Consistent Hydro-Structure Interface For Partial Structural Models

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Abstract

We present the development of a consistent hydro-structure interface providing an efficient way to transfer hydrodynamic pressures loading to a partial (3-cargo-hold) structural model. Unlike the full structure model in which the complete ship structure is modeled, additional difficulties raised in treating the missing fore and aft parts of the ship are solved by constructing an equivalent full structure model, recomputing all pressure components at points on the structure model and diffraction & radiation loads, and solving the motion equation to obtain the accelerations which give the balanced inertia loads.

1 Introduction

The difficulties related to the balancing of the 3D FE structural model, in the context of hydro-structure interactions in sea keeping are discussed. Different philosophies in modeling the structural and hydrodynamic parts of the problem, usually lead to very different meshes (hydro and structure) which results in unbalanced structural model and consequently in doubtful results for structural responses. The procedure usually employed consists in using different kinds of interpolation schemes for transfer of the total hydrodynamic pressure from hydrodynamic panels to the centroids of the structural finite elements. This approach is not only very complex for complicated geometries, but is also rather inaccurate. The method which solves all these problems was presented in [1] for the complete ship structural model. Here we concentrate on a partial, so-called 3-cargo-hold structural model as illustrated by Figure 1. Indeed, in the preliminary design stage the 3-cargo-hold model is often used in order to quickly perform some preliminary checks. The advantage of using 3-cargo-hold models is the important reduction of the time necessary to build the FE model. The fact that the fore and aft parts of the structural model are missing introduces some technical difficulties related to the balancing of the FE model.

The method that we propose here is based on three main ideas. First, we construct an equivalent full FE model from the 3-cargo-hold model which permits to treat the partial structure model like the full structure model. Second, instead of interpolations or projections of hydrodynamic pressure onto the structure model, all pressure components are recomputed at points of structure model. This is a very robust method since the difficulties related to the interpolation/projection techniques are avoided. Finally, to ensure the perfect equilibrium, the body motions are calculated after pressure integration over the structural mesh to obtain added-mass and radiation damping matrices, and wave excitation loads. In this way, the final numerical code is extremely robust and can be easily adapted to any type of 3D FEM structural software.

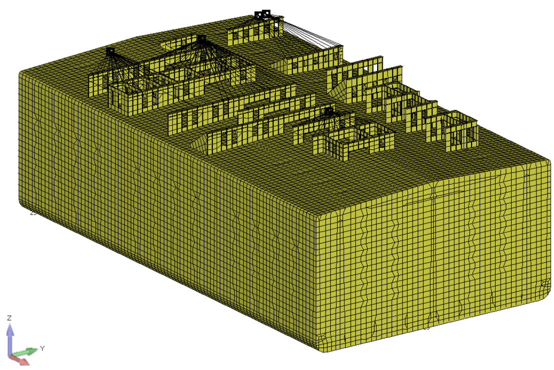

Figure 1: 3-cargo-hold FE model

2 Linear seakeeping analysis

Before considering the hydro-structure interaction problem in more details, and for the sake of clarity, first we briefly describe the basics of the seakeeping model which is used in most of the seakeeping tools based on Boundary Integral Equation techniques.

The problem is formulated in frequency domain under the potential flow assumptions. The total velocity potential is decomposed into the incident, diffracted and 6 radiated components:

$$\varphi = \varphi_I + \varphi_D - i\omega \sum_{j=1}^{6} \xi_j \varphi_{Rj} \tag{1}$$

Where :

ω	-	wave frequency
φ_I	-	incident potential
φ_D	-	diffraction potential
φ_{Rj}	-	radiation potential
ξ_j	-	rigid body motions

At the same time, the corresponding dynamic pressure is found from the linear Bernoulli equation, and the similar decomposition is adopted:

$$p = i\omega\varrho\varphi = p_I + p_D + \sum_{j=1}^{6} \xi_j p_{Rj} \tag{2}$$

In order to obtain the total hydrodynamic pressure, the dynamic variation of the hydrostatic pressure due to the ship motions should also be added to the above expression. The variation of the hydrostatic pressure at a given point of the ship hull with coordinates (X, Y, Z) is:

$$p^{hs} = -\varrho g[\xi_3 + \xi_4(Y - Y_G) - \xi_5(X - X_G)] \tag{3}$$

where the subscript "$_G$" denotes the position of the center of gravity of the ship with respect to which the motion equation is usually written. It is important to note that the motion equation is written in the so called earth fixed reference system, or in the system parallel to it, if the body is animated with forward speed. For that reason the restoring matrix is not obtained directly by integration of the variation of the hydrostatic pressure (3), but also the change of the normal vector should be taken into account. At the end, the total variation of the resulting hydrostatic force is given by:

