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ON THE SHIP STRUCTURAL RESPONSE DUE TO SLAMMING LOADS

B. Donguy*, B. Peseux*, and E. Fontaine†

*Ecole Centrale de Nantes, Laboratoire Mécanique et Matériaux, Divison Mécanique des structures, 1, rue de la Noë, 44321 Nantes Cedex 3, France. bundi.donguy@ec-nantes.fr, <http://www.ec-nantes.fr/Structures/index.html>

†University of California, Ocean Engineering Laboratory, CA 93106-1080, USA.

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Abstract. *Hydroelastic effects associated with ship slamming are investigated by mean of a decoupled approach. A finite element computation of the ship structural response is performed using the pressure field obtained from a rigid body strip theory. Results show the importance of both, hydroelastic and three dimensional effects for realistic impact situations. A numerical approach is then described and implemented to solve the three-dimensional fluid problem. The approach relies on the method of matched asymptotic expansion, associated with a numerical resolution of the simplified problem using finite elements method. Within this approach, the so called “wetted correction” is computed numerically by imposing volume conservation. Preliminary results are given for simple geometries such as wedges and cones for which analytical solutions are available. Good agreement is reported between numerical and theoretical results.*

1 INTRODUCTION

In rough seas where large relative amplitude ship motions occur, the bow may emerge out of the water. The impact phenomenon that follows, as the bow re-enters the incoming wave, is commonly refereed as slamming. Despite the pressure field due to the impact remains localized in space and time, slamming loads can locally create plastic deformations of the hull external structure. They are also at the origin of the high-frequency whipping type response of the global ship structure and lead to an increase of the vertical bending moments. In extreme cases, they have been recognized for being responsible for the loss of ships. In a comprehensive survey of the literature on impact wave loads due to slamming, [17] draw among others the following conclusions: (i) the effects of hydro-elasticity should be accounted in view of the short duration of impact loads, and (ii) if much is known about the two-dimensional water entry problem, few results are available for the three-dimensional case. The purpose of this paper is to give some insight into these two issues.

Severe impact loads arise in “flat geometry” configurations, i.e. when the free-surface and the hull are almost parallel near the contact point. In the two-dimensional case, an analytical solution for the flow can be obtained, based on the method of matched asymptotic expansions and using the deadrise angle as the perturbation parameter [1]. When the ship hull is slender, these classical two dimensional results can be used within the framework of a strip theory to represent the three-dimensional pressure field [9]. Within this approach, the vertical velocity of the hull is assumed to be constant in each cross-section. This assumption is also often used in connection with a beam like behavior of the ship structure so that the coupled fluid-structure mathematical problems can be solved simultaneously (see e.g. [4], [12]). Although these analytical studies lead to very interesting results, the validity of such an assumption remains questionable, especially for describing local structural deformations in the impact region.

In the present study, the simplified pressure field resulting from the strip theory is used to compute numerically the structural response of the ship hull (section 2). Since deformation velocities do not influence the pressure field, the approach is decoupled. Nevertheless, it allows to quantify the relative importance of hydroelastic effects, and exhibit the three-dimensional character of the structural deformation field. In section 3, a new approach is developed in order to compute the three-dimensional pressure field (still within the rigid body assumption). Preliminary results for simple geometries, a wedge in the two-dimensional case and a cone in the three-dimensional one, are presented and succesfully compared with analytical solutions.

2 HYDROELASTIC EFFECTS

2.1 Previous work

State of the art seakeeping simulations, including the modeling of slamming events and the associated retardation effects, have been described by [15]. The relative motions of the ship with respect to the waves is accurately computed using the large amplitude seakeeping simulation code RATANA¹ [14]. The fluid is assumed to be incompressible and perfect, and the body is rigid. Froude-Krylov and hydrostatic forces are computed on the instantaneous hull position, while the time-domain radiation and diffraction forces are computed using the linearised mean body position. This method offers a good compromise between computational time, robustness and accuracy. However, in the case of a slamming event, the local flow associated with the impact is highly nonlinear and occurs on a time scale much shorter than the wave period, thus the need for a local solution in the bow region. In the bow region, the flow is modeled within the framework of a flat ship strip theory summarised below and leading to a quasi-analytic evaluation of the pressure field. The CPU time needed for estimating the vertical force is insignificant and the resulting impact loads can be taken into account directly as external forces in RATANA. An iterative coupling procedure has also been implemented in order to account for the influence of impact loads on the global ship motions. During the global simulations, slamming loads lead to retardation effect which may be important when slamming events occur on consecutive large amplitude waves.

