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NUMERICAL SIMULATION OF THE BEHAVIOUR OF A MOORED SHIP INSIDE AN OPEN COAST HARBOUR

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Abstract. Sea waves inside harbors can affect scheduled port operations. Hence it is important to correctly predict and characterize the wave field inside ports and to describe the movements of the ship and forces acting upon it. A classical approach is to assume that ship-wave interaction is linear, [1]. Then it is possible to decompose it in the so-called radiation and diffraction problems. Numerical models that solve such problems have been developed and used by the offshore industry for quite a while, [2], to study the interaction of sea-waves with floating objects. However, these models cannot be used to solve the diffraction problem of ships inside harbor basins where nearby reflecting boundaries and shallow depths create very complex nonlinear wave fields.

A new set of procedures using coupled models is proposed in this work. First, a Boussinesq-type finite element wave propagation model is used to determine the wave field in the numerical domain containing the harbor. Then the velocity potentials are evaluated at the ship's hull and finally, the Haskind relations [3] are used to determine the wave forces on the ship along the six modes of motion (heave, sway, surge, roll, pitch and yaw). This new methodology for the evaluation of diffraction forces on a ship inside a harbor basin is presented and tested in this paper. Movements of the moored ship and tensions on the mooring system are obtained using a numerical solver for the motion equations of a moored ship. An application to an open coast harbor is presented.

1. INTRODUCTION

Sea waves inside a sheltered basin can cause excessive motions on moored ships which can lead not only to interruption of loading and unloading operations but also to collisions with other ships or port infrastructures with significant economic losses.

Coupling a numerical model for wave propagation with a numerical model for moored ship behavior subjected to the wave action can identify potentially adverse sea states and help planning safe harbor activities.

A numerical tool called SWAMS has been developed to tackle this problem. The great advantage of such a tool is the ability to provide time series of ship's movements, as well as of forces and extensions in the mooring elements once the offshore sea-wave characteristics are known. This information can be derived from buoy measurements or prediction models, making this a very useful tool, both for design of port infrastructures and for planning of port activities.

For sea-wave propagation SWAMS may use a linear model based upon the mild slope equation, DREAMS [4], that is able to simulate the propagation of monochromatic waves into sheltered areas taking into account refraction, diffraction and reflection or a more complex model, BOUSS-WMH, [5], that is capable of a more accurate description of sea states evolution along varying-depth sheltered regions by taking into account also nonlinear interactions and energy dissipation due to bottom friction and wave breaking.

To simulate moored ship behaviour, SWAMS uses the numerical package MOORNAV [6] which resorts to the frequency domain results of the WAMIT model [2] for the radiation and diffraction problems of a free floating body to get the hydrodynamic forces necessary to BAS model [7]. This model assembles and solves, in the time domain, the moored ship motion equations taking into account incident sea waves and the geometry and constitutive relations of mooring system elements.

WAMIT was initially developed to evaluate the wave-induced stresses on floating structures deployed offshore. Within a harbor basin, waves are diffracted by the harbor structures which invalidates the use of WAMIT model to solve the diffraction problem unless one considers several floating bodies, some of them immobile and occupying the whole of the liquid column. However, this implies the solution of a huge system of linear equations. A possible alternative is to use the so-called Haskind relations [3] involving the potential flow associated with the waves radiated by the ship and the potential of incident waves at the position where the ship is placed.

In this paper we describe: the basic equations of moored ship behaviour, the SWAMS package, the application of this package to evaluate moored ship motions in a very special condition in which the model can be used directly with WAMIT; the new implemented procedures based on Haskind relations and the first test results obtained with these procedures. The paper ends with the presentation of final remarks on the work.

2. MOORED SHIP EQUATIONS

Assuming small amplitude of the ship movements along each of its six degrees of freedom, it is easy to define the part corresponding to the quasi-static variation of submerged hull form. This leads to the hydrostatic restoring matrix C_{kj} whose coefficients are the force along mode k due to a unit change, in still water, of the ship position along mode j.

The same assumption on ship movement amplitude leads to the linearity of the interaction between the hull and the incident waves. Such linearity allows the decomposition of that problem into two simpler problems, [1]: The radiation problem in which one determines the forces along each degree of freedom that are needed for an arbitrary hull movement in otherwise calm water, and the diffraction problem in which one determines the force along each degree of freedom k that is exerted by incident sea waves on the motionless ship hull.

