Ocean Engineering 111 (2016) 369–383

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

Experimental and numerical study of the slamming load on the bow of a chemical tanker in irregular waves

Shan Wang, C. Guedes Soares *

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

ARTICLE INFO

Article history:
Received 28 November 2014
Accepted 16 November 2015

Keywords:
Slamming occurrence
Slamming load
Bow slamming
Irregular wave
Ship motions
Arbitrary-Lagrangian Eulerian

ABSTRACT

This paper presents calculations of ship motions, slamming occurrence probability and slamming loads on the bow of a ship hull in irregular waves. The results are compared with the experimental data from model tests of a 170 m chemical tanker with $F_n = 0$ in head seas. Ship motions are calculated by using a partially nonlinear time domain code based on strip theory. The probabilities of slamming occurrence at the bow are studied numerically and statistically, and compared with the experimental data. The experimental data are analysed statistically, to determine the relationships between the measured pressure and the entry velocity and with wave parameters. Two estimated significant slamming events are simulated by using the Arbitrary-Lagrangian Eulerian (ALE) algorithm, based on the calculated relative entry velocities in the numerical procedure.

1. Introduction

When a ship travels in rough seas, it will impact with water because of large vertical relative motions between the ship and the wave surface. This hydrodynamic impact phenomenon is defined as slamming. This is one of the most complicated dynamic phenomena of a ship operating in rough sea. The impulsive pressure loads induced by slamming may cause local damage on the bottom structure or endanger global ship strength due to the contribution of the whipping bending moment to the wave bending moment. In rough seas, this impact force is so large that many ships have reported local structural damages due to the slamming loads, especially in head sea waves with high forward speed. In the initial stage of ship design, the complete information on slamming, including where the slamming occurs, the frequency of slamming occurrence, the characteristics of slamming loads and the flexible responses due to the slam-induced loads, are required. This work will focus on the frequency of slamming occurrence and the slamming loads due to the impact between the ship hull and the water surface.

A slam will occur when the relative vertical motion between a ship section and wave surface is equal to the still water draft of the section and at the same time the relative vertical velocity is negative, i.e. the ship section enters the water. The other condition to be satisfied is that on the previous time moment the section must have been out of the water. Some authors define that a slam occurs when the relative velocity is higher than a critical value (Ochi and Motter, 1973). For the SWATH cross-structure, Zarnick and Hong (1986) developed a method to estimate the expected number of water impacts per unit length. The occurrence of a cross-structure slam is dependent upon at least three conditions: entry of the cross structure into the water; second an entry velocity exceeding some threshold velocity; a small angle between the cross-structure and free surface. Today the most widely accepted probabilistic slamming model requires only the first two conditions to be true, e.g. Psaraftis (1978), Faltinsen (1993) and Senjanovic and Parunov (2001). Guedes Soares and Pascoal (2005) have studied the probability distributions of green water on deck and showed that based on a relative motion formulation the predictions of the theory agreed well with the measurements. However their results were obtained with a model with basically vertical sided bow, while the ones of Buchner (1998, 2002) account for a different flare and introduce the corrections for that effect. Guedes Soares et al. (2007) performed an experimental programme to determine the instants when impact occurs for a specific bow shape, and it was found that wave impact at the bow is highly correlated with the local wave steepness.

Of interest are the impact loads such as bow-flare slamming, bottom slamming, stern slamming, and green water. These impact loads are of a transient nature and can cause severe structural damages. Although the loads are widely varying in their characteristics – magnitude, rise time, duration, etc., all involve the impact at high relative velocity between the free surface of nearly

* Corresponding author. Tel.: +351 218417957.
E-mail address: c.guedes.soares@centec.tecnico.ulisboa.pt (C. Guedes Soares).

http://dx.doi.org/10.1016/j.oceaneng.2015.11.012

incompressible seawater and the hull structure. The transient impact loads can be highly non-linear and may be strongly affected by the dynamic response of the hull structure. The structural analysis of ship hulls due to the impact loads has relied on simplified approaches for years, considering the hydrodynamic loading calculated by assuming a rigid structure, and the loading is then applied to the structure in a quasi-static manner.