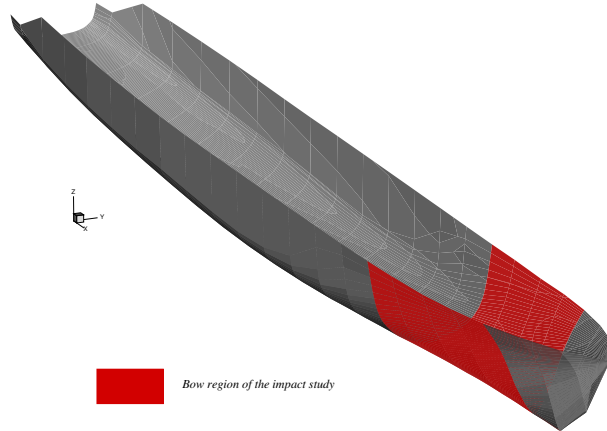


Figure 1: Hull form used in the numerical simulation. Emphasis is given to the bow region where a local approximation of the flow is performed.

In the bow region, the flow acting on the bottom of the ship as it re-enters the free-

¹French Navy, Bassin d'Essais des Carènes, Val de Reuil.

surface is modeled within the framework of the strip theory described by [9] and summarised here. The modeling assumes the body is slender and flat (see fig. 2), and the vertical impact velocity is sufficiently high, so that the effect of gravity is negligible. Under these assumptions, the method of matched asymptotic expansions justifies the development of a strip theory which can be viewed as the limiting case of the $2D + t$ or $2D + 1/2$ theory (e.g. [16], [7]) as the draft goes to zero. Since gravity effects are neglected, there is no interaction between the strips. The flow around each cross section is similar to that around a flat plate of equivalent length (see fig. 2) and a jet solution is introduced at the edges of the plate to remove the singularity. A proper treatment of the jet is essential since, during the impact, half of the energy transferred from the body to the fluid is kinetic energy within the spray [18]. The previous two-dimensional asymptotic results [1] have been extended so that shapes of arbitrary cross section and time-varying velocity can be accounted for. Relative velocity is used to derive the impact pressure distribution and the cross section slamming loads.

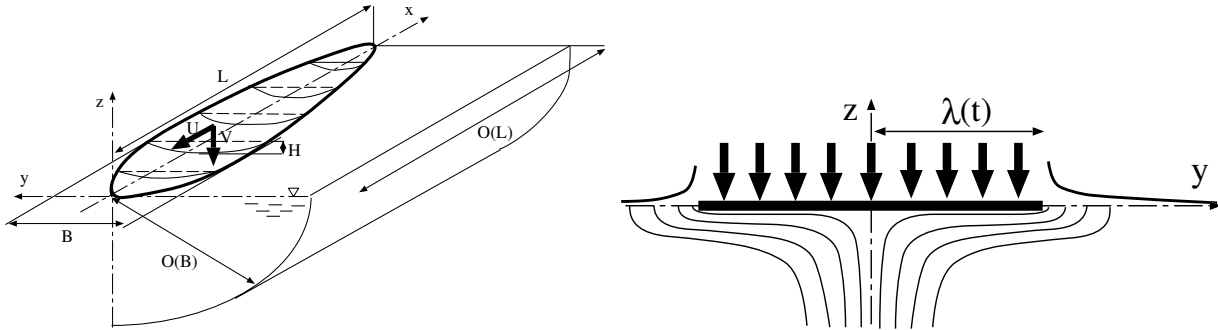


Figure 2: Geometrical definitions for the impact of a slender and flat rigid body (left), and the associated simplified fluid problem in each cross section (right). Figures are from [9].

