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A long-term joint probability model for metocean circular and linear characteristics

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ABSTRACT

Structural performance analysis of offshore structures extremely depends on the smart selection of design environment. In this paper, a joint probability model is developed to provide the designers with the joint probability of occurrence of all possible sea states including their circular and linear variables. The presented Joint PDF consists of a marginal PDF for circular variable and two conditional PDFs for linear variables. The marginal PDF for wave direction as a circular variable is a mixture of von-Mises Fisher distribution and the conditional PDFs are assumed to be a conditional Weibull distribution for wave height and a conditional lognormal distribution for wave period. An extreme value analysis is also applied to make sure that the model covers all possible ranges of wave circular and linear parameters in the desired lifetime. Design scenarios can be chosen from the highest probable combinations of wave height, period and direction. The proposed method was applied on Caspian Sea 45-years and Persian Gulf 11-years hindcast data. The results indicate the acceptable accuracy and practicality of this methodology for the directionality dependent design approaches.

1. Introduction

The demanding need to new resources of energy especially from wind and wave entails the designers to assure reliability of structures exposed to harsh sea environment. Many design codes require precise prediction of design environment in the lifetime of the structure. However the aleatory nature of ocean environment characteristics complicates the design procedures. Long-term design methodologies oblige even more rigid requirements. One of these requirements is associated with mathematical description of ocean environment.

For this purpose most researchers utilize hindcast or recorded data from the structure installation site to predict the forces and motions of structure. Remarkable works has been published recently on this subject. Karadeniz presented a comprehensive methodology for the analytical method of stochastic dynamics of offshore structures [1]. Naess and Moan paid special attention to probabilistic design and long-term wave models [2]. There are also studies on the long-term response of structures and comparison of different models [3,4]. Different ways of extreme wave analysis was compared and reviewed by Johannessen et al. [5].

Long-term wave height distribution and extreme value in a desired lifetime [6,7], joint probability distribution of wave height and period [8–10] and short-term wave height distribution [11] have been properly developed during the last decades.

Most of researchers focused on describing joint probability of wave height and period. However the dependence between wave height and direction is not yet well described. Many aspects of circular data like wave direction were comprehensively explored by Jammalamadaka and SenGupta [12]. They suggested different distributions for circular data. Later on some researchers expanded regression and correlation for circular data [13]. These methods were discussed for combination of linear and circular variables by Pewsy et al. [14]. Nonparametric methods like kernel density estimators have also been used for description of univariate and multivariate metocean parameters [15]. To the best of authors' knowledge a joint probability distribution function was not properly developed yet. Such a distribution is required for a long-term analysis plan regarding the wave directionality effect. Therefore the purpose of this paper is to present a framework for dependence modeling of linear and circular metocean data utilizing conditional modeling approach.

This paper is organized as follows: Firstly the basic methodology of long term modeling of metocean variables is explained. Then the developed Joint probability distribution function (PDF) of metocean circular and linear variables is described. The application of model

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in prediction of occurrence of combinations of wave parameters is presented in the next section. Since the probability of all combinations of wave direction, height and period should be assessed, an extreme value analysis was implemented to define the bounds of probability integral. Then the model in combination with environmental contours method has been applied to find the design values specified with different return periods. Afterwards the data sets are explained and the results of the implication of the developed model are discussed.

2. Long-term modeling: circular and linear variables

Most of the structures in the ocean environment need to be analyzed in different environmental conditions. However the simultaneous probability of occurrence of waves in different directions is somehow critical. Development of a method for description of relation between wave circular and linear variables is vital.

To set a relation between metocean circular and linear variables the conditional modeling approach was utilized. This approach was first applied for establishment of a relation between wave height and period by Haver and Nyhus [9] and has been used by many researchers [16–18]. The method was expanded to three variables describing the relation between wind speed, wave height and period [5]. It consisted of a marginal Weibull distribution for wind speed and two conditional distributions. First for wave height dependent on wind speed and the second one was a conditional PDF to relate wave period to wave height and wind speed. This distribution was adopted by means of many coefficients and interpolation functions. So another simplified version was developed in which they assumed wave period to be dependent on wave height and not wind speed.

Using the same approach, the probability of occurrence of each combination of wave height, period and direction can be designed. The main assumption of this research is that the wave characteristics mainly depend on the wave direction, especially in confined and semi-confined bodies of water (which is the case of our study in the Persian Gulf and Caspian Sea broadly described in Sec.4). So we assume that the marginal distribution function is the distribution of mean wave direction. Then, wave height and period can be defined by conditional distributions. So the joint PDF of wave direction, height and period can be written as:

$$f_{\Theta_w,H_s,T_z}(\theta,h,t)=f_{\Theta_w}(\theta)\,f_{H_s|\Theta_w}(h|\theta)f_{T_z|H_s,\Theta_w}(t|h,\theta) \tag{1}$$

The right-hand side of Eq. (1) is defined as the product of three functions. Calculation of the third function ($f_{T_z|H_s,\Theta_w}(t|h,\theta)$) needs multivariate surface fitting efforts and a large number of fit parameters will be added to the model. So here the wave period is assumed to be dependent on the wave height and not wave direction, while wave height is a function of wave direction. The joint probability distribution of wave direction (circular variable) and wave height and period (linear variables) can be written as:

$$f_{\Theta_w,H_s,T_z}(\theta,h,t)=f_{\Theta_w}(\theta)\,f_{H_s|\Theta_w}(h|\theta)f_{T_z|H_s}(t|h) \tag{2}$$

The first building block of Eq. (2) is to find an appropriate distribution for circular variables. There are different kinds of distributions for description of statistical behavior of circular or directional data [19]. The von-Mises Fisher or Circular Normal Distribution is the most naturally observed distribution for circular data [19] and has been used by researchers for description of directional environmental parameters [20,21]. So it has been utilized in this model. It is a unimodal symmetric distribution characterized by a mean value $\mu\in(0,2\pi)$ where density is concentrated and a concentration parameter $\kappa\geq0$ [12]. It is defined as:

$$f(\theta)=\frac{1}{2\pi I_0(\kappa)}\exp[\kappa\cos(\theta-\mu)] \tag{3}$$

where $I_0(\kappa)$ is the modified Bessel function of first kind and zero order. In case of multimodal data a mixture of von-Mises distributions can be applied. So the PDF of wave directions is written as:

$$\begin{aligned}&f_{\Theta_w}(\theta)=\sum_{i=1}^{n}\omega_i f_i(\theta)\\&0<\omega_i\leq1\\&\sum_{i=1}^{n}\omega_i=1\end{aligned} \tag{4}$$

where ω_i is a weighting coefficient.

Parameters of a mixture of von-Mises distributions are estimated by an Expectation Maximization (EM) algorithm for the log-likelihood of the mixture. The movMF package [22] was applied for this purpose.

The second step in wave direction modeling was creating the conditional distribution of wave height on direction. It's assumed that wave height in each class of wave direction obeys a Weibull distribution as:

$$f_{H_s|\Theta_w}(h|\theta)=\beta_w\frac{h_s^{\beta_w-1}}{\alpha_w^{\beta_w}}\exp(-(\frac{h_s}{\alpha_w})^{\beta_w}) \tag{5}$$

A Weibull distribution was fitted to the values of H_s in each class of θ_w to find α_w and β_w. Finding a relation between wave height distribution parameters and direction may seem physically meaningless. It is because wave characteristics are dependent on the location of under consideration site and the dominant wave direction. Concerning the applications of Fourier series to model different functions, it's applied to resemble the shape of α_w and β_w as functions of mean wave direction. The wave direction span $(0,2\pi)$ was divided into 30 parts. Wave heights in each block of θ_w are assumed to follow a Weibull distribution and the parameters of fit are estimated by nonlinear least squares method. Then the dependency of α_w and β_w on the θ_w is described by fitting a Fourier series as follows:

$$\alpha_w=a_0+\sum_{i=1}^{n}a_n\cos(n\theta_w)+b_n\sin(n\theta_w) \tag{6}$$

and

$$\beta_w=a_0+\sum_{i=1}^{n}a_n\cos(n\theta_w)+b_n\sin(n\theta_w) \tag{7}$$

The next step toward completion of Eq. (2) is to set on an expression to describe the dependency of wave period to wave height. The following model was applied for this purpose that is the product of marginal PDF of H_s and conditional PDF of T_z:

$$f_{H_s,T_z}(h_s,t_z)=f_{H_s}(h_s)f_{T_z|H_s}(t_z|h_s) \tag{8}$$

The marginal PDF of H_s is a marginal Weibull distribution and the conditional probability density function of T_z is formulated by a conditional lognormal distribution as follows:

$$f_{T_z|H_s}(t|h)=\frac{1}{\sqrt{2\pi}\sigma_{\ln T}t}\exp(-\frac{(\ln(t)-\mu_{\ln T})^2}{2\sigma^2{}_{\ln T}}) \tag{9}$$

Dependency of T_z on H_s is set in a way that mean value (μ_{lnT}) and standard deviation ($\sigma^2{}_{lnT}$) of T_z are the functions of H_s:

$$\mu_{\ln T}=c_1+c_2h_s^{c_3} \tag{10}$$

$$\sigma^2{}_{\ln T}=d_1+d_2\exp(-d_3h_s) \tag{11}$$

To find c_1,c_2,c_3 and d_1,d_2,d_3 nonlinear least squares method should be applied to the wave scatter diagram. The probability of