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Wind and structural modelling for an accurate fatigue life assessment of tubular structures

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ABSTRACT

Based on the joint probability with regard to wind speed and its main direction, the current paper presents a practical and efficient approach for calculating wind induced fatigue of tubular structures, the effects of the wind direction, across wind and wind grid size on the high cycle fatigue of the structure are addressed. In each time step of the dynamic response calculation, the large deformation effects and the wind induced drag forces due to the updated structural deformations are taken into account. It is found that, the directional wind effects on the fatigue damage mainly depend on the orientation of the structure, the location and the support condition of the selected joints, and the relative probability of occurrence for the high winds speed in each direction, etc. Furthermore, the across wind components are proved to be a significant contributor on the fatigue damage and cannot be ignored. The fatigue damage is also found to be rather sensitive to the wind grid size for generating the wind fields. It is also concluded that vibration of each individual member interacts with the global dynamic response and the wind loading, and a fatigue check should therefore be against both individual member and global response. The wind fatigue calculation procedure presented in the current paper has the merit of reducing uncertainties without degrading a required safety level, this may lead to a positive economic impact with regard to construction and maintenance costs. It has been applied on quite a few industry and research projects and can be widely applied on the similar study of structures.

1. Introduction

As structures tend to become lightweight and slender, the knowledge obtained from traditional engineering practice may not be applied directly on the slender structure, sophisticated analysis approaches have to be adopted in the design and reassessment process. Among those analyses, the wind induced vibration calculation on slender tubular structures is one of the challenging studies. The major challenge involved is the nonlinear behaviour due to the geometric nonlinearity and fluid-structure nonlinearity. For small and medium size structures, the effects due to geometric nonlinearity are small and can be accounted for by safety factors or even be neglected. Some nonlinearity effects can also be locally taken into account in post processing procedures. However, for high rise slender structures, these effects cannot be neglected.

Wind loading is by its nature dynamic and therefore normally induces vibrations at the structure's natural frequencies. These vibrations produce fluctuating stresses which lead to the fatigue damage accumulation and can cause the structural failure without exceeding the design wind actions. At the global level the lateral wind load comprises in order of 10% and 25% of the total lateral load for fixed and floating platforms, respectively. While only very few researchers have studied the individual module contribution to the overall wind load for the design of offshore platforms [1]. Under extreme wind loading, the structure may reach ultimate strength and lead to local or global structural failures. This requires substantial repairing or even replacement. Damage to the deck structures due to extreme wind loads has been reported by Kareem and Smith [2]. Deoliya and Datta [3] studied the reliability of a 75 m tall microwave tower under wind loads with different combinations of mean wind speed and direction. They concluded that the probability of strength failure for the studied steel lattice tower increases with the increase in the standard deviation of mean wind speed, the zero crossing rate and the correlation between the velocities in two directions.

Quite a few pieces of research work have been reported concerning wind induced fatigue. Repetto [4] proposed a method that is applied to several different bimodal processes which are usual in dynamic response of structures. Based on a bimodal representation of the along wind induced stress power spectral density functions, Repetto and Solari [5] formulated a counting method to estimate the fatigue damage for only along wind actions on structures. Since the wind-induced fatigue is sensitive to moderate wind velocities for which stable or unstable atmospheric conditions can occur [6],

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Repetto and Solari [7] evaluated the wind-induced fatigue by taking the stable, unstable and neutral condition of the wind field into account and applied this approach to the fatigue calculation of a steel chimney. By including viscoelastic dampers in the modelling, Palmeri and Ricciardelli [8] had studied the fatigue life of structural components of tall buildings due to the buffeting response.

Since the directional effects of wind on the structural response may give engineers a better understanding of the structural response with regard to wind resistance, life-time extension and maintenance, and structures' reorientation, their influence on the dynamic structural response has been studied by Davenport [9], Simiun and Filliben [10], and Wen [11] using simplified structure models. The latter two articles conclude that the worst direction approach used for evaluating wind induced response may significantly overestimate the response. It should be noted that for a complex structure like a high rise flare boom, a simplified structural modelling may lead to an inaccurate estimation of fatigue damage.