2.2 Structural computation

For the impact event already simulated, the relative importance of hydro-elastic effects is roughly estimated through a decoupled approach. The pressure field (see fig. 3) previously computed assuming the structure to be rigid is used to provide unsteady loads as input to a structural computation. Hydro-elastic effects that may occur during slamming events will result in a decrease of the pressure acting on the hull. Using the pressure field obtained within the rigid body assumption yields therefore to a conservative estimate of the structural deformations and stresses so that the present decoupled approach can be used as a simple first level design tool.

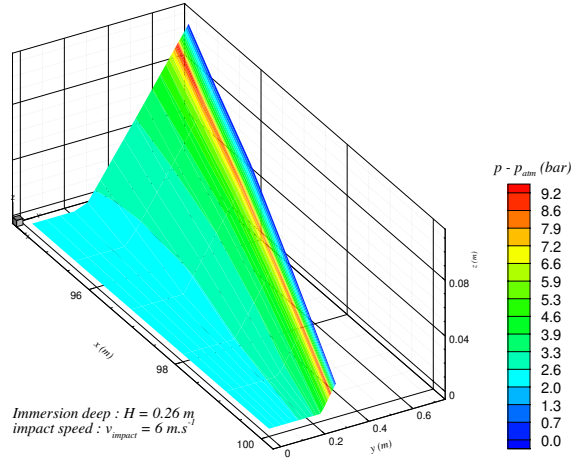


Figure 3: Example of pressure field acting on the hull in the bow region. The pressure peak corresponds to the spay root of the jet which develops along both sides of the hull.

The structural computation is performed in the time domain using the finite elements computational software Samcef (Samtech). During the simulation, it is important to accurately model the high frequency contents of the structural response because of the Dirac like character of impact loads. For this purpose, Newmark’s implicit time integration scheme is used with $\beta = 1/2$ and $\gamma = 1/4$. The hull structure in the bow region is modeled using shell and beam elements. These two types of elements represent respectively, sheets of steel with variable thickness which are placed side by side, and the framework of the ship.

As far as the boundary conditions are concerned, it is assumed that both the external deck of the ship and the mid-ship cross-section do not deform during the laps of time of the slamming event. The corresponding nodes move therefore with the rigid body velocity. Translation is also prohibited for the nodes corresponding to the main and lower decks. Rotation motion is however allowed at this nodes in order to give some more degrees of freedom for the structure to deform. Finally, translations and rotations are allowed for the nodes located in the region of interest. Unsteady impact loads are computed at each time step by integration of the pressure distribution, and are then applied as external forces at the corresponding nodes.

Relative comparisons between the structural deformation velocities and the impact rigid body velocity give an estimate of hydroelastic effects. In the exemple presented fig. 3 and fig. 4, the impact rigid body vertical velocity has been estimated to 6m/s from previous seakeeping simulations, leading to maximum deformation velocity around 1.5 m/s. Within this decoupled approach, a 25% decrease in the impact velocity is predicted. As expected, fluid-structure interaction should therefore be accounted within the pressure

