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RESEARCH ARTICLE

Numerical Simulation of Marine Vehicle Immersed in Water

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Abstract

This article presents a numerical study of the forces induced by hydrodynamic impact, that is, the impact of a part of the bottom of the hull on the water surface. The prediction of these efforts is often based on numerical simulations to determine the shock intensity of a structure on the surface of a weakly compressible fluid (for example, water). The short duration of the impact is also investigated in this work. This phenomenon occurs especially when a ship encounters a harsh and difficult sea conditions. Under such conditions, it is important to know how to predict the hydrodynamic forces applied to the structure to correctly optimize the ship elements during its design stage or to prevent possible damage. Indeed, various factors such as speed of the ship and height of the swell can cause the hull to partially emerge and then fall violently onto the water surface, which is referred to by naval personnel as tossing or slamming causing vibrations, stresses, and fatigue to the structural elements of the ship. In this work, we present an example of phenomenon modeling and then a numerical study of the different geometries (dihedron) that play a role in different sections of the bow. Then, we compare our present results with the theoretical and experimental results of other researchers in the field. The average interval impact time for a dihedral model corresponding to the section of the chosen ship and other experimental and theoretical data is in good agreement with the experimental and theoretical measurements.

Keywords Slamming · Hydrodynamic impact · Aero-hydro-elastic · Dihedral · Fluid/structure interaction · Marine vehicle

1 Introduction

The designs of modern ships indicate a growing knowledge of the forces induced by hydrodynamic impact. Hydrodynamic impact refers to the aero-hydro-elastic impact of a structure on the surface of a weakly compressible fluid. In this research, we developed different models and technical forecasts, based on the Chuang model (Chuang 1966), and empirical predictions of the impact pressure of the slamming of the bottom of a ship (Hamoudi 1995) to predict the hydrodynamic loadings and even the aero-hydrodynamics generated during impact. However, developing an understanding of the theoretical rules (Nicolas 2004) and implementing experimental studies (Tveitnes et al. 2008) require considerable resources (basin, watertight sensors, dihedral). To monitor the health status of structures subject to the risk of impact such as the slamming of a boat (Ropars 1962; Rouss et al. 1973), it is necessary to characterize the forces acting on the structure by the given impact. The problem can likely be dealt with by two-dimensional (2D) (Derrar and Hamoudi, 2012) and three-dimensional (3D) models and even non-linear numerical models that determine the conditions in which impact occurs, which is linked to the curvature of the lower surface of the dihedral (structure) and its relative vertical velocity with respect to the state of the free surface of the fluid (water). This can then be used to create an impact calculation model based on theories such as the mass-added approach in the Von Karman impact model and the Wagner model (Nicolas

Article Highlights

- The dynamic wave load is the most important and plays an important role in the design of the marine vehicle structure.
- The most stressed part is the submerged part of the hull (the wet surface).
- The pressure due to bottom impact is proportional to the square of the vertical relative velocity.
- The impact pressure distribution on the bottom is given and reaches a maximum in the center of the perimeter and is equal to zero at one-tenth of the draft.
- The most important aspect is the measurement of the impact pressure due to the slam of the bottom.

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2004). These models can then be developed to describe the hydrodynamic loads acting on specific parts of the solid structure.

The circumstances in which an impact occurs must be known for it to be determined to be a serious natural risk (Alan 2010). This requires an environmental study of the occurrence of hydrodynamic impact phenomena (a structure's shock on the water or vice versa). The probability of a strong impact naturally increases with the relative velocity between the structure and fluid. If the frequency of impacts increases (for example, for high-speed vessels), premature fatigue failure can threaten the integrity of the structure. In extreme cases, rupture of the structure is quite possible (Scolan et al. 1999). Under these conditions, it is important to know how to predict the hydrodynamic forces applied to the structure to correctly size the ship during its design or to prevent possible damage (for a ship at sea, for example, the advance speed can be decreased if the frequency of severe impacts becomes too high) (Rouss et al. 1973). In this context, one can appreciate the importance of the naval architect knowing the forces induced by slamming (Souali and Nicolas, 2002).

When a ship is advancing on waves, its structural elements are subject to the varying forces of mainly wind and waves (Van Daalen 1993). Of all these loads, the dynamic wave load is the most important and plays an essential role in the design of the ship hull structure. Therefore, it is necessary to obtain the most accurate structure load response in the basic design phase. The speed of the marine vehicle also plays an important role at the time of impact.

The duration of a given impact pressure is on the order of a few milliseconds and is also very localized in space. The characteristics of this local pressure essentially depend on the angle of incidence (β) and the relative velocity $\boldsymbol{V}$ (Nicolas 2004). In recent years, a number of problems related to structural mechanics have emerged that stand out clearly from the usual empirical model simulations that determine the loading of a structure due to fluid. In these new simulations, the fluid intervenes by solving hydrodynamic equations known as Navier–Stokes equations to determine the loading on the structure.

This approach enables the prevention of very negative consequences on the structural integrity of the marine vehicle. Indeed, the forces induced by hydrodynamic impact are recognized as the most important that ships suffer outside of military or accidental attack. In this context, we understand the important role of the naval architect in knowing the forces induced by hydrodynamic impact.

This work focuses on the slapping of the forward bottom part of a ship, which represents one of the problem types with the greatest impact and necessitates that it be taken into account during the design process and the evaluation of the security of marine structures. The structural response to the impact load varies according to various factors, including the form of the floating structure, the vertical speed of impact, and other factors detailed in this paper.

2 Presentation of the Problem

The restrictive assumptions of analytical approaches do not allow for the treatment of (complex) industrial problems. Some theories provide an interesting basis for a good physical understanding of hydrodynamic impact, as well as its numerical development. The ship's fast vertical movements are important in the study of the impact phenomenon (Albert 2005).

Research has shown that the movements that create hydrodynamic impact are a combination of pitching (V_5) and heave (V_3) movements and sometimes even rolling motions (V_4), as shown in Fig. 1.

In this study, the most stressed part, as shown in Fig. 2, is the submerged part of the hull (the wet surface). To properly locate the region exposed to the impact pressure after a pitching movement occurs (rotational movement about the transverse axis) (Derrar et al. 2014), (Derrar et al. 2013) andTemarel (2006) found that the part situated in the front bottom of the ship hull (the bow) is the most stressed by the impact in the case of an advancing ship. As such, this is the part or area of concern in this work.

In this study, we consider pitching to be a major degree of freedom that causes slamming (Chuang 1966; Chuang 1967; Verhagen 1967; Hamoudi 1995). Therefore, we consider important the coupled movements mentioned above.

