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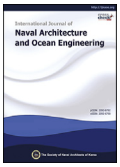

Prediction of the wave induced second order vertical bending moment due to the variation of the ship side angle by using the quadratic strip theory

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Abstract

In this study, the second order bending moment induced by sea waves is calculated using the quadratic strip theory. The theory has the fluid forcing terms including the quadratic terms of the hydrodynamic forces and the Froude—Krylov forces. They are applied to a ship as the external forces in order to estimate the second order ship responses by fluid forces. The sensitivity of the second order bending moment is investigated by implementing the quadratic terms by varying the ship side angle for two example ships. As a result, it was found that the second order bending moment changes significantly by the variation of the ship side angle. It implies that increased flare angles at the bow and the stern of ships being enlarged would amplify their vertical bending moments considerably due to the quadratic terms and may make them vulnerable to the fatigue.

Keywords: Springing; Quadratic strip theory; The second order vertical bending moment; Froude-Krylov force; Hydrodynamic force

1. Introduction

Recently, merchant ships become larger but relatively lighter than before, in terms of the non-dimensionalized displacement, to reduce the transportation costs. In case of container ships recently constructed, for instance, their sizes are capable of carrying more than 20000 TEU and growing continuously. By being larger and lighter, their natural frequencies tend to move down to lower frequencies. Therefore, they are likely to experience resonant vibration, so called springing, more easily in service. This is because their natural frequencies become closer to the excitation frequencies of incoming waves.

The ship's resonant vibration can be induced by the quadratic components of sea waves as well as the first order ones (Tasai and Koterayama, 1976). The amplitude of the response at the resonance produced by the second order components of the sea waves is generally known to be much smaller when compared to that by the first order ones. However in case of ships in severe conditions such as in the Arctic Ocean, the second order resonant vibration could cause significant fatigue problems, because it is proportional to the square of the wave amplitude (Fujino and Yoon., 1985). This situation makes fatigue loads being increased, and consequently shortens the life of ships. Therefore, in terms of the long term response analysis, the accurate estimation of the second order responses should be included, regarding a significant resonant steady-state response. In terms of the fatigue loads, the vertical bending moment would be the primary component. So, in this study the vertical bending moment at midship is of interest.

As ships are enlarged, their bow and stern are flared much because their breadths increase more than their drafts. This shape trend would make the second order vertical bending moment increase due to risen wave loads at the bow and stern. Thus it would be necessary to understand the characteristics of the vertical bending moment for the variation of ship side angle, including the second order components. The ship side

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angle is defined as an angle of a ship side inclined from a vertical line. This study aims to investigate the contribution of the second order terms on the ship's vertical bending moments. The variation of the second order term is introduced by the change of the ship's side angle. In order to make only the second order terms vary, the ship side is allowed to be inclined within slightly above and below the mean water level.

In this study, two ships are chosen; one is an artificial ship with a uniform cross-section and the other is a Flokstra container ship as a practical one. The ships are assumed as Timoshenko beams with free-ends (Bishop and Price, 1979). Fluid forces are applied to the ships as external forces to calculate their responses induced by sea waves. The second order terms of the fluid forces are calculated using the quadratic strip theory that is proposed by Jensen and Pedersen (1979). The second order vertical bending waves are predicted at midship by varying the ship side angle.

2. Theoretical background

In this section, theoretical models used in this study to predict the ship response is explained, regarding the second order terms induced by wave loads. External fluid forces are formulated using a quadratic strip theory, proposed by Jensen and Pedersen (1979), which includes second order terms for the fluid forces (Xia et al., 1998). The second order fluid forces are taken into account by three quadratic parameters. The first parameter is the second order velocity potential for the incident wave, which is obtained from the non-linear free boundary conditions. The second one is associated with a non-vertical side of ship cross-sections, which occurs when the breadth of a ship varies along with the depth about waterline. This variation of the breadth also makes a non-linearity of a restoring force. The last one is a quadratic hydrodynamic coefficient; the variation of the added mass and the damping. Both are dependent on the relative motion between the ship and the wave surface. As a result, the second order hydrodynamic and the Froude−Krylov forces are applied as the external forces in addition to the first order ones.

The structural response of a ship is formulated using a Timoshenko beam theory. The response of the ship is predicted by applying the hydrodynamic and Froude−Krylov force.

