3D ship-seakeeping problem: weak-scatterer theory *plus* shallow-water on deck

M. Greco[1,2] **T. Bazzi**[1] **G. Colicchio**[1,2] **C. Lugni**[1,2]
m.greco@insean.it t.bazzi@insean.it g.colicchio@insean.it c.lugni@insean.it

1 **INSEAN, Italian Ship Model Basin, Roma – Italy.**
2 **Centre for Ships and Ocean Structures (CeSOS), NTNU, Trondheim – Norway.**

Water-on-deck phenomena can be identified as local events caused by severe sea waves interacting with the ship. Their behavior is intrinsically transient and the involved time scales may be shorter or comparable with those of the incident waves. The compact masses of water invading the deck represent a danger for the stability, the comfort, the local structural integrity. The actual consequences depend on the vessel type and operational conditions, as well as on the incident-wave parameters relative to the ship. The need to perform a time-domain nonlinear analysis represents an important limitation in terms of CPU-time requirements when the seakeeping of a 3D vessel is examined. Therefore, as a first attempt to examine the occurrence of water shipping for a real ship, the green-water investigation is coupled with a weakly-nonlinear model for the prediction of the global vessel motions. This is made for sake of efficiency but leads also to reliable predictions in many practical circumstances. Contemporary to the numerical development an experimental study has been started (see the global view of the ship model set-up in figure 1). The aim is to investigate the features of wave-ship interactions when

Figure 1: 3D experiments on a patrol ship model: global view.

varying systematically the incoming wavelength and steepness and the ship forward speed, with attention to occurrence of water shipping and related local and global effects. The model tests also offered the opportunity to validate the developed method and to draw its limits of applicability. Details of the experimental set-up and preliminary results of the ongoing research activity are given in Greco *et al.* (2007).

Numerical model The solution of the seakeeping problem is based on the weak-scatterer theory (Pawlowski 1991): the radiation and diffraction phenomena are governed by linear effects and may be estimated before the global-motion time simulation. The ship motions are not small relative to the incoming waves so that the body-boundary condition must be satisfied on the instantaneous wetted hull. Consistently, the Froude-Krylov and the hydrostatic contributions loads must be estimated along the actual ship configuration, and the square-velocity term must be retained in the pressure. A second-order consistent method can be developed with this approach (see Pawlowski 1991). Both regular and irregular wave systems can be examined. The assumptions require the problem solution in time domain but the resulting solver remains still quite efficient since only variables along the vessel must be estimated. For simplicity the procedure is explained for the case of zero Froude number but the method is applicable also to advancing ships.
Preliminarily the linear radiation and diffraction problems are solved and related added-mass and damping coefficients are estimated. The six radiation problems correspond to forced body motions with local normal velocity equal to the generalized normal component n_i (i=1,..,6) to the vessel. Within the weak-scatterer theory n_i can be used as basis functions to satisfy the body-boundary condition on the instantaneous wetted hull instead of along the mean configuration. In particular, the instantaneous normal velocity at the wetted hull can be expressed as $\boldsymbol{V}_n(\boldsymbol{x},t) = \sum_{i=1}^{i=N} \beta_i(t)\psi_i(\boldsymbol{x})$, with N=6, $\psi_i = n_i$ and β_i unknown coefficients to be determined. At any time instant the vessel impermeability requires that $\boldsymbol{V}_n = \boldsymbol{V}_{ship,n}$-$\boldsymbol{V}_{wave,n}$, where $\boldsymbol{V}_{ship}$ is the local velocity of the ship in $\boldsymbol{x}$ and $\boldsymbol{V}_{wave}$ is the corresponding local incoming-wave velocity. Substituting this in the $\boldsymbol{V}_n$ representation and enforcing the equality through a minimum least-square approach, it furnishes the required equations to be satisfied by the unknown β_i.
The global ship motions can be written in the form

$$\boldsymbol{M}\ddot{\boldsymbol{\xi}} = \boldsymbol{F}_{rsc} + \boldsymbol{F}_{0\,nlin} + \boldsymbol{F}_{h\,nlin} + \boldsymbol{F}_{wod}\,\delta_{wod} \qquad (1)$$