The motion equation for the moored ship can then be written as

$$\sum_{j=1}^{6}\left[(M_{kj}+m_{kj})\ddot{x}_j(t)+\int_{-\infty}^{t}K_{kj}(t-\tau)\,\dot{x}_j(\tau)\,d\tau+C_{kj}x_j(t)\right]=F_k^d(t)+F_k^m(t)+F_k^f(t) \tag{1}$$

where M_{kj} is the mass matrix of the ship and $F_k^m(t)$ and $F_k^f(t)$ are the instantaneous values of the forces due to mooring lines and fenders. Strictly speaking, this is a set of six equations whose solutions are the time series of the ship movements along each of her six degrees of freedom as well as of the efforts in mooring lines and fenders.

In the above equation the mass matrix and the hydrostatic restoring matrix depend only on the ship geometry and on the mass distribution therein. The forces due to mooring lines and fenders can be determined from the constitutive relations of these elements of the mooring system and from the changes in the distance between their ends (for fenders one has account for the no-length variation associated to absence of contact between the ship and the fender).

The impulse response function, $K_{kj}(t)$ (the time-evolution of the force along k coordinate after a ship movement with impulsive velocity at $t=0$ along j coordinate), the infinite-frequency added mass matrix, m_{kj} and the excitation forces due to waves, F_k^d, that arise in the equation above depend on hull shape and on the disturbance caused in wave propagation flow by the motionless hull or on flow generated by hull movement in otherwise calm water.

Assuming that any sea state that acts on the ship can be decomposed into sine waves of known period and direction, the diffraction force associated with this sea state can be obtained from the superposition of the stationary diffraction forces due to each of these sinusoidal components. That is, results from the diffraction problem in the frequency domain may be used to produce a time domain result.

Also the impulse response functions and the infinite-frequency added masses can be determined from results obtained for the radiation problem in frequency domain:

$$K_{kj}(t)=\frac{2}{\pi}\int_{0}^{\infty}b_{kj}(\omega)\cos(\omega t)d\omega \tag{2}$$

$$m_{kj}=a_{kj}(\omega)+\frac{1}{\omega}\int_{0}^{\infty}K_{kj}(t)\sin(\omega t)d\omega \tag{3}$$

where $b_{kj}(\omega)$ is the damping coefficient for frequency ω and $a_{kj}(\omega)$ the added mass coefficient for the same frequency. The added mass and damping coefficients result from decomposing the stationary force associated to the radiation problem for a sinusoidal movement of frequency ω into a part that is in phase with the body velocity (the damping coefficient) and a part in phase with the body acceleration (the added mass coefficient).

3. FREQUENCY DOMAIN APPROACH

The use of frequency-domain results to generate data for a problem in the time domain is due to the greater availability of numerical models to solve, in the frequency domain, the interaction problem of a floating body with the waves.

WAMIT [2] is one of these models. It was developed at the former Department of Oceanic Engineering of the Massachusetts Institute of Technology and it uses a panel method to solve in the frequency domain the diffraction and radiation problems of a free floating body. This model uses Green's second identity to determine the intensity of source and dipole distributions over the panels used in discretization of the hull wetted surface. With such distributions it is possible to generate the harmonic flow potentials of the radiation and diffraction problems of a free ship placed in a constant-depth zone not limited horizontally.

3.1. Velocity potentials

Let X_j designate the j coordinate of a point P in the floating body. Due to the linearity of the floating body / waves system, if ω is the angular frequency of the incident wave then the motion described by X_j has the same angular frequency:

$$X_j = \mathrm{Re}\left[\varepsilon_j e^{-i\omega t}\right] \tag{4}$$

where ε_j designates the complex amplitude of the body motion along j coordinate.

Using the factorization proposed by [8], which assumes that the potential associated to the motion along j coordinate is proportional to the velocity complex amplitude of that motion, the flow potential when the ship moves under sea-wave action can be written as

$$\phi = \left[\varphi_0 + \varphi_7 + \sum_{j=1}^{6} - i\omega\varphi_j\varepsilon_j\right]e^{-i\omega t} \tag{5}$$

where φ_j is a complex stationary potential. This approach enabled the separation of the flow problem from the ship motion problem thus requiring the evaluation of flow potentials for unit velocity along each of the generalized coordinates, only. Each φ_j potential has to satisfy the usual Laplace equation in the whole fluid domain, the linearized free-surface boundary condition at $z = 0$ and the zero flow across the sea bottom boundary condition.

