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Fracture mechanics analysis for a mooring system subjected to Gaussian load processes

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ABSTRACT

An investigation on the fracture mechanics (FM) analysis using various load combination methods for a mooring system subjected to Gaussian load processes is conducted in this paper. Low frequency (LF) and wave frequency (WF) tensions of mooring lines are predicted by a frequency-domain analysis taking into account environmental effects including wind, wave and current. The LF and WF load processes are regarded as two random processes. The narrow-band method, general wide-band methods (Dirlik method and Tovo and Benasciutti method), and dual narrow-band methods (Jiao and Moan method, Fu and Cebon method and modified Fu and Cebon method) are used for predicting the combined load induced by LF and WF motions in the FM analysis. A comparison between mooring fatigue lives predicted by the FM analysis using these load combination methods is performed and the results show that the FM analysis based on the narrow-band method generally offers the most conservative fatigue life prediction and the difference of fatigue lives of mooring chains estimated based on general wide-band methods and dual narrow-band methods is not significant. However, in some cases, the FM analysis based on Dirlik method, Jiao and Moan method, Fu and Cebon method or modified Fu and Cebon method even provides more conservative results compared with the narrow-band method.

1. Introduction

Metal fatigue is one of primary failure modes of offshore mooring systems. In the design phase, most frequency-domain fatigue analyses [7] for offshore mooring systems subjected to Gaussian load processes were performed using the Palmgren-Miner's rule and T-N/S-N curves [11,26] and these practices have been widely accepted by offshore design codes, i.e. [2,9] and Benasciutti and Tovo [5], ISO 19901-7 [13], where narrow-band [3] and wide-band load combination methods [25] are suggested for predicting the combined loads induced by low frequency (LF) and wave frequency (WF) motions in mooring fatigue analysis for an offshore mooring system.

The narrow-band method [3] was developed based on the work of Rice [22] and it estimates fatigue damage correlating with the spectral density function of the load process. This method is generally conservative and may significantly overestimate the actual fatigue damage [2] when the Palmgren-Miner's rule and T-N/S-N curves are used to predict fatigue damage.

Early attempts to predict the fatigue damage induced by wide-band were made by Wirsching and Light [25], in which a correction factor between narrow-band and wide-band fatigue damage according to the fatigue strength exponent of the S-N curve and irregularity factor of load process was suggested. Dirlik [8] approximated the probability density function of the amplitude of cycles in a wide-band load process as the sum of an exponential distribution function and two Rayleigh distribution functions and a fitting formula for wide-band fatigue damage prediction was then proposed. Lutes et al. [16] and Larsen and Lutes [15] applied single-moment spectral method in fatigue analysis for a structure subjected to wide-band load processes and a comparison between the method and the method of Wirsching and Light [25] was made. Tovo [24], and Benasciutti and Tovo [4] attempted to present fatigue damage by the weighted linear combination of a narrow-band fatigue damage and a range counting damage intensity.

A special case of wide-band spectrum is called dual narrow-band spectrum and its spectral density function is the summation of two narrow-band frequency components. This type of the spectrum is characterised by two well-defined loading frequencies and it is a typical example of the load responses observed in offshore mooring systems. Jiao and Moan [14], and Fu and Cebon [10] proposed approximate formulae to predict fatigue damage of structures subjected to a dual narrow-band spectrum. Benasciutti and Tovo [5] compared the two formulae and some modifications to Fu-Cebon method was suggested.

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This paper aims to investigate the fracture mechanics (FM) analysis using various load combination methods for a mooring system subjected to Gaussian load processes. LF and WF tensions of mooring lines are predicted by a frequency-domain analysis taking into account environmental effects including wind, wave and current. The LF and WF load processes are regarded as two random processes. The narrow-band method, general wide-band methods including Dirlik method [8] and Tovo and Benasciutti method [4], and dual narrow-band methods including Jiao and Moan method [14], Fu and Cebon method [10] and modified Fu and Cebon method [5], are used for predicting the combined load induced by LF and WF motions in the FM analysis. A comparison between these methods to predict mooring fatigue life using the FM analysis is performed.

2. Mooring line tension

A mooring system is a set of mooring lines to hold a structure against environmental forces. The function of the mooring line tension T normally can be written as:

$$T = T_M + T_D \tag{1}$$

where T_M is the mean tension due to the pretension and mean environmental loads, T_D is the dynamic tension due to dynamic environmental loads, which is usually taken as a combination of LF and WF tensions.