Seakeeping studies often require an assessment of the movements experienced at a particular point in the marine vehicle, and scholars have found the relative vertical movement to exceed its threshold value in hydrodynamic impact events. These events depend mainly on the amount of vertical relative motion (Hamoudi 1995). The intensity of the impact pressure depends mainly on the relative vertical movement. The relative vertical motion (r) was described by Lloyd (Lloyd 1989) as a superposition of absolute motion (s) less the wave altitude (ζ), as shown in Eq. (1):

$$r = s - \zeta \qquad (1)$$

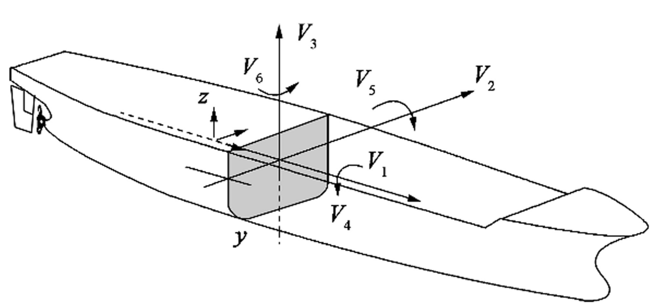


Fig. 1 Ship movements (Derrar et al. 2014)

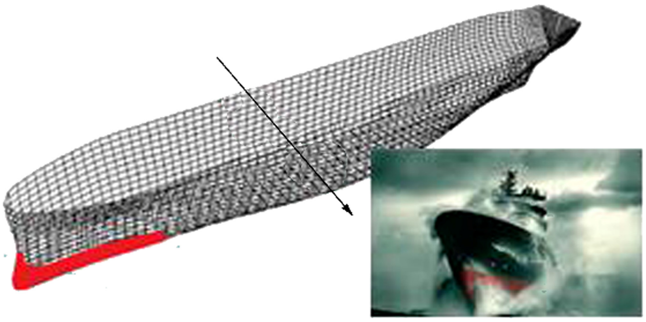


Fig. 2 Most stressed part in a ship

An absolute movement is described as a combination of heave (z) and pitch (θ) at different positions along the ship hull (the distance between the center of gravity of the ship and the considered section), as illustrated in Fig. 3 and calculated using Eq. (2):

$$s = z + \xi\theta \tag{2}$$

Relative motion is the amount of motion that characterizes the occurrence of a hydrodynamic impact event. This relative vertical movement increases if the distance between the gravity center and the considered section increases, knowing that the variation of the impact pressure intensity on the bottom of a section will be limited to one tenth (1/10) the design draft (in the case of a ship), as shown in Fig. 4.

Each lower region (or section) or solicited area of any cross section of a ship represents a simple or complex dihedral with different angles of inclination (β), as shown in Fig. 5.

We can also represent any geometric form by a mathematical equation $f(x)$, which contains partial coefficients (a, b, and c) that are responsible for the lower-side geometric shape that is exposed directly to impact forces.

$$f(x) = \frac{|x|^a}{b} + c; \begin{cases} a > 0 \\ b > 0 \\ c \geq 0 \end{cases} \tag{3}$$

To realize the form of a simple dihedral (triangular form), the partial coefficients are as follows:

CCurvature Intensity Factor $a = 1$;

Width factor $b > 0$;

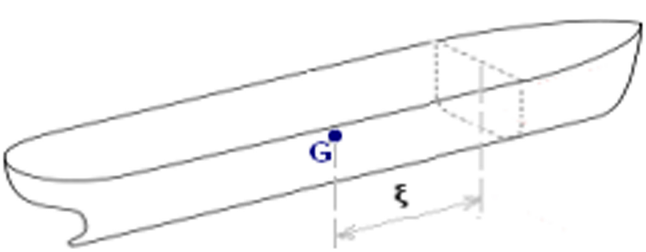


Fig. 3 Distance between the vessel's center of gravity and the section under consideration

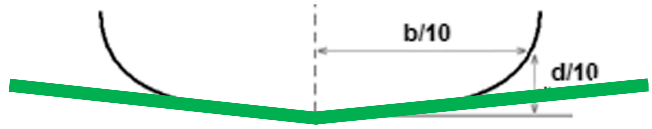


Fig. 4 1/10 of the design draft

Horizontal position factor $c = 0$ (does not influence).

Equation (3) then becomes:

$$f(x) = \frac{|x|}{b}; b > 0 \tag{4}$$

The angle of inclination (β) of the dihedron is expressed as a function of the width factor (b):

$$\beta = \arctan\left(\frac{1}{b}\right) \tag{5}$$

To better understand both the physical and mathematical aspects of the hydrodynamic impact, here, we explain some experimental results, including the experimental study of ship slamming presented by Rouss et al. (2005) and the work of Chuang (1966), which utilized an expression (Eq. (6)) that depends on the resistance of the air flow (C_{air}) and the velocity at the moment of impact (V_0), which is itself dependent on the height of the fall. We used these results to predict the maximum impact pressure of a flat-bottomed rigid body or an angle of inclination less than or equal to 3° after a fall from different heights.

$$P_{max} = 0.0021\rho_{fluid}C_{air}V_0 \tag{6}$$

Equation (6) shows the relative (increasing) variation of the maximum impact pressure (P_{max}) for different initial impact velocities (V_0).

Therefore, we can see that if the fall height increases, the velocity at the moment of impact (V_0) also increases, which causes an increase in the maximum impact pressure (P_{max}).

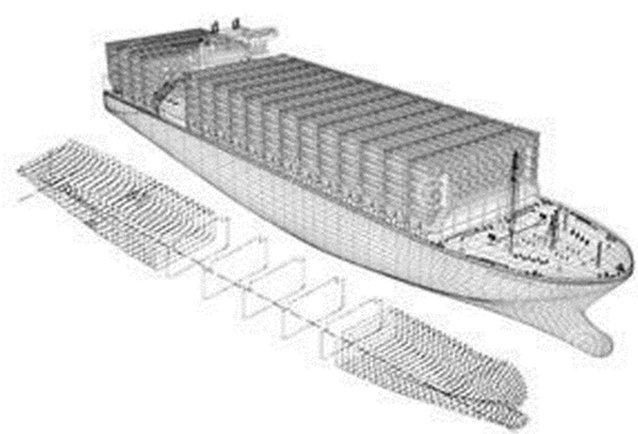


Fig. 5 Different cross sections of a ship

In the same work, Chuang (1966) mentioned the variation of the impact pressure on the bottom of the same flat body (as cited in the previous text) with respect to the time (t) and a half-width (L) of the flat body, and the pulse duration (pulsation) (T).

$$P(t) = 2P_{\max} e^{-1.4t/T} \sin\pi \frac{t}{T} \tag{7}$$

with:

$$T = 4L/C_{\text{air}} \tag{8}$$

Figure 6 shows the variation in the pressure at the moment of impact of three bodies of different half-widths (L_1, L_2, L_3) and under the following conditions:

$$V_0 = 0.6\text{m/s} \Rightarrow P_{\max} = 4.108 \text{ kPa}$$

We note that in Fig. 6 the pressure for each half-width varies over time in both positive and negative ways (pressure and depression). The curves in Fig. 6 represent the impact pressure on the bottom of the body just after the shock. The pressure is positive when the lift is greater than the buoyancy. On the other hand, relaxation on the bottom of the same body results in a negative pressure (depression) when the lift is less than the buoyancy. During this time, this pressure variation decreases until it becomes close to zero. This means that the damping of the body varies after impact until it becomes zero.

The dimensions of the proposed half-widths are required and not random. They represent average values of the half-widths of a flat-bottomed rigid body or an angle of inclination less than or equal to 3°, which are dimensions that can be found in the front part of a ship (the requested piece). Table 1 shows the numerical results of Fig. 6 for the variation of the localization of ($P_{\max}$) with respect to time (t), which increases with

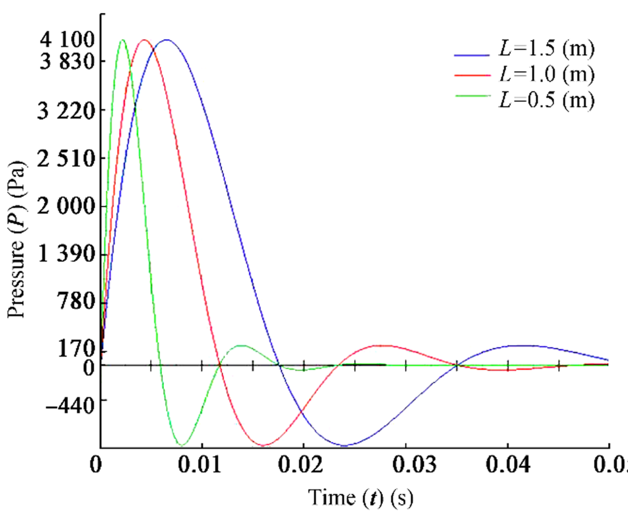


Fig. 6 Variation of the impact pressure/time (t)

Table 1 Variation of the ($P_{\max}$)/time (t)

Half-width L(m)	Impact pressure $P_{\max}$ (Pa)	Localization $P_{\max}/(t)$ (s)
0.5	4100	0.0021
1		0.0043
1.5		0.0064

increases in the half-width of the body. We can observe from Fig. 7 that these increases seem to essentially double.

