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Sensitivity of extreme hydroelastic load effects to changes in ship hull stiffness and structural damping

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Abstract

A new hybrid method for the time-domain nonlinear simulation of the hydroelastic load effects and the peak over threshold (POT) method for the calculation of the short-term extreme responses are briefly described and applied to a flexible SL-7 class containership and a flexible liquefied natural gas (LNG) ship. Three stiffness levels, three stiffness distributions and three modal damping ratios are used to study the influence of the hull flexibility and structural damping on the short-term prediction of extreme vertical hydroelastic load effects. The results give justification for some simplified treatment of the first vertical flexible mode in early design stage when structural details are not available.

Keywords: Hydroelasticity; Structural dynamic effects; Wave-induced ship responses; Nonlinear simulation; Extreme load effects; Computational method; Marine engineering

1. Introduction

Hydroelastic effects are much more significant in structural responses than in motions, particularly in ships with high forward speed, big flare, large length and small depth. Several different sources can contribute to the resonance vibration of the ship hull. One is the wave-induced linear force with the energy from the high end of the incident wave spectrum (linear spring). Others are the wave-induced nonlinear forces. They include the slamming force and the double-frequency effect. The former induces transient whipping responses while the latter causes nonlinear springing. The double-frequency effect comes from the quadratic term of the linear velocity potential and the linear term of the second-order velocity potential in Bernoulli's equation for the fluid pressure on the mean wetted surface. However, the slamming and whipping are associated with the rapid change of the wetted surface due to local relative motion. It is the main cause of the vibratory responses of ship hull in severe seas.

Modal superposition has been widely used to account for hydroelasticity since the pioneer work of Goodman (1971), Bishop et al. (1977) and others. However, the total number of required global flexible modes vary from ship to ship and from response to response. It can only be determined by a convergence study. Generally speaking, more modes are needed to represent shear force than to represent bending moments. Similarly, more modes are needed to calculate bending moments at cross sections towards the ship bow and stern than to calculate the bending moment amidships. If large amount of global flexible modes are required, the modal superposition approach is less attractive because it takes too much time to carry out the nonlinear simulation. More importantly, a convergence study should be done for each and every bending moment and shear force. Sometimes it is very difficult to know if they have converged or not.

To overcome this drawback, Wu and Moan (2005) recently presented a hybrid method for the calculation of bending moments and shear forces in ships and other slender marine structures. It is a combination of the

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conventional direct load evaluation for a rigid body and the modal superposition. It still accounts for the dynamic effects in the few lowest global flexible modes but eliminates the need for calculating the quasi-static responses in the higher global flexible modes. It will, therefore, reduce the simulation time. This time reduction is important for any simulation-based prediction of extreme nonlinear responses.

The hybrid method and its implementation PC code wave-induced ship responses (WINSIR) is a further improvement on the theory published earlier by Wu and Moan (1996) and Wu and Hermundstad (2002). There are three unique features in this approach. Firstly, it avoids convergence study and makes the calculation more efficient. Secondly, it uses 2D, 2.5D or 3D velocity potentials to evaluate hydrodynamic coefficients under different circumstances, such as forward speed and slenderness of the ship hull. Most practical nonlinear simulation methods (ISSC, 2000) are confined to the conventional 2D strip theory. Thirdly, the time-domain total nonlinear response is expressed as the summation of the linear response and the nonlinear modification. The linear and the nonlinear modification parts can be validated or calibrated separately. And other nonlinear modification forces can be easily included later on.

The whipping responses depend not only on the slamming force but also on the dynamic characteristics of the first vertical flexible mode, such as natural frequency, structural damping and modal shape. The natural frequency and the modal shape, in turn, are dependent on the longitudinal distributions of mass and stiffness. The ship hull stiffness cannot be obtained accurately at the early design stage even though an experienced naval architect can estimate the longitudinal mass distribution quite well after the general arrangement is determined. Further, there is no reliable theoretical means to calculate the structural damping of the first vertical flexible mode for any particular ships. As a rule of thumb, the modal damping ratio is around 0.01. But it can go as low as 0.005 and as high as 0.02.

