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Stern slamming of a chemical tanker in irregular head waves

Shan Wang, C. Guedes Soares *

Centre for Marine Technology and Ocean Engineering (CENTEC), Instituto Superior Técnico, Universidade de Lisboa, Portugal

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ABSTRACT

Slamming loads on the stern of a chemical tanker are predicted by using an Arbitrary Lagrangian Eulerian (ALE) algorithm implemented in LS-DYNA and a Modified Longvinovich Model (MLM) which is derived from the potential velocity theory and Wagner's condition. Ship motions in irregular sea states are calculated numerically by a fully nonlinear time domain method based on the strip theory, and then the calculated relative vertical velocity between the ship section on the stern and wave surface is applied in the Arbitrary Lagrangian Eulerian algorithm for slamming load calculation. The problem is solved by simulating water entry of 2D ship sections of the ship model at a constant speed. Model tests of the chemical tanker in irregular seas are conducted to obtain the ship motions and wave-induced loads. The numerical slamming loads are compared with the measured ones and the analytical calculations from the Modified Longvinovich Model.

1. Introduction

Slamming phenomenon commonly occurs with high frequency when a ship advances in extreme seas. The impulsive loads induced by the impact between a ship section and water surface may cause local and global damage to the structure. It has been widely studied, and of interest is the impact load such as bow flare slamming, bottom slamming, stern slamming, green water and bow impact load.

Even though these problems can excite such a broad interest, most of the studies are still limited to the fundamental research, where the analysis is carried out on simplified shapes. An accurate estimate of hydrodynamic loads of slamming events of a ship is still a challenging topic as it involves many complex physical phenomena such as large amplitude ship motion, hydroelasticity, non-linear breaking wave and transient impact load. More commonly they are limited to 2D sections with circular or triangular shapes. von Kármàn (1929) simplified the slamming problem of a ship bottom as a typical two-dimensional wedge impacting with water, neglecting the local uprise of the water. Wagner (1932) proposed an asymptotic solution for water entry of two-dimensional bodies with small local deadrise angles, accounting for piled-up water on the wedge by simply introducing a constant surface wetting factor C_w, which results in overestimation on the impact load. Since then, much work has been done on the predictions of local slamming loads on sections and bodies with simple geometries. Dobrovol'skaya (1969) derived an analytical solution by transferring the potential flow problem for the constant water entry into a self-similar flow problem in complex plane, which took advantage of the simplicity of the body geometry and is valid for any deadrise angle. Guedes Soares (1989) proposed that the slamming force is assumed to be given by the sum of two components. The first one is an impact component related to the impact of bottom on the water surface and characterized by a large peak with small duration. The second one is given by the rate of change of the hydrodynamic momentum as the hull enters into the water. For different types of ship section, the slamming force is dominated by different components mentioned above. Zhao and Faltinsen (1993) proposed a nonlinear boundary element method to study the water entry of a two-dimensional body of arbitrary cross-section and generalized the Wagner (1932)'s theory to presented a simple asymptotic solution for small deadrise angles. Korobkin (2004) investigated the analytical models for the prediction of the hydrodynamic pressure distribution which were based on the classical Wagner theory.

Model test is also a widely used approach for the research in this filed. Ochi and Motter (1973) obtained the slamming loads in terms of slamming pressure, the pressure distribution and the time variation of the total slamming load by analyzing lots of test results. Drop tests for a wedge with deadrise angle 30° and a bow-flare section were carried out by Zhao et al. (1996). Aarsnes (1996) performed free drop tests of two ship sections, i.e., one wedge section and one bow-flared section for different roll angles. The experimental results are in quite good agreement with the numerical calculations from Wang and Guedes Soares (2012, 2013).

* Corresponding author. Postal address: Avenida Rovisco Pais, 1049-001 Lisboa, Portugal.
E-mail address: c.guedes.soares@centec.tecnico.ulisboa.pt (C. Guedes Soares).

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Ramos et al. (2000) conducted an experimental program assessing the slam induced loads on a segmented ship model, which was analyzed with the method used by Ramos and Guedes Soares (1998). De Backer et al. (2009) conducted an experimental study of the impact of 3D bodies during water entry, in order to assess the slamming loads in these buoys appropriate to the wave energy devices under consideration, which validated the numerical investigations of Wang and Guedes Soares (2014a). Clauss et al. (2012) carried out model tests for two types of ship — a LNG Carrier and a chemical tanker, to investigate the ship motions and wave/structure interaction loads in extreme seas.

