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Spectral fatigue analysis of a ship structural detail – A practical case study

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ABSTRACT

The fatigue life of a ship structural detail is calculated by using a spectral approach. The wave-induced vertical and horizontal bending moments, two base vessel loading conditions and the non-operating time have all been taken into account in the spectral fatigue damage calculation. The predicted fatigue life value by using the spectral approach is compared with the one calculated by using the IACS R 56, and various factors inducing uncertainties in the spectral method are further identified and investigated. Finally, recommendations on how to choose the specific parameters and how to model the random wave environment in the spectral approach are outlined.

1. Introduction

Fatigue failure of a structure is caused by repeated loads. In the design and analysis of some ship structural details such as the connections of deck longitudinals to transverse webs, the ocean waves are considered to be the main source of fatigue demand. The cyclic wave-induced hull girder stress, if not kept in certain limits, could cause fatigue failure of local as well as global structures. In order to calculate the fatigue life of a ship structural element, the information of the stress of the structural element is required. Depending on how the stress distribution is determined, the fatigue assessment technique can be categorized as the "Simplified method" [1], the "Spectral-based method" [1] and the "Deterministic method" [1]. In the "Simplified fatigue assessment method", the long-term stress range distribution of a ship structural element is assumed to follow the Weibull probability distribution [2–4]. While this is a simplified fatigue assessment technique, some engineering judgement is still required in applying the method to actual design (e.g., in deciding the Weibull shape parameter and in choosing basic design *S*–*N* curves).

The "Spectral-based fatigue analysis" is a direct calculation method. In the spectral approach, various orders of spectral moments of the stress process are obtained by performing a first principles based seakeeping analysis (i.e. finding the motions and related quantities of a vessel subjected to a sea state) [5] and subsequent mathematical manipulations. Using the spectral moments, the Rayleigh probability density function describing the short-term stress range distribution, the zero-up crossing frequency of the stress response and the spectral bandwidth parameter used in calculating the cycle counting correction factor for a wide band random process are then calculated. The total fatigue damage of a structural element is calculated by adding up the short-term damages over all the applicable sea states [5,6] in a specific wave scatter diagram. Therefore, the spectral method can account for various sea states as well as their probabilities of occurrence.

The "Deterministic method" [1,3,7] may be considered as a "Simplified" version of the spectral method. The main simplification involves how wave-induced load effects are characterized. In the spectral approach, short-term wave spectral formulations (such as the Pierson–Moskowitz wave elevation spectrum) are used to characterize the expected energy in individual sea states. In the deterministic approach, a sea state is simply characterized by using a deterministic wave height and period. Sound engineering judgement based on the designers' practical experience is needed in order to properly select the collection of the deterministic waves that will be sufficient to establish the fatigue demand that the structure element will experience. Therefore, the spectral-based fatigue analysis is preferred as long as the designers have enough time and computational means to do so.

In applying the "Spectral-based method" to the fatigue damage calculation of marine structures, a noticeable work is that of Kukkanen and Mikkola [8]. These authors have applied the spectral fatigue analyses in the ISSC comparative study of a hatch cover-bearing pad on a Panamax container ship. In their study, an assumption was made that the vertical wave bending moment is the only important cyclic loading that induces stresses on the bearing pad. The predicted fatigue life of the structural detail

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Nomenclature

m	fatigue strength exponent	A	fatigue strength coefficient
N	number of cycles to failure	S	a constant amplitude stress range
n	the number of cycles applied to the structure	D	cumulative fatigue damage ratio
M	total number of considered stress range intervals	σ_i	standard deviation of the stress process
T	design life of a ship in seconds	p_i	probability of occurrence of the sea state
f_{0i}	zero-up crossing frequency of the stress response	m_0	spectral moments of the stress process
m_1	spectral moments of the stress process	m_2	spectral moments of the stress process
m_4	spectral moments of the stress process	ε_i	bandwidth parameter
υ	spectral width parameter	β	regularity factor
λ	cycle counting correction factor	μ_i	endurance factor
ω	encounter frequency	H_s	significant wave height
T_z	zero-up crossing period	θ	heading angle
V	the vessel speed	α	the spreading angle
I_{yy}	midship section moment of inertia	ε_v	phase of the stress process

was compared with the fatigue life predictions of the Classification Societies, and a conclusion was drawn by these authors that their methodology in spectral fatigue analysis includes rather significant uncertainties.