$\boldsymbol{M}$ being the mass matrix and upper dots indicating time derivatives. The generalized forces (forces and moments) are decomposed in four terms. $\boldsymbol{F}_{rsc}$ accounts for the disturbance to the wave field due to the presence and motion of the ship. It is given by the integration of the corresponding pressure along the mean hull configuration, $-[\boldsymbol{A}_\infty\dot{\boldsymbol{\beta}} + \int_0^t \boldsymbol{K}(t-\tau)\dot{\boldsymbol{\beta}}(\tau)\, d\tau]$, rotated in the instantaneous ship configuration to account for body motions not small relative to the incoming waves. Here $\boldsymbol{\beta}(t)$ is the vector of the coefficients of $\psi_i(\boldsymbol{x})$ estimated at any time by enforcing the impermeability condition along the instantaneous wetted hull. Further, because $\psi_i = n_i$, $\boldsymbol{A}_\infty$ coincides with the infinite-frequency added-mass vector and $\boldsymbol{K}(t-\tau)$ is the retardation function vector that can be obtained for instance through the integral link with the damping-coefficient vector. $\boldsymbol{F}_{0\,nlin}$ is the nonlinear (up to the second-order) Froude-Krylov load, $\boldsymbol{F}_{h\,nlin}$ is the nonlinear (up to the second-order) hydrostatic term $\boldsymbol{F}_{h\,nlin}$ and $\boldsymbol{F}_{wod}$ is the load caused by water-on-deck occurrence (*i.e.* when $\delta_{wod} = 1$). To improve the stability property of the equations system, in the numerical solution the term $\boldsymbol{A}_\infty\ddot{\boldsymbol{\xi}}$ is added at both sides of (1). $\boldsymbol{M}$ is known from the ship structural properties, while $\boldsymbol{A}_\infty$ and $\boldsymbol{K}(t-\tau)$ are obtained using linear theory, *i.e.* they refer to the mean ship configuration and can be estimated within a pre-processing. $\boldsymbol{\beta}$, $\boldsymbol{F}_{0\,nlin}$, $\boldsymbol{F}_{h\,nlin}$ and $\boldsymbol{F}_{wod}$ must be evaluated at any time instant. In particular, $\boldsymbol{F}_{h\,nlin}$ and $\boldsymbol{F}_{0\,nlin}$ account for the instantaneous body configuration and $\boldsymbol{F}_{wod}$ depends on both the ship motions and their first and second time derivatives.

Water shipping occurs any time the following criterion is satisfied: a portion of the deck contour (i) is characterized by wave elevation greater than the local instantaneous freeboard (*i.e.* water level h greater than zero) and (ii) has a water flux entering the ship deck. When conditions (i) and (ii) are satisfied or when water is already present on the deck because of previous events, a local problem is studied for the water flow along the deck and described within a local Cartesian coordinate system (x, y, z) with z normal to the deck. As basic assumption, because h is usually small compared with the ship deck longitudinal extension, shallow water conditions are considered and wave dispersion effects are fully neglected so that the governing equations can be approximated consistently with the nonlinear shallow water theory for the unknowns h and the in-plane velocity components u and v, respectively, along x and y. This can be suitable for water-on-deck events with global dam-breaking behavior, which are the most common, while it can not be applied for instance to plunging-wave type water shipping (see *i.e.* Greco *et al.* 2007). The shallow-water equations must account for the deck motion and are formally dependent on x, y and t. The problem is completed by the initial and boundary conditions along the deck contour and along the deck house or other obstacles along the deck. The deck contour can be characterized both by inflow conditions, occurring when conditions (i) and (ii) are satisfied, and outflow conditions, valid when either (i) or (ii) is not verified. This means that both shipping and off-deck events can be simulated. The internal-obstacle condition is given as a wall condition. The boundary conditions are enforced by applying a level-set technique (see *i.e.* Colicchio *et al.* 2005): first the normal distance with sign ϕ (negative inside the deck/obstacle and positive otherwise) from the deck/obstacle profile is associated at any location (x, y), then the corresponding velocity vector $\boldsymbol{U} = (u, v)$ is expressed as

$$\boldsymbol{U} \;=\; s(\phi)\,\boldsymbol{U}_{deck} \,+\, [1 - s(\phi)]\,\boldsymbol{U}_{ext}\,, \tag{2}$$

