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The effect of some uncertainties associated to the environmental contour lines definition on the extreme response of an FPSO under hurricane conditions

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ABSTRACT

The environmental contour concept, in conjunction with the Inverse First Order Reliability Method, is often used to determine the extreme response of marine structural systems. This technique is a powerful option to determine the extreme response associated to a probability of exceedance without the need to perform a long-term analysis, where a large number of short-term simulations are needed. However, there are significant uncertainties involved in its determination, such as the uncertainties related with the probabilistic model used for the environmental variables, as well as the ones related with the threshold selection when the peaks over threshold (POT) method is applied. This paper shows the results of a comparative analysis of the extreme tension of the most loaded mooring line of an FPSO subjected to environmental conditions in deep water, derived from environmental contour lines which were defined with different probabilistic models to represent the significant wave height and different criteria to establish the threshold for the POT methodology. The results showed that the probabilistic model has an important effect on the extreme response of the FPSO and this epistemic uncertainty should be accounted for in the calibration of the design safety factors.

1. Introduction

The use of the long-term extreme response is the most appropriate method for ultimate resistance design of mooring lines and many other marine structures. However, this method is computationally very expensive because it requires a large number of time-consuming numerical simulations. An alternative approach to perform the long-term analysis is the environmental contour lines method [1]. This procedure has been recommended by some offshore standards and recommended practices [e.g. 2–4] and it has also been applied in a variety of research works [e.g. 5–8]. The basic idea of the environmental contour approach is to solve the long-term integral by means of some few short-term analyses, and using a set of a discrete combinations of the environmental variables which are selected based on the joint probability distribution of the environmental parameters and the Inverse First Order Reliability Method (I-FORM), considering a probability level associated to a given return period [1]. The accuracy of this approach has been investigated in several studies [e.g. 9–12].

The joint probability distribution of the environmental parameters plays a significant role in the contour lines approach. By considering storm prone regions, there are many aspects that impact the development of this joint distribution and, consequently, the design contour lines [13–17]. These aspects involve the definition of storms duration, storm type (winter storm, hurricane and cold fronts), thresholds levels, statistical uncertainties due limited database of storm events, etc. Besides these aspects, for instance, the selection of the probability model for representing the significant wave height can also be subjective. Weibull, Generalized Pareto and Exponential distribution models (considering or not a threshold level) are commonly accepted by many goodness-of-fit tests to represent the significant wave height.

With the contour lines approach, this paper investigates the impact of using different probability models, which are accepted according to some many goodness-of-fit tests to represent the significant wave height, on the extreme design tensions of the most loaded mooring line of an FPSO located in a site in the Gulf of Mexico (GoM). A 48-year wave database was available from a hindcast study for the GoM location [18]. Due to the small amount of storms available in the database, the Nataf-based model [19]

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was used to represent the significant wave height and peak wave period joint probability distribution. It is worth mentioning that this model is based only on the marginal probability distributions, the significant wave height, the wave peak period and their linear correlation coefficient. The significant wave height was modeled by the Weibull, the Generalized Pareto and the Exponential distributions considering the data collected during the occurrence of hurricanes. The most appropriate probability distribution model for the wave peak period, according to the goodness-of-fit tests performed, was the lognormal distribution. Therefore, in the present work, this distribution was kept the same for all probability models used to represent the significant wave height.

All probability models used in this work, to represent the significant wave height, were defined with and without a threshold level whose main goal is to get the best fit in the upper tail of the distribution. Two techniques were used in this paper to define the best threshold level to be employed in the models. The first one is the method proposed by Thompson et al. [14] and the second one is a practical method proposed in this work which is based on the work of Zurita [20].

Thus, in this paper, the impact of some practical issues in defining the joint probability model to be used in connection with the environmental contour approach, such as the threshold level and the distribution model for the significant wave height, is evaluated with respect to the extreme response of the most loaded mooring line of an FPSO in a site in the GoM.

2. Environmental contour method

For the definition of the design environmental contour, only two environmental parameters were considered in the present study, i.e., the significant wave height (H_s) and the wave peak period (T_p). Hence, in the FPSO analysis, the mean wind velocity was assumed to be completely dependent on H_s and a fixed current velocity profile was employed for all short-term analyses. Then, the basis for the definition of the environmental contour lines is the joint probability distribution of the aforementioned environmental parameters H_s and T_p [21]. In the present work, this joint probability function was represented by the Nataf-based model [22,23] which is given by:

$$f_{H_s,T_p}(h,t) = \frac{f_{H_s}(h) f_{T_p}(t)}{\phi(\Phi^{-1}(F_{H_s}(h)))\phi(\Phi^{-1}(F_{T_p}(t)))} \times \phi_2(\Phi^{-1}(F_{H_s}(h)), \Phi^{-1}(F_{T_p}(t)), \rho_N) \quad (1)$$

