Development of Environmental Contours for Circular and Linear Metocean Variables

Zohreh Sadat Haghayeghi*, Mohammad Javad Ketabdari*‡

*Faculty of Marine Engineering, Amirkabir University of Technology, No. 424, Hafez Ave., Tehran, Iran

(z.haghayeghi@aut.ac.ir, ketabdar@aut.ac.ir)

‡ Corresponding Author; Mohammad Javad Ketabdari, No. 424, Hafez Ave, Tehran, Iran.

Tel: +982164543111, Fax: +982164543111, ketabdar@aut.ac.ir

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Abstract- Probabilistic structural analysis of offshore structures is a demanding task due to high number of environmental variables and their uncertainties. Thus methods that reduce the computational effort are always welcomed. The environmental contours approach is one of these favorite methods. However almost all the developed environmental contours methods are limited to combination of linear metocean variables. Wave and wind directions are important parameters especially in the design of coastal and nearshore structures. Thus, this research is concentrated on development of environmental contours for combinations of circular and linear variables. These contours are derived from the Nataf transformation based approach and conditional modelling approach (CMA). In this paper the CMA was modified to be suitable for circular-linear variables. The circular variable is assumed to be independent and follow a mixture of von-Mises distributions. Linear variables were distributed conditionally on the circular variable. The regression between the distribution parameters and circular variable was set by Fourier series. Then, the Nataf-based model was applied to compare the results. The comparison shows that environmental contours based on the CMA illustrate the wave directionality effect much better than the Nataf-based model.

Keywords Persian Gulf Data; Inverse FORM; Circular-Linear Regression; Multivariate Analysis

1. Introduction

Having knowledge of extreme sea states and their probability of occurrence is a critical issue in the design of offshore structures. Design approaches have been expanded to decrease the risk of failure in the desired lifetime of structures. Offshore structures should be built to withstand the environmental loads during this time period. Accordingly the ocean environment should be described in terms of variables with specified return period. Determination of return period for a single variable is performed using the timeseries record of the variable. But it is cumbersome when it comes to define the simultaneous probability of occurrence of two or more variables. The difficulty arises firstly from the dependency nature of variables and the way to describe them. The problem can be solved by development of a joint probability distribution function. Another source of complexity is determination of simultaneous probability of occurrence of variables in the desired return period.

The concept of environmental contours (ECs) was first expressed to overcome the mentioned problems [1]. It applies Inverse First Order Reliability Method (IFORM) to develop surfaces or lines that are locus of points having the same probability of exceedance. Environmental contours method is a favorite tool for design of different offshore structures due to its advantages. As in this method the environmental variables can be uncoupled from the structural response, it is suitable for design of structures with complicated structural response. Once the ECs are derived, they can be used in many design problems.

ECs method have been used and modified during the time by many researchers. The required steps and methodology for establishing ECs and its application in design process has been previously illustrated [2]. In more practical researches this method was applied for determination of design loads on structures such as wind turbines [3]. This method in conjunction with response surface method was used for design of FPSOs [4]. In the most recent researches the method was applied for joint description of metocean variables [5]. A new approach for determination of extreme metocean conditions for design of offshore wind turbines was also applied [6].

Basically, there are two main approaches for the development of ECs. The first method which is based on Rosenblatt transformation [7] is called conditional modelling approach [5]. In this approach the relation between variables is described by a marginal distribution and a set of conditional distribution functions. Application of this method is somewhat limited to cases where a full timeseries of simultaneous data or an adequately sorted set of variables are provided. However this kind of data is not always available. Also if there are more than three environmental parameters, using this method and building Joint Probability Distribution (JPD) is not practical. But its results are often more convex. The second model is based on Nataf Transformation. It applies marginal distribution of variables and correlation coefficient between variables for construction of ECs.

Most of these researches are concentrated on ECs that are developed for different linear metocean variables e.g. wind speed, wave height and period [3, 5, 8, 9]. However for the wave directionality impact on ECs, a few works were performed. Baarholm developed ECs for different wave sectors [10]. But rare publications can be found on the ECs for circular or directional variables.

Therefore this research focuses on derivation and plotting ECs where one of the variables is circular such as wind or wave direction. A review of ECs and how they are derived by IFORM was presented in section 2. Section 3 focuses on derivation of ECs for circular-linear metocean data. The last section discusses the results of both methods to determine their pros and cons.

2. Environmental Contours and Inverse First Order Reliability Method

One of the major problems in multivariate analysis of metocean data is how to associate a set of joint random variables with a specified recurrence period. This problem can be solved by IFORM. The IFORM helps finding input variables that create a specified reliability index β_r. In this method the variables with the same probability of occurrence in the physical space are transformed to a hypersphere with radius β in the uncorrelated standard normal space. The hypersphere is defined by:

$$|\mathbf{U}| = \beta_r \tag{1}$$

If N is the number of occurrence of an event in a year, β which is associated with desired return period (T_R) will be:

$$\beta_r = \Phi^{-1}(1-\frac{1}{NT_R}) \tag{2}$$

So each β_r is accompanied with a T_R where Φ stands for the standard normal distribution function. If the metocean environment is described by a record of **X** vector, the main step in building environmental contours is linking the **X** and **U**. This can be done by two methods as conditional modeling approach and Nataf-based Model.

