Analysis of Wave Load Combination
Including Slamming

by

Dai Yangshan

August 1985
1. Introduction

It is necessary to estimate extreme sea loads when probabilistic and reliability methods are used to analyse the ultimate strength of ship corresponding to the modes of failure due to yielding or inelastic buckling.

The ship response records taken in full-scale tests show that the vertical stress time history consists of a rapidly varying time history with random amplitude and frequency, oscillating about a mean value. The mean value itself is a weakly time-dependent function. The rapidly varying part includes a low frequency component due to the motion of ship as a rigid body, and a high frequency one due to the impact of the ship as a flexible body on the water, i.e. slamming ("springing" of the flexible ship excited by the energy present in the high frequency wave components is not considered in this paper).

Therefore, the total load on the flexible hull in a seaway can be decomposed into three components

\[ M_{\text{total}} = M_0 + M_B + M_S \]

where \( M_0 \) is the mean value of the total load, \( M_B \) is low frequency wave-induced load, and \( M_S \) is high frequency slamming load.

Unfortunately, the nature of present-day tools and procedures for calculating ship load is such that only separate individual components of the response can be calculated rather than the more relevant combined response /1/. A ship designer is, therefore, faced with the important problem of computing the total load from the individual components.

In addition, for design purposes it is not sufficient only to obtain the data of the combined load. One has to estimate the extreme value of the total load during the number of response cycles expected. This is obvious since the designer has to provide sufficient strength for the "worst condition".
It is the purpose of this paper to explore the combination of load components including slamming and estimate the extreme total load.

Slamming is generally a result of large pitch and heave motions in rough seas. It occurs under certain conditions only—depending on sea severity and on ship speed, heading and ship form. When it occurs the hull suffers large impact fluid load which excited a transient vibratory response in the hull, possibly causing serious local damage along with whipping of the hull. To reduce the danger of heavy damage or high vibratory response, the ship master will tend to change ship speed and heading under normal condition so as to keep the frequency and severity of such slamming load within reasonable bounds, according to his experience.

In view of the transient characteristics of slamming response and the practical operation of a ship in rough seas, it is, in the author's opinion, suitable to adopt short-term prediction in head seas and in one or several severe design sea states for computing ultimate strength of the hull including slamming response.

The period of time of short-term prediction is usually from 30 minutes to several hours, during which the mean value in equation (1) can be considered as a constant.

Owing to the nonlinear relation between slamming response and wave height, it is suitable to combine response components in time domain.

The time histories of the rigid body motion and low frequency wave-induced response for the ship in a seaway are calculated by the summation of responses obtained based on linear strip theory to individual regular sinusoidal wave components /2/. Although small variations may exist in the linear theoretical methods, much larger differences occur in the way the transient excitation is defined /3/. After the relative motion between the hull and the wave surface is determined, the transient excitation can be evaluated whenever a slam is encountered. The
slamming response is thus superimposed on the time history of the wave-induced response to obtain the rapidly varying part in the total response of the flexible hull.

From a sufficiently long time history of rapidly varying response (usually 30 minutes), the extreme value of this response in a required time period can be estimated based on the principles of extreme value statistics.

Adding the extreme value to the mean value in equation (1), finally, the extreme total load is determined.

As an example, the method presented in this paper is used to predict the combined load and its extreme value for the S-175 container ship travelling in a specially designated long-crested irregular head seaway. The theoretically predicted results are compared with those of the model experiment made at China Ship Scientific Research Centre (CSSRC) by Sen Jinwei et al. /4/.

2. Model of a seaway

An irregular sea surface in deep water can be represented as the sum of a large number of regular waves, each component having a deterministic amplitude $\xi_a$, frequency $\omega$, wave number $k$, statistically independent uniformly distributed phase angle $\varepsilon$ ($0 \leq \varepsilon \leq 2\pi$) and being a solution of the linearised hydrodynamic equation for deep water waves. To a ship travelling with forward speed $v$ in an irregular head seaway, the elevation of wave surface at any position $X_b$ on the hull is (see Fig. 1)

$$\xi_i(X_b, t) = \sum_{j=1}^{m} \xi_{aj} e^{i(\omega_{ej}t + k_j X_b + \varepsilon_j)} \quad (2)$$

where the real part of the expression is taken, $\omega_{ej}$ is the frequency of encounter of the $j$th wave given by
\[ \omega_{ej} = \omega_j + \frac{\omega_j^2}{g} \nu . \]  

The amplitude of the \( j \)th wave, \( \xi_{aj} \), is determined from the wave spectrum \( S_\xi(\omega) \) as follows

\[ \xi_{aj} = \sqrt{2 S_\xi(\omega_j) \Delta \omega_j} \]  

Equation (2) represents a typical realisation of the surface wave profile of the long-crested unidirectional seaway defined by a given wave spectrum when particular values are assigned to the quantities \( \xi_j \). By changing the values of the component phase angles, \( \xi_j \), other typical realisations are constructed. It can be proved that \( \xi_i(x_b, t) \) is an ergodic random process in the mean, mean square and auto-correlation function statistics.

Fig. 1 Coordinate system and notations
3. Hydrodynamic forces

The hydrodynamic forces on the hull consist of restoring, damping and inertia terms.

It is assumed that the vertical displacement of the ship's centre of gravity is $z$ and the pitch angle with respect to horizontal plane is $\psi$ when a ship travels in a regular head wave given by

$$\zeta = \zeta_a e^{i(\omega t + k x_b)}$$

(5)

By using the modified strip theory of Gerritsma and Beukelman /5/ and taking into account the non-vertical sides of the ship, the real hydrodynamic forces per unit length of the hull can be assumed in the form

$$F_{1r} = -g g (A' - A'_r)$$

$$= F_1' + g g \left[ A'_r - A' + 2y_w (z-x_b \psi - \zeta^*) \right]$$

$$F_{2r}' = -N'_r \frac{D}{Dt} (z-x_b \psi - \zeta^*)$$

$$= F_2' - (N'_r - N') \frac{D}{Dt} (z-x_b \psi - \zeta^*)$$

$$F_{3r}' = -\frac{D}{Dt} \left[ m'_r \frac{D}{Dt} (z-x_b \psi - \zeta^*) \right]$$

$$= F_3' - \frac{D}{Dt} \left[ (m'_r - m') \frac{D}{Dt} (z-x_b \psi - \zeta^*) \right]$$