In addition to these equations, φ_j potential must satisfy also a boundary condition at the wetted surface of the floating body. For the φ_0 and φ_7 potentials, associated to the diffraction problem, the sum of the velocity components orthogonal to the ship hull produced by these two potentials must be zero because the body is motionless

$$\frac{\partial\varphi_0}{\partial n} + \frac{\partial\varphi_7}{\partial n} = 0 \,. \tag{6}$$

For the φ_1 to φ_6 potentials, at any point on the ship hull, the component of the flow velocity orthogonal to the ship hull must equal the same component of the ship local velocity.

$$\frac{\partial\varphi_j}{\partial n} = n_j \tag{7}$$

n_j being the generalized outer normal to the wetted surface of the ship (component of the ship local velocity normal to the wetted surface when the ship oscillates along j coordinate).

Once the flow potential is known, pressure on the floating body can be evaluated from the linearized Bernoulli equation and from this the force along the k coordinate is given by

$$F_k = i\rho\omega\int_S (\varphi_0 + \varphi_7) n_k e^{-i\omega t} dS + \sum_{j=1}^{6} -\rho\omega^2 \varepsilon_j \int_S \varphi_j n_k e^{-i\omega t} dS \tag{8}$$

The first term in the sum is the force associated to the diffraction problem whereas the second term is associated to the radiation problem. In the previous equations S is the wetted surface of the ship hull and n_k is the normal to that surface along generalized coordinate k. The decomposition of the force associated to the radiation problem into a part that is in phase with the body motion velocity and a part in phase with the body acceleration gives respectively the damping coefficient, b_{kj}, and the added mass coefficient, a_{kj}.

3.2. Haskind relations

The solution of the previous equations produce the quantities needed to model the interaction the floating body with monochromatic waves. As is, they are valid for the interaction of one floating body only with incident waves. By extending the concept of the generalized outer normal, n_j it is possible to study the interaction of monochromatic waves with several bodies some of which may be stationary, i.e. that are obstacles around which waves are diffracted.

Although it is possible to use the WAMIT model to solve the diffraction problem of a ship within a harbor basin, the number of equations that would be attained is too much for most of the currently available computers. An alternative to solve such a diffraction problem is to use the relations established in [3].

Using Green's second identity it is possible to show that there is no need to compute the potential of the wave diffracted by the body, ϕ_7, to evaluate the components of the force associated to the diffraction problem, equation (8). In fact, according to such identity, given a volume Ω where functions φ_j and φ_k are twice differentiable and whose boundary is $\partial\Omega$

$$\int_\Omega \left(\varphi_j \nabla^2 \varphi_k - \varphi_k \nabla^2 \varphi_j\right) dV = \int_{\partial\Omega} \left(\varphi_j \frac{\partial \varphi_k}{\partial n} - \varphi_k \frac{\partial \varphi_j}{\partial n}\right) dS \tag{9}$$

n being the boundary outer normal. $\partial\Omega$ is made of the solid boundaries of the domain, the free-surface, the body wetted surface, S, and of a vertical cylindrical surface away from the body. Since both φ_j and φ_k satisfy the Laplace equation in the whole domain, the volume integral at (9) is zero. The linearized boundary condition at the free-surface leads to the conclusion that at this part of the $\partial\Omega$ boundary the integral on the right hand side is zero. At the vertical cylindrical surface away from the body, φ_1 to φ_7 potentials comply with a radiation boundary condition. For such potentials the surface integral on that part of the $\partial\Omega$ boundary is also zero. Then it may be concluded that for φ_1 to φ_7 the following is valid

$$\int_S \varphi_j \frac{\partial \varphi_k}{\partial n} dS = \int_S \varphi_k \frac{\partial \varphi_j}{\partial n} dS \tag{10}$$

Given this and the boundary conditions for the radiation and diffraction problems at the solid boundaries of the domain, the diffracted force can be written in the form presented in [3] usually known as Haskind relations:

$$F_k^D = -i\rho\omega \int_S \left(\varphi_0 \frac{\partial \varphi_k}{\partial n} - \varphi_k \frac{\partial \varphi_0}{\partial n} \right) dS e^{-i\omega t} \tag{11}$$

So, instead of evaluating the diffraction potential φ_D to compute the force along k coordinate exerted by the incident waves on the stationary ship, using the previous equations it suffices to know the incident wave potential at the wetted body surface, φ_0, as well as the radiation potential at the same surface, φ_k.