In this paper, we briefly describe the hybrid time-domain simulation and introduce the peak over threshold (POT) method as one of the stochastic analysis procedures to predict the short-term nonlinear extreme hydroelastic responses. We then use a SL-7 class containership and a modern liquefied natural gas (LNG) ship as example vessels to investigate the influence of the hull flexibility and structural damping on the short-term prediction of extreme vertical load effects. Three stiffness levels, three longitudinal stiffness distributions and three modal damping ratios are employed in this study in order to justify some simplified way of treating hull flexibility and structural damping and gain knowledge of possible errors it may bring. This simplification is necessary in the early design stage when structural details are not available.

2. Time-domain simulation

In the modal superposition approach, any time-domain hydroelastic response $r(t)$, such as bending moment or shear force, is expressed as an aggregate of dynamic flexible modal responses $p_i^{\mathrm{d}}(t)$,

$$r(t) = \sum_{i=1}^{\infty} c_i p_i^{\mathrm{d}}(t), \tag{1}$$

where c_i are the modal contribution coefficients. If global structural dynamic effects are insignificant in any of the flexible modes, the dynamic modal responses $p_i^{\mathrm{d}}(t)$ reduce to quasi-static ones, $p_i^{\mathrm{q}}(t)$, and

$$r(t) = \sum_{i=1}^{\infty} c_i p_i^{\mathrm{q}}(t), \tag{2}$$

is equivalent to that obtained by the conventional direct response evaluation familiar to naval architects. Since the global structural dynamic effects exist only in the few lowest flexible modes, particularly the first two-node mode, the hydroelastic response can be approximated adequately by

$$\begin{aligned} r(t) &= c_1 p_1^{\mathrm{d}}(t) + \sum_{i=2}^{\infty} c_i p_i^{\mathrm{q}}(t) \\ &= c_1[p_1^{\mathrm{d}}(t) - p_1^{\mathrm{q}}(t)] + \sum_{i=1}^{\infty} c_i p_i^{\mathrm{q}}(t) \\ &= c_1[p_1^{\mathrm{d}}(t) - p_1^{\mathrm{q}}(t)] + r^{\mathrm{rb}}(t), \end{aligned} \tag{3}$$

where $r^{\mathrm{rb}}(t)$ is the response calculated by the conventional approach where the ship hull is regarded as a rigid body. $p_1^{\mathrm{d}}(t)$, $p_1^{\mathrm{q}}(t)$ and $r^{\mathrm{rb}}(t)$ are composed of their respective linear parts and nonlinear modification parts. The linear response is obtained from its frequency-domain counterpart through inverse fast Fourier transformation (FFT). The nonlinear modification comes from the convolution of the impulse response function and the nonlinear modification forces caused by slamming and other components that are not accounted for in the linear theory. Details of this method can be found in Wu and Moan (2005).

When simulating ship responses in the short-term sea states, the irregular incident waves are often described by the modified Pierson–Moskowitz spectrum, also known as the ISSC spectrum, for the design of ships with worldwide operation,

$$S(\omega) = \frac{5}{16}\left(\frac{2\pi}{T_{\mathrm{p}}}\right)^4 \frac{H_{\mathrm{s}}^2}{\omega^5} \exp\left[-\frac{5}{4}\left(\frac{2\pi}{T_{\mathrm{p}}\omega}\right)^4\right]. \tag{4}$$

This wave spectrum represents fully developed sea states. The significant wave height H_{s} and the spectrum peak wave period $T_{\mathrm{p}} = 1.408T_{\mathrm{z}}$ are two independent parameters. T_{z} is the average zero-crossing period.

Eq. (4) shows the wave energy distribution with respect to wave frequency. But it does not give any information about the wave direction or wave spreading. A general