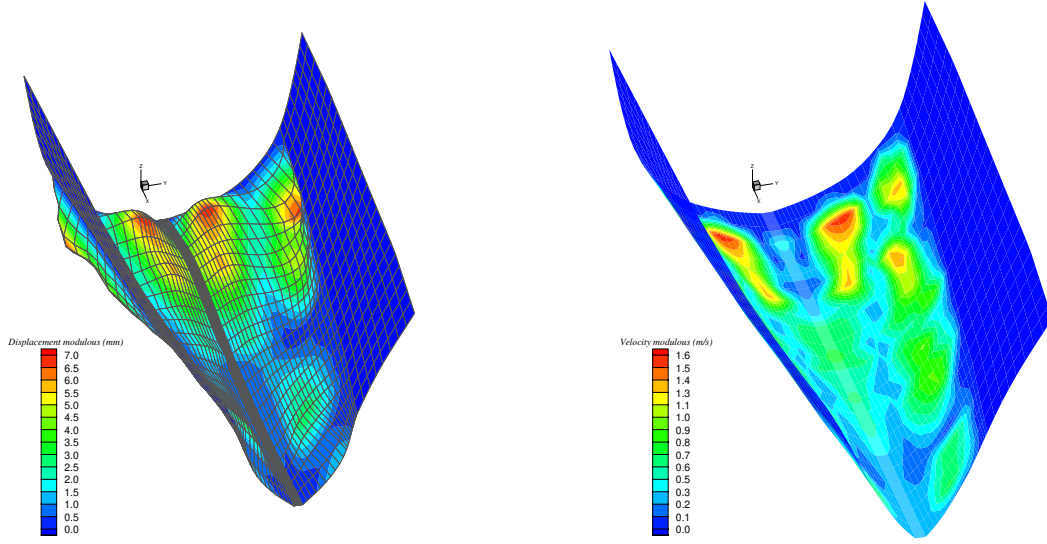


Figure 4: Structural deformations (left) and deformation velocity modulus (right). Note the three-dimensional aspect of the velocity field in a given cross-section.

field computation. Other computations with different impact velocities leads to similar conclusions. The spatial variations of both structural deformations and velocities can be observed in fig. 4. In a given cross section, the deformation velocity can not be considered to be constant but seems rather to oscillate. Clearly, this simulation exhibit the three-dimensional character of the fluid-structure interaction which arises during a slamming event. Both, transverse and longitudinal variations of the deformation velocity field should be accounted within the pressure field computation.

3 THREE-DIMENSIONAL EFFECTS

In this section, attention is focused on the resolution of the three-dimensional fluid problem. Compare to the previous approach, the new method still assumes the shape of the body to be flat and rigid but the slender body assumption is dropped so that three-dimensional effects are accounted. The numerical tools developped here allow in principle the resolution of the coupled problems for arbitrary shapes, i.e. not necessarily flat. In the present study, attention is focused on the feasibility, capability and accuracy of the approach. In particular, analytical solutions are available for flat bodies, giving a solution of reference to compare with.

3.1 Exact formulation

The problem is formulated within the framework of potential flow theory. The velocity field in the fluid is such that $\vec{v} = \text{grad}\phi$. The potential ϕ is harmonic in the fluid domain :

$$\Delta\phi = 0 \tag{1}$$

and must satisfy the following boundary conditions :

$$\frac{\partial\phi}{\partial n} = -\vec{V} \cdot \vec{n} \quad \text{on the body} \quad z = f(x, y) - Vt \tag{2}$$

$$\frac{\partial h}{\partial t} + \text{grad}\phi \cdot \text{grad}h = 0 \quad \text{on the free surface} \quad z = h(x, y, t) \tag{3}$$

$$\frac{\partial\phi}{\partial t} + \frac{1}{2}\text{grad}\phi \cdot \text{grad}\phi + gh = 0 \tag{4}$$

$$\|\text{grad}\phi\| \rightarrow 0, \quad \text{at infinity, i.e.} \quad (x^2 + y^2 + z^2) \rightarrow \infty \tag{5}$$

Here, V is the vertical velocity of the body, $z = f(x, y)$ is the formal equation describing the shape of the hull in a frame of reference moving with the body, and finally $z = h(x, y, t)$ is the equation describing the free surface deformation. Initial condition should also be added to close the problem. The mathematical problem (1) to (5) has been largely simplified. The fluid is assumed to be perfect and incompressible, the flow is irrotational and the body is rigid. The free surface is treated as a material surface along which the pressure is constant. Despite all these assumptions, the mathematical problem remains difficult to solve mainly due to the free surface conditions, which are imposed on a surface which is itself part of the unknown. It is possible to solve directly the fully nonlinear problem using boundary element method within a Mixed Lagrangian Eulerian approach (MEL) [13]. However, this method can not be used directly for the impact problem because of the violent motions of the free surface, experienced by the formation of jets near the intersection between the free surface and the hull. Direct non-linear numerical simulation have been achieved in two-dimension using a cut-off algorithm [21], [8]. The tip of the jet is cut and the numerical solution is matched to an analytical one describing the flow within the jet. If such an approach has been possible in two-dimension, its extension to the three-dimensional case is far from being obvious. At this stage, three-dimensional non-linear simulation including a surface piercing body (see e.g. [5]) remain limited to simple geometric configuration and moderate nonlinearities associated with the free surface ².