where $\boldsymbol{U}_{deck}$ is the solution as obtained from the in-deck problem and $\boldsymbol{U}_{ext}$ is the boundary condition given by the external flow conditions around the vessel/ by zero velocity along an internal obstacle. Further, $s(\phi)$ is a smoothed approximation of the Heaviside function equal to one onto the deck and zero otherwise(*i.e.* outside the deck contour/inside an obstacle). In the vicinity of the deck contour, condition (2) is used if the close deck region is subjected to water flux entering the deck, otherwise $\boldsymbol{U} = \boldsymbol{U}_{deck}$ is enforced which corresponds to an outflow condition. Condition (2) is always applied near an internal obstacle. The boundary condition for the water level is treated similarly to that for $\boldsymbol{U}$ in the case of the deck contour. Along an internal obstacle h is treated as an unknown of the in-deck flow problem if the flow is toward the obstacle, otherwise dh/dn is enforced. To limit the CPU-time requirements associated with the numerical solution, following Zhou *et al.* (1999) the two-dimensional shallow-water problem is converted in the *summa* of two quasi one-dimensional sub-problems, respectively, along the x and y directions. A first-order scheme is used for the time integration whose generic step consists of a sequential solution of the two sub-problems. This is performed using the solution from the first sub-problem as initial solution for the other, so that the x-y flow interactions are accounted for. The quasi one-dimensional sub-problems are solved using a Godunov's method (see *i.e.* Toro 2001) to estimate the main convective terms. All the spatial derivatives involved are calculated using a first order up-wind scheme to preserve the direction of the convective terms. This is made introducing a Cartesian grid with N_x and N_y collocation points along x and y directions, respectively. The water-on-deck model was validated simulating 2D and 3D dam-breaking cases without and with an internal obstacle. Main comparisons with model tests and numerical 3D results have been reported in Greco *et al.* (2007).

The in-deck problem may require a smaller time step, say Δt_{wod}, than the global motions time step, say Δt. If this is the case, the body motions are frozen and the water flow onto the deck is simulated from t to $t+\Delta t$ using the time step Δt_{wod}. Then the global loads due to the water on deck can be evaluated. More in detail the empirical formula for the deck pressure by Buchner (1995) is applied in the form $p = -\rho(a_n\, h + V_{ship,n}\partial h/\partial t)$. Here a_n is assumed as the fluid acceleration normal to the deck (i.e. the gravity acceleration projected normally to the deck and corrected by the deck acceleration) and $V_{ship,n}$ as the ship velocity component normal to the deck. This pressure expression is characterized by the shallow-water hydrostatic term (accounting for the body accelerations in a_n) and by a dynamic contribution associated with the time derivatives of the water level onto the deck and of the ship motions (related to the time change of fluid mass). Multiplying p with the generalized normal vector and integrating along the wetted deck it provides the generalized water-on-deck force

$\boldsymbol{F}_{wod}$ which can be introduced in the motion equations (1) to calculate $\boldsymbol{\xi}$ at the new time instant. The numerical solution of equations (1) is performed using a Runge-Kutta fourth order scheme. The convolution integrals involved are evaluated assuming a local linear interpolation in time of the $\boldsymbol{K}(t-\tau)$ and $\dot{\boldsymbol{\beta}}$ components and then integrating analytically.

3D seakeeping model tests Three-dimensional experiments were performed at the INSEAN towing tank on a patrol ship model (INSEAN model C2364, scale 1:20) interacting with incident wave systems. In the first experimental campaign, the model was tested without forward speed and free to oscillate only in heave and pitch because of its interaction with regular incoming waves. The structural design ensured negligible elastic deformations. During the model tests the generated waves were checked through suitable wave probes in the tank, a video camera was used to visualize the water-on-deck events and was synchronized with motion, pressure and force measurements to permit a proper analysis of the wave-ship interactions. To this aim, twelve markers have been distributed symmetrically on each side of the deck. Heave and pitch ship motions were measured both directly and indirectly. In the first case the motions are followed through an optical device; in the second case they are calculated through time integrations once an inertial platform system measured three angular velocities and three accelerations at a known location of the model. The local green-water loads on the deck were recorded by nine pressure sensors non-uniformly distributed along the ship centerplane going from the deck edge until the vertical deck superstructure. The horizontal force induced on the deck vertical superstructure by its interaction with the shipped water was measured by a high-frequency acquisition device.