On the other hand, for triangular bodies (dihedrons) with an angle of inclination (β) greater than 3°, if we neglect the vertical acceleration and take into consideration the vertical speed at the moment of the impact (V_0) taken into consideration, as given by (Chuang 1967), the impact pressure on the keel can be expressed as shown in Eq. (9):

$$P_{\text{keel}} = \frac{1}{2}\rho V_0^2 \frac{\pi}{\tan\beta} \tag{9}$$

3 Preliminaries

To theoretically present the hydrodynamic impact phenomenon, we have two dominant analytical approaches, i.e., the Zhao and Faltinsen approaches (Nicolas 2004), and we can compare them by defining their limits. These methods each have their own characteristics. The method of similarities respects the free surface conditions and is only applicable for dihedrals immersed in a fluid at constant speed. The asymptotic method is limited to angles of small incidence (angle of dihedral), i.e., less than 30°, and is based on a series of articles, the first being that of Von Karman (Hamoudi, 1995), who pioneered the study of the snapping phenomenon. This is why we use his theory as the formal object in this step of our hydrodynamic impact study.

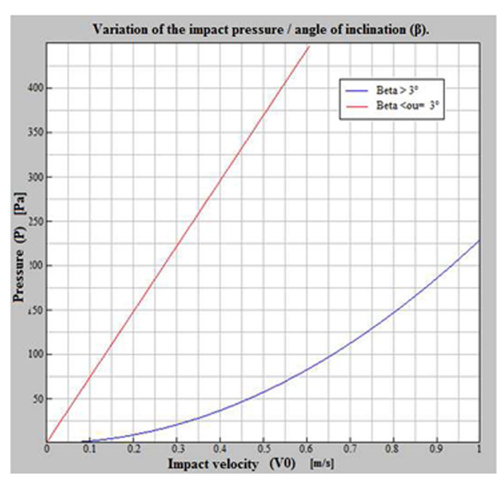


Fig. 7 Variation of the impact pressure/angle of inclination (β)

The evaluation of the impact pressure by the similarity method (which is based on the added mass or Von Karman's theory) provides a good order of magnitude. However, since it does not take into account the elevation of the free surface, the estimation of the immersed part is imprecise, which leads to underestimation of the load on impact. Wagner used the asymptotic approach to demonstrate that the actual wet width is (π/2) greater than (c), the half-bottom of the submerged dihedral. The mass of added water is then estimated according to Fig. 8. Wagner's asymptotic theory is a more realistic model for small angles (β) that as it takes into account the hydrodynamic effects, as shown in Fig. 8.

By linearizing the equations of the Wagner approximation problem, we can determine the flow around a dihedral with a small inclination angle (β), by the flow around a plate plunged into a uniform flow (Nicolas 2004). This theory thus confirms Von Karman's intuitive approach, which can be applied to any form of solid provided that the angle (β) is not too small to remain in an incompressible frame or limit the depreciation. The potential of the flow velocities is given by Eq. (10).

Zhao and Faltinsen (Nicolas 2004) used Wagner's work to obtain a multiple pressure solution and compared this approach with the similarity and boundary element methods (Alan 2010).

$$P(x) = \frac{1}{2}\rho V^2 \left[\frac{\pi \cot(\beta)}{1 - \frac{x^2}{c^2}} - \frac{\frac{x^2}{c^2}}{1 - \frac{x^2}{c^2}} + \frac{2V}{V^2}\sqrt{c^2 - x^2} \right] \tag{10}$$

The results obtained by the Wagner model show the distribution of the pressure on the lower bottom of the dihedral (in contact with water) with an angle of inclination $\beta = 10°$ and a speed of fall (at the moment of impact) or so-called impact velocity $V_0 = 0.6$ (m/s). The pressure is minimal on the sides or upper parts of the dihedron and it will increase when approaching the lower side until it becomes extreme at the level of the acute part.

We note that the half wet width $c(t)$ is also a problem unknown. The evolution of its magnitude is governed by an equation which involves the form of the body, the depth of penetration, and the elevation of the free surface, called the Wagner condition. Equation (4) expresses the geometrical coincidence between the free surface and the impacting body at the point of contact, as shown in Fig. 9.where $f(x)$ and $\eta(x, t)$ are, respectively, the functions describing the shape of the body and the elevation of the free surface. These functions satisfy the following conditions:

$$\begin{cases} f(x) = 0 \\ \quad \text{and} \\ \eta(x, 0) = 0 \end{cases}$$

The penetration depth $h(t)$ is obtained by integrating the impact velocity over time $h(t) = \int_0^t |V_z| \mathrm{d}t$ and the elevation of the free surface $\eta(x, t)$ is obtained by integrating the instantaneous velocity at the level of the free surface over time. This speed is obtained from the analytic solution of the problem.

Extensions of the connected asymptotic expansions method have been developed and are the subject of recent work. Thus, we use this method to justify a slice approach to the impact problem of a flat-shaped body or one with a low angle of inclination on a free surface. Faltinsen (2002) provides a solution for the internal domain that is valid for any angle and a generalization of the impact phenomenon at time-dependent input speeds. For the latter, a Laplace equation is solved for the velocity and displacement potentials, which makes it possible to determine the position and velocity of the free surface, which then enables the evaluation of the pressure exerted on the structure.

We can refer to Oliver (2002) for a special introduction and a more detailed study of his theories. In that work, the Wagner bi-dimensional (2D) and axisymmetric problem is presented and some aspects of the problem are addressed.

By neglecting physical phenomena other than the inertia of the fluid during impact, it is possible to describe the flow around the area exposed to the impact on the surface of the fluid at a velocity $V = (V_x, V_y, V_z)$, by the velocity potential theory under the following hypotheses:

- there is a solid zone in contact with the water whose contact surface increases over time;
- the fluid is not viscous and is incompressible;

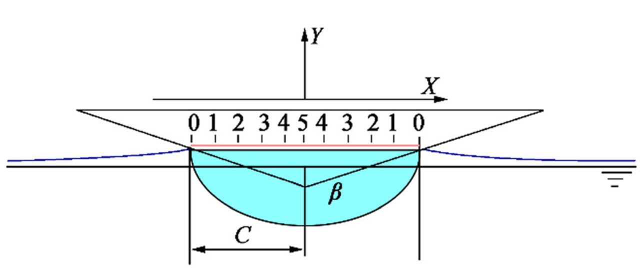


Fig. 8 Wagner model (half-bottom variations)

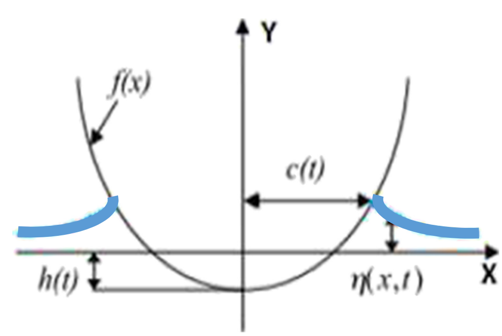


Fig. 9 Half wet width $c(t)$

- the flow is irrational;
- the gravity is neglected.