²i.e. the acceleration within the fluid are comparable to the gravity one, but not much higher.

3.2 Three-dimensional asymptotic problem

In the present study, we have chosen to develop a three-dimensional asymptotic approach based on the assumption that the shape of the body is flat in the impact region. The perturbation parameter is the ratio between the draft and the beam or the length of the body, these last two quantities being of the same order of magnitude. The formal asymptotic leading to the simplified problem can be found in [10] and will not be presented here. Instead, physical interpretations of the simplifications are given.

Since the shape of the body is flat, its normal vector is essentially directed along the vertical axis, the other components being one order of magnitude smaller. The free surface conditions can be linearised on $z = 0$ based on the fact that the free surface elevation is of the same order of magnitude of the immersion depth and neglecting higher order nonlinear terms. Gravity effects are neglected for short time, i.e. $gT/V \ll 1$, where T is the characteristic time. To first order with respect to the perturbation parameter, the following simplified problem is found :

$$\Delta\phi_0 = 0 \quad \text{in } \Omega_f \quad (6)$$

$$\frac{\partial\phi_0}{\partial z} = -V \quad \text{for } z = 0, \quad (x, y) \in s(t) \quad (7)$$

$$\phi_0 = 0 \quad \text{for } z = 0, \quad (x, y) \notin s(t) \quad (8)$$

$$\frac{\partial h_0}{\partial t} = \frac{\partial\phi_0}{\partial z} \quad \text{for } z = 0, \quad (x, y) \notin s(t) \quad (9)$$

where $s(t)$ is the projection on $z = 0$ of the contact line between the free surface $h(x, y, t)$ and the shape of the body $z = f(x, y, t)$. Since the free surface is deformed in the vicinity

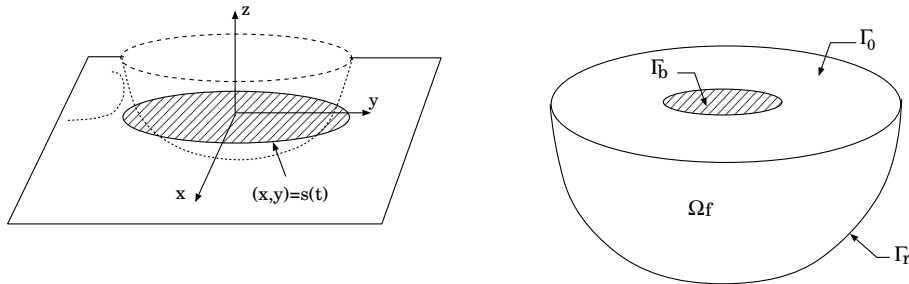


Figure 5: Geometrical aspect of three-dimensional asymptotic problem : $s(t)$ is the projection of the contact line (left) and, far-field point of view with surface notations (right).

of the body, $s(t)$ does not correspond with the intersection curve between the shape of the body and the undisturbed free surface (plane $z = 0$). Clearly, the linearised problem (6) to (9), can not be used to describe the flow in the immediate vicinity of the body where the free surface overturns to create a jet. The solution of the problem must be interpreted

as a first order approximation in the outer domain. Eventually, the solution is singular at the intersection between the fluid and the structure and a local solution is introduced like in the two-dimensional case.