2.1 Environmental Contours by Conditional Modelling Approach

In CMA, dependence modelling is carried out by means of a set of distribution functions. The first distribution is a sole marginal PDF but the others are conditional ones. The conditionality is assured so that distribution parameters are functions of previous variables. Then it is assumed that each Cumulative Distribution Function (CDF) is identical to a component of **U** in the standard normal space. The transformation is also called as Rosenblatt transformation by the following relations:

$$\begin{aligned} U_1 &= \Phi^{-1}(\mathrm{F}_{X_1}(X_1)) \\ U_2 &= \Phi^{-1}(\mathrm{F}_{X_2|X_1}(X_2)) \\ &\vdots \\ U_n &= \Phi^{-1}(\mathrm{F}_{X_n|X_1,\ldots,X_{n-1}}(X_n) \end{aligned} \tag{3}$$

where $\mathrm{F}_{X_i|X_1,\ldots,X_{i-1}}$ is the conditional distribution of X_i given values of X_i to X_{i-1}. The vector **U** should be selected so that it creates a hypersphere with radius β. Thus in 2D case where i=2, it can be expressed as follows:

$$\begin{aligned} U_1 &= \beta_r \cos\theta \\ U_2 &= \beta_r \sin\theta \\ -\pi &\le \theta \le \pi \end{aligned} \tag{4}$$

Eq. (4) produces a circle. For 3D case, the sphere is defined by:

$$\begin{aligned} U_1 &= \beta_r \sin\varphi\cos\theta \quad 0 \le \theta \le 2\pi \\ U_2 &= \beta_r \sin\varphi\sin\theta \quad 0 \le \varphi \le \pi \\ U_3 &= \beta_r \cos\varphi \end{aligned} \tag{5}$$

This method was used by Winterstein for two variables H_s and T_p [1]. Then a model was extended to be applicable for three variables of U_w, H_s and T_p [11]. These methods are widely used by the researchers. However their explanation is out of the scope of this paper.

2.2 Environmental Contours by Nataf Model

ECs were first developed from Nataf transformation by taking the advantage of concept of conditional mean and standard deviation [12]. In their model, X_i is presented in terms of uncorrelated standard normal variables U_i by the following relations:

$$X_1 = F_{x_1}^{-1}(\Phi(U_1)) \tag{6.a}$$

$$X_i = F_{x_i}^{-1}(\Phi(U_i\sigma_{ci} + \mu_{ci})) \quad i = 2,...,n \tag{6.b}$$

where F_{x_i} denotes the cumulative distribution function of X_i .while μ_{ci} and σ_{ci} are the conditional mean and variance. For two and three variables they can be written as:

$$\mu_{c2}(X_1) = \rho_{12}\Phi^{-1}(F_{x_1}(X_1)) \tag{7.a}$$

$$\sigma^2_{c2} = 1 - \rho^2_{12} \tag{7.b}$$

and

$$\mu_{c3}(X_1, X_2) = \frac{1}{1-\rho^2_{12}}((\rho_{12} - \rho_{13}\rho_{23})\Phi^{-1}(F_{x_1}(X_1)) + (\rho_{23} - \rho_{13}\rho_{12})\Phi^{-1}(F_{x_2}(X_2))) \tag{8.a}$$

$$\sigma^2_{c3} = \frac{1}{1-\rho^2_{12}}(1 - \rho^2_{12} - \rho^2_{23} - \rho^2_{13} + 2\rho_{12}\rho_{13}\rho_{23}) \tag{8.b}$$

By replacing Eq. (7) and Eq. (8) in Eq. (6) environmental contours are defined for the associated β of any return period.

The Nataf-based model needs marginal PDF of each variable and then correlation coefficient between each pair of variables.

3. The Proposed Environmental Contours for Circular and Linear Variables

The dependence structure between linear and circular variables is somewhat different from the sole linear-linear dependency. Finding marginal or conditional distribution functions including circular variables should concern certain issues. Some issues should be taken into account while trying to find the distributions for circular or directional parameters with adequate accuracy. For example if one simply calculates the mean of 1° and 359° it will be 180 °, while the resultant vector of these angles is 0 °. So in this case appropriate definition of statistical parameters is inevitable. In addition to usual requirements of a distribution function, it should have some specifications as applied to a circular random variable. It should be periodic and defined on the whole circle. There are several circular distribution functions like von-Mieses or Circular Normal distribution, Wrapped Normal distribution, and Wrapped Cauchy distribution [13, 14]. A circular normal distribution is defined by:

$$f(\theta) = \exp[\kappa\cos(\theta - \mu)] / 2\pi I_0(\kappa) \tag{9}$$

where $I_0(\kappa)$ is modified Bessel function of first kind and zero order and κ is the concentration parameter. A mixture of von-Mises distributions is applied for presenting PDF of wave direction as:

$$f(\theta) = \sum_{i=1}^{n} \omega_i f_i(\theta) \\ 0 < \omega_i \le 1 \\ \sum_{i=1}^{n} \omega_i = 1 \tag{10}$$

where ω_i denotes the weight of i^{th} component of the mixture. Estimation of parameters of a mixture of von-Mises distributions is performed by an expectation maximization algorithm for the log-likelihood of the mixture. The movMF package is applied for this purpose [15].

