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A novel hybrid frequency-time domain method for the fatigue damage assessment of offshore structures

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ABSTRACT

The cumulative fatigue damage analysis plays a key role during offshore structural design. Although many methods have been developed, there is not yet a method that can predict fatigue life effectively and efficiently. A hybrid frequency-time domain method, which can be considered to be a hybrid of the spectral method and the time-domain analysis method, is proposed in this paper. In the newly developed method, the spectral density function of structural stress is first obtained in the frequency domain and then converted into a stress time history by using an improved signal conversion approach. With this methodology, the fatigue damage of structures can be assessed easily with the rain-flow counting method and Palmgren–Miner rule. In contrast with the traditional fatigue damage assessment methods, the Rayleigh distribution assumption of the stress range, which is associated with narrow band random process and is commonly used in the spectral method, is not required for the hybrid frequency-time domain method. At the same time, the newly developed damage assessment method can avoid the complicated coupled dynamic analysis used in the time domain method, greatly reducing computation time. To verify the effectiveness of the present method, a case study for a monopile platform was conducted. Numerical results illustrate that the fatigue life assessed by the new method is more accurate than that by the spectral method, and the new method takes much less computational time than the time-domain method.

1. Introduction

For offshore structures, fatigue damage is one of the main types of damage, and it has attracted much attention from many scientists and engineers. Cumulative fatigue damage, which was originally suggested by Palmgren and later developed by Miner, is an old but not yet well-resolved problem (Wirsching et al., 2006). In practice, the spectral method, the deterministic method and the time-domain analysis method (Ariduru, 2004) based on the rain-flow counting rule (Matsuishi and Endo 1968; Rychlik, 1987) are commonly used.

The spectral method is a stochastic approach based on several assumptions. Load analysis and the associated structural analysis are linear, and the short-term stress variation in a given sea state is considered to be a random narrow banded stationary process that follows the Rayleigh distribution. However, the Rayleigh distribution method only relates to narrow band random processes whose bandwidth parameters are less than 0.5 (Gao and Moan, 2008). Generally, the stress response of offshore structures under the combined action of wind, waves and currents is wide-banded (Hu et al., 2009). For a wide-band random process, the Rayleigh distribution for the peak response values will result in a conservative estimation of the fatigue damage (Low, 2011). Therefore, many scientists, including Rice (1944), Wirsching (1980), Benasciutti and Tovo (2005), Braccesi et al. (2005) and Kim et al. (2007), have done extensive work to find a relevant spectral bandwidth correction parameter to calculate the cycle counting correction factor for a wide-banded process. The cycle counting correction factor is used to reduce the conservatism due to the narrow band assumption. In general, formulas for the factor are always very complicated, and they are not always very effective. For a random processes with a bandwidth parameter greater than 0.5, when considering the bandwidth correction parameter, the spectral method would also, on average, overestimate the fatigue damage. The larger the bandwidth parameter is, the grosser the overestimate will be (Gao and Moan, 2008).

The deterministic method may be considered to be a 'simplified' version of the spectral method (ABS, 2003). The main simplification involves how the wave-induced load effects are characterized. In the spectral method, a relationship to characterize the expected energy in an individual sea state is employed (such the Pierson-Moskowitz or JONSWAP spectral formulations) with a 'scatter diagram' that describes the expected long-term probability of occurrence information for sea-states at a platform's

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installation site. In the deterministic method, every single sea state in the wave scatter is simply characterized using a deterministic wave height and period. Nevertheless, this method neglects the stochastic nature of sea waves.

In the time-domain analysis method, coupled dynamic analysis in time domain is employed. It is therefore able to consider the effects of non-linearity adequately during the fatigue damage assessment. The accuracy of the fatigue damage prediction is benchmarked against the result from the time-domain analysis along with its associated rain-flow counting technique (Low, 2011). However, the calculation procedure of the time domain analysis is quite complicated and requires a long computational time. It is mainly applied to scenarios with strong nonlinearity, such as the fatigue analysis of pipelines and risers due to wave-induced forces, TLP tethers and Spar structures due to low frequency motions, and so on.

