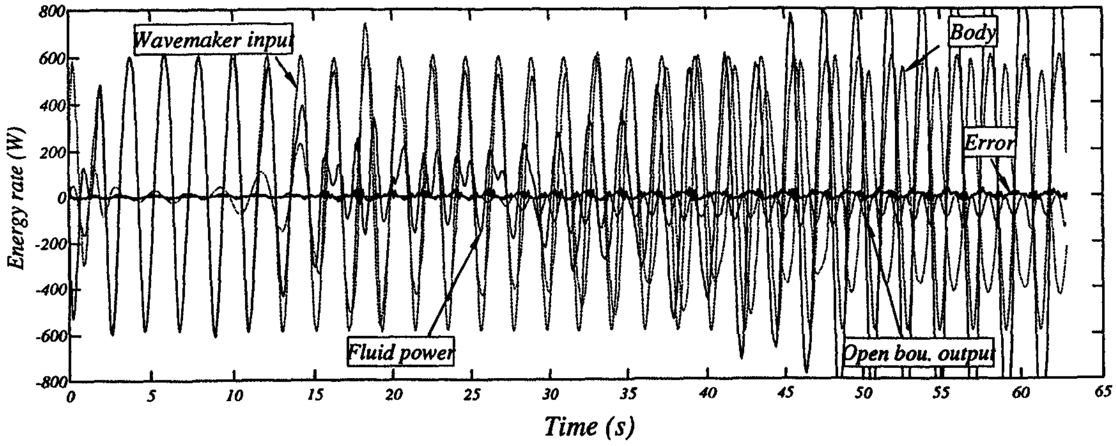


Figure 5. Energy rate balance for the case of Fig. 3 (left) with incident wave steepness 1/40.

DISCUSSION

King, A.: Will your code deal with the slamming problem where (a) a self-similar structure should appear in the deep water - constant velocity case; (b) thin jets form and may overturn?

Contento, G. : Impulsive pressure is in principle detectable by the method but the overturning of waves is not allowed by the model. It is not clear how to advance the solution when the wave crest touches the free surface again. Since the slamming usually implies the occurrence of thin jets and their possible overturning, this kind of load prediction is still frustrated.

As shown by Zhao, & Faltinsen in JFM (1993), the slamming problem requires a very accurate grid in the zone where the jet occurs, a grid which is ultimately truncated by a jet flow approximation with a loss of mass. They did this for a single prescribed entry. The present method has been thought of for long term simulations more than for the study of the local behaviour of the flow so a solution to this event has to be introduced.

Yeung, R. W.: The work Yeung et al. (1992) that you cited, I believe, is Yeung & Vaidhyananthan in *J. Num. Meth. Fluids.* It exploited two types of open boundary conditions for convenience, since its main purpose at the time was to test an adaptive grid that can accommodate wave motion. This grid methodology was later used to solve a number of viscous-flow problems (see Yeung & Ananthakrishnan, 1992, *J. Engrg. Math.)* A more complete absorption condition for inviscid flow was given by Yeung & Cermelli (8th Workshop) using the convolution idea presented in a review paper of mine (Yeung, 1985, IUTAM Symp. of Wave Energy Utilization, Portugal). In terms of linear theory, the matching technique discussed is exact. But a fully rational matching with non-linear theory has yet to be developed.

Contento, G. : The main effort in the present work was put into the scheme for a stable and accurate computation of the pressures on the body and into the regridding scheme in the presence of steep waves. As far as the non reflective boundary is concerned, the efficiency tests were conducted just to be conscious of the available time to observe the motion of the body without interferences. At present the implementation is ready for other techniques and your suggestions are welcome, thank you.