$$\{\mathbf{F}^{hs}\} = [\,\mathbf{C}\,]\{\boldsymbol{\xi}\} = \iint_{S_B^H} [p^{hs}\mathbf{n} - \varrho g Z \boldsymbol{\Omega} \wedge \mathbf{n}] dS \tag{4}$$

where $\boldsymbol{\Omega}$ denotes the rotational component of the motion vector $\boldsymbol{\Omega} = (\xi_4, \xi_5, \xi_6)$, and S_B^H denotes the hydrodynamic mesh of the wetted body surface. Note that the compact notation is used throughout whole the paper, so that the normal vector $\boldsymbol{n}$ denotes (n_x, n_y, n_z) for $i = 1, 2, 3$, and $(\mathbf{R} - \mathbf{R}_G) \wedge \mathbf{n}$ for $i = 4, 5, 6$ where $\mathbf{R}$ stands for (X, Y, Z) and $\mathbf{R}_G$ for (X_G, Y_G, Z_G).

After integrating the pressure over the wetted body surface, the corresponding forces are obtained and the rigid body motion equation, in frequency domain, is usually written in the following form:

$$\Big(-\omega^2([\,\mathbf{M}\,] + [\,\mathbf{A}\,]) - i\omega[\,\mathbf{B}\,] + [\,\mathbf{C}\,]\Big)\{\boldsymbol{\xi}\} = \{\mathbf{F}^{DI}\} \tag{5}$$

where:

$[\,\mathbf{M}\,]$	-	genuine mass matrix
$[\,\mathbf{A}\,]$	-	added mass matrix
$[\,\mathbf{B}\,]$	-	damping matrix
$[\,\mathbf{C}\,]$	-	hydrostatic restoring matrix
$\{\mathbf{F}^{DI}\}$	-	excitation force vector

The final expressions for the excitation, added mass and damping coefficients are:

$$F_i^{DI} = i\omega\varrho \iint_{S_B^H} (\varphi_I + \varphi_D) n_i dS \tag{6}$$

$$\omega^2 A_{ij} + i\omega B_{ij} = \varrho\omega^2 \iint_{S_B^H} \varphi_{Rj} n_i dS \tag{7}$$

Note also that, in the general case, the total restoring matrix is a sum of the pressure part (4) and the gravity part which is zero in the present case because the motion equation is written with respect to the center of gravity.

Within the Bureau Veritas's numerical code HYDROSTAR, the Boundary Integral Equation (BIE) method based on the source formulation is used to solve the Boundary Value Problems (BVP) as presented in Chen (2004).

In the case of zero forward speed, the general form of the BVP is:

$$\left.\begin{array}{ll} \Delta\varphi = 0 & \text{in the fluid} \\ -\nu\varphi + \dfrac{\partial\varphi}{\partial z} = 0 & z = 0 \\ \dfrac{\partial\varphi}{\partial n} = V_n & \text{on } S_b \\ \lim\big[\sqrt{\nu R}(\dfrac{\partial\varphi}{\partial R} - i\nu\varphi)\big] = 0 & R \to \infty \end{array}\right\} \tag{8}$$

where V_n denotes the body boundary condition which depends on the considered potential:

$$\frac{\partial\varphi_D}{\partial n} = -\frac{\partial\varphi_I}{\partial n}, \qquad \frac{\partial\varphi_{Rj}}{\partial n} = n_j \tag{9}$$

Within the source formulation, the potential at any point in the fluid is expressed in the following form:

$$\varphi = \iint_{S_B^H} \sigma G dS \tag{10}$$

where G stands for the Green function, and σ is the unknown source strength which is found after solving the following integral equation:

$$\frac{1}{2}\sigma + \iint_{S_B^H} \sigma \frac{\partial G}{\partial n} dS = V_n\,, \quad \text{on} \quad S_B^H \tag{11}$$

This equation is solved numerically, after discretizing the wetted part of the body into a number of flat panels over which the constant source distribution is assumed.

3 Equivalent full model

The fact that in a 3-cargo-hold model, the fore and aft parts of the model are missing introduces some technical difficulties in the FE model equilibration. Two main inputs are needed in the hydro-structure coupling method developed in [1]. They are the wetted part of the full FE model that is used for pressures integration and the full FE model mass matrix that is used to solve the motion equation. Therefore the method developed for the 3-cargo-hold models is based on :

1. Construction of an equivalent full FE model wetted part from 3-cargo-hold FE model wetted part and hydro model.

2. Construction of an equivalent full FE model using concentrated masses and rigid elements.

Those two points transform the problem of equilibration of a 3-cargo-hold FE model into the equilibration of a full FE model.