The Hugoniot shock approach (Sébastien 2013) is regularly used to numerically simulate the state of water and impact of a solid on a fluid (Constantinescu 2006; Jacques et al. 2007; Carmine 2010).

The decomposition of the stress tensor (σ) is used to resolve this problem [$\sigma = S + pI$], according to the constraints of the tenant deviator(S),which is linked to the deformation (ϵ) by viscosity (μ), ($S = \mu\epsilon$) and the hydrostatic pressure (p), which is expressed by the state equation of the Mie–Grüneisen model (Constantinescu 2006).

A simplified finite element 3D model of impact on water has been tested against results found in the literature. Constantinescu (Constantinescu 2006) conducted instrument tests of the tossing of a dihedron, and measured the force during constant impact speed (fixed at 10 m/s) as a function of the wet distance. Good consistency between the experimental and simulation results were obtained, as well as with those of previous research on the intensity of the impact force.

4 Methodology

4.1 Structure of the Research

The computer methods and programs currently available can more precisely determine the response to the hydrodynamic impact when the load is properly defined. In this work, we constructed a hydrodynamic influence model to address the basic characteristic of marine equipment movement problems in water (on a ship, for example). The use of numerical simulation to understand coupled phenomena has grown steadily in recent years.

In this study, our first step was to obtain the theoretical data needed to validate the numerical codes, taking into account the impact occurrences, and then we determined the sensitivity of loadings to kinematic parameter variations (motion study). This phenomenon, which is caused by the impact of a part of a ship on calm water, is particularly complex and non-linear.

It also appears necessary to better understand the physical aspects of this impact phenomenon. The front part of the ship, for example, has been the object of experimental study (Hamoudi 1995) and serves as a reference for comparison with the study object in our simulation. However, there is a lack of experimental data on the numerical codes used for complex three-dimensional forms and on the non-linearity of this phenomenon, despite the fact that this problem affects the designs of all ships.

4.2 Choice of Model

As introduced earlier, the hydrodynamic impact is a major problem confronting marine equipment (for this study, a vessel of fine shapes) such as container ships and warships in rough weather and/or if the forward speed is great. This is because the reaction of the hull to a repetitive dynamic loading caused by impact varies according to the type of boat. Specifically, this impact occurs in the lower forward zone (the bow), as shown in Fig. 2. Complete details of the model hull shape of the proposed S175 container ship for comparison with the results of this study are provided in references by Hamoudi (1995) and Constantinescu (2006). Our choice of model will be based on the different principles outlined above, for which the structure representing the simulation domain is represented in Figs. 8 and 9.

4.3 Multiphysics COMSOL Use

Creating an application often requires a collaborative effort with respect to different areas, including physical aspects, digital analysis, programming, user interface design, and graphic design.

Using the Fluid–Structure Interaction multiphysics interface (Roger 2011), we can model phenomena for which a fluid and a solid (deformable or non-deformable) are in contact. This interface models both the fluid and solid domains (structure) and includes a predefined condition for interaction at the fluid–solid boundaries. We use an arbitrary Lagrangian–Eulerian (ALE) formulation to incorporate geometric changes into the fluid domain.

The fluid can be either compressible or incompressible, and the flow regime may be laminar or turbulent (if a CFD module is available). The solid domain has the same options as those in the Solid Mechanics interface, including the contact conditions and non-linear materials, if the structural material module is non-linear.

Using a stationary or a time-dependent study, the Fluid–Structure Interaction interface (Roger 2011) models the bidirectional coupling between the solid and fluid. However, there are also special steps available for modeling unidirectional coupled phenomena.

The Solid Mechanics interface (Roger 2011) is intended for the general structural analysis of 3D, 2D, or axisymmetric bodies. In 2D, we can use plane constraints. The Solid Mechanics interface is based on the resolution of Navier's equations and generates results such as displacements and constraints.

The Laminar Flow interface (Roger 2011) is used to calculate the velocity and pressure fields for the flow of a monophasic fluid in a laminar flow regime. At higher

Reynolds numbers, disturbances tend to grow and cause a transition to turbulence.

The Physical interface (Roger 2011) supports incompressible and compressible flows at low Mach numbers (typically less than 0.3). It also supports non-Newtonian fluids.

The equations solved by the Laminar Flow interface are Navier–Stokes equations for the conservation of momentum and a continuity equation for mass conservation. The Laminar Flow interface (Roger 2011) can be used for stationary and time-dependent analyses.

The Fluid–Structure Interaction multiphysics interface with fixed geometry (Roger 2011) can be used to model phenomena in which a fluid and a deformable solid structure affect each other. The fluid load on the structure and the transmission of the structure velocity to the fluid can be taken into account. This interface can model situations in which the displacements of the solid are assumed to be small enough such that the geometry of the fluid domain is considered to be fixed during the interaction. The Deformed Mesh branch has two physical interfaces. The Deformed Geometry interface (Roger 2011) considers the behavior of different forms of an original object and its geometric deformations.

The Moving Mesh interface (Roger 2011) can be used to create models in which the geometry, represented here by the mesh, changes shape due to certain physics factors in the model. It can be used to study both stationary states and time-dependent deformations in which the geometry changes shape in response to the dynamics of the problem.

5 Description of the Benchmark (Near Simulations)

5.1 Research Structure

1.1- Choice of the interface in the calculation module
1.2- Definition of the geometry of the domain
1.3- Generation of the mesh
1.4- Definition of the aero-hydrodynamic properties of the domain
1.5- Definition of the boundary conditions
1.6- Location of the distribution of the loads in the computation domain
1.7- Use of post-processing capabilities in COMSOL Multiphysics and Matlab to calculate (or define)

- The impact speed (fall) for different cases
- Configurations of the structure phase (dihedral characteristics)
- Configurations of the fluid phase (characteristics of the fluid)
- Configurations of the interaction phase (fluid/structure)

5.2 Mathematical Model

In this work, we study a body (with a very detailed form) that falls with a given initial velocity into a fluid that is initially at rest (characteristics well detailed). The significant pressures that appear on the bottom of the structure at the moment of impact on the fluid are responsible for the interaction of local and global deformations with the fluid flow, which thus modify the pressure distribution profiles. Mathematically, the action of a fluid on the body is taken into account by imposing a contact force on the structure; the action of the body on the fluid is reflected by the kinematic conditions applied to the surface of the fluid.

Producing a program is part of the general objective of describing the hydrodynamic loadings or impact pressure, in particular, those related to slamming (Fig. 10) that act on a wide range of floating structure models (Howison et al. 1991), which are expressed by mathematical equations (previously mentioned) such as the general form equation. During this phenomenon, one or more parts of the structure being studied violently penetrate the liquid medium (water). The very first phase of penetration is now well defined, based on several studies, via the Chuang theory, Von Karman impact model, and even the Wagner approximation.