3.3. Numerical Implementation

The Green theorem is used to transform the differential equations for radiation and diffraction potentials into integral equations that are assembled and solved by the numerical model WAMIT. Instead of having a set of equations valid in the whole domain one ends up with a set of equations to be satisfied at the domain boundaries, which happens to be the relevant region when flow induced forces are to be evaluated. By approximating the average position of the floating body wetted surface by a set or triangular or quadrangular panels where a constant value of the flow potential can be assumed, the integral equations become a set of linear equations for velocity potential values at each of those panels.

The surface integral in equation (11) is computed using the same panel discretization for the ship hull and a four-point Gauss quadrature formula. The normal derivative of the radiation potential φ_k at the Gauss quadrature points on each panel can be evaluated from the kinematics of the moving ship, equation (7). The value of the radiation potential is constant at each panel and is computed by the WAMIT model.

So, what needs to be evaluated are the incident wave potential, φ_0 and its normal derivative, $\partial\varphi_0/\partial n$, at the Gauss quadrature points. These quantities can be evaluated from the complex amplitude of the free surface elevation, $\eta(x_i, y_i)$, and of the horizontal components $U_0(x_i, y_i)$ and $V_0(x_i, y_i)$ of the wave-induced flow velocity.

Assuming that the mild slope hypothesis is valid, the vertical variation of the velocity potential can be written as $\varphi_0(x_i, y_i, z_i) = \varphi_0(x_i, y_i, z=0)\cosh[k(d+z_i)]/\cosh kd$. Then, once the free-surface elevation is known, the potential $\varphi_0(x_i, y_i, z_i)$ can be evaluated by

$$\varphi_0(x_i, y_i, z_i) = \frac{g}{\omega}\eta(x_i, y_i)\frac{\cosh[k(d+z_i)]}{\cosh kd} \tag{12}$$

The same mild slope hypothesis enables the relation between the complex amplitudes of the velocity horizontal components at any level and their complex amplitudes at $z=0$:

$$\frac{\partial\varphi_0}{\partial x} = u(x_i, y_i, z_i) = U_0(x_i, y_i)\frac{\cosh[k(d+z_i)]}{\cosh kd} \tag{13}$$

$$\frac{\partial\varphi_0}{\partial y} = v(x_i, y_i, z_i) = V_0(x_i, y_i)\frac{\cosh[k(d+z_i)]}{\cosh kd} \tag{14}$$

To get the complex amplitude of the vertical component of the wave induced flow velocity one just has to derive equation (12) in order to z to get

$$\frac{\partial \varphi_0}{\partial z} = \frac{gk}{\omega}\eta(x_i, y_i)\frac{\sinh[k(d+z_i)]}{\cosh kd} \tag{15}$$

From the scalar product of the velocity vector by the panel normal one gets the velocity vector component normal to the panel or the normal derivative of the flow potential associated to the incident wave.

4. SWAMS NUMERICAL TOOL

SWAMS - Simulation of Wave Action on Moored Ships - is an integrated tool for numerical modeling of wave propagation and of moored ship behavior inside ports to help in the decision making process for planning port operations.

It consists of a graphical user interface and a set of modules for running numerical models. The user interface enables data storage and manipulation, numerical model execution and enables graphical visualization of results. Each model corresponds to a module to which are attached the databases that bring together all the project information. With this application one may conduct studies in a more efficient way since the work related with the construction of the data files for each model, the model calculations and results visualization are easier.

SWAMS was developed in Microsoft Access™, which has the advantage of including the event-driven object programming language Visual Basic for Applications (VBA). An advantage of this language is the possibility to use and handle different Microsoft Windows applications.