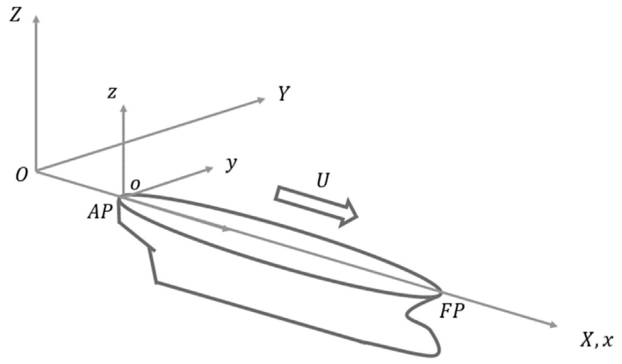

Fig. 1. The coordinate system.

In this study two Cartesian coordinate systems are adopted as shown in Fig. 1. The global coordinate *OXYZ* is fixed with an origin in still water level while the local coordinate *oxyz* is attached on the ship with the origin at the stern of the ship. These two coordinates coincide when the ship is at rest. The ship is assumed to have a forward speed U toward the positive X direction, corresponding to a heading angle of 180°, called the ‘head sea’.

2.1. Quadratic strip theory for fluid force

The fluid force per unit length applied on a ship is formulated using a quadratic strip theory that considers the change of added mass, damping and restoring terms depending on the relative motion between the ship and the wave surface. For a ship with a sectional breadth $B(z,x)$ and draft $T(x)$, this fluid force per unit length is given by

$$F(x,t) = -\left[\frac{D}{Dt}\left\{m(\bar{z},x)\frac{D\bar{z}}{Dt}\right\} + N(\bar{z},x)\frac{D\bar{z}}{Dt} + \int_{-T}^{-\bar{z}} B(z,x)\left.\frac{\partial p}{\partial Z}\right|_{z+w} dz\right], \tag{1}$$

where $\frac{D}{Dt}$ denotes the total derivative with respect to time as $\frac{D}{Dt} = \frac{\partial}{\partial t} - U\frac{\partial}{\partial x}$, $w(x,t)$ is the vertical displacement of the ship and $\bar{z}$ is the relative displacement of $\bar{z} = w - \kappa h$, $\kappa(x)$ is the Smith correction factor, $h(x, t)$ is the wave elevation, $m(\bar{z}, x)$ and $N(\bar{z}, x)$ denote the added mass per unit length and the damping at the water surface respectively, and $p(x, Z, t)$ is the Froude−Krylov pressure. Eq. (1) has the same form as the linear strip theory which contains only the linear terms of the fluid forces (Gerritsma and Beukelman, 1964). In order to take into account the second order terms of the fluid forces, Taylor series expansion is applied to the added mass m, the damping N and the breadth B with respect to the relative motion $\bar{z}(x,t)$ at a mean water level. Applying Taylor series about $\bar{z}$,

$$m(\bar{z},x) = m(0,x) + \bar{z}\left.\frac{\partial m}{\partial \bar{z}}\right|_{\bar{z}=0} + \frac{1}{2}\bar{z}^2\left.\frac{\partial^2 m}{\partial \bar{z}^2}\right|_{\bar{z}=0} + \ldots \cong m(0,x) + \bar{z}\left.\frac{\partial m}{\partial \bar{z}}\right|_{\bar{z}=0} = m_0(x) + \bar{z}m_1(x), \tag{2}$$

$$N(\bar{z},x) = N(0,x) + \bar{z}\left.\frac{\partial N}{\partial \bar{z}}\right|_{\bar{z}=0} + \frac{1}{2}\bar{z}^2\left.\frac{\partial^2 N}{\partial \bar{z}^2}\right|_{\bar{z}=0} + \ldots \cong N(0,x) + \bar{z}\left.\frac{\partial N}{\partial \bar{z}}\right|_{\bar{z}=0} = N_0(x) + \bar{z}N_1(x), \tag{3}$$

$$B(\bar{z},x) = B(0,x) + \bar{z}\left.\frac{\partial B}{\partial \bar{z}}\right|_{\bar{z}=0} + \frac{1}{2}\bar{z}^2\left.\frac{\partial^2 B}{\partial \bar{z}^2}\right|_{\bar{z}=0} + \ldots \cong B(0,x) + \bar{z}\left.\frac{\partial B}{\partial \bar{z}}\right|_{\bar{z}=0} = B_0(x) + \bar{z}B_1(x), \tag{4}$$

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