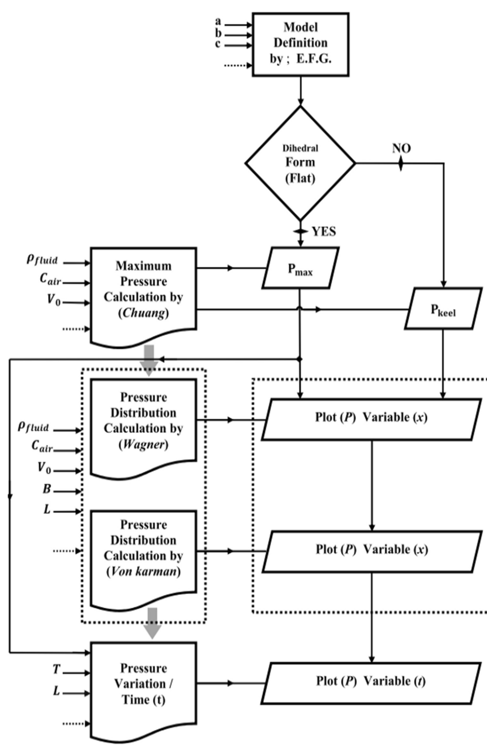


Fig. 10 General flowchart for hydrodynamic impact pressure measurement

5.3 Simulations

The physical phenomena to be taken into account are complex, having a non-linear transient aspect, the presence of a free surface, and coupling between the pressure field in the fluid and the free surface as well as the structure. As such, it was necessary to proceed in stages.

Today, due to the significant development of computational computing resources and digital simulators, the study of hydrodynamic impact has become possible, with the level of complexity being linked to the actual phenomenon and the nature of the desired results. The main difficulty lies in modeling the interactions between a fluid and a structure in the case of a fast and transient dynamic regime. Knowledge of the structural behavior of the body is no longer an obstacle, as computation codes now enable very precise simulations, such as the free fall of a structure, which can include complex breaks. Similarly, the modeling of fluid flows has reached a high level of accuracy. It remains to model the influence of one environment on the other.

The purpose of this study, which focuses on the prediction of the behavior of the system and the calculation of the impact pressure of a solid body impacting the fluid, is therefore to determine the movements of the geometry such as its position, fall velocity, and impact pressure. The chosen numerical method must be able to model the coupling of two different domains (fluid–structure interaction), because only the fluid pressure demand is essential. For this reason, we adopt an explicit finite element approach, which we developed to study this structure–fluid interaction phenomenon, and use the COMSOL Multiphysics calculation code (Roger 2011).

5.4 Modeling Approach

The 2D model in this study demonstrates the ability of COMSOL Multiphysics to simulate a falling dihedral of different shapes onto a fluid at rest using a dynamic mesh. We also model the movement of fluid using equations of incompressibility such as Navier–Stokes. The liquid is initially at rest in a rectangular tank, as shown in Fig. 11.

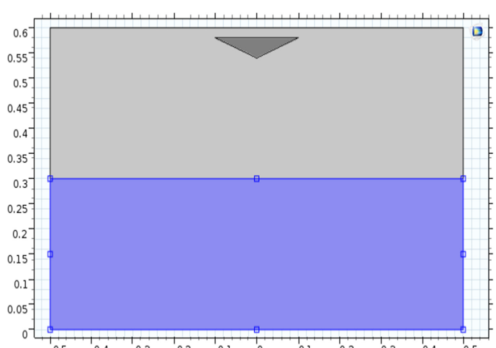


Fig. 11 Model definition

The movement of the dihedral is driven by the gravity vector and/or with a speed imposed in the air (atmospheric media) until making contact with the fluid causes a significant pressure exchange at the moment of impact between the two media, i.e., structure/fluid. This represents the maximum impact pressure (P_{max}).

Since the fluid surface is free to move, this model performs a non-standard computational task. However, the ALE technique is well suited for solving such problems. Not only is it easy to configure using the Moving Mesh interface in COMSOL Multiphysics, it also has the advantage of representing the free surface with a domain boundary by a moving mesh. This enables an accurate assessment of surface properties such as curvature and elevation, which enables an effective analysis of the free surface tension, without neglecting the effects of surface tension.

5.5 Meshing and Boundary Conditions

Since the dihedron has a downward vertical trajectory with a recommended speed (Scolan et al. 1999) onto the free surface and the whole domain is symmetrical, we can consider only half the dihedron. Therefore, we consider the plane ($Y = 0$) to be a plane of symmetry.

The computation domain begins at the moment the dihedral motion is driven by the velocity vector $\boldsymbol{V}$ passing through the air until the dihedral strikes the free surface of the fluid with a velocity of about 0.6 (m/s), which represents the relative velocity of a ship tossing on the fluid (wave) surface (Scolan et al. 1999) and is also referred to as the velocity at the moment of impact (V_0) or even the initial velocity. The length of the basin in the calculation is assumed to be about five times the length of the dihedral, which allows for a good analysis with respect to the behavior of the fluid in general and of the free surface in particular. The bottom of the basin is about four times the width of the dihedral. The mesh is generated using both the Mesh and Moving Mesh interfaces in the calculation code, which is an unstructured automatic mesh controlled by the study physics as explained in Fig. 12. This mesh is a fine free triangular type. The full mesh consists of 9104 domain elements and 449 boundary elements. Figure 13 shows an overview of the mesh for the entire calculation domain.

For the surface of the dihedral, the choice of a dimensionally stable wall geometry corresponds to an elastic law, whereas for the fluid (the air is compressible, and the water is incompressible or weakly compressible), a condition is used. The inter-domain interaction is integrated into the fluid–structure interaction interface. For both planes at a constant Y, a symmetry condition can be used. The water in the basin is simulated using free motion conditions such as the free deformation condition that takes into account the effect of a well-defined depth and the open boundary condition on the upper

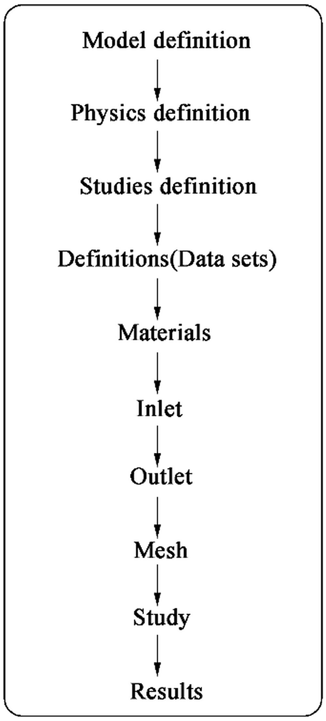


Fig. 12 Diagram of the calculation code

line of the fluid (water) in the basin, which allows for deformation of the free surface.

6 Results and Interpretation

In this article, the simulation discussion includes the following:

1) Evaluation of the impacting pressure distribution due to the slamming of the bottom of the proposed geometries (dihedron), which we selected according to the work conducted previously on models of ships (front sections) (Hamoudi 1995; Rouss et al. 1973) that have the same geometrical characteristics as those used in this problem;

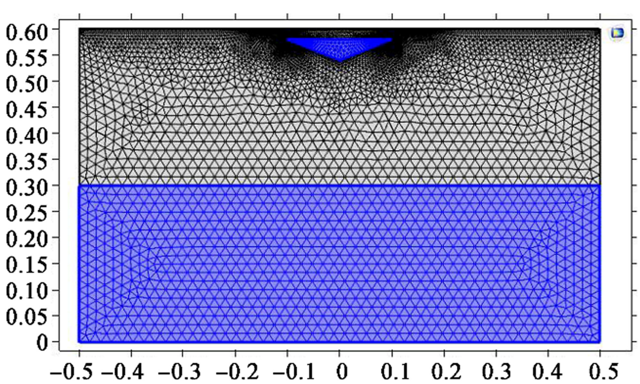


Fig. 13 Mesh and domain of calculation

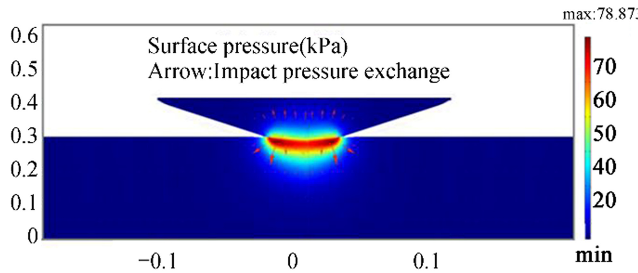


Fig. 14 Pressure distribution exchange

2) Evaluation of the pressure on the fluid at the moment of impact;
3) The movement of the free surface during impact;
4) Location of the maximum impact pressure on different forms of a dihedron;
5) Limitations of the proposed model.