To improve the efficiency and effectiveness of fatigue damage assessment, some other methods have been developed. Hu (1991) introduced an efficient and accurate method to characterize a long-term random ocean wave by using 'probabilistic' wave spectrum. Pillai and Meher Prasad (2000) developed a methodology for estimating the reliability of fixed offshore structures with respect to fatigue and extreme stress, and the analysis results indicated that the methodology was useful for planning in-service inspections. Xiao and Yamada (2004) presented a new method for evaluating geometric or structural stress in welded constructions. Their method was based on the computed stress value 1-mm below the surface in the direction corresponding to the expected crack path. The validity of the method is further verified by analyzing fatigue test results for several typical welded joints reported in the literature. Drummen et al. (2009) proposed an approach for applying response conditioned wave methods to long-term nonlinear fatigue analyses and investigated their accuracy and efficiency. Low (2010) and Low and Cheung (2012) devised an accurate method for calculating the fatigue damage in a bimodal Gaussian process and a novel customized approach adopting a multi-peaked third-order asymptotic approximation. Zhao (2012) developed an affordable and feasible method with moderate accuracy to realize fatigue reliability assessment and life prediction, including a super long life regime (SLLR). Availability and feasibility of the present method are validated by a successful application on a railway axle steel. However, most of these assessment methods have complex expressions, which add to the difficulties of application in actual design, and they can only be applied to specific situations. In addition, some of these new methods do not have sufficient efficiency.

From the above description, one can see that the traditional methods and several new ones for fatigue damage assessment all have disadvantages. The spectral method and deterministic method are not accurate enough, and the deterministic method cannot take the stochastic behavior of sea waves into consideration. The time-domain analysis method is quite time-consuming. The new methods are always complex but not sufficiently efficient.

The primary objective of this paper is to develop a new method to make fatigue assessment of offshore structures more effective and efficient. This newly developed method, named the hybrid frequency-time domain analysis method, is a combination of the spectral method and time-domain method. The key feature of this method is that the power spectral density function of structural stress is first obtained in the frequency domain and then converted into a stress time history by using an improved signal conversion approach. After that, fatigue life prediction can be assessed easily with the rain-flow counting method and Palmgren-Miner rule. The novelty of this method is due to the effective combination of the first half part of the spectral method and the latter part of the time domain method, where an improved signal conversion algorithm is adopted as the bridge between the frequency domain and time domain. Our damage assessment method possesses several advantages. The Rayleigh distribution assumption for the stress range, which is associated with narrow band random processes and is commonly used in the spectral method, is not required for the hybrid frequency-time domain method. At the same time, our damage assessment method can avoid the complicated coupled dynamic analysis used in the time domain method, greatly reducing computation time. To this end, the remainder of this paper is organized as follows. In Sections 2 and 3, the preliminaries of fatigue analysis and the traditional fatigue assessment methods are introduced, respectively. Details of the proposed hybrid frequency-time domain method are presented in Section 4. In Section 5, a numerical example of a monopile platform is given to demonstrate the effectiveness of the new method. Finally, the conclusions drawn from this work are presented in Section 6.

2. Preliminaries of fatigue analysis

In this section, the preliminaries of fatigue analysis, including the rainflow counting method, S-N curves and Palmgren–Miner rule, are introduced briefly.

2.1. Rainflow counting method

Cycle counting is used to summarize the irregular load-versus-time histories (often lengthy) by providing the number of cycles of various sizes occurring in the time-domain analysis method. The definition of a cycle varies with the methods of cycle counting including level-crossing counting, peak counting, simple-range counting, range-pair counting, rainflow counting and so on. Among these cycle counting methods, the rainflow counting method (RFC), which was first proposed by Matsuishi and Endo (1968), is based on the principle of hysteresis due to the random variation of loadings and ignores the sequence of stress series. Furthermore, the RFC is capable of identifying stress range cycles associated with the low frequency (LF), wave frequency (WF) and high frequency (HF) components. Many practical cases and experiments indicate that the RFC leads to the best estimators for fatigue damage (Dowling, 1971).

2.2. S–N curves

Stress–life (S–N) curves based on the results of experiments can be used for calculating nominal stress fatigue lives (ABS, 2003). Fig. 1 shows a typical two-segment S–N curve.

$$N = AS^{-m} \quad (1)$$

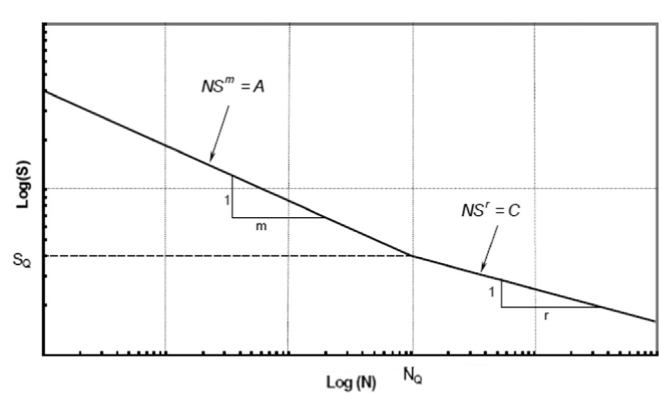

Fig. 1. Two-Segment S–N Curve.