3.1 ECs from CMA for Circular and Linear Variables

In this section a joint model is proposed for dependence modeling between circular and linear data. The mentioned model is adopted to be used in the Rosenblatt transformation. The marginal PDF of circular variable is selected as the independent PDF. Then the PDF of other variables is defined as conditional distributions. The distribution parameters are functions of primary variables such as wind or wave direction. Among different functions, the Fourier series seems to be a proper choice for presenting dependency of distribution parameters on the primary variable, since it is periodic and can resemble different function shapes.

3.1.1 ECs of Wind Direction and Speed

At the first stage the JPDF of wind speed (U_w) and direction (θ_{wind}) should be introduced. The JPDF is a mixture of von-Mieses distributions for wind direction and a conditional Weibull distribution for wave speed:

$$f(\theta_{wind}, \mathrm{U}_w) = f(\theta_{wind}) f(\mathrm{U}_w | \theta_{wind}) \tag{11}$$

where

$$f(\theta_{wind}) = \sum_{i=1}^{n} \omega_i f_i(\theta_{wind}) \tag{12}$$

Then the conditional PDF of wind speed and direction is a Weibull distribution:

$$f(\mathrm{U}_w \left| \theta_{wind} \right.) = \frac{\beta}{\alpha}(\frac{u}{\alpha})^{\beta-1} \exp(-(u/\alpha)^{\beta}) \quad (13)$$

Now we are seeking a relation between α and β and wind direction tod propose a function as $\alpha(\theta)$ and $\beta(\theta)$. It is not easy to find a mathematical relation between wind direction and speed. Because it's dependent on the location of the site under consideration and physically the proposed equations may seem meaningless. A function should be fitted for representation of $\alpha(\theta)$ and $\beta(\theta)$. This function is periodic since it's defined over a circle. A Fourier series is proper to show the relation between wind direction and the shape and scale parameters of Weibull distributions. It is also helpful in building the favorite shape of fitting function.

The calculation process begins with a scatter diagram of U_w and θ_{wind} with n bins of wind speed. Then a Weibull distribution is fitted to wind speeds located in each bin of wind direction. The parameters of Weibull distribution of each bin of wind direction are related to the representative wind direction θ_i and a Fourier series is fitted to them:

$$\alpha_{wind} = a_0 + \sum_{i=1}^{n} a_n \cos(\mathrm{nx}\,\omega) + \mathrm{b}_n \sin(\mathrm{nx}\,\omega) \quad (14)$$

and

$$\beta_{wind} = a_0 + \sum_{i=1}^{n} a_n \cos(\mathrm{nx}\,\omega) + b_n \sin(\mathrm{nx}\,\omega) \quad (15)$$

The coefficients of Fourier series are listed in Table 2. To drive and plot ECs, U_1 and U_2 are selected from Eq. (5). While ECs are derived for this JPDF from Eq. (3).

3.1.2 ECs of Wave Direction, Height and Period

The ECs for wave direction, height and period are derived similar to what was described for wind ECs. The model prescribed for wave is composed of three variables. As previously stated, it is not always practical to establish the JPDF for more than two variables. The first conditional PDF defines the dependency between two variables. But the second conditional PDF should build functions for connecting three variables. The process was applied for U_w, H_s and T_p [11]. It is a cumbersome process and needs some simplifying assumptions. In this approach wave period is just a function of wave height. In this way the calculation process was reduced.

Therefore in this paper the same assumption of above approach was adopted. The JPDF of wave direction, height and period is written as:

$$f(\theta_{Wave}, H_s, \mathrm{T}_p) = f(\theta_{wave}) f(H_s \left| \theta_{wave} \right.) f(\mathrm{T}_p \left| H_s \right.) \quad (16)$$

where $f(\theta_{wave})$ is presented by Eq. (12).

After defining $f(\theta_{wave})$, the conditional distribution of H_s given θ_{wave} should be defined. The distribution is a Weibull PDF similar to Eq. (13). The only difference is the scatter diagram prepared for wave direction and height.

The last conditional distribution needed for completion of the model is conditional distribution of T_p given H_s and θ_{wave}. To build this model, it is assumed that T_p follows a lognormal distribution. The parameters of this distribution should be dependent on H_s and θ_{wave}. But as mentioned in the previous section, in this research dependency of T_p on θ_{wave} is neglected. The trend of changes in T_p shows that it is just dependent on H_s:

$$f_{T_p|H_s}(t \left| h_s \right.) = \frac{1}{\sqrt{2\pi}\sigma_{\ln T}\, t} \exp(-\frac{(\ln(t) - \mu_{\ln T})^2}{2\sigma^2_{\ln T}}) \quad (17)$$

where

$$\mu_{\ln T} = a_1 h_s^{a_2} + a_3 \quad (18)$$

$$\sigma^2_{\ln T} = b_1 \exp(b_2 h_s) + \mathrm{b}_3 \quad (19)$$

Having a look at the relationship between wave height and period may be helpful in understanding the final shape of wave direction, height and period ECs.

The model described by Equations (17-19) is the second part of a known model that is widely used by researchers as JPDF of H_s and T_p [16]. Its first part is a distribution for H_s that may be Weibull or lognormal-Weibull. The method applied in this research, defines this Weibull distribution as a conditional distribution of wave direction. Here the distribution is assumed independent to see the relation between H_s and T_p as:

$$f(H_s, \mathrm{T}_p) = f(H_s) f(\mathrm{T}_p \left| H_s \right.) \quad (20)$$

where $f(H_s)$ is a Weibull distribution and conditional distribution of H_s and T_p is as equations (17-19).

It should be noted that recalling this model and plotting these ECs is useful for imagination of 3D environmental contour surface.

Using Eq. (18) and Eq. (19) is a potential source of uncertainty as it is suspect of neglecting the dependency of T_p on θ_{wave}. To investigate this, the normalized value of μ_{lnT} and its relative error were estimated. In this case the maximum calculated error value was less than 6%. Thus for practical applications neglecting the effect of wave direction on period is a way to avoid high amount of fitting functions and coefficients.

3.2 ECs for linear-circular variables by Nataf- based model

Marginal distribution functions of all variables are required for the Nataf-based model. However the Rosenblatt-based environmental contours need marginal PDF of some variables. The marginal PDF of circular variables was fully explained in previous section.

As stated before, the correlation coefficient between each pair of variables is needed to make their ECs. The correlation coefficient between two linear variables *u* and *v* is determined by:

$$\rho_{uv} = \frac{\sum_{i=1}^{n} (\mathrm{u}_i - \bar{\mathrm{u}})(\mathrm{v}_i - \bar{\mathrm{v}})}{\sqrt{\sum_{i=1}^{n} (\mathrm{u}_i - \bar{\mathrm{u}})^2 \sum_{i=1}^{n} (\mathrm{v}_i - \bar{\mathrm{v}})^2}} \tag{21}$$

where $\bar{\mathrm{v}}$ and $\bar{\mathrm{u}}$ are the mean of vectors U and V. In many cases the correlation coefficient between circular and linear variables like X and Θ is required. So one can calculate $\rho_{X\Theta}$ by the following relation:

$$\rho_{\Phi X} = \frac{\rho_{XC}^2 + \rho_{XS}^2 - 2\rho_{XC}\rho_{XS}\rho_{CS}}{1 - \rho_{CS}^2} \tag{22}$$

where:

$$\begin{aligned} \rho_{XC} &= \rho(\mathrm{X}, \cos\Theta) \\ \rho_{XS} &= \rho(\mathrm{X}, \sin\Theta) \\ \rho_{CS} &= \rho(\cos\Theta, \sin\Theta) \end{aligned} \tag{23}$$

By replacing Eq. (20) in Eq. (19), ρ_{XC}, ρ_{XS} and ρ_{CS} are defined (Soukissian, 2014).

3.2.1 ECs by Nataf-Model for Wind Direction and Speed

To derive ECs for wind direction and speed, we take the marginal PDF of both variables. Their correlation coefficient is also calculated.

3.2.2 ECs by Nataf-Model for Wave Direction, Height and Period

The procedure of ECs derivation was previously explained. According to Equations (6-8), wave height, period and direction are identical to *X1, X2* and *X3* respectively.

4. Results and Discussion

Wave data used in this research is hindcast data of a point (26.75° ′ N, 52° E) located in the SW of Assaluyeh in Persian Gulf (Fig. 1) in a 10-years period from 1993 to 2002. Total data in the record contains 14609 points from which 1461 points are referred to a single year. Scatter diagram of wave height and period is presented in Fig. 2a. Fig. 2b shows a scatter diagram of wave height and wind speed. Fig. 3a and Fig. 3b display contour plots of variables. Finally Fig. 4a and Fig. 4b show the wave and wind rose diagrams respectively.

Fig. 1: Location of study point in the Persian Gulf

Table1: Mixture of von-Mises distribution parameters of mean wind and wave directions

Parameter	Equation	Wind Direction	Wave Direction
ω_1	10	0.21	0.27
$\mu_{\theta 1}$	10	2.1	2.1
κ_1	10	0.74	1.44
ω_2	10	0.79	0.73
$\mu_{\theta 2}$	10	5.54	5.49
κ_2	10	13.11	38.71

Table 2: Distributions and their parameters for linear variables

Variable	Distribution	Parameter	Value
Wind Speed	Weibull	α	5.350
Wind Speed	Weibull	β	1.731
Significant Wave Height	Weibull	α	0.771
Significant Wave Height	Weibull	β	1.338
Peak Wave Period	lognormal	μ	1.466
Peak Wave Period	lognormal	σ	0.313

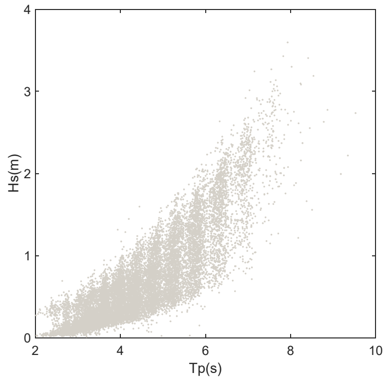

Fig. 2a

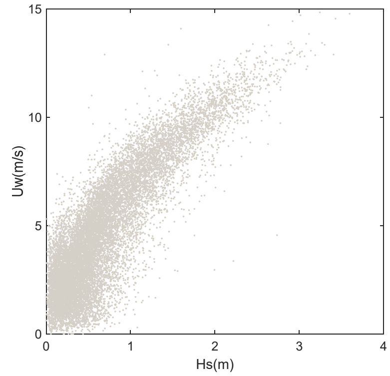

Fig. 2b

Fig. 2: scatter plot of variables. 2a shows dispersion of H_s and T_p. 2b represents U_w versus H_S.

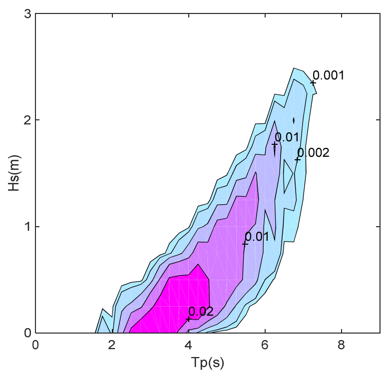

Fig. 3a

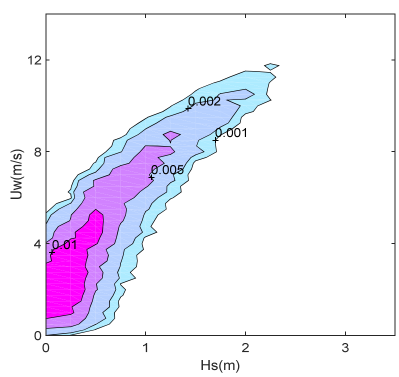

Fig. 3b

Fig. 3: Contour plots of variables. 3a shows contours of H_s versus T_p while 3b illustrates contours of U_w and H_s.

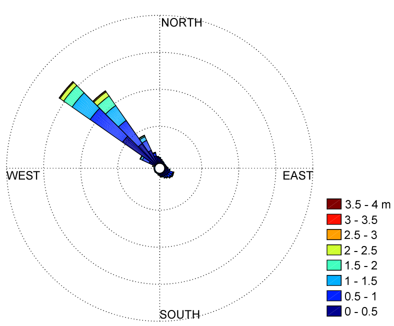

Fig. 4a

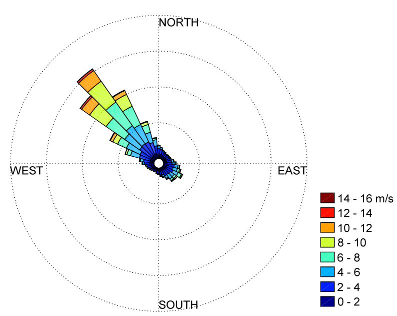

Fig. 4b

Fig. 4: a) Rose of wave height and direction. b)Rose of wind speed and direction.

The first step in the analysis is to derive the marginal PDF of all linear and circular variables. As mentioned before, a mixture of von-Mises distribution is fitted to circular variables. The fit parameters for wind and wave directions are listed in Table 1. Figures 5a and 5b show the fitted distribution versus raw data.

Linear metocean variables follow linear distributions. A Weibull distribution is fitted to wind speed and wave height. A lognormal distribution is properly fitted to wave period. Table 2 and Figures 6a-c display the result of these fitted distributions.

Table 2: Distributions and their parameters for linear variables

Variable	Distribution	Parameter	Value
Wind Speed	Weibull	α	5.350
Wind Speed	Weibull	β	1.731
Significant Wave Height	Weibull	α	0.771
Significant Wave Height	Weibull	β	1.338
Peak Wave Period	lognormal	μ	1.466
Peak Wave Period	lognormal	σ	0.313

The correlation coefficients between variables are calculated by the described method in Sec. 3.2. and displayed in Table 3.

Table 3: Correlation coefficient between different variables

Parameter	T_p	U_w	θ_{Wind}	θ_{Wave}
H_s	0.843	0.863	0.389	0.256
T_p		0.572	0.352	0.348
U_w			0.357	0.182

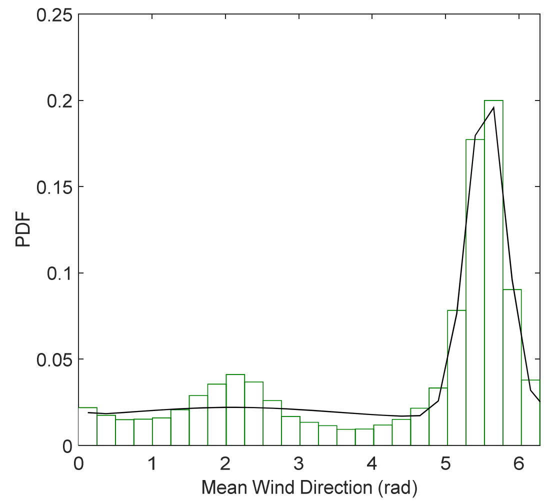

Fig. 5a

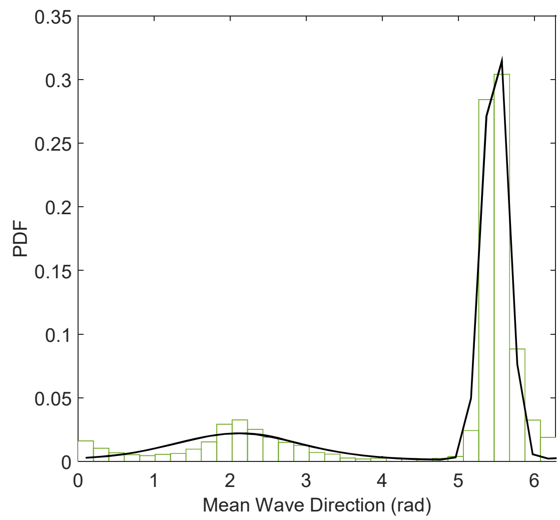

Fig. 5b

Fig. 5 : Marginal PDF of circular variables used in Nataf-based method. a) Mean wind direction, b) Mean wave direction