3.1 Equivalent full FE model

The equivalent full FE model is built using concentrated masses and rigid elements. Two concentrated masses are added to the 3-cargo-hold FE model. They are respectively positioned at the center of gravity of the missing aft and fore parts of the model. The concentrated masses are respectively given the mass and inertia properties of the fore and aft parts of the ship. Each concentrated mass is linked to a set of nodes of the 3-cargo-hold model sections that represents the actual link with the missing fore and aft sections. The rigid elements have no mass and the dependent and in degrees of freedom can be defined for each particular node in order to represent the physical link with the missing parts of the model. The so build equivalent full FE model has the same mass and inertia properties as a full FE model (Figure 2).

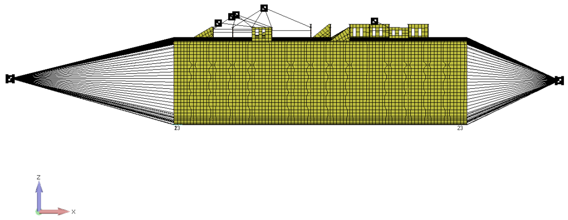

Figure 2: Equivalent full FE model.

3.2 Wetted part of the equivalent full FE model

The FE model wetted part is used for the integration of the pressures. In order to build the equivalent full FE model wetted part from the 3-cargo-hold model wetted part, the missing fore and aft part are taken from the hydro model. To achieve this, the hydro model is cut at the fore and aft sections of the 3-cargo-hold FE model. The fore and aft parts of the hydro model are then added to the 3-cargo-hold FE model wetted part (Figure 3).

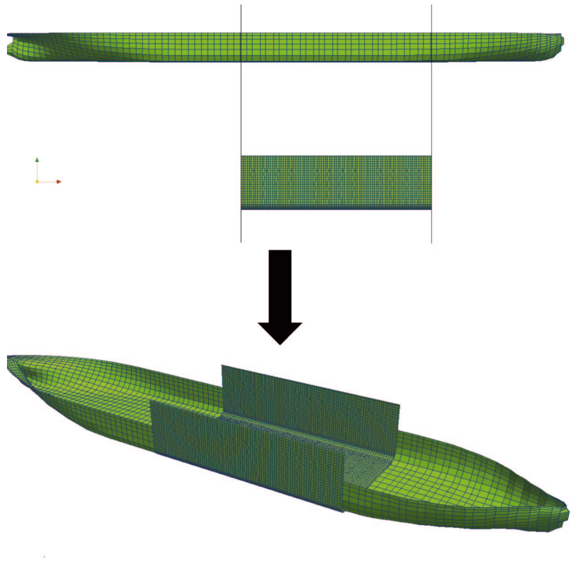

Figure 3: Equivalent full FE model wetted part.

4 Loading on the structure model

The loading on the structural model is composed of the inertia loads and external pressure loads. Inertia loads can be included straightforwardly by associating the acceleration vector to each finite element. Concerning the pressure loading, most of the methods nowadays use the different interpolation schemes in order to transfer the total hydrodynamic pressure (2,3) from hydro model (centroids of the hydro panels) to the structural model (centroids or nodes of finite elements). Besides the problems of interpolation, it is important to note that the motion amplitudes, which are present in the definition of the total pressure, were calculated after integration over the hydrodynamic mesh. For that reason it is impossible to obtain the completely equilibrated structural model. Indeed, the FE model has its own integration procedure which is usually different.

As briefly stated in the introduction, in order to obtain the perfect equilibrium of the structural model we introduce three main ideas:

1. Construction of an equivalent full model from the 3-cargo-hold model;
2. Recalculation of pressure in structural points, instead of interpolation;
3. Separate transfer of pressure components, and calculation of hydrodynamic coefficients (added mass, damping, hydrostatics & excitation) by integration over the structural mesh.

Here below we discuss the two last points in more details.