It should be noted that a sailing ship will frequently encounter quartering waves, and thus is subjected to horizontal as well as vertical wave bending moments. Consequently, the horizontal and vertical wave bending stresses should all be taken into account in the spectral fatigue analysis of some ship structural details. Some authors [9–12] have already considered the effects of multi-axial random loading and stress decomposition in the spectral fatigue calculations of general structural steel as well as marine structures. In particular, the combined effects of vertical as well as horizontal hull girder bending moments were all considered in Xue et al. [12] in their spectral fatigue analysis of longitudinal stiffeners of oil tankers and container ships. Several examples in their study show the applicability of their methods to real ship structures. However, the authors admitted that the method still needs to be calibrated because of the simplifying hypotheses introduced in the loading conditions, and it is noted that only one base vessel loading condition (or the most severe one of the stress parameters in multiple base vessel loading conditions) is considered in the spectral fatigue analysis in Xue et al. [12]. In the present work, a case study will be performed on the fatigue life prediction of a ship structural detail in order to identify various factors inducing uncertainties in spectral fatigue damage calculations. The wave-induced vertical and horizontal bending moments and more than one base vessel loading condition will all be taken into account in the ship structure spectral fatigue analysis. The influences of using different cycle counting correction factors and different spectral bandwidth parameters for a wide band random process in the spectral fatigue damage calculation will be studied. Finally, the effect of directional spreading in the ship structural detail spectral fatigue analysis will also be investigated.

2. Theoretical background of spectral-based fatigue analysis

2.1. The fatigue damage equation in a specific sea state

Spectral fatigue analysis is based on S–N curves and Palmgren–Miner's linear damage summation rule. The fatigue strength of structural components is described by using the characteristic S–N curve [13]

$$NS^m = A \tag{1}$$

where m and A, determined empirically from fatigue experiments, are the fatigue strength exponent and fatigue strength coefficient, respectively. N is the number of cycles to failure for a constant amplitude stress range S. It is accepted practice that the fatigue damage experienced by a structure from each interval of applied stress range can be obtained as the ratio of the number of cycles (n) of that stress range applied to the structure to the number of cycles (N) that will cause a fatigue failure at that stress range, as determined from the S–N curve. The total or cumulative fatigue damage (D) is the linear summation of the individual damage from all the considered stress range intervals. This approach is referred to as the Palmgren–Miner Rule. It is expressed mathematically by the equation [3]:

$$D = \sum_{i=1}^{M} \frac{n_i}{N_i} \tag{2}$$

where D is the damage ratio, n_i is the number of cycles the structure endures at stress range S_i, N_i is the number of cycles to failure at stress range S_i, as determined by the appropriate S–N curve, and M is the total number of considered stress range intervals. Fatigue failure is predicted to occur when the cumulative damage D exceeds unity. In the following, the stress range is expressed in terms of a probability density function for an individual sea state characterized by a specific significant wave height. Assuming that wave-induced bending stress variation in a ship structural element in a specific sea state is a narrow band Gaussian random process [14], the peak values of the stress ($\tilde{S}_i$) has a Rayleigh probability density function $g_i(\tilde{S}_i)$ which is [15]:

$$g_i(\tilde{S}_i) = \frac{\tilde{S}_i}{\sigma_i^2} \exp\left[-\frac{\tilde{S}_i^2}{2\sigma_i^2}\right] \tag{3}$$

where σ_i is the standard deviation of the stress process in the specific sea state, and the method for calculating this standard deviation will be explained later. If T denotes the design life of a ship in seconds, then the number of stress cycles whose peak values lie between $\tilde{S}_i$ and $\tilde{S}_i + \Delta\tilde{S}_i$ is [16]:

$$n_i = f_{0i} p_i T g_i(\tilde{S}_i) \Delta\tilde{S}_i \tag{4}$$

where p_i is the probability of occurrence of the individual sea state characterized by a specific significant wave height, f_{0i} is zero-up crossing frequency of the stress response in Hz [14],

$$f_{0i} = \frac{1}{2\pi}\sqrt{\frac{m_2}{m_0}} \tag{5}$$

where m_0 and m_2 are spectral moments of the stress process, and the methods for calculating these moments will be explained later. The damage ratio in the specific sea state can then be calculated as: