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# Fluid-structure interaction analysis of ship-ship collisions

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The Arbitrary Lagrangian Eulerian (ALE) fluid-structure interaction (FSI) method is widely used to simulate ship-ship/ship-ice collisions, in which hydrodynamics are incorporated to estimate a more realistic and reliable collision response. The purpose of this paper was to use the ALE FSI method for parametric studies on ship collision results, in which the contact force and the ship motions were calculated simultaneously. Numerical simulations of a collision between two identical ships have been conducted using the ALE FSI analysis technique of the LS-DYNA code, in which the surrounding fluid flow was explicitly modeled. The effects of the forward velocity of the struck ship, the mass of the struck ship and the collision angle on collision response were investigated. Furthermore, the analytical method based on momentum conservation and the constant added mass (CAM) method in which the hydrodynamic effects were treated as a constant added mass were applied to calculate energy dissipation. The results were compared with those in the FSI method. Discussions and conclusions are presented.



## 1. Introduction

Collisions between two ships represent accidents with severe consequences. To control the safety level, it is essential to predict the damage resulting from certain scenarios with sufficient confidence. Recent advances in computers and algorithms for nonlinear analysis have allowed simulations of realistic scenarios. A large number of numerical studies have been reported in the literature [1].

According to the records, both striking and struck ships have a forward velocity before impact. Minorsky [2] proposed the decoupled method and applied it to assess the effect of the forward velocity of a struck ship. The method decouples the collision process into two independent parts: external dynamics and internal mechanics. The external dynamics addresses the energy released for dissipation and the impact impulse of the collision by analysing the rigid motion of the striking ships and considering the effect of the surrounding water. The analysis of the internal mechanics focuses on the structural response and the damage caused at a point where the struck ship is kept fixed in space and the striking ship impacts with it at a constant velocity along a prescribed path. He found that the velocity of the struck ship has an influence on the length and depth of the damaged side area. Kitamura [3] pointed out several uncertain factors involved in the typical simplified analytical approach such as hull girder bending, forward velocity of a collided ship, etc, that may affect the crashworthiness significantly. Wisniewski and Kolakowski [4] investigated the effect of the motion of the struck ship on the crashworthiness of the struck ship. They were concerned with the so-called internal mechanics of collision and thus used the Y−component of the

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velocity of the striking ship instead of the motion of the struck ship. However, the contact force influences the ship motions and vice versa during the collision. Thus, the penetration path should be evaluated in parallel with the ship motions; that is, a coupled approach must be applied.

A few researchers have proposed the coupling approach [5,6] and studied the difference between the coupled and decoupled approaches [7,8]. In most cases, the effect of hydrodynamics has been considered in terms of a constant added mass (CAM) to the struck structures. However, the hydrodynamic forces are complex. The values for the added mass may not be realistic. In general, the added mass of a ship is associated with the mass of the fluid accelerated by a ship's unsteady motions in water. The added mass depends on the size and shape of the ship, the motions of the ship and proximity of a neighbouring ship (including the size and shape of the neighbouring ship). Motora et al. [9] demonstrated that the added mass of the struck ship depends on both the duration of the collision and the relation between the collision force and deformation.

The development of computational fluid dynamics now allows modelling of the governing processes in the fluid. This could be conveniently simulated by applying a moving mesh algorithm and overlap capability of the grid onto the structure mesh using the multi-material Arbitrary Lagrangian Eulerian (ALE) formulation. The ALE method solves the transient equations of motion of the fluid and structure using the explicit time integration method [10]. It can solve the Fluid-Structure-Interaction (FSI) problem during the collision and facilitate a fully coupled collision simulation.

A number of research studies have used the ALE FSI technique of the LS-DYNA code to assess collisions. This method was considered in a numerical model for direct impact simulations between a ship and a rigid structure [11]. Numerical simulations of a collision between a bergy bit and a loaded tanker were performed by Gagnon and Wang [12]. They incorporated hydrodynamics via LS-DYNA's ALE formulation. Load measurements from the lab tests compared reasonably well with estimates from the simulation. Lee et al. [13] carried out a full-scale ship collision simulation to estimate the collision response using the ALE FSI analysis technique of the LS-DYNA code. Song et al. [14] carried out a numerical simulation of a collision between an ice block and a floating structure in the water using both ALE FSI method and CAM method. The comparisons indicated that the ALE FSI method yields better results for the motion of the floater, i.e., the acceleration of the floater wall caused by the ice mass's impact and the relative velocity were in reasonably good agreement with experimental measurements. However, none of these studies have focused on parametric studies on ship collision results using the ALE FSI method.

The aim of this paper is to investigate the effect of the following parameters on ship collision results using the ALE FSI method: the forward velocity of the struck ship, the mass of the struck ship and the impact angle. Numerical simulations of a collision between two identical ships are carried out using LS-DYNA. To address the FSI problem, an ALE formulation and an ALE to Lagrangian formulation coupling algorithm [10] are used. The modelling technique used with the ALE FSI method is presented in detail. To verify that the fluid model provides accurate results, the equivalent added mass coefficients of a rectangular box were calculated and then, compared with the values obtained using the potential flow solver WADAM. In addition, the analytical method based on momentum conservation and the constant added mass (CAM) method in which the hydrodynamic effects are treated as a constant added mass were applied to calculate energy dissipation. The results were compared with those obtained by the ALE FSI method.

The layout of the paper is as follows: Section 2 describes the details of the ALE FSI simulation setup, including the validation of the fluid model; Section 3 presents the ALE FSI numerical simulation results from parametric studies, including the contact force, the energy dissipation and the structure damage; Section 4 presents the comparisons among the analytical method, the CAM method and the ALE FSI method. Section 5 and Section 6 present discussions and conclusions, respectively.

## 2. ALE FSI simulation setup

This section presents the technique and computational details for the ALE FSI numerical models, including the finite element modelling and the model validation process.

### 2.1. Finite element modelling

The modeled region of the water and air for one particular model is shown in Fig. 1, where a central, right-angled collision when the struck ship is lying still is shown. The coordinate system is also shown in Fig. 1, in which the direction of the striking ship's forward motion (i.e., the impact direction) is defined as *Y*-axis and the direction of the struck ship's forward motion is defined as *X*-axis. The dimension of the fluid was 227 m × 81 m × 28 m + 86 m × 224 m × 28 m, including 10 m air on the top. The length of each vessel was 161 m, the breadth was 27.4 m, the depth was 13.5 m, the draught was 9 m, and the displacement was 24000 t.

The simulation requires a coarse mesh for the vessel as it needs to move through water for some distance to produce a reasonable bow wave. However, the much finer mesh for the contact region is needed to attain accurate collision response. To address this challenge of the mesh size in the simulation, both the entire striking ship and the entire struck ship were meshed with rigid shell elements of large size, and one tank section attached to the rigid-struck ship body at the impact location was meshed with deformable shell elements of small size, in which the deformable segment was overlapping the rigid mesh. The interaction between the rigid-vessels and the water was defined using the LS-DYNA coupling command "Constrained Lagrange in Solid" [15]. The coupling algorithm computes the coupling forces at the fluid-structure interface. These forces are added to the fluid and structure nodal forces, in which fluid and structure are solved using an explicit finite element