where $F_{H_s}(h)$ and $F_{T_p}(t)$ are the fitted marginal cumulative probability functions of H_s and T_p, respectively, $f_{H_s}(h)$ and $f_{T_p}(t)$ are their corresponding marginal probability density functions, $\phi(.)$ is the probability density function of a standard normal variable and $\Phi^{-1}(.)$ stands for the inverse of its cumulative probability function, $\phi_2(.,.,\rho_N)$ stands for a joint bi-dimensional density function of two standard normal variables and the Nataf equivalent correlation coefficient, ρ_N, is obtained by solving Eq. (2)

$$\rho_{H_s,T_p} = \int_0^\infty \int_0^\infty \left(\frac{F_{H_s}^{-1}(\Phi^{-1}(x)) - \mu_{H_s}}{\sigma_{H_s}}\right)\left(\frac{F_{T_p}^{-1}(\Phi^{-1}(y)) - \mu_{T_p}}{\sigma_{T_p}}\right) \times \phi_2(y, x, \rho_N)\,dx\,dy \quad (2)$$

where ρ_{H_s,T_p} is the linear correlation coefficient between H_s and T_p computed from the available data, $F_{H_s}^{-1}(.)$ and $F_{T_p}^{-1}(.)$ stand for the inverse of the marginal cumulative probability function of H_s and T_p, respectively. μ_{H_s} and μ_{T_p} are the mean values of H_s and T_p and σ_{H_s} and σ_{T_p} are their corresponding standard deviations.

By using a suitable probability transformation, the joint probability distribution of H_s and T_p can be equivalently represented by a joint distribution of two independent standard normal variables U_1 and U_2. This is accomplished by means of the Nataf transformation given by:

$$\begin{aligned} h &= F_{H_s}^{-1}(\Phi(u_1)) \\ t &= F_{T_p}^{-1}\left(\Phi\left(u_1 \rho_N + u_2\sqrt{1-\rho_N^2}\right)\right) \end{aligned} \quad (3)$$

Then, in the standard normal space, represented by the two random variables U_1 and U_2, the environmental contour is defined as the circle satisfying the following condition [1]:

$$\beta = \sqrt{u_1^2 + u_2^2} \quad (4)$$

where the radius, β, is associated with the probability of occurrence of an event with a given return period of T_R years. In the present work, the data analyzed are those associated to hurricanes events, and this parameter can be defined as [23]:

$$\beta = -\Phi^{-1}\left(-\frac{\ln(1-1/T_R)}{\lambda_H}\right) \quad (5)$$

where λ_H is the expected annual mean rate of hurricanes, i.e.,

$$\lambda_H \approx \frac{N}{T_o} \quad (6)$$

where N is the total number of hurricanes observed within the time period T_o (in years). The environmental contour on the $H_s - T_p$ original space is obtained using the points on the circle defined by

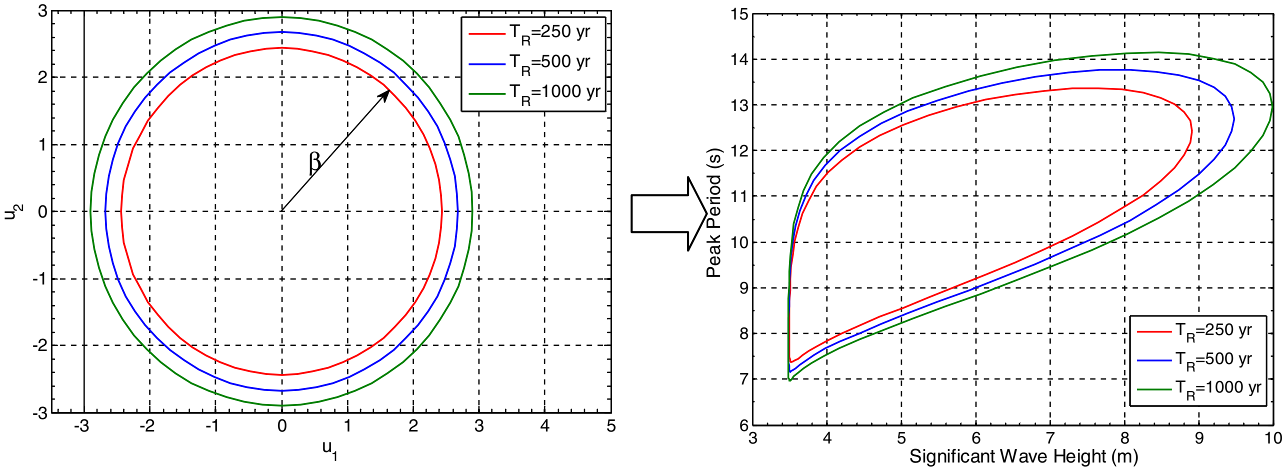

Fig. 1. Contour lines in the standard normal and $H_s - T_p$ original spaces.