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A generalized adaptive mesh pressure integration technique applied to progressive flooding of floating bodies in still water

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ABSTRACT

A new time domain numerical scheme is presented, which can be applied to model the flooding of any floating object such as ships, offshore structures, pontoons or Very Large Floating Structures (VLFS). The generic nature of the input process regarding geometric, mass and inter-compartment openings characteristics, gives way to straightforward pre-processing procedures and flexible simulations. The proposed code architecture makes it ideal for parametric damage studies required for reliability assessments or for compartment connections optimization studies. The developed code is based on the pressure integration technique evaluated at unstructured meshes composed of quadrilaterals. Polyhedral and polygonal intersection algorithms work together with a quad-tree mesh subdivision and cutting adaptive process to become the kernel of the domain setup and intra-simulation dynamic modification, on which analytic formulations of pressure calculations are evaluated. Comparisons with model experimental results and with other codes are presented regarding the progressive flooding of a box-shaped barge in still water.

1. Introduction

The possibility to predict the behavior of floating bodies, as fluids flow through their external breaches and progress throughout the internal subdivisions, constitutes a fundamental problem that has seen several approaches to its solution published in the past. The straightforward application of field methods, based on 3D-cell discretization of interior spaces, such as Volume of Fluid (VOF), involves a cumbersome workload in mesh modeling and overall preprocessing, regardless if no internal surface waves are being considered. Additionally, processing times may become prohibitively high as coupling of the interior problem with the exterior one is imposed, or, alternatively, sliding/adaptive 3D-mesh schemes are introduced to account for the body-floodwater motion coupling. Having this in mind, it is clear that such approaches only become appropriate when studying some particular – highly complex situations, in the hydrodynamic point of view – problem where the initial and bounding conditions are not to be varied considerably between test configurations, and where limited processing power/time does not present itself.

Consequently, there is a need to simplify the procedure if the simulations are to be carried out within a more generic approach, such as by seamlessly changing the input of different inter-compartment openings or damage orifices in an automatic way. A process of this kind is sure to be an objective when embracing reliability and design optimization studies, where the geometry of the openings is modified between simulations. Problems exhibiting time variant openings' geometries are also prone to benefit tremendously from such automatic processes, in contrast with traditional approaches to these problems, which usually include a vast number of *a priori* produced models and resort heavily to interpolation of the computed cases in order to assess the quantities of interest.

If the floating structure has a considerable size, presents a significantly subdivided interior, or the orifices, through which the fluid is allowed to flow, are small relative to the whole body, the flooding of spaces up to the equilibrium stable condition is lagged and the initial abrupt transient phase of flooding is quickly terminated without major consequences. In that case, a steady flood progression is achieved, where dynamical aspects of the fluid surface can be neglected and the problem may be numerically reduced, with good accuracy, to a quasi-static time domain marching scheme, governed by hydrostatic considerations. One such scheme is presented in this paper.

1.1. Past studies on damaged ship analysis

The capsizing of the ro-pax ferry "Herald of Free Enterprise", in 1987, and the sinking of "Estonia", in 1994, made a strong contribution to the motivation for developing methods which could

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simulate the behavior of damaged ships, particularly of ro–ro vessels with their large continuous vehicle deck. Nevertheless, some pioneering studies were already taking place, such as the ones by Spouge (1986) and Sen and Konstantinidis (1987). The latter included an artificial damping of the motion in order to force the convergence of the solution, while both considered a semi-empirical variation of the center of gravity of the flooding ship as the sole effect of the progressive flooding.

In the next decade, attention of other researchers to the prediction of damaged ships' behavior resulted in the development of several numerical models. Investigations carried out by Vredeveldt and Journée (1991), Turan and Vassalos (1994), Zaraphonitis et al. (1997), van't Veer and de Kat (2000) and Xia et al. (1999), constitute a good set of known numerical tools developed in this decade. Later, many of these initial versions of the models were subjected to improvements of several kinds, mostly on the flow between compartments' calculation and ship's behavior in waves. An additional numerical method was developed by Santos and Guedes Soares (2001), which included a pressure integration technique application to the progressive flooding problem of ro–ro ships. Later, in Santos et al. (2002), asymmetric flooding modeling was introduced in their scheme; experimental validation of this method was carried out by Alvarez et al. (2006).

Several experimental studies were published regarding the validation of the aforementioned codes, yet, considering still water, the one by Ruponen (2006), where a set of flooding tests of a barge is carried out, is of particular interest due to its systematic approach. Some results from these tests were compared with existing tools in Walree and Papanikolaou (2007) and a full comparison of the output of the cases where the model is freely floating was conducted by Santos et al. (2009), taking their own code into consideration. Walree and Carette (2008) made a further benchmark test considering a passenger ship with a much more complex subdivision.