4.1 Hydrodynamic pressure

What we propose here for the pressure transfer from hydrodynamic model to the structural model, is to recalculate the pressure at the required locations instead of interpolating it from hydrodynamic model (see Blandeau et al. 1999). This becomes possible thanks to the particularities of the BIE method which gives the continuous representation of the potential through the whole fluid domain $Z \leq 0$. In this way the communication between the hydrodynamic and structural codes is extremely simplified. Indeed, it is enough for the structural code to give the coordinates of the points where the potential is required and the hydrodynamic code just evaluates the corresponding potential by:

$$\varphi(\boldsymbol{x}_s) = \iint_{S_B^H} \sigma(\boldsymbol{x}_h) G(\boldsymbol{x}_h; \boldsymbol{x}_s) dS \tag{12}$$

where $\boldsymbol{x}_s = (x_s, y_s, z_s)$ denotes the structural point and $\boldsymbol{x}_h = (x_h, y_h, z_h)$ the hydrodynamic point.

In the case of linear seakeeping without forward speed, this operation is sufficient because the pressure is directly proportional to the velocity potential and, within the source formulation, the potential is continuous across the body surface. This is very important point because, due to the differences in the hydrodynamic and structural mesh, the structural points might fall inside the hydrodynamic mesh.

Once each pressure component has been transfered onto the equivalent full FE model wetted part, the "new" hydrodynamic coefficients are calculated by integration over the equivalent full FE model wetted part:

$$F_i^{ID^S} = i\omega\varrho \iint_{S_B^S} (\overset{S}{\varphi_I} + \overset{S}{\varphi_D}) n_i dS \tag{13}$$

$$\omega^2 \overset{S}{A_{ij}} + i\omega \overset{S}{B_{ij}} = \varrho\omega^2 \iint_{S_B^S} \overset{S}{\varphi_{Rj}} n_i dS \tag{14}$$

where the superscript " ^{S} " indicates that the quantities are taken on the structural mesh.

4.2 Hydrostatic pressure variations

Here we concentrate on the calculation of the hydrostatic restoring matrix which is obtained after the integration of the hydrostatic pressure variations due to the body motions (3). The procedure is rather similar to the hydrodynamic pressure, and we just need to integrate the expression (3) over the structural mesh. For the sake of clarity, let us first rewrite the hydrostatic pressure variations in the following compact form:

$$p^{hs} = \sum_{j=1}^{6} \xi_j p_j^{hs} \tag{15}$$

Where:

$$p_1^{hs} = p_2^{hs} = p_6^{hs} = 0\,, \quad p_3^{hs} = -\varrho g \tag{16}$$

$$p_4^{hs} = -\varrho g(Y - Y_G)\,, \quad p_5^{hs} = \varrho g(X - X_G) \tag{17}$$

With these notations, the first part of the hydrostatic restoring matrix becomes:

$$C_{ij}^p = \iint_{S_B^S} p_j^{hs} n_i dS \tag{18}$$

In order to obtain the complete hydrostatic restoring matrix, one additional term accounting for the change of coordinate system should be added to the above expression as shown in equation (4). In the earth fixed coordinate system, this additional term is accounted for by the change of the normal vector (4). However, the structural response is calculated in the body fixed coordinate system in which the normal vector do not change. It can be shown (e.g. see Malenica(2003)) that, in the body fixed coordinate system, the change of normal vector is equivalent to the change of the gravity action, so that we can write:

$$\{\mathbf{F}^g\} = [\ \mathbf{C}^g]\{\boldsymbol{\xi}\} \tag{19}$$

where the stiffness matrix coefficients C_{ij}^g come from the following contribution only:

$$\boldsymbol{F}^g = -mg\boldsymbol{\Omega} \wedge \mathbf{k} \tag{20}$$

with :

m	-	mass of the equivalent full FE model.
g	-	acceleration of gravity.
$\mathbf{k}$	-	unit vector of earth fixed coordinates system.

Note that the only non zero elements of the matrix $[\ \mathbf{C}^g]$ are C_{24}^g and C_{15}^g which will be canceled by the contributions implicitly present in $[\ \mathbf{C}^p]$.
The total restoring matrix becomes:

$$[\ \mathbf{C}\ ]^S = [\ \mathbf{C}^g] + [\ \mathbf{C}^p] \tag{21}$$

where the superscript " ^{S} " indicates hat the pressure related part was calculated by integration over the structural mesh.