Many methods have been developed to calculate the slamming pressure on a rigid body that penetrates the wave surface with a prescribed velocity. Among the earliest was the method of von Kármàn (1929) who estimated the pressure on sea plane floats. Wagner (1932) proposed an asymptotic solution for water entry of two-dimensional bodies with small local deadrise angles within the assumption of potential-flow problem without gravity and no air cavity formed during the impact. Armand and Cointe (1987) and Howison et al. (1991) developed this work by accounting for the effect of nonlinear jet flow in the intersection region between the body and free surface using asymptotic matching expansions. When the wedge impacts vertically with water at a constant velocity, 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 takes advantage of the simplicity of the body geometry and is valid for any deadrise angle within the limits that compressibility and hydroelastic effects do not matter and air entrapment does not occur. Zhao et al. (1996) generalised the work of Wagner (1932) by applying linearised free-surface boundary conditions on the horizontal plane at the splash-up height and imposing the body boundary condition on the actual position of the body. They solved the problem numerically using a boundary-integral equation method. For wedges and a section with flare, their results agree well with experimental data and calculations from a fully nonlinear boundary element method presented by Zhao and Faltinsen (1993) for the slamming force and the body pressure distribution. Initial asymmetric wedge-impact flows with horizontal as well as vertical impact velocity were examined by Judge et al. (2004), which employed the method of two-dimensional vortex distributions to model the initial-boundary-value problem. Their numerical calculations agreed well with the experimental study of drop tests for small degrees of asymmetry and small ratios of horizontal to vertical impact velocity. Hermundstad and Moan (2005) studied numerically and experimentally the bow flare slamming on a Ro–Ro vessel in regular oblique waves. The relative motion of ship and wave was calculated by a nonlinear strip theory, and the slamming loads prediction was conducted by using a simplified 2D BEM method, which is based on a generalised two-dimensional Wagner formulation and solved by the boundary element method. Kapsenberg and Thornhill (2010) developed an approximation method based on momentum theory enhanced with pile-up effects due to the wave surface, to predict the impact pressure and force induced by bow-flare slamming. Recently, much work about the two-dimensional and three-dimensional bodies impacting a calm water surface was investigated by using SPH and ALE algorithm, e.g. Veen and Gourlay (2012), Wang and Guedes Soares (2013), and Wang and Guedes Soares (2014a). The two-dimensional slamming pressure calculated by Veen and Gourlay (2012) was applied to the estimation of the slamming loads on a ship in head waves. The general conclusions from their results are that this method is capable of predicting the time history of total slamming force, slamming pressure distribution and pressure peaks on ship-sections and three-dimensional bodies, when proper related parameters are used. Application of these methods on water impact problems is still a big challenge for some issues involved. The numerical convergence is very sensitive to mesh size and contact stiffness of the model. At the beginning of water impact, fluid compressibility matters for bodies with very small deadrise angle and it is not usually considered in numerical model.

Wang and Guedes Soares (2014b) studied the probability of slamming occurrence of a chemical tanker subjected to irregular waves. Their work focused on the bottom slamming probability, and the results showed that the extreme seas referred causes severe slamming problem at the bow and stern of the chemical tanker even without forward speed. The present work focuses on the analysis of the slamming induced loads on the ship sections at the bow. The relative ship motions and velocities between a chemical tanker and irregular seas surface are calculated numerically by a nonlinear time domain method based on strip theory, which are implemented in an ALE algorithm to predict the impact loads on the ship hull. Model tests are conducted for the vessel with $F_n = 0$ to study the seakeeping performance under extreme seas. The measurements include the wave surface elevation, ship motions, vertical bending moment and also the wave-induced pressure on the bow and stern of the ship hull. Statistical analysis of the experimental data is conducted. The numerical relative motions are compared with the measured ones for several positions, achieving good agreement. The predicted slamming pressures from numerical method are compared with the results from pressure transducers at the bow in the model test.

2. Methodology

In the ship design stage, the flexible responses of the ship due to the wave-induced loads are of great significance. An analysis of slamming induced responses may require an accurate prediction of not only of the slamming loads but also of the conditions under which slamming occurs, where the slamming occurs and the frequency of the occurrence. In this paper, ship motions in three irregular sea states are numerically calculated by using a fully nonlinear time domain code. Based on the calculated relative vertical motions and velocities between the ship hull and wave surface, the slamming probabilities on the bow of the vessel are estimated and discussed. The slamming pressures on concerned ship sections are numerically calculated by ALE algorithm, by considering the ship sections enter into calm water with a constant entry velocity. Numerical results of ship motions, slamming probability and slamming pressures on the bow are compared with the experimental data from model tests. Statistically analysis of the experimental data is performed, regarding the relation between the peak pressures and the impact velocities and the free surface elevation. It is assumed that the ship hull has negligible deformations due to the slam-induced loads and the slamming loads are not affected by the whipping vibrations of the hull. Unless otherwise specified, data are presented in full scale.

2.1. Probability of slamming occurrence

Consideration is given to a ship advancing at a constant velocity U in irregular waves. Slamming occurrence in head seas depends on relative ship motion with respect to the wave surface.

When the heave and pitch motions are considered, the relative vertical motion of the ship is given as follows:

$$\xi_{RM} = \xi_3 - x\xi_5 - Ut\xi_5 - \xi_a \tag{1}$$

where ξ_3 is the heave motion, ξ_5 is the pitch motion of the ship at a coordinate system as shown in Fig. 1. ξ_a is the irregular water surface elevation, which can be obtained by linear superposition principle. For a long-crested irregular sea described by a sea spectrum $S(\omega)$, the wave elevation can be given as follows:

$$\xi_a = \sum_{j=1}^{N} A_j \sin\left(\omega_{ej} t - k_j x + \varepsilon_j\right) \tag{2}$$