2.1. Quasi-static low frequency (LF) tension

A quasi-static analysis method is used for evaluating the LF tension of a mooring system in which the LF tension is taken into account by vessel offsetting induced by the second order waves and wind dynamics. In this approach, dynamic effects associated with mass, damping and fluid acceleration on the mooring lines are neglected.

In a quasi-static analysis, the tension at the fairlead is assumed to depend only on the horizontal distance (x) and vertical distance (z) from the touch down point of the top end as shown in Fig. 1. The tension T can be expressed as [12]:

$$T = T(r) \tag{2}$$

where $r = (x,z)$ is the distance vector from the anchor point to fairlead and T can be solved by:

$$T(l) = T_H + wz \tag{3}$$

$$l = \frac{T_H}{w}\sinh\left(\frac{xw}{T_H}\right) \tag{4}$$

where T_H is the horizontal tension force at fairlead, w is the unit mooring line wet weight, and l is the mooring line length of suspended section.

2.2. Dynamic analysis for wave frequency (WF) tension

The variation in mooring tension caused by the first order wave frequency motions is calculated by a dynamic method. In this approach, the mooring line is modelled as a multi-degree-of-freedom dynamic system:

$$M_a\frac{d^2x}{dt^2} + C\frac{dx}{dt} + K_s x = F_{static} + F_{WF} + T \tag{5}$$

where x is the displacement vector. M_a, C and K_s are matrices of mass, damping and stiffness, respectively. F_{static} is the static load, F_{WF} the first order wave load, T the tension force from the mooring system.

3. Combination of LF and WF tensions

Processes of LF and WF mooring line tensions are regarded herein as two independent narrow-band Gaussian load processes, namely $X_L(t)$ and $X_W(t)$, in which $X_L(t)$ is a low frequency process and $X_W(t)$ is a high frequency process. $X(t)$ is defined as the combined process of $X_L(t)$ and $X_W(t)$ and it represents the dynamic mooring line tension process. In this section, the narrow-band method, general wide-band methods, and dual narrow-band methods are briefly introduced to explain how to achieve the $X(t)$, the combined process of $X_L(t)$ and $X_W(t)$.

3.1. Narrow-band method

In this method, the combination of the LF and WF load processes, $X(t)$, is assumed to be a narrow-band Gaussian process and it is given by:

$$X(t) = X_L(t) + X_W(t) \tag{6}$$

The spectral density function $G(f)$ of $X(t)$ is then expressed as:

$$G(f) = G_L(f) + G_W(f) \tag{7}$$

where f is the frequency in hertz, $G_L(f)$ and $G_W(f)$ are spectral density functions of load processes $X_L(t)$ and $X_W(t)$, respectively.

As $X(t)$ is a narrow-band Gaussian process, the n^{th} order spectral moment of $X(t)$,m_n can be characterised by the spectral density function $G(f)$ as:

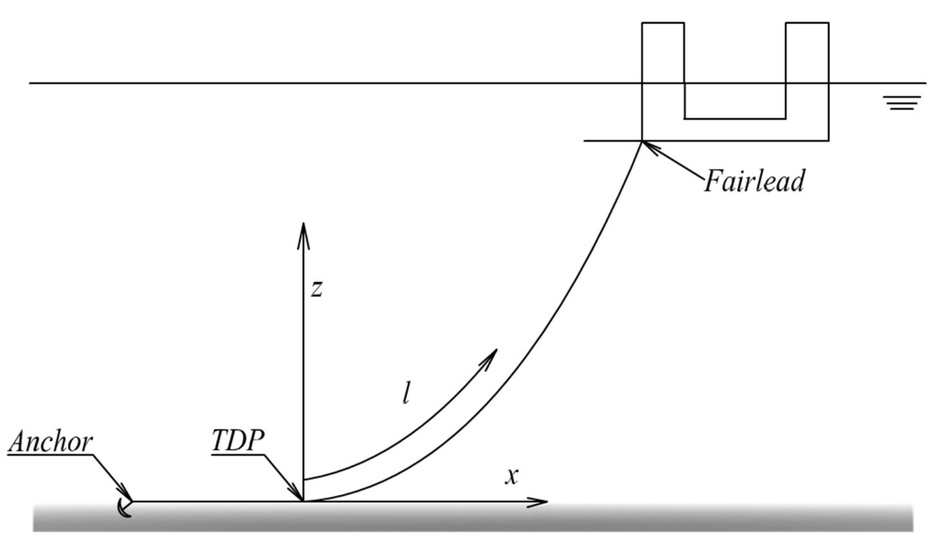

Fig. 1. Geometry of a 2D catenary mooring line.