4.3 General principle for pressure loading

The pressures are recalculated at structural points on the equivalent full FE model wetted part. The equivalent full FE model is loaded with nodal forces on each node of the 3-cargo-hold FE model wetted part and nodal forces and moments on the two concentrated masses defined in 3.1 (Figure 4). The nodal load approach has prove to be more efficient than the elemental pressures approach. The pressures on the fore and aft part of the equivalent full FE model wetted part are integrated using the center of gravity of the fore and aft part as reference points and the nodes holding the concentrated masses are loaded with the resulting force tensors. The integration of a given pressure component $p(x,y,z)$ gives the total loading to be applied on the equivalent full FE model. This loading is made of three distinct parts:

1. Nodal forces applied on the wetted elements of the 3-cargo-hold FE model:

$$\sum_{i=1}^{N} \mathbf{F}^i = \iint_{S_c} p(x,y,z)\mathbf{n}dS \qquad (22)$$

   Where the normal vector $\mathbf{n}$ denotes (n_x, n_y, n_z) and N is the total number of the wetted FE nodes.

2. Load tensors applied to the artificial FE node at G_a:

$$\{\mathbf{F}_a\} = \iint_{S_a} p(x,y,z)\mathbf{n}dS \qquad (23)$$

   where the normal vector $\mathbf{n}$ denotes (n_x, n_y, n_z) for the translational components and $(\mathbf{R} - \mathbf{R}_{G_a}) \wedge \mathbf{n}$ for the rotational components.

3. Load tensors applied to the concentrated mass at the fore part of the ship:

$$\{\mathbf{F}_f\} = \iint_{S_f} p(x,y,z)\mathbf{n}dS \qquad (24)$$

   where the normal vector $\mathbf{n}$ denotes (n_x, n_y, n_z) for the translational components and $(\mathbf{R} - \mathbf{R}_{G_f}) \wedge \mathbf{n}$ for the rotational components.

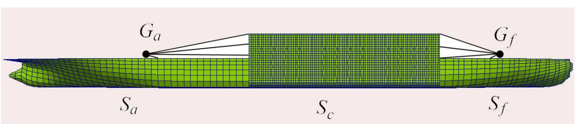

Figure 4: Pressures integration and loading of structural model

4.4 Motion equation and final loading of the structural model

Once the pressure integration over the structural FE model done for each particular pressure component, the corresponding hydrodynamic coefficients can be deduced and the following motion equation can be written in the form:

$$\left(-\omega^2([\,\mathbf{M}\,]+[\,\mathbf{A}\,]^S)-i\omega[\,\mathbf{B}\,]^S+[\,\mathbf{C}\,]^S\right)\{\boldsymbol{\xi}\}^S=\{\mathbf{F}^{DI}\}^S \qquad (25)$$

Solution of this equation gives the body motions $\{\boldsymbol{\xi}\}^S$ so that the total linear pressure can be written in the form

$$p^S = p_I^S + p_D^S + \sum_{j=1}^{6} \xi_j^S (p_{Rj}^S + p_j^{hs}) \qquad (26)$$

In summary the final loading of the structural model will be composed of the following 3 parts:

$-\omega^2 m_i \boldsymbol{\xi}_i^S$	-	Inertial loading
p_i^S	-	Pressure loading
$-m_i g \boldsymbol{\Omega}^S \wedge \mathbf{k}$	-	Gravity term

The inertial loading and the gravity term are to be applied on each finite element. The pressure loading is to be applied only on wetted finite elements. It is clear that the above structural loading will be in perfect equilibrium because this equilibrium is implicitly imposed by the solution of the motion equation (25) in which all different coefficients were calculated by using directly the information from the structural FEM model.

4.5 Viscous roll damping

In addition to the wave radiation damping, given by potential theory, there exist some other sources of damping in reality. These additional sources of damping are usually attributed to the phenomena like flow separation, skin friction, etc, and are usually called viscous damping. Viscous damping mostly affects the roll motion for which the potential part of damping is too low and leads to very unrealistic roll motions. There are several approximate ways to take into account the viscous roll damping and probably the simplest one is the addition of the overall roll damping coefficient B_{44}^v as the percentage of the critical damping B_c. This method is one option in the BV's hydrodynamics code HYDROSTAR and, here below, we briefly describe the basic principles for the loading of the FE model when this approximation is used.