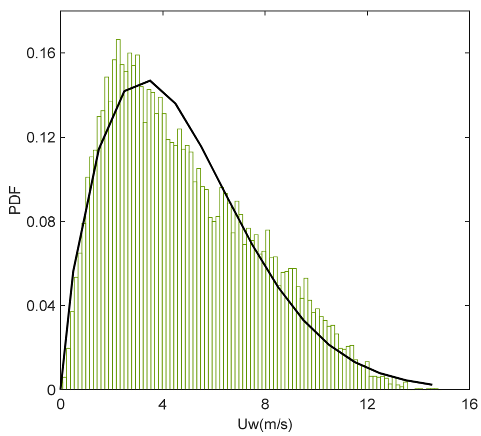

Fig. 6a

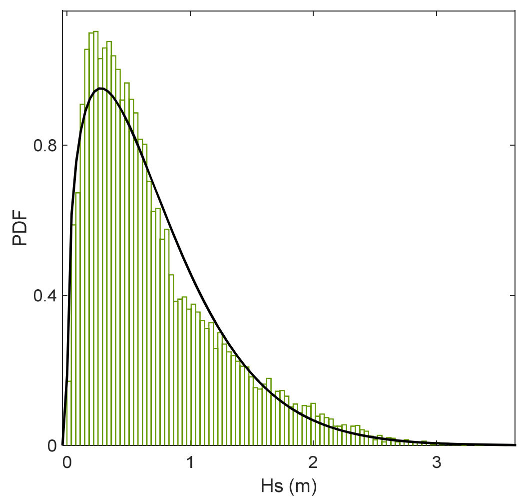

Fig. 6b

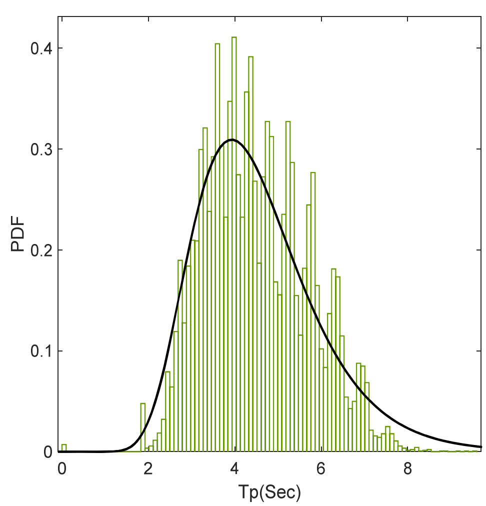

Fig. 6c

Fig. 6: Marginal PDF of linear variables used in Nataf-based method. a) Wind speed, b)Wave height, c)Wave period.

4.1 Environmental Contours by CMA

In this section three different sets of environmental contours are displayed. Using Eq. (14) and Eq. (15) the conditional distribution of H_s dependent on wave direction and U_w dependent on wind direction are presented in Table 4.

Table 4: Fourier series coefficients for conditional Weibull distribution of wind and wave

	Wind Speed Distribution		**Wave Height Distribution**	
	α	β	α	β
a_0	3.75	1.91	1.43	1.06
a_1	0.69	0.24	0.04	0.02
b_1	-0.28	-0.13	-0.5	-0.15
a_2	-0.42	-0.08	-0.54	-0.23
b_2	-1.64	-0.17	0.19	-0.05
a_3	-0.32	-0.01	-0.13	-0.04
b_3	-0.4	-0.03	0.17	0.03
a_4	-0.53	-0.11	0.15	-0.04
b_4	0.19	0.03	-0.05	0.11
a_5	-0.18	-8e-4	0.09	-0.05
b_5	0.22	3e-3	-0.28	0.02
a_6	0.14	0.06	-0.27	0.03
b_6	0.14	0.02	-0.11	0.03
a_7	0.06	0.06	-0.25	0.01
b_7	0.04	0.02	-0.05	0.04
a_8	0.06	4e-3	-0.06	-0.02
b_8	-0.03	-0.01	0.15	-0.05

The first set of ECs developed by CMA are related to direction as described by Eq. (11) and displayed if Fig. 7. A similar set of ECs are developed for wave height and direction according to Eq. (16) and illustrated in Fig. 8.

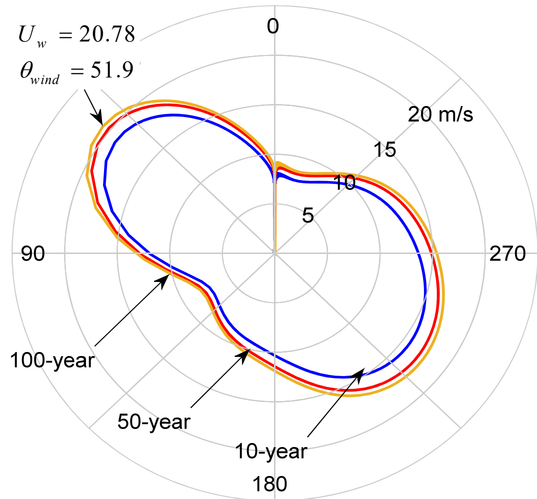

Fig. 7: Environmental contours for wind direction and speed from CMA. The radial lines show wind speed and wind direction is shown on the circle.