The most attention has been paid to the slamming events that happen on ship bows. High forward speed of the vessel and rough sea states usually lead to the most severe water entry events. In such circumstances, the probability of water entry is the largest at the bow region. When it comes to a vessel with zero or low forward speed, the ship's stern with small draft may come out from the water surface and reenter frequently, particularly in following waves. At the bottom of a ship stern, high amplitude with short-duration impact-related slamming loads may occur when this part enters the water, due to the flattened geometry of the section. These loads may not only cause local damage of the hull structure, but also increase hull girder loads that contribute to long-term fatigue of the hull girder structure. Kapsenberg et al. (2002) described an experimental method to measure slamming loads on the aft body of a ship model. The impact force was derived from the integration of the pressures from a large number of pressure gauges. Kim et al. (2008) performed a stern slamming analysis based on three-dimensional computational fluid dynamics (CFD) simulation with an application to a liquefied natural gas (LNG) carrier with twin skegs. Oberhagemann et al. (2009) described a one-way coupling method for predicting global design loads and flexible responses of hull girder due to stern slamming loads.

For a chemical tanker, the hull length to depth ratio is generally large, so the bending moment is also large. In the process of investigating the zero or low speed stern slamming and vibration problem, questions began to arise with respect to a possible hull girder fatigue life problem. The impulsive nature of slamming caused hull girder structural vibrations, known as whipping, in a wide range of frequencies. Wang and Guedes Soares (2015) studied the slamming probability of a chemical tanker subjected to irregular waves numerically comparing with experimental results. The probability of bottom slamming was estimated statistically as the joint probability between the cross section's emergence and exceedance of the threshold velocity during the re-entry. The results showed that bottom slamming occurs most likely at the bow and stern of the ship hull, and the occurrence frequencies were highest at the aft part due to the small draft and severer pitch motion. To evaluate the effects of the stern slamming on the longitudinal bending moment, the prediction of the slamming load is of great significance.

While the bow slamming of a chemical tanker is studied in Wang and Guedes Soares (2016), the present study concentrates on stern slamming. In this work, the ship motions of a chemical tanker in irregular seas are determined numerically by a nonlinear time domain method based on the strip theory. The calculated relative velocity between the ship sections and the wave surfaces are applied in an ALE algorithm and a simplified MLM for predicting the slamming loads on the stern of the ship hull. The predictions of the slamming pressure on several 2D sections are compared with the experimental measurements from model tests of the chemical tanker in irregular head waves and the analytical calculations from MLM.

2. Methodology

2.1. Model tests

Experimental data of the ship motions and slamming pressure on the ship hull of a chemical tanker advancing in head waves at zero speed (Froude number=0), are obtained from model tests. The model tests were conducted in the seakeeping basin of the Ocean Engineering Division of the Technical University Berlin by Clauss et al. (2012) at a model scale of 1:70. The basin is 110 m long, the width is 8 m and the water depth is 1 m, while the measuring range is 90 m long. An electrically driven piston type wave generator is installed on one side of the basin. The wave generator is fully computer controlled and a software is implemented which enables the generation of transient wave packages, deterministic irregular wave states with defined characteristics as well as tailored critical wave sequences. During the tests, the model is fixed with an elastic suspension system using a triangular towing arrangement pulling the model without inducing a moment. The longitudinal motions are restricted by a spring in front of and a counter weight behind the model. With this arrangement, heave and pitch motions as well as the measure forces and moments remain unrestrained.

The main particulars of the chemical tanker and the associated ship model are listed in Table 1. The sketch of the chemical tanker and the manufactured model are plotted in Fig. 1. The origin for all the following parameters related to the positions on the model is located at the aft perpendicular at keel level. The model is made of fiberglass reinforced plastic and segmented at $L_{pp}/2$. The segments are connected with force transducers. Some pressure sensors are mounted on the bottom of the bow and stern, to obtain the time history of the local pressure on the ship hull. The present work focuses on the pressure loads at the stern.

Fig. 2 illustrates the arrangements of the pressure sensors on the bottom of the stern and the sketch of the model in irregular waves. The positions of the five pressure transducers at the stern are listed in Table 2.The information only provides the X and Z coordinates with the origin located at the aft perpendicular at keel level. A miniature threaded pressure transducer (HKM-375-1.7Bar) is used. The hexagonal head and O-ring seal make it easy to mount and simple to apply. This type of pressure transducer utilizes a flush metal diaphragm as a force collector. A solid state piezoresistive sensing element is located immediately behind this metal diaphragm which is protected by a metal screen. The advanced construction results in a highly stable, reliable and rugged instrument with all the advantages of micro circuitry, significant miniaturization, excellent repeatability, low power consumption, etc. The miniaturization process also yields a marked increase in the natural frequencies of the transducers (up to 1600 KHz), making them suitable for use in the slamming pressure measurements. During the model tests, it was observed that an unusual behavior of some pressure transducers occurs, because of the different temperature compensation behavior of the sensors. As seen in the left sketch of Fig. 2, there are another two sensors 31

Table 1
Main particulars of the chemical tanker.

Items	Full scale	Model scale
Length(Loa)(m)	170.000	2.428
Length(Lpp)(m)	161.000	2.300
Breath(m)	28.000	0.400
Depth(m)	13.000	0.186
Draft(m)	9.000	0.129
Displacement(ton)	30,666	0.089