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An innovative block partition and equivalence method of the wave scatter diagram for offshore structural fatigue assessment

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ABSTRACT

The fatigue assessment plays an increasing role for the offshore structural safety. Many fatigue assessment methods have been developed for this purpose. Among those methods, the time domain method is regarded as the most accurate method but less adopted in practice due to time consuming. In order to improve the efficiency of the time domain method, an innovative block partition and equivalence method of the wave scatter diagram is developed for offshore structural fatigue assessment. After the wave scatter diagram is partitioned into several blocks, the newly developed method, involves determination of the equivalent wave height, wave period and occurrence probability of the representative sea states based on modified energy equivalent principle. The equivalent wave period of the representative sea state is calculated via the spectral moment formula in which the equivalent spectral moments of zero and second order are obtained based on the weighted averaging principle. Combining with the determined wave period, the equivalent significant wave height can be determined by reversing the wave spectrum integral formula, where the equivalent wave energy of a divided block of the wave scatter diagram is modified by introducing a factor to compensate the effect of low- and high-amplitude cycles fatigue damage. The equivalent occurrence probability is equal to the summation of the original sea states' occurrence probability within the divided block. The developed method has the advantage of preserving the stochastic characteristics of the short term sea states within the divided block during determining the representative sea state. At the same time the newly developed method has no limitation on block partition and can be applied on different offshore structure. Two structural models, a fixed mono-pile platform and a floating semi-submersible platform, are demonstrated in the numerical examples. Results indicate that the newly developed method is robust, computationally affordable, and accurate within engineering expectations.

1. Introduction

The offshore platforms are designed to resist random loading which may lead to significant fatigue damage on structural components, therefore the fatigue life is a design-driving criterion for the offshore structure. To estimate the fatigue damage of offshore structure, the linear fatigue damage cumulative rule was first proposed by Palmgren and Miner [1]. Based on this rule, many kinds of fatigue assessment methods had been developed such as deterministic method, spectral based method and time domain method combined with rain-flow counting technique [2,3]. Among those methods, the deterministic method just utilizes a regular wave which generated from characteristic wave parameters to represent the sea state and ignored its stochastic characteristic completely [4]. This simplification will result in underestimating the structural fatigue damage in some extent. Different from the deterministic method, the spectral based method takes the stochastic nature of sea state into consideration by utilizing wave spectrum to depict its energy distribution, but it can hardly properly handle the nonlinear effects for it assumes the load and the response are linear system and the structural stress response to a given sea state is considered to be a random narrow banded stationary process that follows Rayleigh distribution [5]. It should be noted that the load and the response are not linear system in most cases and the structural stress response to a given sea state is a wide banded process if the nonlinear effects are taken into consideration. So it will underestimate structural fatigue damage if the narrow banded assumption is adopted directly. Generally, the wide banded correction factor is introduced to reduce wide banded influence [6–8]. For the time domain method, the fully coupled dynamics analysis is adopted

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to obtain structural stress response and the rain-flow counting technique is used to count the stress ranges and corresponding cycle numbers. Therefore, this method can take nonlinear effects into consideration adequately and is regarded as the most accurate method among these methods which based on fatigue curve [9]. However, the fully coupled dynamics analysis is rather complicated and must be conducted for every sea states within the wave scatter diagram, so the time domain method is time consuming and usually applied to scenarios with strong nonlinearity condition that the deterministic method or spectral based method is not suitable, such as mooring lines and risers fatigue damage assessment.