The main difficulty associated with the impact problem is the determination of $s(t)$, in particular another equation is needed at this stage to close the problem. As in the two-dimensional case, at first and second orders [10], [6], $s(t)$ is obtained by imposing volume conservation. To first order, volume conservation equation leads to :

$$h_0(x, y, t) = f(x, y, t), \quad (x, y) \in s(t) \quad (10)$$

i.e., there must exist an intersection point between the first order outer asymptotic expansion of the free surface elevation and the shape of the body. In order to ease the numerical resolution of the simplified problem (6) to (10), we follow [11] and introduce the displacement potential :

$$\Psi_0 = \int_0^t \phi_0(x, y, z, \tau) d\tau \quad (11)$$

The new boundary value problem for Ψ is :

$$\Delta \Psi_0 = 0 \quad \text{in } \Omega_f \quad (12)$$

$$\frac{\partial \Psi_0}{\partial z} = f(x, y) - V t \quad \text{for } z = 0, \quad (x, y) \in s(t) \quad (13)$$

$$\Psi_0 = 0 \quad \text{for } z = 0, \quad (x, y) \notin s(t) \quad (14)$$

$$h_0 = \frac{\partial \Psi_0}{\partial z} \quad \text{for } z = 0, \quad (x, y) \notin s(t) \quad (15)$$

There are several advantages of using Ψ_0 instead of ϕ_0 . The analytical time integration of the equations allows to take into account directly the memory effects associated with the free surface displacement along the body. As a result, Ψ can be computed independantly through an iterative procedure at any desired time.

3.3 Variational formulation and discretised problem

In some special cases, it is possible to derive an analytical solution of the simplified problem (12) to (15). Exact solutions for spheres, cones and ellipsoids are available in the litterature. It is also possible to extend the existing analytical solutions like [19] who assume $s(t)$ to be known and then compute semi-analytically the corresponding body shape. However, this can not be applied for bodies of arbitrary geometry where the solution includes $s(t)$ and has to be found numerically.

In the present study, the boundary value problem is solved using an integral formulation of the weighted residual method. The method consists in searching for function Ψ which

cancel the integral quantity :

$$W(\Psi) = \iiint_{\Omega_f} \Pi \cdot R(\Psi) dD \quad (16)$$

for all weighting function Π . In our problem, the residue $R(\Psi)$ is equal to $\Delta\Psi$. Integrating (16) by part leads to the integral form :

$$\iiint_{\Omega_f} \vec{grad}\Pi \cdot \vec{grad}\Psi dD = \iint_{\Gamma_b \cup \Gamma_0 \cup \Gamma_r} \Pi \cdot \frac{\partial\Psi}{\partial n} dS \quad (17)$$

where Γ_b , Γ_0 and Γ_r are defined in fig. 5. This weak formulation allows to choose Ψ in C^1 which satisfies only the boundary condition on the free surface and imposes to Π to be in C^1 and to vanish on the free surface too. Under these conditions and imposing vanishing velocities on the outer surface, it remains :

$$\iiint_{\Omega_f} \vec{grad}\Pi \cdot \vec{grad}\Psi dD = \iint_{\Gamma_b} \Pi \cdot \frac{\partial\Psi}{\partial n} dS \quad (18)$$

The discretization of the integral formulation (18) is performed using Galerkin's method. The potential and weight functions are approximated over each element using the same interpolation functions :

$$\Pi = \{N_f\}^T \{\Pi\}_e, \quad \Psi = \{N_f\}^T \{\Psi\}_e \quad (19)$$

where $\{\Pi\}_e$ and $\{\Psi\}_e$ are the nodal variables and $\{N_f\}$ are the interpolation (or shape) functions [3]. The latters depend on the chosen type of elements. Using this approximation in (18) and introducing the body boundary condition (13) leads to the linear system :

$$[H]\{\Psi\} = \{G_{f_2}\} \quad (20)$$

where :

$$(H_{ij})_e = \iiint_{\Omega_e} \vec{grad}N_i \cdot \vec{grad}N_j dD \quad (21)$$

and :