6.1 Evaluation of Impact Pressure Distribution

After the assessment, we compared the results of the experiments conducted using the S175 container ship model presented by Hamoudi (1995) with those of model experiments by Albert (2005) and Scolan (2012) to allow for a broader evaluation of the results we obtained using our proposed calculation model and the appropriate calculation code to use.

At the beginning of the simulation, we evaluated the pressure exchange between the structure (dihedron) and fluid (water) just after impact (the first contact of the interaction). Fig. 14 shows the pressure distribution at that instant ($t=$ 5ms), for an impact velocity $V_0 = 0.6$ (m/s) and a dihedral with a $\beta = 15°$of inclination.

Figure 15 shows the average variation of the exchanged pressure distribution with respect to time (just before impact), whereas the pressure in the initial stage before the fall is zero. When the body begins to vertically fall, the pressure on the lower surface of the dihedral immediately begins to change due to the presence of air (friction). Immediately after the impact of the dihedral on the fluid, as shown in Fig. 14, the impact pressure value increases sharply for a specific period of time until it reaches a maximum.

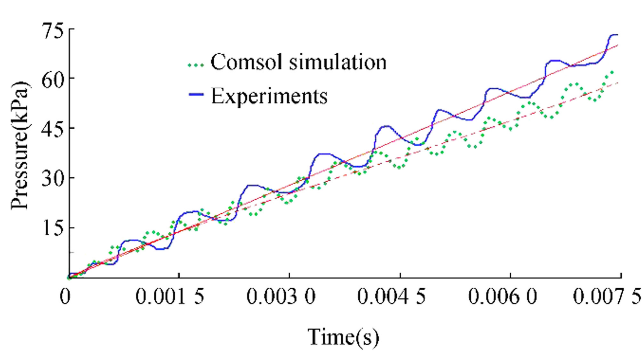


Fig. 15 Pressure change before impact

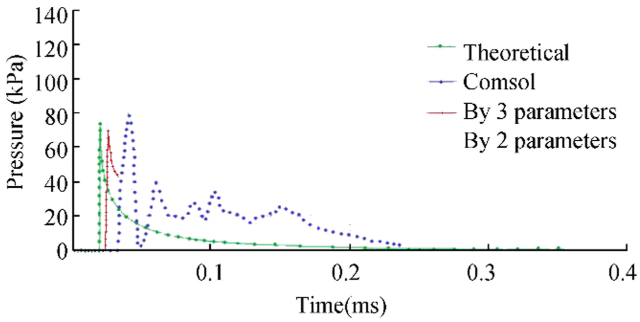


Fig. 16 Maximum impact pressure

6.2 Evaluation of the Maximum Pressure at the Moment of Impact

For the simulation in this phase, the most important aspect is the measurement of the impact pressure due to the slamming of the bottom of the proposed geometry (dihedron with 15° inclination). We compared this pressure with those obtained in the experiment presented by Carmine (2010), from the model of the container ship S175 (with sections proportional to the shape of the studied dihedral), and in the research findings of earlier model experiments presented by Souali and Nicolas (2002). Doing so serves as a test of a model with the same bottom characteristics as the container ship S175 and form of the proposed dihedron in the simulation. Again, this allows for a broader evaluation of the results obtained by our proposed calculation model as well as of the calculation code used in this study.

The validation of the results calculated by others, both experimentally and theoretically, as shown in Fig. 16, indicate that the frequency of the variation of impact pressure occurs very quickly(about 5 ms), which clearly explains that the phenomenon of impact occurs suddenly and rapidly.

From the measurements of the maximum impact pressure shown in Table 2, we can compare the different experimental

Table 2 Validation of simulation results by COMSOL by order of quantities of other references (Malleron 2009; Rouss et al. 1973; Hamoudi 1995)

Theoretical	Model test	Parameters calculation	COMSOL
a. Section 9 and $\beta = 15°$			
	1st test 54.941	2 parameters 50.217	
74.884			78.873
	2nd test 69.938	3 parameters 81.389	
b. Section 8.5 and $\beta = 12°$			
	1st test 91.04		
		2 parameters 87.112	105.182
–	2nd test 92.147		
		3 parameters 108.01	
	3rd test 100.08		

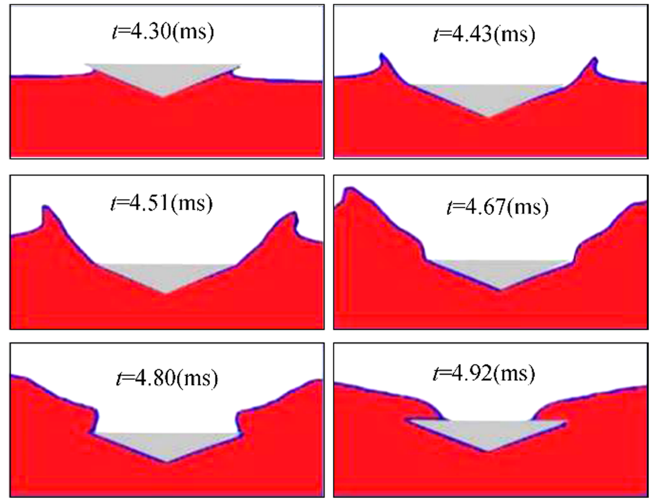


Fig. 17 Development of the free surface during impact

results obtained in various references (Souali and Nicolas 2002; Jacques et al. 2007; Scolan 2012), as well as the theoretical results (Ribet 1997; Malleron 2009; Destuynder and Fabre 2012), and the results of the simulation proposed in this work regarding the forms (dihedral) that are compatible with the logic of this study. For this reason, we base the comparison on section 9 of the prototype and the model of ship S175 because they are at the level of the areas most affected by the impact (Hamoudi 1995).

The results displayed in Table 2 bare in the order of magnitude of the impact pressures of the various experimental and theoretical works. We compared the model tests results for the slam of the bottom of a ship with those of the simulation. These experiments are detailed in references (Malleron 2009; Alan 2010; Destuynder and Fabre 2012; and Antoinat et al. 2013). To widen the comparison to several fields, we also present some preliminary theoretical research results. We found there to be good compatibility in the results, which confirms the reliability of the data and the model used to validate the numerical simulations.

Thus far, our comparisons of the experimental, numerical, and theoretical results have shown good concordance, but this should be extended to more complex motion laws than those

Table 3 Variation of pressure on the keel and side of the keel

Inclination (β) (°)	Pressure P_{keel} (kPa)	Pressure $P_{sidekeel}$ (kPa)	$\lvert P_{keel} - P_{sidekeel} \rvert$ (kPa)
Plat 0	1.672	1.672	0.000
1	1.537	1.539	0.002↑
3	0.583	2.323	1.740↑
6	175.278	5.187	170.091↑
10	105.182	11.583	93.599↓
15	78.873	6.618	72.255↓
18	65.727	8.092	57.635↓

for heave and pitch. There has been ongoing work focused on this aspect of validation and some efforts have also been made to reduce the computation time required by larger domains regarding fluid–structure interaction as well as by complex geometries in which there is a real appearance of the front end of a vessel (the bow). These obstacles represent limitations of the proposed model in this study.