The critical damping can be expressed as:

$$B_c = 2\omega_r(I_{44} + A_{44}(\omega_r)) \qquad (27)$$

Where :

ω_r	-	roll resonant frequency
I_{44}	-	roll moment of inertia
$A_{44}(\omega_r)$	-	roll added moment of inertia

Since this additional damping term is used to solve the motion equation, it should also be applied on the equivalent full FE model in order to have it perfectly balanced. In the approach proposed here, the roll damping is assumed to be induced by the bilge keels on the sides of the hull only! The viscous roll damping term is applied to the equivalent full FE model by means of the forces on the bilge keels. Even if the bilge keels are not modeled in the equivalent full FE model, the coupling code MARGE defines a set of nodes on the model that correspond to the position of the bilge keels (figure 6). Each node of the bilge keel is loaded with a force vector that is normal to the axis defined by the center of gravity of the ship and the node itself, and lies in the (Y, Z) plan (figure 5). The viscous damping force on each node is proportional to the relative velocity between the bilge keel and the fluid at the node location so that the force on each node can be written as:

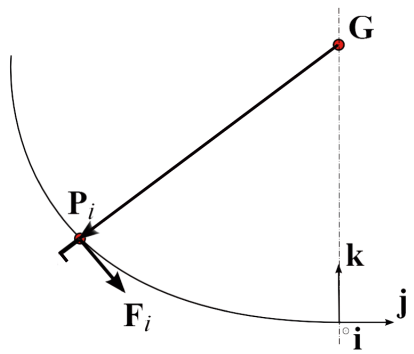

Figure 5: Load on bilge keels.

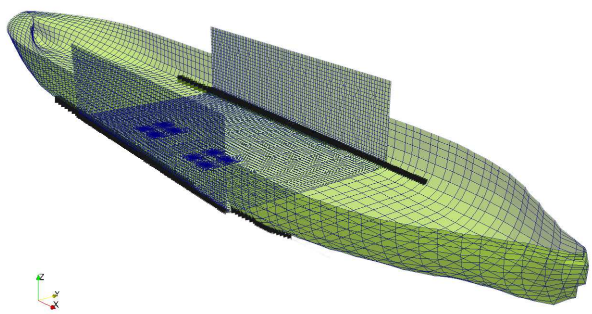

Figure 6: Set of nodes defining bilge keels.

$$\mathbf{F}_i = C^v \dot{\xi}_4 \mathbf{i} \wedge \mathbf{GP}_i^0 \tag{28}$$

where the vector $\mathbf{GP}_i^0$ is the projection of the vector $\mathbf{GP}_i$ on the plan (YZ):

$$\mathbf{GP}_i^0 = 0\mathbf{i} + (Y_G - Y_P^i)\mathbf{j} + (Z_G - Z_P^i)\mathbf{k} \tag{29}$$

The viscous constant C^v, in the above equation, needs to be determined by equating the total nodal force action with the action of the overall viscous damping coefficient B_{44}^v.

Following the above notations, the roll moment resulting from the summation of the nodal forces, expressed at the center of gravity of the ship, becomes:

$$M_x^v = -\sum_{i=1}^{N^v} \mathbf{F}_i \wedge \mathbf{GP}_i^0 \tag{30}$$

Where N^v is the number of nodes used to define the bilge keels.

On the other hand we can also write:

$$M_x^v = \dot{\xi}_4 B_{44}^v \tag{31}$$

so that the following expression for damping coefficient C^v can be deduced:

$$C^v = \frac{B_{44}^v}{\sum_{i=1}^{N^v} |\mathbf{GP}_i^0|^2} \tag{32}$$

from introducing (28) to (30) and making the equation of (30) and (31).

5 Numerical implementation

The calculation of the hydrodynamic coefficients (added mass, damping, excitation & restoring) by integration over the structural mesh (13,14,18) can be done in different ways and usually depends on the type of finite elements that are used by FEM solver. Here below we propose the method which applies for the most typical shell elements.

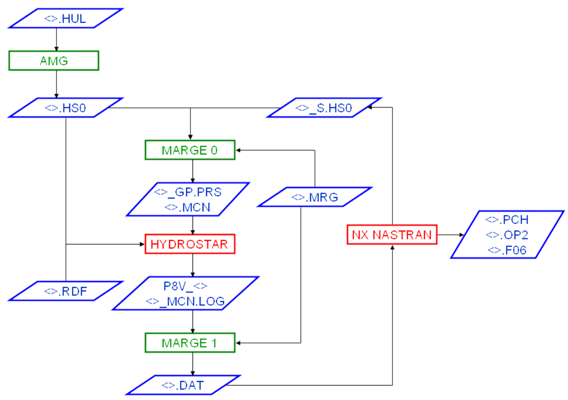

Figure 7: General coupling scheme for typical FEM package.