The SWAMS ensemble includes:

- DREAMS module, corresponding to the numerical model DREAMS, [2], which is based on the mild-slope equation for monochromatic wave propagation;
- BOUSS-WMH module, based on the nonlinear finite element model BOUSS-WMH, [5], which solves the nonlinear Boussinesq equations presented in [9];
- MOORNAV module, [6], that assembles and solves the moored ship motion equations assuming the linearity of the floating body / waves system, proposed in [1]. This module is made of two numerical models: WAMIT, [2], that solves, in the frequency domain, the radiation and diffraction problems associated to the interaction between incident waves and a free-floating body; BAS, [7], that assembles and solves, in the time domain, the motion equations of a moored ship at berth taking into account the time series of the wave forces on the ship, the impulse response functions of the ship and the constitutive relations of the mooring system elements (mooring lines and fenders).

SWAMS databases are MS Access ™ databases, corresponding to the numerical models modules, which contain all the project information together with several folders where all the created files are stored.

The graphical representation of data and results in SWAMS is made with Tecplot™ (for DREAMS and BOUSS-WMH modules) and with MS Excel ™ (for WAMIT and BAS modules) and with Autocad (for WAMIT module). All these graphical visualization programs are run by event-driven macros that automate the entire process of creating maps and graphs.

5. MOORED SHIP IN A SCHEMATIC HARBOUR

This section presents one application of the numerical package for the evaluation of the behavior of a ship moored inside a schematic harbor basin under a sea state whose characteristics outside that basin are known. This numerical application illustrates SWAMS functioning, ie, of the set of models BOUSS-WMH, WAMIT, and BAS and draws attention to the modifications needed for a widespread application. It must be pointed out that Haskind relations produced diffraction forces in the frequency domain. For this the monochromatic incident wave field at the ship location was evaluated with numerical model DREAMS.

The wave propagation calculations were performed on a LINUX CORVUS workstation with four AMD Opteron ™ 265, 2GHz and 8GB of RAM, while the calculations of the behavior of the ship are made on a personal computer Intel Quad Core ™ Q6600 2.4Ghz and with 1.97GB of RAM.

5.1. Incident waves

The computational domain is 2000 m wide and 4000 m long. The schematic port located on the right hand side of the domain consists of two breakwaters: the North breakwater with two stretches, one horizontal and the other vertical of 750 meters and 1000 meters in length, respectively and the South Breakwater with one horizontal stretch, 400 m long, defining a quadrangular basin whose side length is approximately 700m, Figure 1.

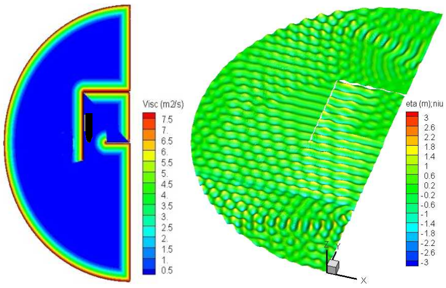

Figure 1: Calculation domain. Regular waves with a period of 10 s and amplitude 0.6 m from South (North coincides with the direction of the y axis).

The finite element mesh of the harbor domain was generated having a minimum of 8 points per wavelength, the depth in the whole area is 17 m and the incident regular waves had a period of 10 s and an amplitude of 0.6 m, resulting in a mesh with 185 599 elements, 93 616 points, 1 631 boundary points and a bandwidth of 322.

Figure 2 shows the time series of free surface elevation at a point within the port, where the ship is to be moored 600 s after the start of the calculation with the BOUSS-WMH module with regular waves from South (propagating in the positive direction of the y-axis) with 10 s period and 0.6 m amplitude.

5.2. Moored ship response

The ship has a volume of 108 416 m3, a waterline length of 243 m, a maximum beam of 42 m and a draft of 14 m. Since it is intended to illustrate the operation of the numerical model for moored ship behaviour only, the adopted mooring scheme was very simple, with

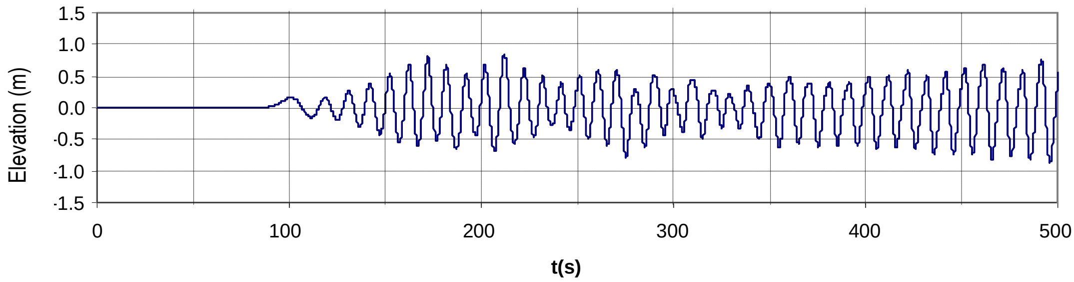

Figure 2: Free surface elevation in the area where the ship is moored.