6.3 Development of Free Surface During Impact

The simulation presented in this work enables the determination of the evolution of the free surface during impact.

In results presented previously, we have found the time needed to reach maximum pressure to be very short, and the transmission of movement and pressure fields in the fluid to vary rapidly. The pressure decreases with increasing fluid depth.

The 2D model shown in Fig.17 has a dihedral angle of inclination $\beta = 15°$ and a free fall that causes an impact velocity $V_0 = 0.6$ (m/s) and with the fluid at rest.

Figure 17 shows the deformation of the free surface for the proposed dihedral model at different stages.

This set of images respectively represents the symmetry of the elevation of the free surface at different moments of impact.

The movement of the dihedral slows after impact and the slowing varies with different parameters such as the angle of inclination of the dihedral, the density of the fluid, the speed of impact, and others.

6.4 Location of Maximum Impact Pressure on Bottom of a Dihedron

Next, we investigated the hydrodynamic pressure applied on different dihedral shapes (different angles of inclination) and on different parts of each dihedral (on the keel and sides of the keel). We do so with the help of an in-house Matlab program, with which we will collect various computational data and use them in the numerical equations developed by Chuang (1967), who found a linear relationship between the dihedral angle and the pressure due to impact (Fontaine et al. 1997) based on a set of launch tests on the snapping of rigid bodies.

Table 3 shows the pressures on the keel and keel sides of different types of dihedrons for an impact velocity of $V_0 =$ 0.6 (m/s), which clarify the position of maximum pressure at the moment of impact.

From the results shown in Table 3, which are based on the Chuang estimate (Tveitnes et al. 2008), we can see that the maximum pressure is located at the keel of the dihedral (on its lower part). This is true for a dihedron with an angle of inclination $\beta > 3°$. In the other results, perturbations prevent us from locating the site of maximum pressure on the bottom of a dihedron with an angle of inclination $\beta \leq 3°$. This disturbance is caused by a phenomenon in which air is trapped between the structure (dihedron) and the fluid (water). As shown in a number of experiments, the air layer between a flat body and the water surface plays an important role in determining the maximum pressure occurring during impact. Research conducted by Chuang (Chuang 1966) and Lewison (Lewison 1970) has shown that the escape of air from under a flat bottom is not complete; a large bubble is formed at the moment of impact.

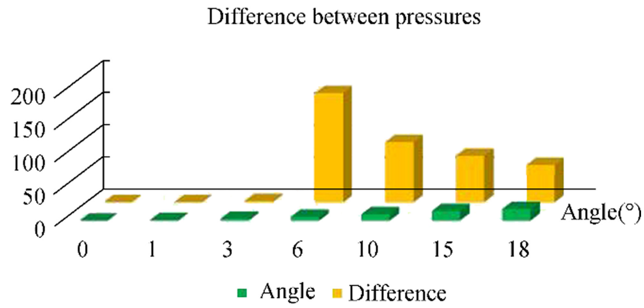


Fig. 18 Difference between pressures on the keel and on the sides of the keel

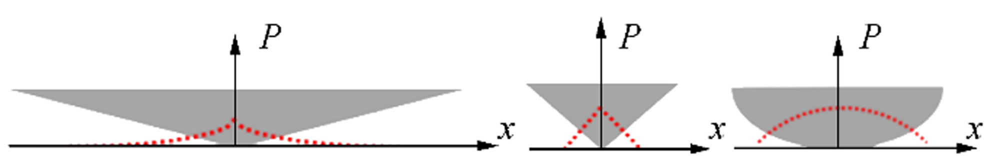
Overall, we can see from Fig. 18 that the difference between the maximum pressure on the keel (P_{keel}) and the pressure on the side of the keel (P_{max}), decreases as the angle of inclination (β) increases.

As such, $\beta\uparrow \Rightarrow |P_{keel} - P_{max}|\downarrow$.

6.5 Limitations of the Proposed Model

If the proposed model is suitable for triangular or flat bodies, it is certain that its accuracy will be less good for bodies with very large curvatures. This point was not addressed in this work because we concentrated on the study of a very precise part (1/10 the bow of the ship). Our study is based on the localization of the maximum pressure and also the distribution of the impact pressure on the bottom of a dihedron. The considered bodies exhibit little curvature. This study has shown that if the pressure forecasts obtained based on the transition between the three areas (air/fluid/structure) are always very good, the pressure fields may exhibit significant differences in the calculations. Another limitation became evident during the study of the so-called vertical impact (the only degree of freedom

Fig. 19 Pace of impact load distribution for different shapes



considered is represented by the movement of heave) (Xia 2005). In this case, the forecasts of our model are not satisfactory. This indicates that additional terms must be included in a future investigation to take into account pitch and roll (Xia 2005). This would be sufficient to account for changes in the speed-induced pressure distribution at the moment of impact (Guilmineau et al., 2010).

In a free fall, the first point that will make contact with the free surface (water) at impact represents the region where the impact pressure is maximum.

The inverted bottom geometric curve represents the shape of the distribution of the impact load, as shown in Fig. 19 (in the case of a triangular dihedral, this has been verified for dihedrals less than 5°).

7 Conclusions

In this work, we investigated the hydrodynamic impact between a fluid in equilibrium (seawater) and a structure (ship). An example of the application of this study is the dimensioning of the impact forces exerted on structures with different geometries. We presented results from various studies of this hydrodynamic impact problem, highlighting the state of the art of theoretical and numerical developments on this subject. These approaches enable accurate modeling of the anticipated application.

The pressure due to bottom impact is proportional to the square of the vertical relative velocity and this proportionality constant is determined by the pressure coefficient or the ship form factor, which depends mainly on the shape of the lower part of the section studied.

The pressure coefficient can be determined using several methods:

- The geometric projection method that performs prediction based on two or three parameters,
- Prediction based on the dihedral angle,
- Prediction based on the width and draft (to one tenth of the draft), and
- Experimental methods.

The impact pressure distribution on the bottom is given and reaches a maximum in the center of the perimeter and is equal to zero at one tenth of the draft.

We used a model of the S175 container ship as a reference in this study. We also studied characteristics related to the impact phenomenon by taking measurements and performing experimental tests under different conditions, such as draft, pitch, and even heave.

The vertical relative velocity and vertical acceleration at which impact has been observed are below their threshold values.

The importance and occurrence of impact pressure differ from those presented in the experiments. This difference is thought to be due to the non-linear hydrodynamic impact or forces that are ignored in the calculation, such as

- The compressibility of the air/water.
- The effect of air damping (depression of the air boundary layer at the water surface just before impact).
- Limitations in the degrees of freedom.
- Experimental errors.
- Modeling errors or simplifications.

The most important aspect is the measurement of the impact pressure due to the slam of the bottom, which is 78.873 kPa for a dihedron with a 15° inclination. This corresponds to a vertical relative speed of 0.6 m/s. The calculated impact values are lower and sometimes higher than the measured values. However, when the calculated and measured pressures are compared, we found there to be compatibility between the results, whereas in the case of the measured values there is not much uniformity. Thus, we can conclude that it is more appropriate to use the theoretical prediction method of the three parameters due to the consistency of the results.

The average time interval of impact is about 5 ms for a dihedral model corresponding to the section of container ship S175 and other experimental and theoretical data. The impact interval is in good agreement with the experimental and theoretical measurements.

