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Analytical study of the responses of bottom panels to slamming loads

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ABSTRACT

The responses of boat hull bottom panels under slamming loads are studied analytically using a linear elastic Euler–Bernoulli beam as a representation of the cross section of a bottom panel. The slamming pressure is modeled as a high-intensity peak followed by a lower constant pressure, traveling at constant speed along the beam. The slamming response essentially consists of an initial slamming load arriving phase, followed by a vibration phase. The response of the beam is solved analytically. Deflection and bending moment as functions of time and position for different slamming speeds, bending stiffnesses, etc. are given. The response during the two phases are studied and compared. The maximum deflection and bending moment occur approximately when the time it takes for the slamming load to traverse the beam is comparable to the lowest natural period of the beam. At higher slamming speeds the response is less, and the responses do not peak out until after the slam has traversed the beam (i.e., it occurs during the vibration phase). The importance of the leading high-intensity pressure peak often encountered during slamming is also studied. It is seen that a high peak pressure does not necessarily lead to a large structural response, whereas the total load of the peak of the slam does influence the structural response significantly. For relatively slow moving slamming loads, this influence is limited. However, for faster moving loads it can be substantial.

1. Introduction

The slamming between water and the bottom structure of a ship may induce critical loads or even structural damage. Slamming pressures have been experimentally measured to reach 8 MPa or even more (e.g., Faltinsen, 2000). Typically, a slamming event starts with a high-intensity pressure peak and is followed by a lower and essentially constant residual pressure. This pressure distribution travels rapidly over the bottom from the keel towards the chine. The pressure peak magnitude and propagation speed critically depend on the impact velocity and deadrise angle of the impacting body. When local loads become very high or the structure is flexible, hydroelastic effects may also be important; the hull structure deforms in response to the slamming load, and the flow field is affected by this deformation.

Slamming is a complex phenomenon with many effects and mechanisms, including non-stationary flow, compressibility, inertia effects, air cushions and air entrapment, vibration induced cavitation and ventilation, etc. These effects may combine and be coupled, depending on the structure and the particular slamming event. A number of experimental studies show some of the complexities of slamming (e.g., Portemont et al., 2004; Peseux et al., 2005; Battley et al., 2009; Battley and Allen, 2012).

On the other hand, today's high-speed craft designs strongly rely upon semi-empirical design methods provided by Det Norske Veritas (DNV) (2012), American Bureau of Shipping (ABS) (2013), Germanischer Lloyd (G Lloyd) (2012) and other classification societies, where slamming in essence is considered equivalent with a static uniformly distributed pressure on the bottom. The design pressures are considerably lower than experimentally measured peak pressures. Albeit simple to use, these semi-empirical design methods may be at the cost of accuracy, structural efficiency or even risk of damage. It is desirable to develop more refined and rational design methods that can accurately judge and predict the structural responses under non-uniform hydrodynamic slamming loads. One component of this work is the development of analytical models.

Von Karman (1929) was a pioneering researcher in the field of bottom slamming. He developed an analytical model based on a momentum approach when studying seaplane water landings. His work was followed by many others. Wagner (1932) studied two-dimensional water impact on solid bodies. His work was based on potential flow theory. Dobrovol'skaya (1969) proposed an analytical method for a wedge entering water vertically at a constant speed, known as the similarity solution. More recently, Zhao and Faltinsen (1993) and Faltinsen (1999) used a boundary element method and indicated a superposition of asymptotic expansions of high pressure at the spray root and a following lower pressure distribution. Faltinsen (1999, 2005) reported that hydroelastic effects are mainly relevant for local impacts when the deadrise angle is small and the

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duration of the impact is shorter or comparable to the structure's natural period. A conformal mapping technique was used by Mei et al. (1999) to study the impact pressure on a two-dimensional body. Lu et al. (2000) developed a method for analyzing hydroelastic interaction between a structure and water by solving coupled equations with the boundary element method and the finite element method. Wet deck slamming was studied theoretically by Kvalsvold and Faltinsen (1995) and Faltinsen (1997) using beam models. An initial structural inertia phase and a subsequent free vibration phase were identified. An asymptotic theory showed that the maximum bending stresses are proportional to an effective drop velocity but are not sensitive to the curvature of the wave surface or where waves hit the beam.

In general, a slamming event appears to consist of an initial slamming load arriving phase followed by a vibration phase. The real slamming on the bottom of a high speed craft running in rough seas is a highly random event. The angle between the bottom and the water surface as well as the impact velocity vary every second. Understanding the bottom response under various conditions is thus important. This paper is an attempt to shed some light on this complex problem by analytically studying a simplified model of a bottom panel subjected to a non-uniform pressure distribution traveling at various speeds across the bottom.