only two breast lines (l1 and l4), two spring lines (l2 and l3) and two fenders (f1 and f2) as shown in Figure 3. The ship's longitudinal axis is parallel to the jetty, her bow being 98 away from the south end of that jetty. All mooring lines were made of polyethylene with the same maximum traction force of 1274 kN and had the same length (hence the same constitutive relations). The constitutive relation of one of these mooring lines is shown in Figure 3a). The pneumatic fenders had a maximum compression force of 3034 kN, the constitutive relations shown in Figure 3b) and the hull´s friction coefficient is 0.35. In this study, it is assumed that the wave hitting the ship propagates with straight crests perpendicular to the jetty where the ship is moored. This assumption makes the analysis simpler and allows one to use directly the results of the numerical model WAMIT for the free ship diffraction problem.

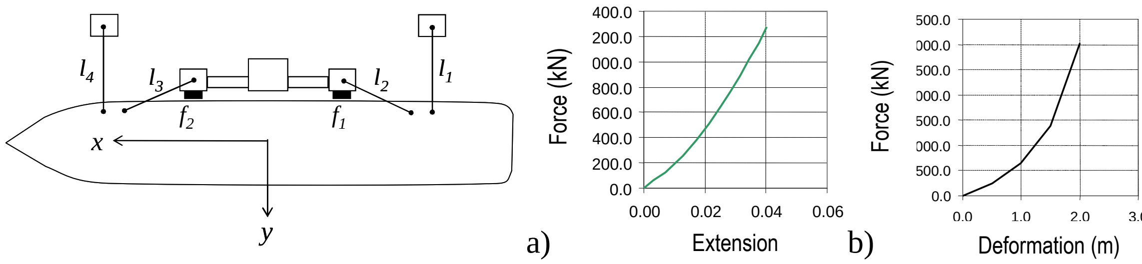

Figure 3: Mooring scheme. Constitutive relations: a) lines; b) fenders.)

For the interaction between the free ship and the incident waves (in the frequency domain), it was considered that only the pier wall close to the ship has some influence in this interaction. Thus it was modeled the ship near a vertical wall 750 m long, 50 m wide that occupied the whole of the water column, that is, with a height of 17 m. The ship's side close to the wall was 30 m apart from the wall and the ship's bow was 98 m away from the end wall.

The wet surface for the ship hull was divided into 3732 panels whereas the wall surface was divided into 1284 panels. Figure 4 shows a perspective of those panel distributions. The numerical model WAMIT was used to solve the radiation problem of the ship for 76 frequencies evenly spaced between 0.0125 rad / s and 0.95 rad / s.

Forces due to incident monochromatic waves were calculated using the Haskind relations with the incident wave field given by the DREAMS numerical model. As expected, the proximity of the vertical wall destroys the symmetry of the flow around the ship that existed when there was no wall. An example of this is the transverse force and the yaw torque on the ship that appear for head waves when there is a wall near the ship, Figure 5.

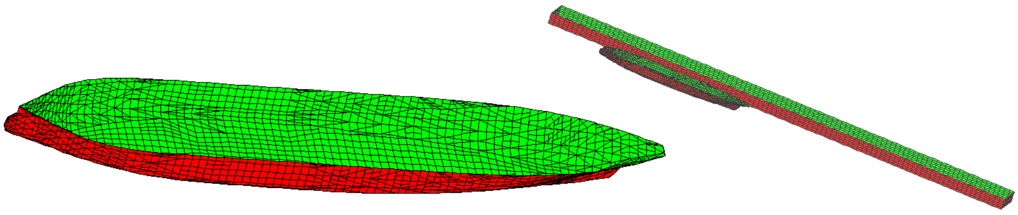

Figure 4: Panel discretization of the ship and the wall.