$$\{G_{f_2}\}_e = \iint_{\Gamma_e} \{N_f\} (f(x, y) - Vt) dS \quad (22)$$

At each time step, the simplified problem (12) to (15) is solved using an iterative procedure illustrated in fig. 6. Starting with an initial guess of the wetted length, typically the intersection between the body shape and the flat free surface, the finite element method described above is used to solve for the displacement potential. It is then possible to evaluate the normal derivative of the displacement potential on the undisturbed free-surface elevation and to compute the position of the new intersection line between the free surface and the body. Equation (15) is used as a compatibility condition between $s(t)$ and Ψ and the procedure is repeated until convergence. The iterative procedure is illustrated in

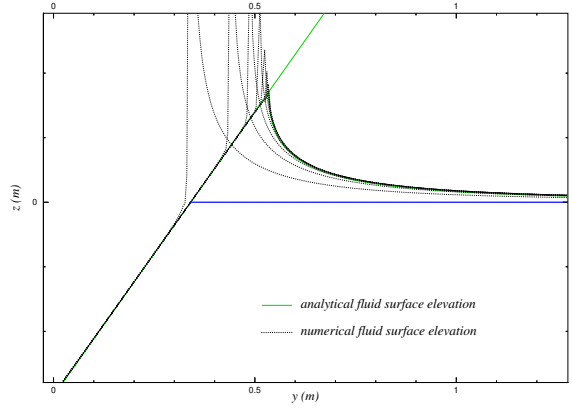


Figure 6: Illustration of the iterative procedure use to compute the wetted length at a given time. Two-dimensional numerical result corresponds to the wedge entry problem with small deadrise angle.

fig. 6. Typically, the position of the intersection point converges in less than 10 iterations.

The displacement potential has been introduced instead of the potential in order to ease the determination of $s(t)$. However, in order to compute the pressure on the body, the second derivative with respect to time of the displacement potential has to be evaluated. Solving for the potential itself allows to gain accuracy in the evaluation of pressure since only the first derivative with respect to time are required. The variational formulation previously developed to evaluate the displacement potential can be also applied to evaluate the potential, leading to a linear system similar to (20). Since the two functions satisfy Laplace's equation, the matrix $[H]$ remains unchanged. $\{\Psi\}$ has to be replaced by $\{\phi\}$ and the right hand side of the equation reads in view of (7):

$$\{G_{f_1}\}_e = - \iint_{\Gamma_e} \{N_f\} V dS \quad (23)$$

3.4 Numerical results

The numerical method described above has been implemented in two and three dimensions using respectively quadrilateral and hexahedron elements. Numerical simulations of the impact of a wedge and a cone with small deadrise angles, typically 10° , have been performed. Fig. 7 (left) show the finite element mesh used for the resolution of the flow around a wedge. Numerical results are successfully compared (right) with the analytical ones. In particular, the wetted width is correctly predicted as a function of time. Fig. 8 and fig. 9 show the finite element mesh used in three-dimension and the free surface elevation around the cone. Again, numerical and analytical results are in good agreement. In these simple test cases, the evaluation of the wetted area is simplified due to the geometry configuration. Although results are globally good, the resolution procedure remains sensitive to the mesh. One has also to keep in mind that the analytical solution

is singular at the contact point since the slope of the free surface tends to infinity. A high density of points is necessary near the contact line.