Within this method, the pressure integration is still performed over the structural mesh, but only the most typical finite elements are considered. The advantage of the method is that hydrodynamic coefficients are calculated outside the FEM package (MARGE module in this case). The disadvantage is that the small disequilibrium might persist for the FEM codes which use a different integration scheme. However, this disequilibrium is likely to be very minor. The general coupling scheme is shown in Figure 7. As we can see the procedure is quite simple and can easily be adapted to any particular FEM package. The Automatic Mesh Generator AMG builds a hydro model from the hull lines of the vessel. The 3-cargo-hold FE model wetted part is extracted from the 3-cargo-hold FE model and the MARGE code uses the hydro model to build the full equivalent FE model wetted part and write the structural points file for HYDROSTAR. Then HYDROSTAR computes the pressures at the structural points and write them in files for MARGE. Finally, MARGE creates the load files for NASTRAN or any FEM package, the FE computations can be ran.

6 Numerical results

We present below some numerical results showing the efficiency of the proposed approach. The example concerns a FPSO vessel with the following main dimensions: Length over all $Loa = 230m$, Breadth $B = 40m$, Draught $D = 11.14m$. The corresponding structural and hydrodynamic meshes are shown in Figures 2, 1 and 3. In Figures 9, 10, 11 and 12, the added mass coefficients, damping coefficients, excitations and motion RAO's are presented ($V = Loa * B * D$). The differences which exist between FEM and Hydrostar results are expected and are due to the differences in two meshes (hydro and structure). These differences are exactly the ones which ensure the equilibrium of the structural model. The fact that these differences are not very important shows that the overall coupling procedure is very efficient.

The structural problem is solved using NX NASTRAN. The method give perfectly balanced FE model as seen in Figure 8.

7 Conclusions

As far as the linear seakeeping analysis is concerned, the fully consistent transfer of hydrodynamic loading from hydrodynamic model to the 3D FE structural model is never perfect, even if the two meshes coincide. However, depending on the method of pressure transfer, the coupling can be more or less efficient/consistent. The main difficulty lies in the fact that two meshes (hydro and structural) are usually very different, which ends up with the unbalanced structural model if the coupling procedure is not correctly performed. In the preliminary design stage 3-cargo-hold models are usually considered. The use of such models adds some difficulties to the coupling procedure and balancing of the FE model. In this paper we presented a method that overcomes those difficulties and leads to completely balanced 3-cargo-hold structural model. The presented method can easily be adapted to any structural FEM packages because the balancing procedure is done after hydrodynamic computation and before structure analysis, i.e., outside of both hydrodynamic code and structural FEM code.

Acknowledgements

Important part of the present work was done within the MARSTRUCT European project.

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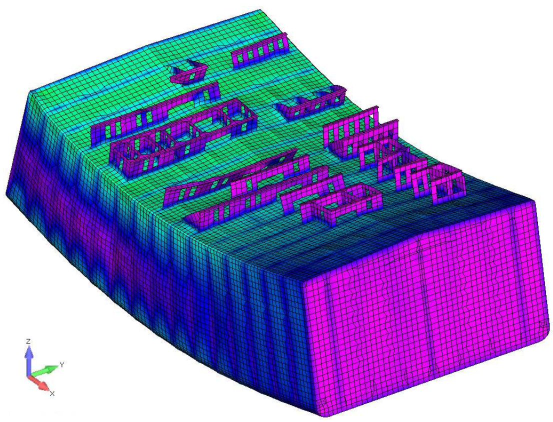

Figure 8: Balanced FE model after structural problem resolution, displaying Von-Mises stress