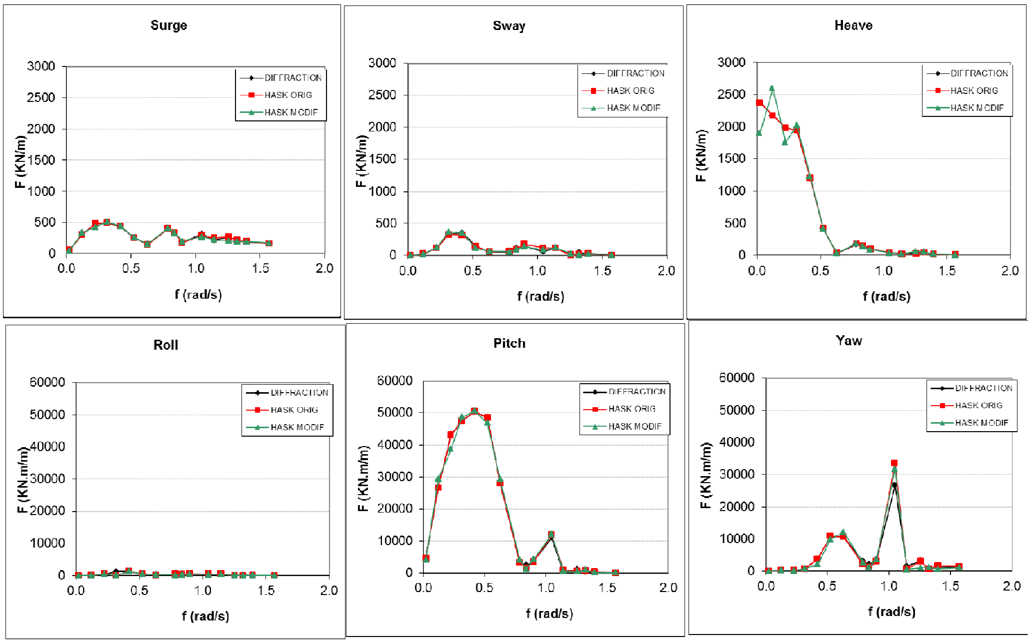

Figure 5: Forces due to incident head waves along the six degrees of freedom of the ship.

With the results from the frequency domain radiation and diffraction forces, it was possible to determine impulse response functions and the infinite-frequency added mass coefficients that are needed to mount the moored ship motion equations. All impulse response functions were calculated with a time interval of 0.1 s and a maximum duration of 200 s.

Starting from the impulse response functions for the 36 possible pairs (force along k coordinate due to motion with impulsive velocity along j coordinate) and the corresponding added mass coefficients for the various frequencies for which the radiation problem was solved in the frequency domain and using equation (3) several estimates for the infinite-frequency added mass added were obtained.

The time series of the forces due to incident waves on the ship were determined by using the time series of the free wave elevation estimated for a point in the area where the ship is to be moored together with the results from the frequency-domain diffraction problem for bow waves. Given the limitations of the procedure for obtaining the force time series, which is based on the Fast Fourier Transform, one might only consider the first 500 s of the free-surface elevation time series. Figure 6a) shows the time series of longitudinal force exerted by the incident waves on the ship. In the figure it can be seen another limitation of the procedure implemented to calculate time series: oscillations in the force time series do occur before the incident wave arrival to the location where the ship is moored (around t = 90 s) something which is not physically possible.