Nevertheless, the numerical approach can be extended to more complex impact cases including the air entrapment effect for small angles.

An experimental investigation is recommended as a follow-up to the results obtained in this work, which may enable the establishment of a data bank and the realization of more secure industrial projects.

References

Alan T (2010) Modélisation Tridimensionnelle d'Impacts Hydrodynamiques pour l'Etude du Tossage des Bulbes d'Etrave. P.hD. thesis, Laboratoire Brestois de Mécanique et des Systèmes. Ecole Doctorale SICMA (E.D. 373). EA4325 ENSIETA. Université de Bretagne Occidentale. ENIB.:2010

Albert Z (2005) Ship load model on large amplitude waves. Revue. Faculty of Engineering, Department of Naval Architecture and Ocean Engineering. University of Rijeka, Croatia. https://doi.org/10.1201/9781439833728.ch39

Antoinat L, Kubler R, Achard G, Barrallier L (2013) Etude d'un Programmateur d'Impact Solide Equivalent à un Impact à l'Eau. ParisTech, laboratoire MSMP, 21ème Congrès Français de Mécanique, Bordeaux

Carmine C (2010) Numerical simulation of fluid/structure interaction comparing SPH and ALE approaches. Sixth pegasus-AIAA student conference. Sevilla, Spain

Chuang SL (1966) Experiments on flat-bottom slamming. J Ship Res 10(1):10–17
Chuang SL (1967) Experiments on slamming of wedge-shaped bodies. J Ship Res
Constantinescu A (2006). Modélisation 2D de l'Impactd'une Structure sur l'Eau. Ph.D thesis, Initiation de l'endommagement. Université de Bretagne Occidentale
Derrar B, Hamoudi B (2012) Etude Numérique d'Impact Hydrodynamique entre une Structure et une Surface Libre. 1er Congrès International d'Aéro-Hydrodynamique Naval (CIAHN-2012). Oran, Algérie
Derrar B, Hamoudi B (2013) Etude Théorique d'Impact et d'Immersion entre une Structure et une Surface Libre. 1èreConférence Internationale sur les Sciences Aéronautiques (I.C.A.S' 01). Oran, Algérie
Derrar B, Hamoudi B, Nadji C (2014) Etude, Evaluation Formulaire d'Impact Hydrodynamique d'une Structure Flottante. 3eme Conférence Internationalesur les Matériaux et les Structures en Composite (CIMSC'14). Oran, Algérie
Destuynder P, Fabre C (2012) Modélisation du Comportement Hydrodynamique des Bateaux. Cours donné à l'Ecole d'Ingénieurs de Kénitra, Maroc (ENSA) du 25 au 28 juin 2012 dans le cadre du projet MNOTSI
Faltinsen O (2002) Water entry of a wedge with finite deadrise angle. J Ship Res 46(1):39–51
Fontaine E, Boudet L, Leguen JF, Magee A (1997) Etude Impact Hydrodynamique d'un Corps Allonge et Plat: Application au Tossage. 6ème Journées de l'hydrodynamique. ECOLE Centrale de Nantes, France
Guilmineau E, Leroyer A, Visonneau M, Naciri M, Ory E (2010) Numerical Simulation of a Moored Ship. Equipe Modéliation Numérique, Laboratoire de Mécanique des Fluides, CNRS UMR 6598. Ecole Centrale de Nantes, 12ème Journée de l'Hydrodynamique, Nantes, France
Hamoudi B (1995) Dynamic response of hull due to bottom slamming and deck wetness. Ph.D thesis, University of Glasgow
Howison SD, Ockendon JR, Wilson SK (1991) Incompressible water-entry problems at small deadrise angels. J Fluid Mech 222:215. https://doi.org/10.1017/S0022112091001076
Jacques N, Constantinescu A, Kerampran S, Neme A (2007) Comparaison de Déférentes Méthodes pour la Simulation Numérique de l'Impact Hydrodynamique. Laboratoire de Mécanique des Structures Navales (MSN). 11èmes Journées de l'Hydrodynamique.Brest, France
Lewison GRG (1970) On the reduction of slamming pressures. Trans. RINA, 2, and, National Physical Laboratory, Ship Report 138
Lloyd ARJM (1989) Seakeeping: ship behaviour in rough weather, London. Ellis Horwood Ltd. The Royal Institute of Navigation
Malleron N (2009) Contribution à l'Etude des Interactions Fuide/Structure pour l'Analyse de l'Impact Hydrodynamique d'un Système de Flottabilité d'Hélicoptère. Cours Physics, Université de la Méditerranée - Aix-Marseille II, 2009. France
Nicolas A (2004) Modélisation de l'impact hydrodynamique par un couplage fluide/structure. Ph.D thesis, Université des Sciences et technologies de lille, Villeneuve d'Ascq, France
Oliver J M (2002) Water-Entry and Related Problems. PhD thesis, Oxford
Ribet H (1997) Modélisation Numérique d'Impact sur l'Eau d'une Structure Souple par une Méthode Élément Finis Explicite. Convention de Recherche Université Paul Sabatier (Toulouse) - Aérospatiale, 6ème Journée de l'Hydrodynamique, Nantes, France
Roger WP (2011) Multiphysics modeling (using) Comsol a first principles approach. Copyright by Jones and Bartlett Publishers, LLC
Ropars J (1962) La Théorie du Navire Appliquée au Navire de Commerce. Suivie d'une étude sur les fatigues du navire. Éditions Maritimes et d'Outre-mer Bordeaux, Paris
Rouss JM, Pettinotti B, Quillard O, Toularastel JL, Ferrant P (1973) Slamming experiments on a ship model. Hydrodynamics and Ocean Eng. Group, Fluids Mech. Lab. - UMR 6598 CNRS/Centrale Nantes, France
Rouss JM, Couty N, Toularastel JL, Pettinotti B, Ferrant P (2005) Etude Expérimentale du Tossage sur un Navire. 10ème Journées de l'hydrodynamique. Equipe Hydrod-ynamique et Génie Océanique. Nantes, France
Scolan YM (2012) Hydrodynamic loads during impact of a three-dimensional body with an arbitrary kinematics. ENSTA-Bretagne. Verny 29806 Brest Cedex 9, France
Scolan Y-M, Coche E, Condray T, Fontaine E (1999) Etude Analytique et Numérique de l'Impact Hydrodynamique sur des Carènes Dissymétriques. Revue. 7ème Journées de l'hydrodynamique, Marseille, France
Sébastien E (2013) Propagation d'une Onde de Choc en Présence d'une Barrière de Protection. P.hD. thesis, Ecole Doctorale Energie, Materiaux, Sciences de la Terre et de l'Univers. Universitéd'Orléans
Souali M, Nicolas A (2002) An overview of fluid/structure interaction. In: Recent development and applications. Revue Laboratoire de mécanique de Lille, France
Temarel P (2006) Loads on ships, Volume 1. 16th international ship and offshore structures congress. Southampton, UK
Tveitnes T, Fairlie-Clarke AC, Varyani K (2008) An experimental investigation into the constant velocity water entry of wedge-shaped sections. Ocean Eng 35(14–15):1463–1478. https://doi.org/10.1016/j.oceaneng.2008.06.012
Van Daalen EFG (1993) Numerical and theoretical studies of water waves and floating bodies. Ph.D thesis, University of Twente. Enschede, Pays-Bas
Verhagen JHG (1967) The impact of flat on a water surface. J Ship Res 11:211–223
Xia J (2005) A consistent strip-theory approach for wave loads and ship motions in rough seas. Proc 20th Int workshop on water waves and floating bodies IWWWFB, Norway