Because the frequency domain analysis cannot properly take the non-linear load effects, large deformation as well as the plasticity into account, and also because the power spectrum of the critical stress due to the dynamic wind loading may not be narrow banded initiated from the influence of the background components of incident turbulence [12], crosswind induced vibrations, wind directional effects and structural damping etc., the inappropriate use of frequency domain based spectral methods developed for Gaussian processes may then significantly underestimate the fatigue damage contribution [13]. While in the mean time, the spectral methods based on non-Gaussian process are still under development. This is because if stress time history cherishes a greater probability than Gaussian probability regarding taking large stress values, this is then likely to induce a large stress range, and may consequently cause significantly accelerated fatigue damage [14–16]. Therefore, in recent years, the time domain dynamic analysis of wind sensitive slender structures such as high rise towers, flare booms, and long span bridges has attracted a lot of research efforts [17–19]. Based on the linear finite element calculation in the time domain, Gioffrè and his co-workers [20] studied the wind induced response of a guyed mast for mobile phone networks under the influence of along wind and across winds separately. Their study proves that the across wind forces cannot be neglected when calculating the response of the mast, especially when dealing with severe prescriptions on the allowable displacements. Repetto and Solari [21] proposed a mathematical model to derive a histogram of the stress cycles, the accumulated damage and the fatigue life of slender vertical structures (e.g. towers, chimneys, poles and masts) in along wind vibrations. In order to provide the information for the vibration of the Nanjing TV tower with passive and/or active mass damper, Feng and Zhang [22] performed a stochastic dynamic response of the tower under turbulent wind and included both along and across wind effects involving vortex induced vibration, drag and lift force. By taking the joint probability density function of mean wind speed and direction into account, Gu and his co-workers [12] presented a method in the mixed frequency-time domain for estimating the fatigue life of steel girders of the Shanghai Yangpu cable-stayed Bridge due to buffeting (under along wind loading). They predict that the fatigue life from the calculation is much longer than the design life of the bridge and shows significant dependency on the wind direction.

Offshore flare booms are mostly constructed with tubular components due to their low drag coefficients and high strength to weight ratio characteristics. However, due to the reason that tubular members give rise to significantly high stress concentrations in the joints and a flare booms are normally slender and show significant dynamic effects in low frequency ranges, the fatigue life is then one of the major concerns. Wind turbulence is the governing load with regard to fatigue for flare booms. It is obvious that the failure of flare booms can lead to the substantial damage through oil slicks as well as fire hazards on the deck. In addition, due to its slender characteristics, the structural nonlinearities due to large deformation may significantly influence the calculated structural response through creating a significant additional bending moment compared to that based on small deformation assumptions. The procedures established in existing standards only consider vibrations of individual members due to vortex shedding. However, vibration of each structural member interacts with the global structural response and the wind loading. Severe vibrations have been reported on several platforms in the North Sea, the actual vibration amplitudes were up to 20 times higher than the ones obtained from the model testing of individual members. Cracks have also been found on several flare booms caused by a combination of individual member and global vibration of the structure. It is then not sufficient to assess the fatigue damage of a structure only based on the behaviour of each isolated individual member. Due to the effects of S–N curves, the fatigue damage is much more sensitive to the variation of loads, structural modelling and the calculation algorithms than that of the stress, thus a careful consideration of load and structural modelling must be made before calculating the fatigue damage.

By discussing the wind field simulation and nonlinear finite element analysis, the current paper first presents a practical approach for establishing the Fatigue Limit State (FLS) model through calculating the wind induced fatigue life of a typical flare boom installed on an offshore oil platform. In order to include the nonlinear structural and load effects into consideration, the current paper adopts the direct integration method (implicit method): the HHT-α method in the FE code USFOS [23] for calculating the dynamic response. Dynamic analysis is performed to simulate the response of the flare boom with 72 wind load cases/blocks, and calculating the fatigue damages by taking the probability of each individual wind load case/block. The high cycle fatigue has been calculated by applying the 'rain-flow' counting method and the Miner rule. Both the along and across wind components are applied. It is found out that the directional wind effects on the fatigue damage mainly depends on the orientation of the structure, the location and the support condition of the selected joints, and the relative probability of occurrence for the high wind speed in each direction. Furthermore, the across wind components are a significant contributor to the fatigue damage and cannot be neglected. The fatigue damage is also found to be rather sensitive to the wind grid size for generating the wind fields. The wind fatigue calculation procedure presented in the current paper can be widely adopted on the similar study on high rise tubular structures.

2. Simulation of wind field

It is assumed that the instantaneous wind speed comprises a mean wind part and a fluctuating part as shown in Fig. 1. By denoting the turbulent wind components u, v, and w in the along wind (x), horizontal across wind (y) and vertical across wind (z) direction and the mean wind component as U', a wind velocity vector at time t can then be expressed in a Cartesian coordinate system as expressed in Eq. (1):

$$V\{x, y, z, t\} = \left[U' + u, v, w\right]^T . \tag{1}$$

2.1. Mean wind speed U' for along wind

The mean along wind speed at height z above the sea surface and corresponding the mean period T (s) not more than 3600 s can be calculated by a mean wind profile as expressed by Eq. (2) [24].

$$U'(z, T) = U(z) \cdot \left[1 - 0.41 I_u(z) \cdot \ln\left(\frac{T}{3600}\right)\right] \tag{2}$$

where the one hour mean wind speed $U(z)$ (m/s) is given by