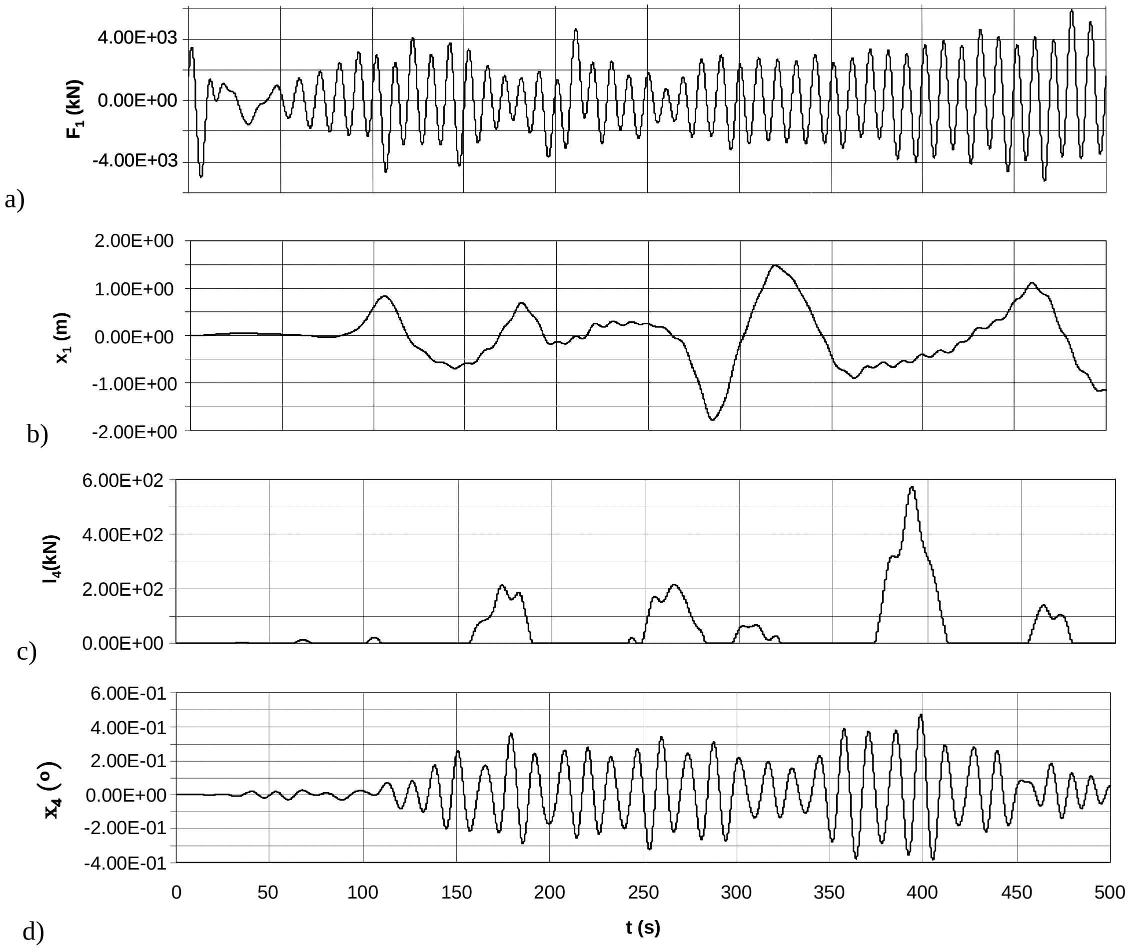

Figure 6: Moored ship time series: a) Longitudinal forces; b) Longitudinal motion; c) Tension on mooring line l1; d) Roll motion.

The time series of the movements along the longitudinal axis of the moored ship shown in Figure 6b), illustrates the non-linear response of the ensemble ship + mooring system. In fact, for oscillations in the free-surface elevation whose period is about 10 s, there are moored ship oscillations with a much higher period. The period of these oscillations is controlled by the existence of mooring lines and fenders, as can be confirmed in Figure 6c) with the time series of the forces in the bow breast line. Since the mooring system elements produce forces acting on the ship in the horizontal plane only, it is for the movements in this plane that the non-linear behavior is most evident. This can be confirmed with the time series shown in Figure 6d) with the roll motion where it is observed that the oscillation period is similar to the period of the incident wave on the ship.

6. FINAL REMARKS

This paper presents the results obtained with the numerical package SWAMS in modeling the behavior of a moored ship inside a schematic harbor. The time series of the ship's movements and tensions in the mooring system clearly illustrate the nonlinear behavior of the system ship-moorings-fenders.

A Boussinesq-type model was used to determine the time series of the incident waves. Results were obtained for a wave whose propagation direction coincided with the breakwater's length, which facilitated the determination of the diffraction forces. To solve more complex problems, where the incident waves are significantly diffracted by the harbor's infrastructures or other obstacles, a new procedure was tested based on so-called Haskind relations. So far, the velocity potentials of incident waves needed for this were obtained with a linear wave propagation model. The initial results presented here are very promising and the wave propagation model will soon be replaced by a more complex Boussinesq-type model.

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