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Development of empirical formulations of slamming loads for displacement vessels

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A B S T R A C T

The paper presents an empirical method to calculate slamming load acting as bottom impact pressure on the forward region of the vessel. Firstly, hull shape coefficient as a function of the deadrise angle of the section is derived. Relative velocity is derived in terms of the extreme motions, viz. heaving and pitching due to extreme waves. Forward speed is considered in terms of threshold slamming velocity. Finally limiting condition for slamming load is derived. CFD simulations are performed to obtain the variation of the slamming load along the length of the vessel. Various hull shapes with varying block coefficients, speed and length are considered for slamming load calculations. Results are validated against the rules formulation of bottom impact pressure as given in published classification society rules. Reliable formulation for slamming loads with due consideration of geometry of the vessel, seakeeping characteristics and probability of slamming is achieved for various types of displacement vessels. Application of slamming loads on the vessel for scantling calculations of bottom plating is also discussed.

1. Introduction

Waves can cause loads at much higher frequencies due to impact of the ship's hull on water surface, commonly known as slamming. This type of load usually occurs when some part of the bottom of the ship comes out of the water and re-enters consecutively. Theoretically slamming can happen at any point along the length, but it is most predominant at the bottom in the forward part of the hull. Significant slams can also occur at the stern in following seas and at flare in the bow.

The necessary and sufficient conditions for vessel to experience bottom slamming impact pressure are

1. Bow emergence and
2. Certain magnitude of relative velocity.

That is, for slam impact at a location along the ship length the location has to emerge out of the water surface. However, only this is not a sufficient condition for slamming when a ship is moving in waves since the impact at re-entry may be insignificant if the bottom just causes wave surface breaking. At the bow flare location velocity of re-entry further gets modified since after the impact of bow the velocity of the section under consideration gets reduced. Flow in the flare region is tangential to the section. Thus relative angle made by the flare location with reference to the water surface also plays vital role. However, in the present work impact pressure only at the bottommost location of the bow of the vessel is discussed. This impact is referred as slamming in the present work.

Various methods and empirical formulae are available in literature to determine impact pressure due to slamming. Mizoguchi and Tanizawa (1996) reviewed the state of the art of studies on slamming which included theories, numerical methods, elastic responses due to impact loads and stochastic theories. Ramos and Guedes Soares (1998) have reviewed and compared the results of some methods to quantify the slamming loads to be used as input to obtain corresponding responses.

Extensive model tests for Mariner model were carried by Ochi (1964) for slamming load computations. Various speeds and sea states were considered. Extent of slamming along the length was also discussed. Performance of the 'U' and 'V' forms of the vessel (Challenger and Townsend) in irregular waves was discussed in detail by Ochi (1967). Severity of slamming for two forms for same wave conditions, variation of slamming along the length of the vessel was also discussed in detail.

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Ochi and Motter (1973) described the principles and detailed procedure of the prediction method for slamming characteristics such as frequency of occurrence of slamming, ship speed free from slamming, extreme slamming pressure for design consideration, slamming extents along the length of the vessel and girth of the section, etc. Also the application of the prediction method to practical ship design using numerical examples was discussed by Ochi and Motter (1973).

Many classification society rules for bottom impact slamming are based on the comprehensive design paper by Ochi and Motter (1973). Charts for determining hull shape coefficient, k, are given by Ochi and Motter (1973) wherein the sectional properties such as area, breadth, 1/10th of the local draft are considered. Formulation of e.g. ABS (2017b) utilizes same parameters for slamming load as given by Ochi & Motter on the other hand 'k' defined in LRS (2017a) rules is a function of deadrise angle with limits of k being in-line with Ochi and Motter charts. Local draft is considered for calculating probability of slamming which is also in accordance with the procedure outlined by Ochi and Motter.

Relative velocity (V_r) is a function of the heaving and pitching motion in combination with wave elevation. Forward speed component also affects the relative velocity. Detailed derivation for finding the relative velocity at bow can be referred in Bhattacharyya (1978). Based on these formulations maximum relative bow velocity as a function of the Froude number of the vessel for various types of vessels is also suggested in this reference. Relative velocity formulation given in KRS (2017) is in-line with Bhattacharyya (1978), whereas, V_r is empirically calculated in LRS (2017a).

Slamming pressure on a barge model was measured for varied sea conditions by Huang and Sibul (1971). The basic assumption of slamming pressure variation with square of the impact velocity was verified in this work. Also the factor 'k' introduced by Ochi was concluded to be applicable for barges as well. 3D model tests were recommended compared to the 2D drop tests for practical purpose.

