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A comparative analysis of the fluid-structure interaction method and the constant added mass method for ice-structure collisions

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ABSTRACT

The constant added mass (CAM) method and the fluid-structure interaction (FSI) method are widely used to simulate ship-ship and ship-ice collisions. In the CAM method, the hydrodynamic effect of the surrounding water is treated as a constant added mass, whereas in the FSI method the surrounding fluid flow is explicitly modelled. The objective of the paper is to compare the two methods and to explain the causes of the differences in the results. We considered collision between a freshwater ice mass and a floating steel structure. For both methods, the numerical simulations were performed with the LS-DYNA software. The behaviour of the ice mass was modelled using an elliptic yield criterion and a strain-based pressure-dependent failure criterion. To ensure realistic ice behaviour, the ice model was calibrated using general trends found in laboratory and in-situ indentation tests with focus on the laboratory-grown ice and the fluid model in the LS-DYNA was verified by comparing the added mass coefficients for a spherical body and a rectangular block with the corresponding WADAM results. To validate and benchmark the numerical simulations, experimental data on ice-structure interactions in water were used, including the acceleration of the floater wall measured with the dynamic motion unit (DMU), the relative velocity between the ice mass and the floater before the impact and some images extracted from video recording of the test. The comparisons indicated that the 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. It was also found that the CAM method was faster but predicted a higher peak contact force and more dissipated energy in the ice mass than in the FSI method.

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1. Introduction

Collisions with massive ice floes can directly result in the loss of human life, environmental damage and structure loss, and it is important to design engineering structures (i.e., bridges, ships and offshore structures) that have sufficient resistance to ice collisions (e.g., IACS [1] and DNV GL [2]). With the rapid development of computer technology in recent years, numerical simulations have been increasingly used in analyses of collisions between ice and ships to predict structural damage and to complement physical testing during the early stage of the design process (e.g., [3,4]). Experimental studies remain either very expensive or difficult to conduct.

The hydrodynamic effect of the surrounding water plays an important role in the analysis of ship-ship collisions, ship-platform collisions and collisions between ice and movable structures [5]. For instance, hydrodynamic forces cause a struck ship or floating body to move before the actual impact, which affects its response to the collision [6]. It is necessary to take into account the hydrodynamic effect of the surrounding water when dealing with the absorbed energy in collision [7].

A review of studies of ice-structure collisions that use the finite element method reveals that there are two common methods of considering the hydrodynamic effect of the surrounding water in assessments of the amount of energy absorbed in platform-ice and ship-ice collisions. One is the *constant added mass* (CAM) method, in which the effect of the surrounding fluid is treated as a constant added mass, and the other is the *fluid-structure interaction* (FSI) method, in which the surrounding fluid is explicitly modelled. However, only few studies have focused on the differences between the CAM method and the FSI method with respect to the energy dissipated during a collision. As a contribution to knowledge, there is a strong need for an investigation and comparison of the two methods.

The objective of the present study is to compare the CAM and FSI methods for numerically simulating a collision between an ice mass and a floating structure. To the authors' knowledge, this is the first comparative analysis of these methods for ice-structure collision problems.

All the simulations described in this paper are performed by LS-DYNA. We address the FSI problem using an ALE formulation and an ALE to Lagrangian formulation coupling algorithm [8]. The modelling technique used with the FSI method is presented in detail. The focus is on validating the model's input parameters and the key numerical results using experimental data on freshwater ice-steel structure collisions. First, the ice model parameters and LS-DYNA's fluid model are validated. Second, the results of laboratory collision experiments in water are used to verify the FSI technique and to evaluate the two methods. Finally, the results of the two methods, including the acceleration of the floater wall measured with the dynamic motion unit (DMU), the contact force, the energy dissipation and the central processing unit (CPU) time, are compared and discussed.

The layout of the paper is as follows: Section 2 describes the advantages and drawbacks of the CAM method and the FSI method; Section 3 presents the experimental data that were used for the validation and evaluation of the numerical models; Section 4 presents the details of the two methods, including the simulations' setup, validation and major results; Section 5 presents a comparison of the results obtained using the FSI and CAM methods; and Sections 6 and 7 present a discussion and the conclusions, respectively.

2. CAM method and FSI method

2.1. The CAM method

In a collision scenario, the analysis procedure is decoupled into two independent parts: the external dynamics and the internal mechanics. The external dynamics addresses the energy released for dissipation and the impact impulse of the collision by analysing the rigid motions of the colliding ships and by accounting for the effect of the surrounding water. The internal mechanics is concerned with how the strain energy is dissipated in the striking and struck objects. That these are decoupled implies that there is no interaction between the ships' motions and structural deformations. A simplified decoupled method for colliding ships was first presented by Minorsky [9]. In the force-acceleration relationship, he proposed using a constant value of 0.4 for the sway added mass coefficient of the struck ship, and since then, this value has been used in analyses of ship-ship and ship-ice collisions (e.g., [10,11]).

Because of its simplicity, the CAM method has attracted the most attention in marine engineering. Within the framework of the decoupled method, the majority of ship-structure (or ice) collision problems have been solved using the CAM method (see Table 1), including the external dynamic analysis [12–14] and the internal mechanic analysis [15,16]. In the coupled method, Wang et al. [10] and Zhang and Suzuki [17] used the CAM assumptions for finite element analysis of ship-ship collisions. However, most of them used other simulations or some simplified formulations to validate their results as there is a lack of experiments to validate the CAM method directly.

There are several limitations of the assumption of constant added mass:

1. In reality, the added mass coefficient depends on the acceleration and is frequency dependent. The acceleration in term depends on the collision force level, the temporal variation and duration.
2. Using the CAM method means neglecting the effects of the presence and the motion of the other body during the approach and the collision processes.