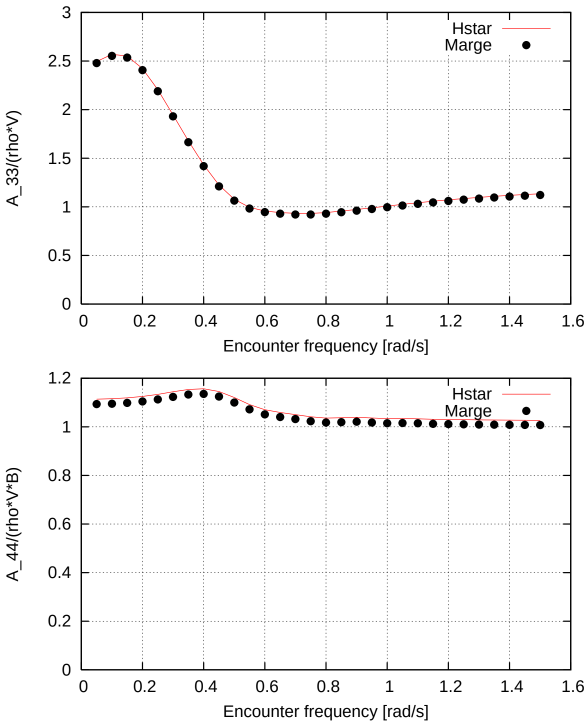

Figure 9: *Added mass coefficients.*

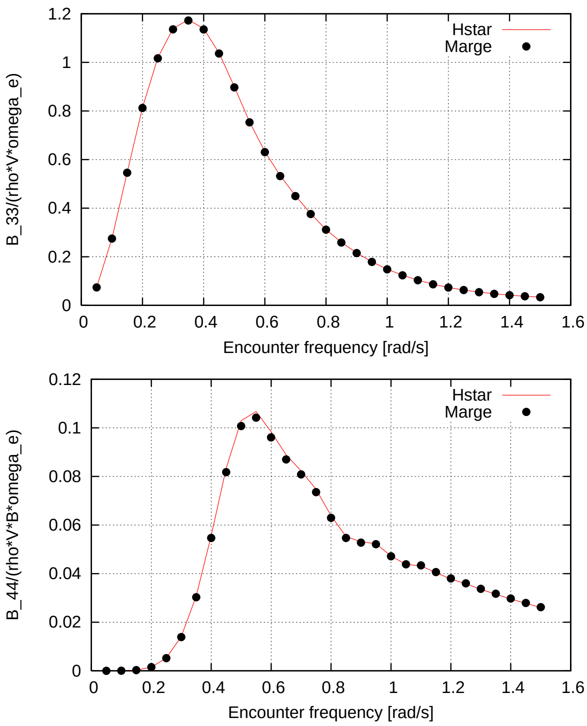

Figure 10: Damping coefficients.

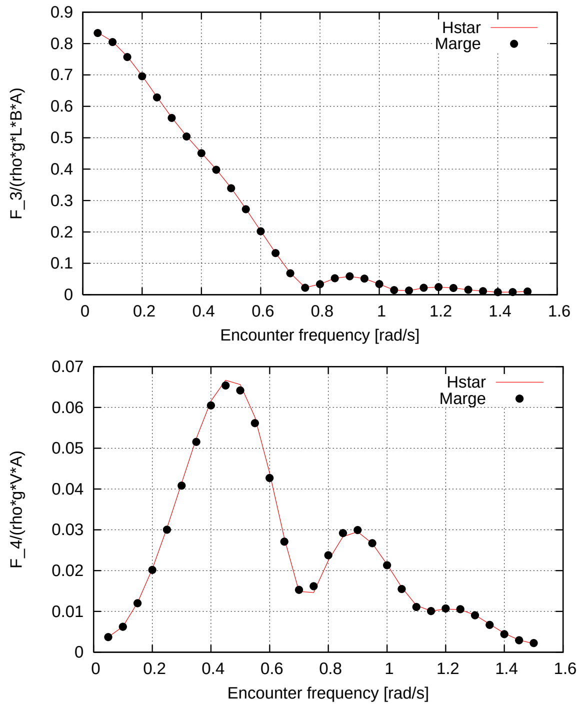

Figure 11: Excitation forces for wave incidence $\beta = 120^o$.

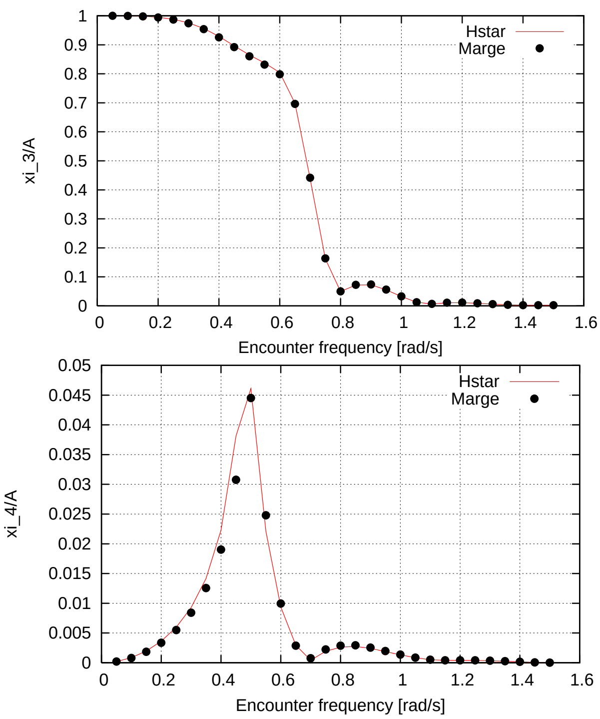

Figure 12: RAO's of ship motions for wave incidence $\beta = 120^o$.