Tajima et al. (1998) simulated impacts of a vessel on water surface by Cubic Interpolated Pseudoparticle/Propagation (CIP) scheme. These simulations demonstrated that the air layer between vessel and the water surface plays important role to determine pressure profile. Haugen et al. (1997) presented the results of extensive studies carried out for catamaran's wet deck slamming, both theoretically and experimentally by means of drop test. The main objective was to derive simple relationships to account for the forward speed effects and predicting associated stresses in the structure including any potential hydroelastic effects. Establishment of correct criteria for voluntary speed reduction and change of course is considered to be very important in this work.

Wet deck slamming measurements are interpreted by theory by Faltinsen (1999). The effect of structural vibrations on the fluid flow is incorporated, and hydrodynamic and structural error sources are discussed. Hydroelasticity as a function of deadrise angle and impact velocity is studied. A key finding is that the larger the impact velocity and smaller the deadrise angle the greater the influence of hydroelasticity.

2D theories of slamming, e.g. by Wagner and Von Karman are popular because of the ease of its application and practical difficulty to incorporate 3D model. In the recent times generalized Wagner models (e.g. de Lauzon et al., 2015) are introduced by numerical improvements. Limitation of using 2D theory for very small angles are overcame by solving Dobrovol's Kaya's boundary integral equations (Wang and Faltinsen, 2017). Free fall of finite wedge is investigated with potential non-linear model by Bao et al. (2017). All these works are based on potential theory which is the base for most of practical engineering purposes at present. However, more sophisticated models which can account for actual flow physics e.g. numerical simulation using CFD are more relevant for slamming. Recent research in this field e.g. by Hong et al. (2017), Charles Monroy et al (2017) deals with benchmarking of various codes to assess slamming loads. A wedge and a ship section were investigated. In general CFD results were found to be in better agreement with experiments (data provided by WILS III JIP). Mesh and time step sensitivity are crucial in CFD based analyses which requires enormous time as compared to potential codes.

The fluid structure interaction in local structural areas might be important, indicating that the elasticity of the structure has influence on impact loads. In this regard, one of the main conclusions of Faltinsen et al (2004) was that slamming should be considered together with the dynamic response of the structure and very high pressures concentrated in time and space may not matter. Also the global effects such as slamming induced bending moments can be accurately predicted only by nonlinear hydroelastic methodologies (Jensen and Mansour, 2003). However, these methods are still not well suited for use in the routine design process due to their high computational demands. In this regard it is very important to provide the designer with relatively simple tools, applicable at early design stage. Kapsenberg et al. (2003) used such a simple analytical model, calibrated by hitting the segmented flexible model at the aft end and comparing predicted and measured responses. In this work it was shown that the hydroelastic effects on local loads can be neglected. The practical consequence of this finding is the possibility of calculating whipping response using local pressures from rigid body approximation. Bacicchi et al. (2004) concluded that the simpler numerical methods, and in particular analytical model, were all well suited for use during the first stages of structural design as they require far less detailed information on structural characteristics by comparison to 3D FE models.

Present paper attempts to derive the simple analytical formulation for slamming load which takes into account the actual physical phenomenon involved. Bottom impact pressure as obtained is useful for appropriate bow design (scantlings). Variation of the slamming pressure along the length of vessel and section girth is derived based on CFD simulations for various types of vessels.

2. Slamming pressure

2.1. Nomenclature

$L = Length\ between\ perpendiculars\ of\ the\ vessel,\ m$

$T = \text{Local draft of a section, m}$

$T_d = \text{Design draft of the vessel, m}$

$T_{bal} = \text{Draft of the vessel at forward perpendicular (FP) in ballast condition, m}$

$d = 1/10^{th}$ of local draft of a section, m

$B = \text{Full breadth of vessel, m}$

$b = $ Half breadth at $1/10^{th}$ of local draft of a section, m

$b^* = $ Half breadth at flat bottom of a section, m

$b' = $ Full breadth at $1/10^{th}$ of local draft of a section, m

$k = Hull\ shape\ coefficient$

$U = Vessel\ design\ Speed,\ m/s$

$g = \text{Gravitational acceleration} = 9.81 \text{m/s}^2$

$F_n = Froude\ number\ = U\Big/\sqrt{gL}$

$\theta = $ Oscillatroy *pitching motion*, *rad*

$\theta_a = $ Amplitude of *pitching motion*, *rad*