In this research, the boat bottom is modeled as a one-dimensional linear elastic Euler–Bernoulli beam. The slamming pressure is modeled during the initial phase as a high intensity peak followed by a lower constant pressure, traveling at constant speed along the beam. When this load reaches the end (chine) of the beam, all load is removed. The beam then continues its deformation as free vibration. The assumption that the load travels at constant speed across the beam in essence implies that the vertical velocity of the boat bottom is constant during the slamming event. Fluid–structure interactions are ignored in this paper, but an added mass term is included in an approximate manner.

The calculations will in the near future be compared to experimental measurements from the Numerette research craft. Since the composite sandwich bottom panels of the Numerette are quite stiff, it appears reasonable to assume that linear-elastic beam theory is valid and that the geometry of the deformed bottom is not significantly different from the undeformed one. Stenius et al. (2013) experimental results indicate that the influence of geometrical nonlinearities on the center deflection is small for stiff glass fiber/foam core sandwich panels.

For the present calculations, inertia effect of the water is simply included as a constant added-mass term. Air entrapment that may have a large influence at lower deadrise angles is ignored. It is assumed that the slamming event consists of an initial slamming load arriving phase followed by a vibration phase. The initial phase was analyzed analytically in a previous paper by Lv and Grenestedt (2013). The equations for the initial phase were solved using a Fourier sine integral transformation in space and a Laplace–Carson integral transformation in time, as done by Fryba (1999). In the present paper the response during the vibration phase, when loads on the beam are neglected, is obtained by solving an eigenvalue problem using separation of variables. The structural response during the vibration phase is presented and compared with the response during the initial phase. Multiple figures show the effect of the slamming load traveling speed on structural response, as well as the effect of the high-intensity pressure peak typically encountered during slamming.

2. Simplified analytical model of slamming, two-step load on beam

The wedge-shaped bottom section of the vessel is partially modeled as a flexible simply supported Euler–Bernoulli beam. Since the lower vibration modes are typically dominant (Faltinsen, 2000), it is most likely sufficient to consider only pure bending of the beam (Euler–Bernoulli kinematics), ignoring shear deformation and rotary inertia (Timoshenko kinematics). Simply supported edges were chosen as a reasonable approximation of the bottom panels of the Numerette research craft; its bottom consists of ten sandwich panels whose cores taper off and vanish by the edges, resulting in a fairly compliant single skin "collar" along the perimeter of each panel. The thin single skin collar is considerably more compliant in bending than the thick sandwich and modeling the edges as simply supported is presumably a decent approximation. Faltinsen (2000) also indicated that an Euler beam may be a satisfactory model to investigate the structural response under slamming load. The transient slamming load $q(x,t)$ is presently modeled as a two-step load with two constant pressures, q_1 and q_2, that move with constant velocity c from one end to the other (Fig. 1). The deflection of the beam is $w(x,t)$, where x $(0 \le x \le L)$ is the position within the beam and t is time. In Fig. 1, L is the length of the beam and l_1 is the length of the high-intensity pressure peak.

It is assumed that the slamming event can be separated into two phases: the slamming load initial phase and the subsequent elastic (free) vibration phase. When the speed of the slamming load is high, a large slamming load will cause high acceleration of the bottom during the initial phase but due to the short time that the load is applied it results in only small deflections but potentially significant transverse velocities at the end of this first phase. The time scale may be short relative to the subsequent vibration phase. The behavior in the second phase is vibration with initial conditions obtained from the first phase. It is a periodic event with a characteristic time scale on the order of the longest natural period of the structure. The slamming load initial phase was analyzed by Lv and Grenestedt (2013) using two different loads, the "two-step load" and the "point-step load". The deflection and the velocity of the beam at the end of the first phase are briefly reviewed in the following sections. They will be used as the initial conditions for the subsequent vibration phase. By using the method of separation of variables, with the initial conditions in the form of a Fourier sine series, the free vibration problem was solved.

2.1. Slamming load initial phase

For the slamming load initial phase, the governing equation is (Lv and Grenestedt, 2013)

$$EI\frac{\partial^4 w(x,t)}{\partial x^4}+\mu^*\frac{\partial^2 w(x,t)}{\partial t^2}=q(x,t) \tag{1}$$

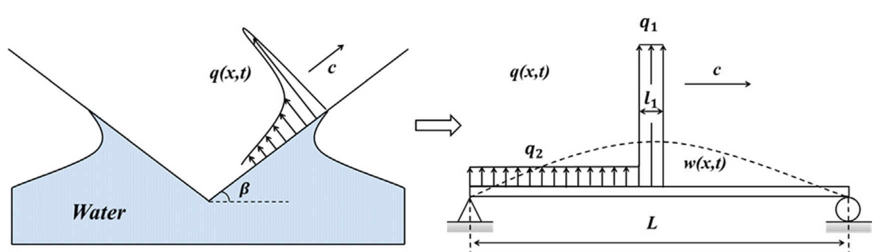

Fig. 1. Left: cross-section of boat during slamming, showing the moving slamming pressure $q(x,t)$. Right: simplified model where the bottom panel is represented by a beam and the slamming pressure $q(x,t)$ as two constant pressures, q_1 and q_2, traveling at a constant speed c.