To improve the efficiency of the time domain method, a common practice is to lump several sea states into a smaller number of manageable blocks and the representative sea states are adopted to replace the original sea states within the blocks to estimate the structural fatigue damage. In this way, the number of sea states used for fully coupled analysis is significantly reduced and a lot of computation time can be saved. Generally, the wave scatter diagram is adopted to depict a long term wave condition and it is typically delineated by the joint statistic of the significant wave height, the up-crossing period and the occurrence probability. Therefore, the key issues of the block equivalent method are how to determine those characteristic parameters. Several block equivalent method have been developed. The DNV standard [10] specified that the representative sea state of a partitioning block is one sea state selected from the divided block which can contribute a greater fatigue damage than those original sea states within the block and the occurrence probability of the representative sea state was the summation occurrence probabilities of all original sea states within the partitioning block. Because it is difficult to ascertain which sea state can contribute to a conservative result, the representative sea state selected from the block may generally be much larger than needed and the overestimation level of fatigue damage is hard to evaluate [11]. To avoid determining the representative sea state in random, Sheehan [12] proposed a criterion for determining representative sea state from the divided blocks. Following the criteria, the maximum significant wave height in the divided block is selected as the significant wave height of the representative sea state, and the period is equal to the weighted average period of the original sea states within the divided block. Similar with DNV standard recommended method, this method overestimated the fatigue damage as well. To improve the accuracy of assessment, some block equivalent methods which are limited to block partitioning had been developed. In some methods, the wave height distribution is keep unchanged and the wave period of the representative sea state can be determined based on averaging of wave frequencies principle [13] or averaging of wave periods principle [14]. For a given significant wave height, the associated period can easily be obtained. However, the influence of the structural dynamics is disregarded for the individual wave frequencies or wave period. Burton [15] had developed a lumping block equivalent method which can takes the structural effect into consideration. This method kept the wave period distribution unchanged and calculated the associated wave height based on the assumption that fatigue loads are proportional to the occurrence probability and the mth power of the significant wave height. The ‘m’ is the fatigue curve slope. However, the method was only suitable when the wave inertia force was in dominance. This block equivalent method was adopted by Jia [16] to study the wave induced fatigue damage on offshore structure. In his research paper, the ‘m’ was equal to 3 and the period of the representative sea state was calculated based on the weighted average principle. To further improve the assessment accuracy of the block equivalent method, Passon and Branner [17] developed a novel method to determine the representative sea state. In this method, the unit fatigue damage matrix was first calculated. Then, keeping the fatigue damage distribution and wave height or wave period unchanged, the associated wave period or wave height was calculated by means of interpolation technique. Compared with other methods, this method can estimate fatigue damage more accurate, but limited by the complexity procedure. Low and Cheung [11] developed a multi-peaked third-order asymptotic approximation method which can produce high precise fatigue damage assessment. But the implement procedure of this lumping block equivalent method was rather complicated. Du et al. [9] simplified Low & Cheung’s method, and make it easy to implement. However, the method was still sensitive to wave scatter diagram and offshore structures. Form the literature review one can see that the existing methods on block lumping block equivalence have disadvantages, including significant overestimation of the fatigue damage, lack of theoretical motivation, severe sensitivity to block partitioning, and no robustness to wave scatter diagram and/or offshore structures. There is still a great need to develop an efficient lumping block and equivalence method for accurately assessing the fatigue damages of offshore structures. And it is more interesting and expecting to develop an equivalent method which has robustness to the block partition, and is applicable to a variety of offshore structural types such as fixed and floating platforms.

This study develops an innovative block partition and equivalence method of the wave scatter diagram to improve the efficiency of time domain fatigue assessment for offshore structure. The basic idea of the developed method is to use the energy equivalent principle to determine the equivalent wave parameters of the partitioned block. With this energy equivalent principle, the total wave energy, summed over each sea state within the partitioned block, is equal to the energy of the equivalent wave after the block is represented by an equivalent sea state. In this developed method, the characteristic period, significant wave height and the occurrence probability of the representative sea state which associated with the divided blocks are determined from the modified energy equivalence principle. The equivalent period of the representative sea states is calculated via a spectral moment formula and the equivalent zero and second order spectral moments involved in the formula are calculated based on the weighted averaging principle. In conjunction with the determined period, the significant wave height is determined by theoretically or numerically inversing the wave spectrum integral formula, where a correction factor of equivalent wave energy is introduced to consider the influences of low amplitude cycles fatigue damage and of the high amplitude cycles fatigue damage. The occurrence probability is equal to the summation of the occurrence probability of original sea states within the divided block. Because the equivalent wave parameters of the representative sea state are determined via the spectral moments based on equivalent energy distribution, the newly developed method has the advantage of preserving the stochastic characteristic of the short term sea state during determining the representative sea states. Furthermore, the developed method has no limitation on block partition and can be applied on different offshore structural fatigue assessment. For verifying the accuracy and effectiveness, also for studying the robustness, of the developed method, two numerical models and two wave scatter diagram are provided in this paper. To this end, the reminder of this paper is organized as follows. In Section 2, the preliminaries of time domain fatigue assessment method are introduced briefly. Details of the developed block partition and equivalence method are presented in Section 3. In Section 4, a series of numerical study for two structural models and two wave scatter diagram are given to demonstrate the effectiveness and robustness of the developed method. Finally, the conclusions drawn from this work are presented in Section 5.