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Impact mechanics of ship collisions and validations with experimental results

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ABSTRACT

Closed-form analytical solutions for the energy released for deforming and crushing of structures and the impact impulse during ship collisions were developed and published in Marine Structures in 1998 [1]. The proposed mathematical models have been used by many engineers and researchers although the methods were only validated with time domain numerical simulation results at that time. Since then, model and full-scale measurements have been carried out and experimental results are available in the public domain. The purpose of the present paper is to use such experimental results to further analyze the validity and robustness of the closed-form analytical methods as well as to further improve some parameter's accuracy. In total, 60 experimental results have been analyzed and compared with the analytical results and this paper presents the outcome. It can be concluded that the analytical methods give a reasonable agreement with the experimental results. The paper also introduces a simple concept to account for the effective mass of liquids with free surface carried on board of a ship and it is shown how the analytical analysis procedure can be expanded to take into account the effect of ship roll on the energy released for crushing.

1. Introduction

Ship-ship collision events constitute a major hazard for ship operations. It can result in loss of human lives and severe environmental damages. This has leaded the maritime community to increase the efforts to mitigate the probability and consequences of ship collision accidents.

To develop effective rules and procedures to reduce the risk associated with ship-ship collision events requires firstly a procedure to evaluate the probability of ship collision events in specific sea traffic conditions, secondly, given a ship-ship collision then a procedure is needed to estimate the energy which will be released for structural damage of the involved ship structures. Knowing the energy to be absorbed by structural damage the final step is then to estimate the structural damage to the striking and the struck ship.

The present paper deals with analytical procedures to determine the energy released to provoke structural damage in a given ship-ship collision scenario. In a ship-to-ship collision event only part of the initial available kinetic energy is consumed

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in the crushing of the bow of the striking ship and the side structure of the struck ship. The analysis of the external dynamics of ship collisions aims at predicting the loss of the initial kinetic energy to be absorbed for plastic deformation and rupture of the ship structure, accounting for the ships' rigid motions and the effect of the surrounding water [1,2]. On the other hand, the subsequent internal mechanics analysis estimates the resulting structural damages to the ship, e.g. Refs. [2,3].

In 1998, closed-form analytical solutions to estimate the energy released for deforming and crushing of ship structures and the impact impulse during ship collisions were developed by Pedersen and Zhang [1]. This analytical method is restricted to ship motions in the plane of the water surface and is valid for arbitrary ship-ship collisions including different impact locations and collision angles. The analysis procedure is based on rigid body mechanics, where it is assumed that there is negligible strain energy for deformation outside the contact region and that the contact region is local. This implies that the collision can be considered as instantaneous and each body is assumed to exert an impulsive force on the other at the point of contact. The model includes friction between the impacting surfaces so that situations with glancing blows can be identified. At the start of the calculation, the ships involved in the collision can have forward and sway speeds, and the influence of the hydrodynamic forces due to the sudden acceleration of the ships are approximated by simple added mass coefficients. The derived expressions were also extended to the case of ship collisions with rigid walls and to collision between ships and flexible offshore platforms.

At the time of the publication, the collision energy results determined by the close-form expressions were only validated with the results obtained by one of the first time domain simulations capable of treating oblique collisions in two dimensions, Petersen [4]. The agreement with such time simulations indicated that the applied rigid body mechanics procedure is sufficiently accurate for conducting analysis of ship-ship collisions. Later, in 2002, Brown [5] compared this analytical method with more comprehensive time simulation results finding good agreement; this further confirmed the robustness of the method.

One important feature of this analytical model is that it is so fast that it can be used together with a Monte Carlo based ship collision probability model to calculate a set of energy reference values for a specific struck vessel and collision probabilities on various shipping routes. This was recently highlighted by Pedersen [6] in a review article addressing ship collision and grounding analysis procedures. Most importantly, the analytical method has been a valuable reference for many engineers in academia and industrial bodies when conducting ship collision analyses [5–9]. For this reason it is considered important to further validate the analytical expressions with recently published model-scale and full-scale ship-to-ship collision experiments [8–12] so that to provide additional confidence in using the analytical method.

Tabri et al. [8] demonstrated that the external dynamic behavior measured in full-scale perpendicular ship collision experiments can be mimicked quite well by model-scale experiments in a water tank. They reported 13 perpendicular model-scale collision experiments which were designed, and validated, with two full-scale experiments conducted by the Dutch Institute for Applied Physical Research (TNO) in 1998 [11] and 2003 [12]. The same scaled ship models were used by Tabri et al. [9,10] to conduct additional 24 collision experiments for evaluating the influence of the impact angle and location on the energy released, and other 21 for investigating the effect of sloshing in liquid filled tanks carried on board of the striking ship. These 58 model-scale collision tests and the two full-scale collision experiments have been selected for the present validation of the analytical method.

For easy reference the paper first re-produces the closed-form formulations from Refs. [1,2] for the collision energy to be absorbed by deforming ship structures. In addition, a simple concept is proposed to account for the effective mass of liquids with free surface carried on board of a ship, so that to predict the experimental response of the experiments with sloshing interaction [10]. It can be concluded that the analytical methods give a reasonable agreement with the experimental results, though differences for some cases are slightly bigger than expected.

Since the analytical method only considers the ship motions in the waterline plane, the effect of the roll motions of the struck ship on the energy released during the collision is a concern. Therefore, this has also been evaluated by deriving new expressions for estimating the energy loss to roll. The outcome of this study is presented in Appendix A where it is concluded that the effect of the roll motion of the struck ship in general is small and can be neglected.

2. The analytical formulation

The closed-form formulations from Refs. [1,2] for the collision energy to be absorbed by deforming ship structures are briefly re-produced here for easy reference.

The collision scenario considers that two ships collide each other where a **Ship A** sails with a forward speed V_{ax} and a sway speed V_{ay}, and a **Ship B** sails with a forward speed V_{b1} and a sway speed V_{b2}.

An XYZ-coordinate system is fixed to the sea bottom. The Z-axis points in a direction out of the water surface, the X-axis lies in the symmetry plane of the Ship A pointing towards the bow, and the origin of the XYZ-system is placed so that the midship section is in the YZ-plane at the moment of contact, $t = 0$. The origin of a $\xi\eta$-system is located at the impact point C, the ξ-direction is normal to the impact surface, the angle between the X-axis and the η-axis is α, and the collision angle between the two ships is β, as shown in Fig. 1.

For the Ship A, the mass is M_a, the radius of the ship mass inertia around a vertical axis through the centre of gravity is R_a, the centre of gravity of the ship is at $(x_a, 0)$, the coordinate of the impact point is (x_c, y_c), the added mass coefficient for the surge motion is m_{ax}, i.e. the total mass is $M_a{}^*(1 + m_{ax})$, the added mass coefficient for the sway motion is m_{ay}, and the added mass coefficient of moment for the rotation around the centre of the gravity is j_a.