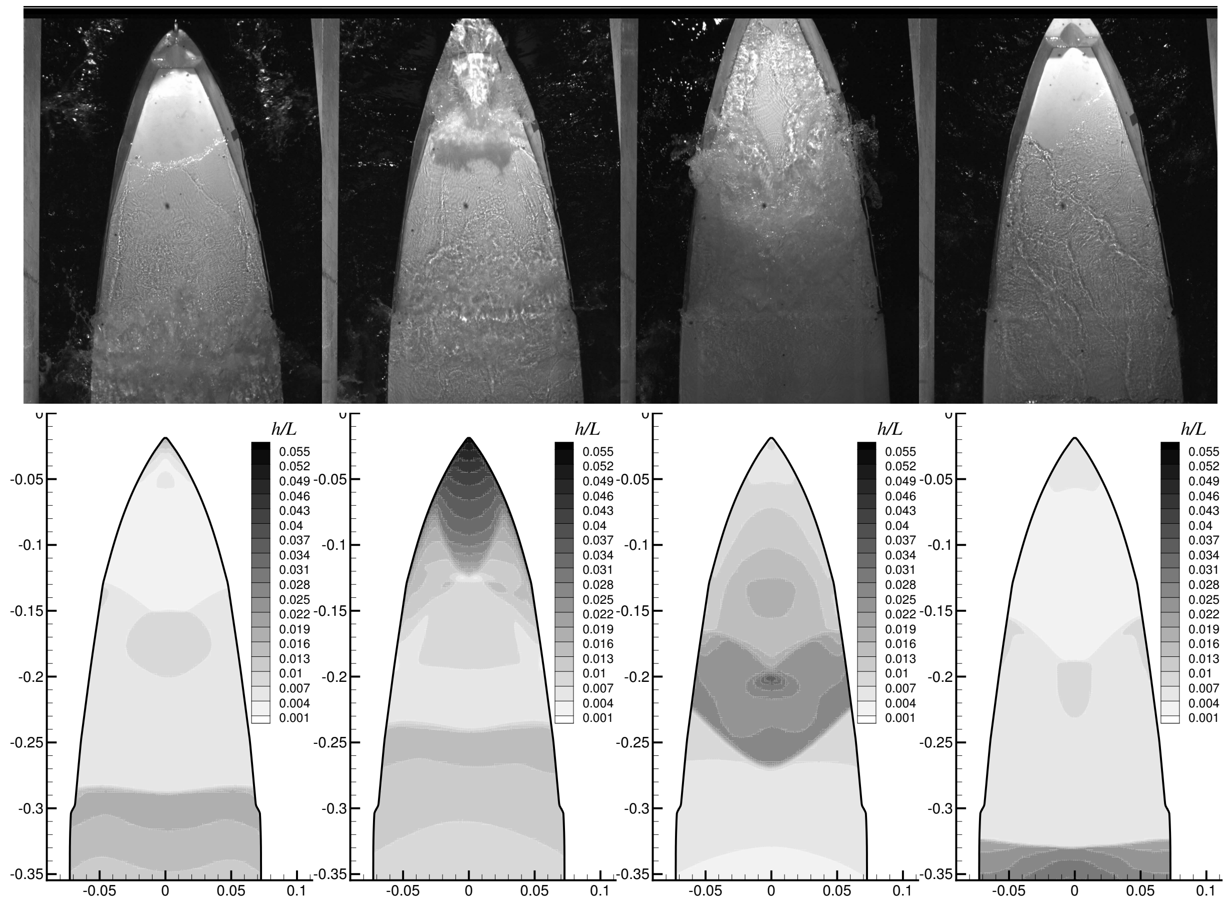

Figure 2: Water-on-deck event: top view. Top: experiments. Bottom: numerics. Time increases from left to right with time intervals: 0.2s, 0.4s and 0.7s. Regular incoming waves long $\lambda = L$ and steep $kA = 0.2474$. Numerical simulations with $\Delta x = \Delta y \simeq 0.0015L$ for the in-deck problem and with $\Delta t = 0.01T$ for the global-motion time integration. T is the incoming-wave period.

Analysis of green-water effects Here an experimental case is examined and measurements and numerical results are used to highlight features and global effects of water-on-deck events. The case refers to incoming waves long $\lambda = L$ and steep $kA = 0.2474$, with L the ship length, λ the wavelength, k the wavenumber and A the wave amplitude. The cyclical interaction with the vessel is responsible for significant water shipping with liquid remaining onto the deck between two following water-on-deck events. Figure 2 shows the water-on-deck scenario associated with these wave parameters, as recorded in the tests (the images are in the carriage reference frame) and predicted numerically (the results are in the deck reference frame). The water enters from the top and eventually interacts with a vertical superstructure placed on the bottom but not visible in the images. The water-on-deck phenomenon appears like a plunging *plus* dam-breaking type event (see *i.e.* Greco *et al.* 2007). The initial plunging is supported by the presence of a freeboard slightly higher than the deck height. The newly shipped water develops in the form of an inner faster tongue and hits the liquid remained on the deck from a previous water shipping which is mainly moving toward the bow to exit the deck. The impact induces some water to leave the deck laterally and causes experimentally a conspicuous amount of spray. The water entering the deck is more energetic so that after the impact most of the liquid moves toward the vertical superstructure, hits the wall and rises along it. Later the gravity action causes the water fall and induces a flow leaving the deck, in the meanwhile the wave-ship interaction is setting a new water shipping event. The comparison between numerical and experimental results shows a promising agreement. Figure 3 documents the experimental and numerical heave and pitch time histories. Numerically