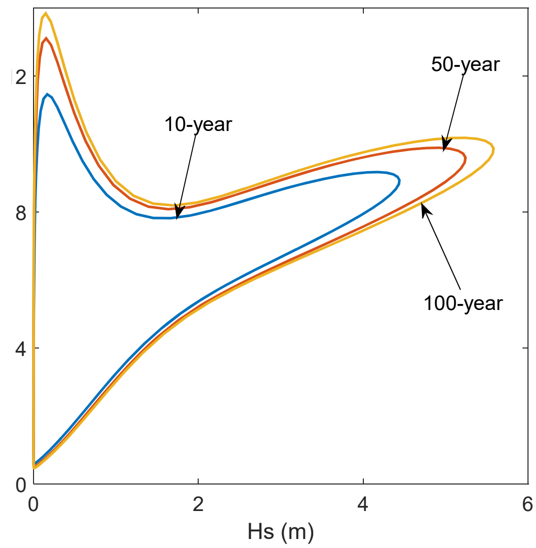

Fig. 9: Environmental contours for wave height and period from CMA in case of independent wave height.

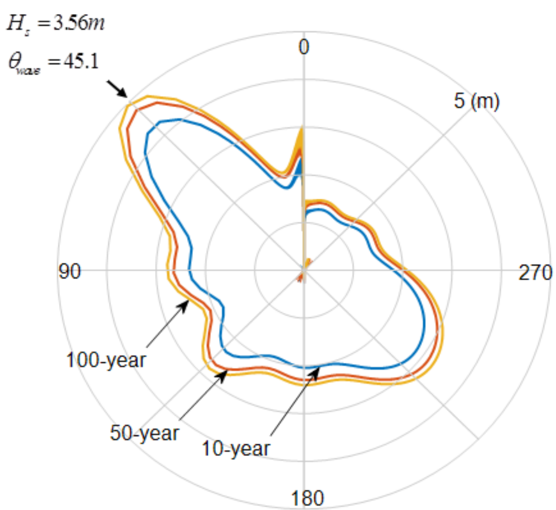

Fig. 8: Environmental contours for wave direction and height from CMA. The radial lines show wave height and wave direction is shown on the circle.

Fig. 9 shows the ECs of two linear wave variables: Hs and Tp. As shown by Eq. (20). Figure 10 is a combination of ECs presentes by Figures 8 and 9. This figure shows the surface developed using Eq. (16) and Figure 11 shows the contour plot of this surface.

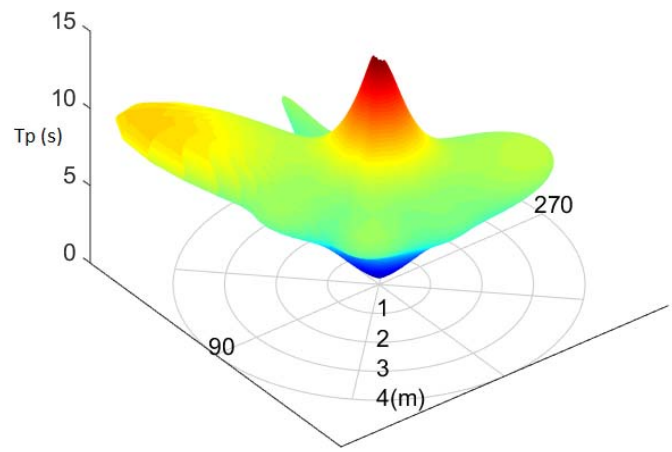

Fig. 10: Environmental contour surface for wave direction, height and period from CMA. The radial lines show wave height and the elevation is wave periond. Wave direction is shown on the circle. The surface is associated with 100-year return period.

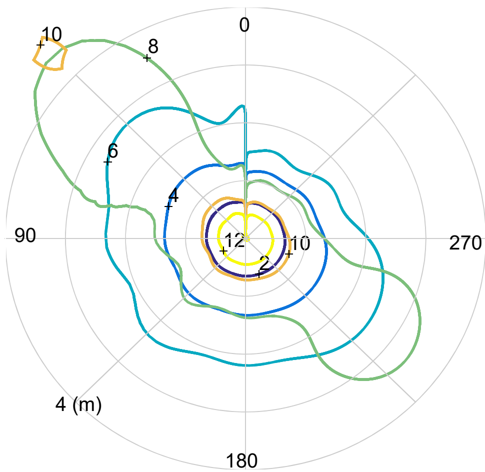

Fig. 11: Contour lines of wave period derived from surface shown in Fig. 8 . Contour labels are wave period in seconds.

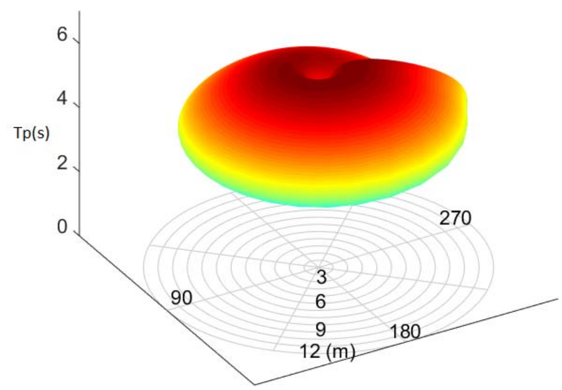

Fig. 13: Environmental contour surface for wave direction, height and period from Nataf-based method. The radial lines show wave height and the elevation is wave period. Wave direction is shown on the circle. The surface is associated with 100-year return period.