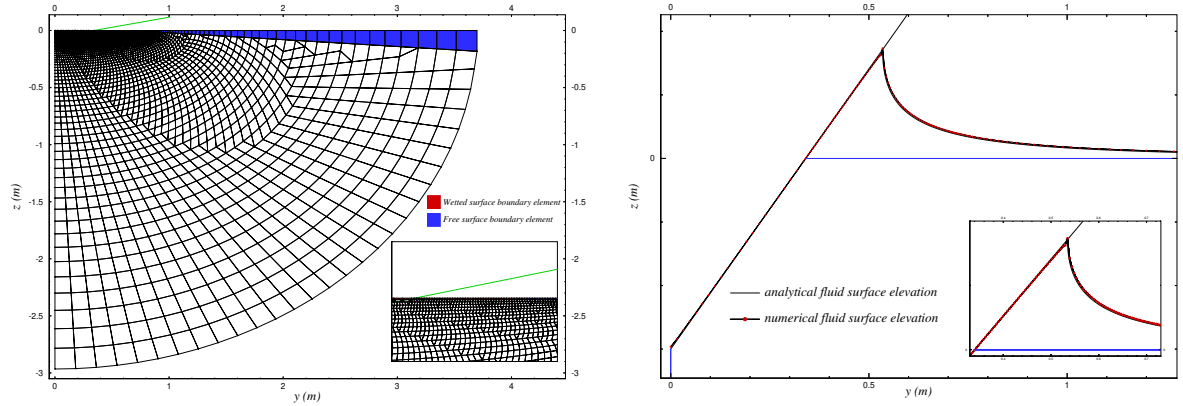


Figure 7: Two-dimensional numerical result for the wedge entry problem with small deadrise angle. The finite element mesh is presented (left), and the numerical solution is compared to the analytical one (right). Note that the vertical and horizontal scales are not the same.

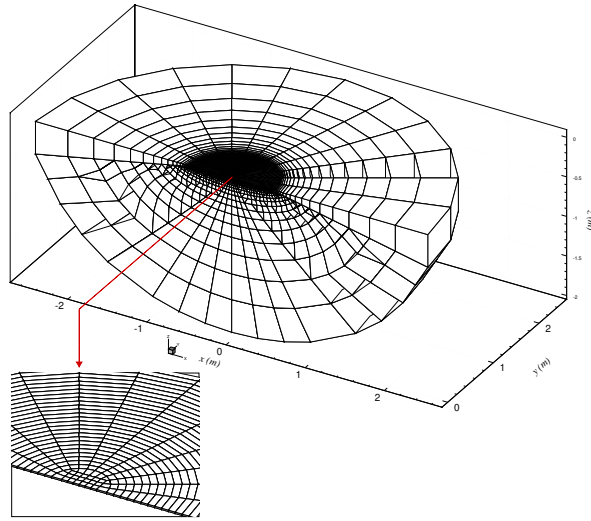


Figure 8: Three-dimensional mesh used in the finite element method to solve for the displacement potential around a cone.

4 CONCLUSION

The present study focus attention on hydro-elastic and three-dimensional effects associated with ship slamming. A decoupled approach has been presented, wherein impact loads are estimated assuming the body to be rigid and are then used as external forces in

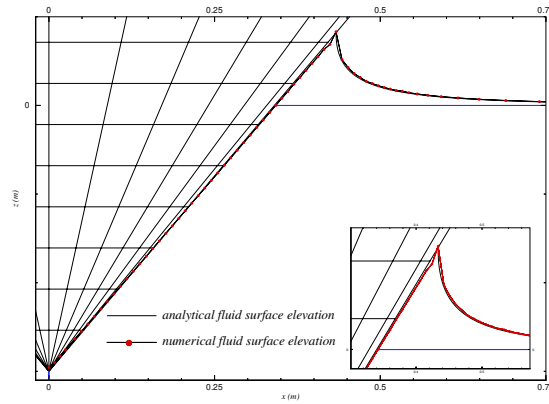


Figure 9: Free surface elevation in the vicinity of the cone. The numerical solution is compared to the analytical one.

a structural computation. This simplified approach gives a conservative estimate of the structural deformations and stresses, and allows to exhibit the importance and the three-dimensional character of the fluid-structure interaction. A new approach is developed wherein three-dimensional character of the flow can be taken into account. The approach relies on the method of matched asymptotic expansion, associated with a numerical resolution of the simplified problem using finite elements method. The numerical scheme is then validated by considering simple problems such as the water entry problem of a wedge with small dead-rise angle in two dimension, or a cone for the three-dimensional case. For these test cases, good agreement is obtained between numerical and analytical solution giving confidence into the resolution procedure.

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