Ruponen (2007) introduced yet another approach to the solution of the problem of a flooding ship and implemented an implicit scheme for the flooding progress, by assuming constant water surface geometry, at each time step, on flooded compartments. Regarding the specific problem of flow through damage openings or internal structural arrangements, in Stening et al. (2011) several experiments were conducted to study the effect of head losses in a cross flow duct and later, in Ruponen et al. (2012), results of a CFD study of the same problem were published.

In recent years, Khaddaj-Mallat et al. (2011) and Papanikolaou et al. (2013) make a review on the damaged ship analysis methods and discuss some of its unresolved issues. The full scale experimental study on the effect of trapped air inside a compartment, while flooding, is reported by Ruponen et al. (2013) and Dankowski (2013) has presented an explicit solution scheme based approach to the progressive flooding problem. Finally, the formulation of an adaptive time step scheme in progressive flooding simulation has been published by Ruponen (2014).

Also worth addressing are the efforts on modeling the floodwater dynamics, inside the compartments and/or its progression between these, by the use of RANS turbulence modeling computations. Van't Veer and de Kat (2000) had already applied a Volume of Fluid (VOF) method for the simulation of progressive flooding in an engine room; the results were found to be in good agreement with model tests, but the grid generation modeling and the computation time were found cumbersome, even with considerably coarse meshes. Cho et al. (2005) and Woodburn et al. (2002) also carried out VOF implementations to the flooding progression modeling, where the former excluded the motions of the ship whereas the latter included full coupling of both parts. Smooth Particle Hydrodynamics (SPH) methods were applied to the problem by González et al. (2003), Souto-Iglesias et al. (2004) and Skaar et al. (2006). SPH based methods have been found to be particularly suitable for capturing the free-surface, when sloshing is significant; yet these methods are also terribly slow when computing the flow. More recently, Gao et al. (2011) produced VOF based simulations of a fixed, and free floating, barge subjected to progressive flooding and later, in Gao et al. (2013), a similar approach was used with a damaged passenger vessel, but where the ship motions are calculated by a seakeeping code developed by Jasionowski and Vassalos (2001).

1.2. Proposed scheme

The presently proposed scheme introduces a generalized use of an adaptive mesh technique to calculate the flooding progression and the volume of fluid in each compartment, together with the introduction of exact pressure integration formulations for computations of the forces acting on the floating body's structure. It is, therefore, a pressure integration technique based method which has its origins in the seminal works of Witz and Patel (1985), Santen (1986) and Shalck and Baatrup (1990). The algorithm responsible for the adaptive mesh process and the derivation of the exact expressions for pressure integration, based on a methodic use of Green's Theorem, has been developed by Rodrigues and Guedes Soares (2014), where a generalized application to bodies in the presence of waves is described. The method relies on the working out of intersections between damage and internal openings' 3D regions, defined by polyhedra composed of quadrilaterals, and the boundaries of, otherwise, watertight surfaces – these areas are also discretized by quadrilateral panel meshes. The method employs particularly robust algorithms regarding inclusion of points in polygons and in polyhedra tests, developed by Feito et al. (1995) and Feito and Torres (1997), respectively. In the present application of the method, a quasi-static approach has been considered and the state of the floating object attitude is computed resorting to a 4th order Runge Kutta explicit scheme with problem specific gain and convergence constants. The progressive flooding flow is calculated through the application of the Bernoulli equation and the net flow assessment on each compartment.

The developed method is believed to be a significant improvement of the pressure integration technique application presented by Santos and Guedes Soares (2001) due to its general applicability and automatic resolution of openings' meshes from polyhedral intersection and, most notably, due to the inclusion of the mesh cutting/subdivision adaptive scheme coupled with the introduction of robust analytic integration expressions to the pressure, force and moments' calculations. On the other hand, the method does not rely on 3rd party software to work out some of the necessary integrations as in Ruponen (2007) and Dankowski (2013). Also worth mentioning is the ability to compute, with arbitrary accuracy, within the paradigm of incompressible and inviscid fluids, the flows between compartments. These are dependent on prescribed discharge coefficients, i.e. nondimensional values similar to head losses to be multiplied by the velocity of the flow at some point of the opening, and on mesh subdivision parameters.

2. Problem formulation and governing equations

2.1. Flooding phases

A floating body, such as a ship, which is subjected to a sudden breach in its hull, will usually undergo through three different stages, regarding the consequent flooding. The first is the transient phase, in which a sudden ingress of water, carrying a significant