4.2 Environmental Contours by Nataf-Model

The results of applying Nataf method for wind speed and direction is shown in Fig. 12. The Environmental contour surface of wave variables is plotted in Fig. 13 and the associated contours are then displayed in Fig. 14.

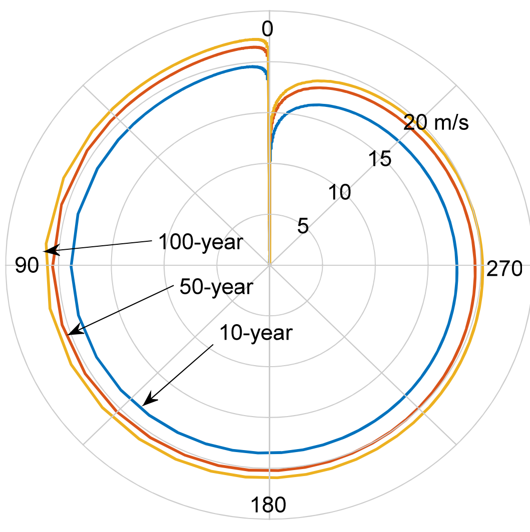

Fig. 12: ECs for wind speed and direction from Nataf-based method

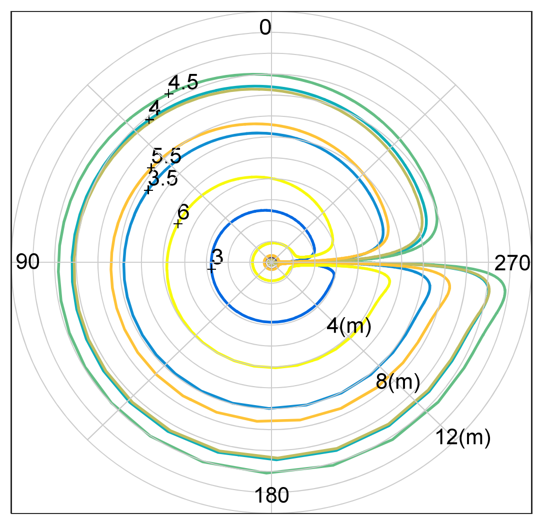

Fig. 14: Contours of wave period from surface shown in Fig. 13. Contour lines refer to wave period in seconds and radial lines are wave height.

Derivation of ECs by Nataf-based model is obviously easier than CMA. It doesn't need a simultaneous record of data and is constructed just from marginal PDF of variables and their mutual correlation coefficient. As shown in Figures 12-14, the ECs give no special suggestion for wind or wave direction. They are widely spread over the whole perimeter of circle. These contours mean that probably no wave or wind direction is dominant on other directions. This result is different from what can be concluded from the waverose and

PDF of circular variables. The waverose and windrose both show a strong trend to the NW direction, while the CMA-based contours show approximately identical probability for all directions. Figure 15 shows the difference between ECs derived by two methods.

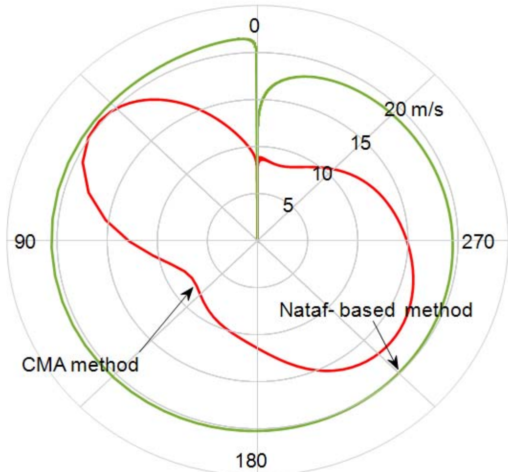

Fig. 15: ECs for wind speed from Nataf-based method and CMA. Contours are associated with return period of 100-year.

Another observed issue is the difference between the parameters obtained from two methods in Figures 10 and 13. The max range of *Hs* shown in Fig. 10 related to CMA is about 4 m and T_p varies between 2-14 s. While the order in the Nataf-based method is about 12 m for wave height and 2-7s for wave period as shown in Fig. 13. Therefore the values obtained from Nataf-based method are far from what is usually expected as return period from this range of hindcast wave height and periods.

A focus on contours of environmental surface of wave variables shown in Figures 10 and 11 reveals that the maximum values of wave height with a dominant wave direction happen is the 8 s and 10 s contours, while the maximum contour of wave period is 12 s. This shows a low value of wave height and no dominant wave direction. This can be concluded also from Fig. 7 that the maximum value of H_s happens about the period of 8 s, not about T_{pmax}.

5. Conclusion

Environmental contours method is a favorable tool for design of offshore structures, since it helps avoiding high amount of computational effort. It reduces the required number of structural analysis by the advantage of IFORM. A powerful combination of metocean variables is the one who considers the effect of wave and wind directionality. In this research a method was presented to develop ECs for linear-circular variables. The results showed that among two main approaches for derivation of ECs, the CMA gives more sensitive results to the directionality effect. The low amount of sensitivity to directionality that is shown by the Nataf model can be related to the basic assumption of this model. The correlation coefficients in the Nataf model are assumed in cases that the variables distribution is somewhat near to Normal distribution. Since the mixture of von-Mises distribution and Weibull distribution are far from Normal distribution, the resulted ECs cannot reflect the directionality effect at all.

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