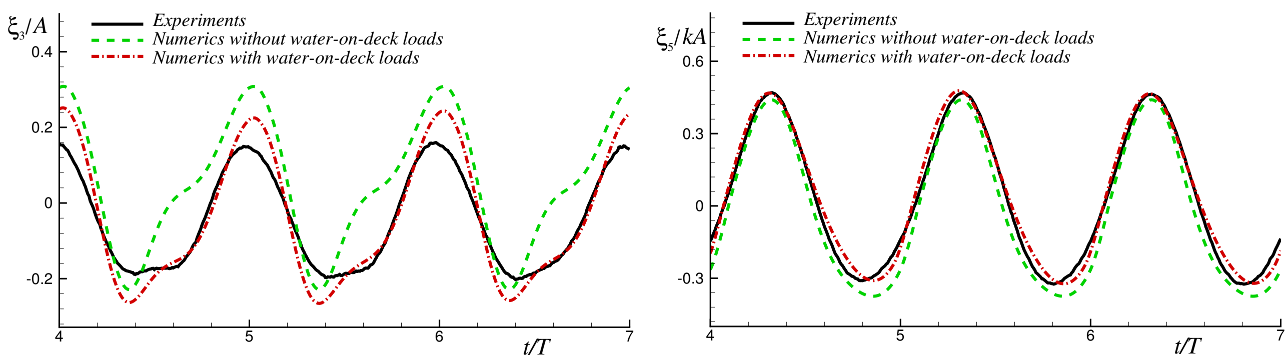

Figure 3: Heave (left) and pitch (right) time histories. Regular incoming waves long $\lambda = L$ and steep $kA = 0.2474$. Heave is positive upwards and pitch is positive with bow down. Numerical simulations with $\Delta t = 0.01T$ for the global-motion time integration. T is the incoming-wave period.

two simulations have been performed, respectively, neglecting and accounting for F_{wod} in the global-ship motions. The comparison of the two results with the experimental data highlights the importance of water-on-deck occurrence for the heave motion. In particular, the shipped water acts as a damping and as a source of nonlinearities. The effect on the pitch moment is limited and mainly localized near the minimum values which are reduced by water on deck. The results will be further investigated at the Workshop. Presently the pressure and force measurements are under investigation. Related results and comparison with the numerical solution will be also presented at the Workshop.

This research activity is partially supported by the Centre for Ships and Ocean Structures (CeSOS), NTNU, Trondheim, within the "Violent Water-Vessel Interactions and Related Structural Loads" project, partially supported by the Italian Navy within the "6-dof RANSE" project and partially done within the framework of the "Programma di Ricerca di Idrodinamica Navale 2007-2009" funded by *Ministero Infrastrutture e Trasporti*.

References

BUCHNER, B. (1995). On the impact of green water loading on ship and offshore unit design. In *Proc. Int. Symp. Practical Design of Ships and Mobile Units, PRADS'95*, Seoul, pp. 430–443. The Society of Naval Architects of Korea.

COLICCHIO, G., M. LANDRINI, AND J. CHAPLIN (2005). Level-set Computations of Free Surface Rotational Flows. *Journal of Fluids Engineering, Transactions of the ASME 127*(6), 1111–1121.

GRECO, M., G. COLICCHIO, T. BAZZI, AND C. LUGNI (2007). Numerical and Experimental Investigation of Violent Seakeeping Flows. In *Proc. of Int. Comference of Violent Flows VF-2007*, Fukuoka, Japan.

GRECO, M., G. COLICCHIO, AND O. M. FALTINSEN (2007). Shipping of Water on a Two-dimensional Structure. Part 2. *J. of Fluid Mech. 581*, 371–399.

PAWLOWSKI, J. (1991). A theoretical and numerical model of ship motions in heavy seas. In *SNAME Transactions*, Volume 99, pp. 319–315.

TORO, E. (2001). *Godunov Methods: Theory and Applications*.

ZHOU, Z. Q., J. Q. D. KAT, AND B. BUCHNER (1999). A nonlinear 3-d approach to simulate green water dynamics on deck. In PIQUET (Ed.), *Proc. 7th Int. Conf. Num. Ship Hydrod.*, Nantes, France, pp. 5.1–1, 15.